RACECAR CHASSIS DESIGN (VOLUME II) – ROLL CAGE

A thesis submitted to the
faculty of the Mechanical Engineering Technology Program
of the University of Cincinnati
in the partial fulfillment of the
requirements for the degree of

Bachelor of Science

In Mechanical Engineering Technology
at the College of Engineering & Applied Science

by

RYAN CARTER

Bachelor of Science University of Cincinnati

May 2011

Faculty Advisor: Amir Salehpour
ACKNOWLEDGEMENTS
Thanks to Greg Brown for supplying the car and materials, our professor for all of the help throughout the process, and my project partner John Elrod. None of this would have been possible without you guys.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................... II
TABLE OF CONTENTS ........................................................................................................... II
LIST OF FIGURES ................................................................................................................ III
LIST OF TABLES ...................................................................................................................... V
ABSTRACT ................................................................................................................................ VI
INTRODUCTION ........................................................................................................................ 1
  BACKGROUND ...................................................................................................................... 1
  CURRENT ROLL CAGE DESIGNS ....................................................................................... 2
CUSTOMER FEEDBACK, FEATURES, AND OBJECTIVES ..................................................... 3
  SURVEY ANALYSIS .............................................................................................................. 3
  PRODUCT FEATURES AND OBJECTIVES ........................................................................... 4
RULES FOR AMERICAN IRON RACING SERIES ................................................................. 6
  NASA PRO RULES .............................................................................................................. 6
  15.6 ROLL CAGE ................................................................................................................ 6
  ADDITIONAL RULES ......................................................................................................... 12
TORSIONAL RIGIDITY AND DESIGN .............................................................................. 12
  INTRODUCTION .................................................................................................................. 12
  TESTING .............................................................................................................................. 13
  ANGLE OF TWIST ............................................................................................................. 14
  TORQUE............................................................................................................................... 14
  K VALUE: MEASURE OF TORSIONAL RIGIDITY ................................................................ 14
  APPLICATION ON CAGE ................................................................................................... 15
DESIGN AND ANALYSIS .................................................................................................... 16
  DRAWINGS .......................................................................................................................... 16
  CASE 1 ................................................................................................................................ 17
  CASE 2 ................................................................................................................................ 18
  CASE 3 ................................................................................................................................ 19
  CASE 4 ................................................................................................................................ 20
  CASE 5 ................................................................................................................................ 21
  CASE 6 ................................................................................................................................ 22
  CASE 7 ................................................................................................................................ 23
  CASE 8 ................................................................................................................................ 24
  CASE 9 ................................................................................................................................ 25
  CASE 10 ............................................................................................................................... 26
  CASE 11 ............................................................................................................................... 27
Figure 8-Basic Frame ................................................................. 13
Figure 9-Uy Deflection ............................................................ 14
Figure 10-Basic Cage 3d ............................................................ 16
Figure 11-Maximum Cage Tubes ............................................... 16
Figure 12-Case 1 Deflection ...................................................... 17
Figure 13-Case 1 Stresses(axial/bending) .................................... 17
Figure 14-Case 2 Deflection ...................................................... 18
Figure 15-Case 2 Stresses(axial/bending) .................................... 18
Figure 16-Case 3 Deflection ...................................................... 19
Figure 17-Case 3 Stresses(axial/bending) .................................... 19
Figure 18-Case 4 Deflection ...................................................... 20
Figure 19-Case 6 Stresses(axial/bending) .................................... 20
Figure 20-Case 5 Deflection ...................................................... 21
Figure 21-Case 5 Stresses(axial/bending) .................................... 21
Figure 22-Case 6 Deflection ...................................................... 22
Figure 23-Case 6 Stresses(axial/bending) .................................... 22
Figure 24-Case 7 Deflection ...................................................... 23
Figure 25-Case 7 Stresses(axial/bending) .................................... 23
Figure 26-Case 8 Deflection ...................................................... 24
Figure 27-Case 8 Stresses(axial/bending) .................................... 24
Figure 28-Case 9 Deflection ...................................................... 25
Figure 29-Case 9 Stresses(axial/bending) .................................... 25
Figure 30-Case 10 Deflection .................................................... 26
Figure 31-Case 10 Stresses(axial/bending) .................................. 26
Figure 32-Case 11 Deflection .................................................... 27
Figure 33-Case 11 Stresses(axial/bending) .................................. 27
Figure 34-Case 12 Deflection .................................................... 28
Figure 35-Case 12 Stresses(axial/bending) .................................. 28
Figure 36-Case 13 Deflection .................................................... 29
Figure 37-Case 13 Stresses(axial/bending) .................................. 29
Figure 38-Case 14 Deflection .................................................... 30
Figure 39-Case 14 Stresses(axial/bending) .................................. 30
Figure 40-Case 15 Deflection .................................................... 31
Figure 41-Case 15 Stresses(axial/bending) .................................. 31
Figure 42-Case 16 Deflection .................................................... 32
Figure 43-Case 16 Stresses(axial/bending) .................................. 32
Figure 44-Case 17 Deflection .................................................... 33
Figure 45-Case 17 Stresses(axial/bending) .................................. 33
Figure 46-Case 18 Showing X modification ............................... 34
Figure 14-Case 18 Deflection .................................................... 34
Figure 48-Case 18 Stresses(axial/bending) .................................. 35
Figure 49-Optimized Cage Model ............................................. 36
Figure 50-Tubing Bender/Notcher ............................................. 38
Figure 51-Hydraulic Shear Figure 52-Shock Tower Plates ............. 38
Figure 53-Plasma Cutting ......................................................... 39
Figure 54-Mig welding of plates ................................................. 39
Figure 55- John using abrasive cutoff saw ................................................................. 40
Figure 56- Abs Rapid Prototype ................................................................................... 41
Figure 57- Install of rear plates .................................................................................... 41
Figure 58- Rear main hoop and diagonal ...................................................................... 42
Figure 59- Front down tubes and lower window bar ................................................... 42
Figure 60- Rear down tubes .......................................................................................... 43
Figure 61- Passenger side door bar ............................................................................. 43
Figure 62- Petty Bar ....................................................................................................... 44
Figure 63- Upper window bar and rear diagonal .......................................................... 44
Figure 64- Driver’s side door bar .................................................................................. 45
Figure 65- Front shock tubes ....................................................................................... 45
Figure 66: Testing - Gap under Rear Passenger Side Jack Stand .................................. 46
Figure 67: Testing - Applying Load of 200lbs ............................................................... 47
Figure 68: Testing – Measurement of Deflection ......................................................... 47
Figure 70: Testing - Loading Conditions of Computer Model ...................................... 48
Figure 70: Driver Clearance Seated Figure 71- Seat to bar clearance ......................... 49
Figure 72- Weld Test Rig Figure 73- Tested weld sample .............................................. 50

LIST OF TABLES
Table 1- Survey Results .................................................................................................. 3
Table 2- Engineering Characteristics ............................................................................. 5
Table 3- Base Cage Data ............................................................................................... 17
Table 4- Final Cage Data .............................................................................................. 34
Table 5- Door Bar Weight ............................................................................................. 35
Table 6- Torsional Rigidity .......................................................................................... 37
Table 7- Testing ............................................................................................................. 47
Table 8- Forecasted Budget .......................................................................................... 51
Table 9- Actual Budget ................................................................................................. 51
Table 10- Important Due Dates .................................................................................... 52
ABSTRACT

Predictable handling of a racecar may be achieved by increasing chassis stiffness so that chassis stiffness is due almost entirely to the suspension input. In this work, the effects of overall chassis flexibility due to torsional twist response will be determined using a finite element analysis (FEA) of a 2005 Ford Mustang chassis. The FEA of the chassis/suspension is built from an assembly of beam and shell elements using geometry measured from a typical 2005 Ford Mustang Chassis. Care has been taken to model internal constraints between degrees-of-freedom (DOF) at suspension to chassis connections, by pinning the rearward points immovable at the nodes.

To validate the model, deflection was measured on the final product, which was then translated to rigidity and the result was a chassis that agrees closely with the FEA models. To study the effects of roll cage tube additions, various models were developed to obtain data that accurately defines how each member acts in a percentage of rigidity gain to the total model. Results from the finite element analysis indicate that the overall rigidity of the chassis with the roll cage, increased by 813 % over the baseline when compared to a baseline chassis stiffness of 14,157 ft-lb/deg. As the chassis stiffness is increased weight is added, by defining the best additions, rigidity can be increased greatly while adding very minimum amounts of wasted weight. With the total increase of 813% rigidity over the baseline only the addition of 93 pounds can be seen.
INTRODUCTION

BACKGROUND

The focus of this design project is to correct a major safety and structural issue with racing a production vehicle in a professional racing class. A modern vehicle has many safety devices to protect drivers in a highway crash, at moderately slow speeds in comparison to racing speeds. Modern vehicles like the 2005 Ford Mustang as shown in Figure 1 (1) have little to protect the drivers beside the factory sheet metal. The door ways offer little protection for the driver. Individuals typically take factory built cars and modify them to meet the rules of the race class in which they participate. Roll cages of different shapes and sizes are created to protect the driver in the event of a side collision or a roll over instance. The added rigidity is also a huge benefit in a race car providing less body roll in the car resulting in more precise handling characteristics.

Figure 1-2005 Ford Mustang Gt-Interior View
CURRENT ROLL CAGE DESIGNS

There are several existing race car roll cage designs: bolt-in style, pre-bent weld in style, and the custom fabrication route.

The design that allows for the most safety and structural support is the weld-in cage as shown in figure 2 (2). In this design the tubes of the cage are welded to plates at various points in the floor pan of a uni-body vehicle. This design can be seen as required in most racing sanctions. It provides a structurally solid cage and will hold up the best in the event of a collision. These cages are offered for a large variety of vehicles and can be installed by any reputable welding shop. The quality of the weld has a large effect on reliability. If a weld fails it will have a negative impact on the rest of the cage.

The second and worst design is a bolt in style cage. Bolt in style cages are a completely weld free installation for the consumer. Typically a company like Autopower, as shown in figure 3 (4), pre fabricated the cage with bends and welds. It’s then shipped in pieces to the customer and he/she will then have to do nothing more than bolt the parts into their vehicle. These cages are typically used in autox type events where speeds are not very high. Although these bolt in cages are easy to install they can pose serious safety issues if the small area of securing bolts fails or if the bolts pull through the thin sheet metal of the car body.

The third option for a consumer is to have a cage custom built. This is the most expensive route but can offer the best results. These options can be seen in Appendix A. This option is mainly a weld in style. The customer would choose the particular racing class they wish to enter and have a shop fabricate the cage to meet these rules. Companies can get creative in the layout of the cage and can contour the tubes to closely follow the contours of the inside of the car. This provides a tight fit and increases the resistance to crushing in a roll over event.
CUSTOMER FEEDBACK, FEATURES, AND OBJECTIVES

SURVEY ANALYSIS

Ten surveys were distributed among average race car cage buyers who purchased a cage in the past five years. The questions asked for customer importance and their current satisfaction with the factors in the table below. They were collected and the results were analyzed as seen in Appendix B. From the data gathered, the most important factor regarding roll cages was Compliance with Standards while the least important was Ease of Installation. These were calculated in the QFD as seen in Appendix C. The highlighted items are the four most important factors and must be considered while designing the product. The relative weight of each of the factors surveyed can be viewed in Table 1.

Table 1- Survey Results

<table>
<thead>
<tr>
<th>Factor</th>
<th>Avg Customer Importance:</th>
<th>Designer's Multiplier:</th>
<th>Relative Weight:</th>
<th>Modified Importance:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>4.8</td>
<td>1.1</td>
<td>19%</td>
<td>8.3</td>
</tr>
<tr>
<td>Ease of Entry/Exit</td>
<td>4.0</td>
<td>1.1</td>
<td>19%</td>
<td>8.2</td>
</tr>
<tr>
<td>Safety</td>
<td>4.9</td>
<td>1.1</td>
<td>17%</td>
<td>7.1</td>
</tr>
<tr>
<td>Compliance With Standards</td>
<td>5.0</td>
<td>1.1</td>
<td>13%</td>
<td>5.5</td>
</tr>
<tr>
<td>Maneuverability</td>
<td>3.1</td>
<td>1.1</td>
<td>9%</td>
<td>3.7</td>
</tr>
<tr>
<td>Weight</td>
<td>2.5</td>
<td>1.1</td>
<td>6%</td>
<td>2.8</td>
</tr>
<tr>
<td>Affordability</td>
<td>2.3</td>
<td>1.0</td>
<td>5%</td>
<td>2.3</td>
</tr>
<tr>
<td>Appearance</td>
<td>2.1</td>
<td>1.0</td>
<td>5%</td>
<td>2.2</td>
</tr>
<tr>
<td>Ease of Installation</td>
<td>1.3</td>
<td>1.0</td>
<td>3%</td>
<td>1.2</td>
</tr>
<tr>
<td>Ease of Manufacturing</td>
<td>1.4</td>
<td>1.0</td>
<td>3%</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>100%</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The justification for adding design multipliers to Durability, Ease of Entry/Exit, Safety, Compliance with Standards, Maneuverability, and Weight that the designer felt these were the most important factors in developing a new roll cage.

- Durability – the roll cage must survive in the harsh environment of racing
- Ease of Entry/Exit – driver must be able to enter and leave the vehicle easily
- Safety – cage must be safe for the driver and protect the driver in the event of a crash
- Compliance with Standards – cage must pass strict rules provided by the American Iron racing sanction
- Maneuverability – driver must be able to comfortably move around inside to cage for driver comfort in multiple lap races
- Weight – Additional weight will reduce the power to weight ratio of the making it slower
**PRODUCT FEATURES AND OBJECTIVES**

The following is a list of product objectives and how they will be obtained or measured to ensure that the goal of the project was met. The product objectives will focus on a race car roll cage in a 2005 Ford Mustang. The car that was selected is intended for racing in the American Iron Extreme race class.

**Durability (19%)**
1) Chosen materials able to withstand repeated suspension loads due to fatigue on a smooth race track.
2) A recommended top coat to prevent rust and corrosion
3) Tube bending will be addressed and the proper way to bend seam welded tubing.
4) ASME welding standards will be applied to the installation of the roll cage

**Ease of entry/exit (19%)**
1) Car will be possible to get in and out of with the cage applying human standards for a normal to larger than normal human size

**Safety (17%)**
1) Use Cosmos to simulate loading the roll cage in race conditions.
2) Standard roll cage foam wrap will be used to protect driver in case of contact with roll cage tubes to prevent possible injuries

**Compliance with race standards (13%)**
1) Must conform to American Iron Extreme class rules and regulation

**Maneuverability (9%)**
1) Driver is able to easily move around inside the car
   a) Legs able to move 15 degrees each way while seated
   b) Arms able to move 45 degrees each way while seated
2) Able to accommodate a human factors 75\(^{th}\) percentile male +/- 20%

**Weight (6%)**
1) Cage will not add more than 250lbs to the car

**Affordability (5%)**
1) Cage will cost less than $2500.00 to purchase

**Appearance (5%)**
1) Cage will contour the inside body of the car

**Ease of manufacturing (3%)**
1) Cage can be made with standard fabrication tools
   a) Machining for tube notches
   b) Milling for tube lengths
   c) Hydraulic Tube bending for precise angles and bends
**Ease of installation (3%)**

1) Cage can be installed with multiple welding processes  
   a) Mig Welding  
   b) Tig Welding  
2) No unusual tools needed for installation  
   a) Tubes will be pre bent  
   b) Tubes will be pre notched  
   c) Tubes will require no cutting

**Engineering Characteristics**

The engineering characteristics determined for the project describe how the roll cage may achieve its required performance in general terms. These values are calculated in **Appendix C** using the QFD table. These product importance factors represent the Voice of the Designer and are shown in Table 2.

Table 2—Engineering Characteristics

<table>
<thead>
<tr>
<th>Cage Tube Size</th>
<th>Weld Integrity</th>
<th>Weight in Lbs</th>
<th>Material</th>
<th>Paint/Epoxy coat quality</th>
<th>Door Bar Height</th>
<th>Manufacturability</th>
<th>NASA Standards</th>
<th>Leg Movement in Degrees</th>
<th>Arm Movement in Degrees</th>
<th>Driver Size allowable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs. importance 6.08 4.57 1.75 6.02 2.37 2.72 5.18 0.88 3.51 5.18 5.18 4.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel. importance 0.13 0.10 0.04 0.13 0.05 0.06 0.11 0.02 0.07 0.11 0.11 0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The six most important factors are as follows:

- Cage Tube Size: Tube size has a direct relation to safety, weight, durability, and compliance to race standards.
- Material: Has a direct relation to safety, affordability, ease of manufacturing, weight, durability, and compliance to race standards.
- Door Bar Height: Has a direct relation to safety, ease of entry/exit, compliance with race standards, and maneuverability.
- Leg Movement in Degrees: Has a direct relation to safety, ease of entry/exit, compliance with race standards, and maneuverability.
- Arm Movement in Degrees: Has a direct relation to safety, ease of entry/exit, compliance with race standards, and maneuverability.
- Weld Integrity: Has a direct relation to safety, durability and compliance with race standards.
Roll Cage Design

RULES FOR AMERICAN IRON RACING SERIES

NASA PRO RULES

When designing a race car component it is important to check with the given class for the car to know exactly what is allowed and what is not allowed. This saves a lot of leg work when getting the car certified by a tech and not having to redo work and cut parts up that do not meet the specifications of the series. For the American Iron Extreme class the main rules used are from the National Auto Sport Association (Nasa) 2001.4 CCR rule book. These rules are available to anyone online and in their original form, are as follows: (3)

15.6 ROLL CAGE
(See figure 5 at end of section)

15.6.1 Purpose
The basic purpose of the roll cage is to protect the occupant in case of a rollover or a collision. It should be able to withstand the weight of the car landing on the roof. These rules apply to all classes, unless otherwise superseded by the class rules. Vehicles homologated by, or built to the specifications of, FIA Group N, FIA Group C, JAF, SCCA, IMSA, and Grand AM must conform to these rules, or may conform to their respective current class rules for roll cage requirements for guest groups and special events. Any vehicle that does not conform to the NASA cage rules, yet conforms to cage rules of another recognized sanctioning body (SCCA, IMSA, Grand Am, etc.), that wishes compete in NASA events on a regular basis, should be ordered to make modifications within a time frame specified by the Race Director and approved by the Regional Director. Note- It is the responsibility of the driver to furnish a copy of any non-NASA rules applicable to his/her vehicle.

15.6.2 Intent
Chassis stiffening is a side benefit of a good roll cage system, but it is not the intent of these rules. Parts of the cage deemed by the Chief Scrutineer, to serve no practical purpose other than chassis stiffening may be considered in violation of the intent of these rules (Note: Some class rules allow for chassis stiffening.). The Chief Scrutineer may order the removal of said parts, or require that the vehicle owner redesign, reconstruct, and re-certify the roll cage if warranted. The removal or redesign of the cage, whole or in part, to comply with these rules, does not imply that penalties will not be issued for violating the intent of these rules.

15.6.3 Installation
The cage may be removable or may be permanently welded, or any combination thereof, providing that all aspects of the cage meet these rules.
15.6.4 Padding
All roll cage surfaces that may come in contact with the driver should be padded with high-density padding such as Ethafoam or Ensolite. It is recommended that padding meeting SFI specification 45.1 be used.

15.6.5 Bends
None of the tubing may show any signs of crimping or wall failure. All bends must be Mandrel type. The center radius of the bends may not be less than three (3) times the outside diameter of the roll cage tubing.

15.6.6 Main Hoop
The main roll cage hoop should be as wide as the full width of the interior and must be as close to the roof as possible without violating CCR section #15.6.20 Inspection. One continuous length of roll bar tubing shall be used as the main hoop. The main hoop must consist of no more than four (4) bends maximum, totaling one hundred eighty (180) degrees +/- ten (10) degrees.

15.6.7 Diagonal Brace
One (1) diagonal brace shall be used in the same plane as the main hoop. The diagonal should be one continuous path; meaning that it must conform to Diagrams 15.6.7a or 15.6.7b. Note- If the installation method from Diagram 15.6.7b (all seen in figure 4) is used, the builder should pay close attention to alignment. One end of the diagonal brace shall attach to 60 the corner, or horizontal part, of the main hoop above the driver’s head, within twelve (12) inches of the driver’s-side corner. The other end of the diagonal brace shall attach to the mounting plate (or to the main hoop as close to the mounting plate as practically possible) diagonally opposed to the driver’s head (passenger floor).

15.6.8 Forward Hoops (Option 1)
The forward hoops shall extend from the main hoop (in a forward direction) to the floor by following the roof and the “A” pillar of the car. There shall be a bar connecting the two (2) forward hoops at the top of the windshield mounted as close to the roof as possible without violating CCR Section #15.6.20 Inspection. The forward hoops shall incorporate no more than four bends each.

15.6.11 Rear Braces
The main hoop must have two (2) braces extending to the rear. The braces shall be attached as near as possible to the top of the main hoop, and no more than six (6) inches below the top. The braces must not contain any bends*. There must be at least 30 degrees between the plane of the main hoop and the plane of the rear braces. The main hoop rear braces shall be installed to form no more than a one hundred five (105) degree angle or no less than a seventy-five (75) degree angle with the main hoop when viewed from the top. The main hoop braces may be mounted at the rear shock mounts or suspension pickup points (providing that the braces remain in compliance with all other sections of the CCR). They may go through any rear bulkhead(s) provided the bulkhead(s) is sealed around the cage braces. *There may be certain exceptions allowed for cars that cannot possible meet this “no bend” requirement. One exception is
listed [Ref: (15.6.11.A)]. Other exceptions may be made (not guaranteed) if all of the required bars meet the specifications for a vehicle in the next heavier weight classification and the alternative design is submitted to the NASA National Office for special allowance.

**15.6.11.A Rear Braces - Exceptions**
On cars where the rear window/bulkhead prohibits the installation of rear braces (Porsche 914, Pontiac Fiero, etc.) the main hoop must be attached to the body by plates welded to the cage and bolted to the stock shoulder harness mounting location. There must also be a diagonal bar connecting the top of the main hoop to the lower front passenger side mounting point ("Petty bar"). Some cars built for racing in other recognized sanctioning bodies may be granted a waiver of this rule, however they must show proof of compliance with the current published rules for their class.

**15.6.12 Door Bars / Side Impact Protection**
At least one (1) door bar on driver side and one (1) on the passenger side must be used. At least two (2) door bars on the driver side and one (1) door bar on the passenger side must be installed in all vehicles that obtain a new logbook after January 1st, 2007. All vehicles, regardless of date of manufacture or date of logbook issuance will be required to have at least two (2) door bars on the driver side and one (1) door bar on the passenger side starting January 1st, 2011. Unless superseded by class rules, modifications to any non-chassis structure (such as door panels, inner door sheet metal, windows, door internals, etc.) may be made to accommodate any allowed door bar configuration. However, removal of material and / or modifications is limited to 1) the least amount to accommodate the door bar(s), and 2) can serve no other function. Holes in the door jam (B-pillar) may be permitted to accommodate door bars; however the structure should not be “notched” so as to weaken it.

**15.6.13 Mounting Points**
The roll cage shall be mounted to the floor area of the car in six, seven, or eight points. The cage shall not go through the firewall. The seventh and eighth points must attach to the firewall or front fender wells. All cage attachment points must be mounted to plates or a mounting box (plinth). Each required cage bar shall terminate on a plate with a 360 degree weld to the mounting plate, except as specified in Section 15.6.14.B. There shall be only one (1) mounting “point” per plate. This point is defined as where the “required tube” mounts. All additional tubes mounted to that plate must be mounted as close to the required tube as possible [Ref: (15.6.14.B)]. It is recommended that plinth boxes use a bottom support plate in cases where the edges of the box may punch through the sheet metal.

**15.6.14 Mounting Plates**
Each mounting plate shall be no greater than one hundred (100) square inches and no greater than twelve (12) inches or less than two (2) inches on a side. Welded mounting plates shall be at least 0.080-inch thick. Plates may extend onto vertical sections of the structure. Any mounting plate may be multi-angled, but shall not exceed one hundred
(100) square inches total including vertical sections. Each mounting plate should have an area of not less than nine (9) square inches.

15.6.14.B Tube / Mounting Plate Specifications
Any number of tubes may attach to a plate so long as they are touching each other at the plate. There may be a small gap between tubes to allow welding 360 degrees around each tube. If there is no gap between the tubes, they must be welded around the base as much as possible to form a single figure-eight weld, AND the tubes must be welded to each other two (2) inches up from the base plate.

15.6.15 Welds
All welding must be of the highest quality with full penetration and shall conform to the American Welding Society D1.1, 1994 Edition, Structural Welding Code, Chapter 10, Tubular Structures and Standards for the material used. Arc welding should be used whenever possible. It is strongly recommended that the welder inspect all welds using Magnaflux™, x-ray, or other effective methods. All tubes must be welded 360-degrees around the circumference of the tube.

15.6.16 Tube Structure Design / Body
Tubes may touch the body in any place (not to violate CCR section #15.6.20 Inspection), but shall not be attached anywhere except as permitted by CCR Section #15.6.11.A Rear Braces - Exceptions. No deformation of the interior body panels is permitted, except that the horizontal part of the sheet metal (next to the driver’s and/or passenger’s head) between the top of the “B” pillar and the top of the “A” pillar, may be pushed in to accommodate the roll cage. The intent of this allowed deformation is strictly to allow for more headroom for the driver and/or passenger.

15.6.17 Additional Reinforcement
Any number of additional reinforcing bars are permitted within the structure of the cage provided that they are installed strictly for safety and do not violate CCR Section #15.6.2 Intent. This rule does not permit reinforcements in classes with spec cages. All required bars must be made of the same material and meet with at least the minimum specifications for size and thickness.

15.6.18 Roll Cage Tubing Sizes
For the purposes of determining roll bar tubing sizes, vehicle weight is as raced, but without fuel and driver. Note: There is an allowance of minus 0.010 inches on all tubing thicknesses. Minimum tubing size for the roll cage is:
2501 - 3000 lbs.
1.500” x 0.120” Seamless Alloy (4130), Seamless mild steel (CDS Mechanical) or DOM
1.750” x 0.095” Seamless Alloy (4130), Seamless mild steel (CDS Mechanical) or DOM
1.750” x 0.120” ERW* (No issuance of log books for cars with ERW cages 04/30/03)

*Note- Specifications listed for reference for inspection of grandfathered vehicles.

15.6.20 Inspection
A 3/16-inch inspection hole must be drilled in each of the required bars in a non-critical area for the purpose of determining wall thickness. All welds, except those mounted to plates on the floor, must be accessible for inspection (360 degrees).

15.6.21 Head Support-Rear
This section applies to seats without an integral headrest. A head restraint must be used to help prevent whiplash. The head restraint should have a minimum area of thirtysix (36) square inches and be padded with a non-resilient material such as Ethafoam or Ensolite with a minimum thickness of one (1) inch. It is recommended that padding meeting SFI specification 45.2 be used.

15.6.22 Seat Back Support
A seatback support must be made to hold the seat from going back in the event of a crash. A plate should be used to distribute the load. No bolts, corners, or sharp objects should be placed in such a manner that could lead to a possible puncture of the driver in a high impact crash. Proper design and installation is crucial to safety and it is recommended that the driver employ the services of a professional race car builder for this, as well as all other vehicle safety items. An exception may be made for those seats homologated to, and mounted in accordance with, FIA 8855-1999 or 8862-2009 standards. Those seats that qualify for the aforementioned exception must conform to the entire FIA 8855-1999 or 8862-2009 set of regulations, as applicable. This includes a mandatory seat replacement, or use of a seat back brace, for any seat more than five (5) years old (8899-1999) or more than ten (10) years old (8862-2009). Please reference the FIA regulations.
Figure 4-Main Hoop Types

Figure 5-Minimum Cage per Rules
ADDITIONAL RULES

In addition to the Nasa rules America Iron has its own additional rules which in turn supercede certain Nasa rules which allows for more open design in certain aspects. (3)

5.12 Roll Cage
The roll cage must comply with the roll cage standards of the NASA CCR. However, a roll cage may also provide additional chassis stiffening through the use of alternative mounting points. As such, the roll cage mounting points are unrestricted. The roll cage may also pass through the firewall and attach to the front shock towers. Additional bracing may also be welded to the front of the shock tower and extend forward and down to the forward most part of the original frame rail. This bracing may not pass through the shock tower and must not form the upper mounting point for an aftermarket SLA system as the SLA must still remain within the original shock tower. The mounting plate material must conform to the specification in the NASA CCR but the plate size and design is unrestricted. Interior body panels and sheet metal may be bent or altered to accommodate the roll bar design.

5.13 Door Safety Bars
All vehicles must meet the door safety bar requirements found in the NASA CCR at Section 15.6.12 but gutting of the door beyond what is solely necessary to fit cage bars is allowed.

TORSIONAL RIGIDITY AND DESIGN

INTRODUCTION

Torsional rigidity is a very important factor when designing a roll cage. It allows one to quantify how well different variations compare to one another, and gives an increase in overall rigidity that can be noticed by the driver during racing. Increased torsional stiffness of a race car chassis improves vehicle handling by allowing the suspension components to control a larger percentage of a vehicle's kinematics, thus predictable handling can best be achieved if the chassis is stiff enough so that the only body roll comes from the stiffness acting between the sprung mass and the unsprung mass. This would become due almost entirely to the suspension input to the body. In addition, a race car chassis must have adequate torsional stiffness so that chassis structural dynamic modes do not adversely couple with the suspension dynamic modes. This input can be seen in figure 6. The input from the front shocks is then transferred to the body of the car in the shock towers shown in figure 7.
Testing

Testing a design for torsional rigidity requires a few steps to be taken in order to receive accurate results. First of which is creating a base design in which the roll cage will be tested on. This is done by accurately modeling the most important structural members of the existing car design as seen in figure 8 and volume one of the project. Once the model has been created the loading conditions for use in Cosmos analysis are as follows: Rear shock mounts are fixed (immovable) and a 750 lbf load is applied to each shock tower face in opposite directions (normal to horizontal plane). This is done in order to simulate the loading of the suspension into the body of the car. Once a particular design is ran the result will be a deflection in the $U_y$ direction. This is shown in figure 9.
**ANGLE OF TWIST**

Angle of twist is the amount that assembly will twist in relation to the horizontal plane. This value was measured by deflection of front shock tower and normalized by using the average of the $U_y$ for driver’s side shock tower to passenger side shock tower. $L$ is the effective length from the center of each shock tower to the other divided by two. The resulting angle of twist is found in radians but is then converted for the $K$ value for ease of display.

$$\Phi = \frac{U_y}{L}$$

**TORQUE**

Torque is needed in order to solve for a value of torsional rigidity and is found by multiplying the effective length between shock towers by the force in one direction. The resulting value is in foot pounds.

$$T = F \cdot d$$

**K VALUE: MEASURE OF TORSIONAL RIGIDITY**

Torsional Rigidity as a measured value is designated as the relationship of applied torque
versus angular twist (φ). Torsional rigidity is designated by the symbol (K_c). The units thus are in ft-lb/degree once the angle of twist is converted from radians.

\[ K_c = \frac{Torque}{\Phi} \]

**APPLICATION ON CAGE**

In order to test the various ideas of roll cages available on the market, various designs were chosen that would build upon one another to both test their affect on the overall weight of the cage and the percentage of torsional rigidity gained by the member’s addition. This is important in making the decision of which members are really helping the chassis for stiffness, and which members are moreless dead weights. These are done by a case by case approach and graphed using a dual y-axis style graph to show weight and torsional rigidity together.
DESIGN AND ANALYSIS

**DRAWINGS**

Base cage following the rule book includes all the required bars

![Figure 10-Basic Cage 3d](image1)

By case 12 all the members tested during the study are shown in blue for ease of comparison.

![Figure 11-Maximum Cage Tubes](image2)
CASE 1

Case 1 entails using the rules and frame design to create a bare minimum cage that just meets the required rules and nothing more. This would be your typical off the shelf “spec” cage. However placement of tubes is chosen to tie into what is deemed the most structural locations on the car for adding a cage. The data derived is as follows:

Table 3: Base Cage Data

<table>
<thead>
<tr>
<th>Modification Upgrade</th>
<th>Uy: Driver Side (in)</th>
<th>Uy: Passenger Side (in)</th>
<th>Uy: Average (in)</th>
<th>Rigidity Increase (%)</th>
<th>φ (deg)</th>
<th>Kc (ft-lbs/deg)</th>
<th>Cage Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>base model</td>
<td>1.166</td>
<td>1.126</td>
<td>1.146</td>
<td>2.638</td>
<td>14,156.71</td>
<td>104.18</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12-Case 1 Deflection

Figure 13-Case 1 Stresses(axial/bending)
CASE 2

In case 2 the lower x door bar brace was tried. This showed a 1.5% increase in rigidity while adding 13.89 pounds to the total cage.

Figure 14-Case 2 Deflection

Figure 15-Case 2 Stresses(axial/bending)
CASE 3

Case 3 includes the addition of the lower window bar which ties together the window area. This showed a 8.04 pound increase as well as a 25% increase in rigidity.

Figure 16-Case 3 Deflection

Figure 17-Case 3 Stresses(axial/bending)
**CASE 4**

Case 4 is the addition of a short tube on each side at extending from the top door bar to the backside of the front shock towers to tie all suspension loading to the cage. Also a tube ties the front of the shock tower to the front of the frame. This in turn netted a 58.1% gain in rigidity while adding 5.42 pounds to the cage.

Figure 18-Case 4 Deflection

Figure 19-Case 6 Stresses(axial/bending)
**CASE 5**

Case 5 takes Case 4 and ties into the lower window bar thus spreading stress seen in window bar area more uniformly. This gain was slightly less at only 22.6% while adding 8.93 pounds.

![Figure 20-Case 5 Deflection](image)

![Figure 21-Case 5 Stresses(axial/bending)](image)
**CASE 6**

Case 6 adds the addition of a tube from the front bottom right and left door bar to the top corners of the upper window bar only on the driver’s side. This netted an even smaller gain of 0.6% with a 5 pound weight gain.

![Figure 22-Case 6 Deflection](image1)

**Figure 22-Case 6 Deflection**

![Figure 23-Case 6 Stresses(axial/bending)](image2)

**Figure 23-Case 6 Stresses(axial/bending)**
**CASE 7**

Case 7 adds the addition of a tube from the front bottom right and left door bar to the top corners of the upper window bar only on the driver’s side. This netted an even smaller gain of 1.2% with a 10 pound weight gain.

![Figure 24-Case 7 Deflection](image_url)

![Figure 25-Case 7 Stresses(axial/bending)](image_url)
**CASE 8**

Case 8 involves adding a diagonal in the reverse direction of the required diagonal bar in between the rear downward tubes. This showed a very substantial gain of 159% for only an additional 8.23 pounds of weight.

![Case 8 Model](image1.png)

**Figure 26-Case 8 Deflection**

![Case 8 Stresses](image2.png)

**Figure 27-Case 8 Stresses(axial/bending)**
Case 9 builds on case 8 by applying an addition member to form an “X”. The gain was 5.4% for an additional 8.05 pounds of weight to the entire cage.

Figure 28-Case 9 Deflection

Figure 29-Case 9 Stresses(axial/bending)
**Case 10**

Case 10 adds an additional cross bar opposing the required bar in the main hoop. The resulting rigidity is a 7.9% gain while adding an additional 8.4 pounds of weight to the entire cage.

---

**Figure 30 - Case 10 Deflection**

**Figure 31 - Case 10 Stresses (axial/bending)**
CASE 11

Adds addition supports to the upper halo. This results in 26.6% gain while adding roughly 17.5 pounds to the roll cage. This while gaining rigidity lowers the axial bending stresses at points that the bars join.

Figure 32-Case 11 Deflection

Figure 33-Case 11 Stresses(axial/bending)
**Case 12**

Case 12 adds what is known as a petty bar. This joins the midpoint of the halo “X” to the front lower passenger side corner, while joining the midpoint of the petty bar to the rear bottom passenger side corner. This adds 20.3% rigidity while adding 14.35 pounds of weight to the cage itself. This also shows a reduction of axial bending at the lower window bar joints.

![Figure 34 - Case 12 Deflection](image)

**Figure 34 - Case 12 Deflection**

![Figure 35 - Case 12 Stresses (axial/bending)](image)

**Figure 35 - Case 12 Stresses (axial/bending)**
**CASE 13**

Case 13 adds a diagonal bar in the windshield thus joining the upper and lower windshield bars. This gains 11.3% rigidity while adding 8.1 pounds.

---

**Figure 36** - Case 13 Deflection

**Figure 37** - Case 13 Stresses (axial/bending)
CASE 14

Case 14 adds the addition of a strut tower bar which ties the two front shocks together. This showed a gain of 3.2% for 5.9 pounds.

Figure 38-Case 14 Deflection

Figure 39-Case 14 Stresses(axial/bending)
Case 15

Case 15 adds the additions of short diagonal bars from the lower window bar to the shock towers. These bars showed a gain of 10.5% and added 4.6 pounds of weight.
CASE 16

Case 16 removes case 15 for longer bars that meet at the midpoint of the lower window bar. This shows a higher gain of 14.3% while adding 9.23 pounds.

Figure 42-Case 16 Deflection

Figure 43-Case 16 Stresses(axial/bending)
**CASE 17**

Case 17 is the combo of both case 15 and 16. 13.83 pounds are added while adding 25.2% over case 14.

---

**Figure 44-Case 17 Deflection**

**Figure 45-Case 17 Stresses(axial/bending)**
CASE 18

Case 18 adds an X on the bottom of the chassis. This addition is a 50 pound addition while only adding 13.9% to the rigidity.

Table 4 Final cage data

<table>
<thead>
<tr>
<th>Case #</th>
<th>$U_y$ (pass)</th>
<th>$U_y$ (drivers)</th>
<th>Average $U_y$</th>
<th>$\phi$ (rad)</th>
<th>$\phi$ (deg)</th>
<th>$K_c$ (ft-lb/deg)</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Cage with X on bottom</td>
<td>0.070</td>
<td>0.124</td>
<td>0.097</td>
<td>1081.4%</td>
<td>0.223</td>
<td>167,253.56</td>
<td>303.70</td>
</tr>
</tbody>
</table>

Figure 46-Case 18 Showing X modification

Figure 47-Case 18 Deflection
In order to obtain the best model, the highest gaining bars were chosen for a final model also including one lower gaining part (driver’s side upright) for roll over protection. Nascar door bars were opted for on the driver’s side, which were just as strong as the X design though considerably heavier.

**Table 5-Door Bar Weight**

<table>
<thead>
<tr>
<th>Door Bar type</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>nascar</td>
<td>27.13</td>
</tr>
<tr>
<td>x style</td>
<td>23.91</td>
</tr>
<tr>
<td>x style without lower</td>
<td>16.98</td>
</tr>
</tbody>
</table>
SUMMARY OF ANALYSIS

Total cage weight of optimized design (197.2lbs), which is lower than the targeted goal of 250lbs or less.

Optimized design is 813% more rigid than the minimum design.

- Torsional rigidity of minimum design 14,157 (ft-lb/deg)
- Torsional rigidity of maximum design 146,820 (ft-lb/deg)
- **Torsional rigidity of optimized design 129,272 (ft-lb/deg)**

- Max design  = 253.7 lbs
- Min design  = 104.2 lbs
- **Optimized**  = **197.2 lbs**
The final optimized design therefore increases overall rigidity of the basic cage by 813% while only adding an additional 93 pounds to the cage. As seen in table 6, the optimized version is almost as rigid as the last 3 cases while the weight is around the same as case 11. Also to be noted is the distance between the rigidity and weight is the largest distance compared to all other cases. High rigidity while having a low weight makes for the most effective cage. Data chart from testing is available in Appendix G.

FABRICATION

REQUIRED TOOLING

In order to build a custom roll cage many specialty tools are required. To make the bends required in the design a high quality bender must be used. A mandrel bender was used in this case to allow for smooth bends that are crack and dent free. The JB Squared Hydraulic Bender used was borrowed from Modular Depot and allowed for quick, easy, yet accurate bends to be possible. In addition to the bender a tubing notcher was also mounted on the bender itself and is seen in the top left of figure 50. A notcher allows the various tubes to meet up with one another, where they will then be welded.
Another nice tool that was borrowed for the project was a Hydraulic Shear. This was a custom built tool incorporating a set of Shears that were attached to a hydraulic cylinder. This would allow nice clean cut in the flat medal used in the various mounting plates for the cage. The shear is seen in the figure 51 on the left, while an example of what can be made is in the figure 52 on the right. Each piece of the box was made from a template and cut using the shear.
A power max 1000 plasma cutter was allow borrowed from the shop and allowed for quick cuts on intricate parts as well as making cuts on the frame for tube clearance. This was especially helpful while installing the doorbars as they protruded outwards into the door itself. Clearancing of the door area is seen in figure 53, and was done quickly and accurately.

Welding the tubes together required the use of a wire feed welder. This tool was also borrowed from the shop and was a higher end Miller which allowed for precise adjustments to be made to acquire the perfect weld penetration. Welding of a tube plate is seen in figure 54.
Abrasive cutoff saw was used to make the cuts on the tubing lengths. The tubing was bought in 20ft sections and had to be cut to the various lengths prior to bending. In figure 55, the saw is seen being used to make one of the cuts.

![Figure 55-John using abrasive cutoff saw](image)

**Rapid Prototyping**

Due to the length of testing required on the design of the cage a rapid prototype model was opted for a display piece for presentations. This took a huge load off Greg who could not make the presentations and have the actual car there. The model was printed using an ABS plastic machine which cures layer by layer as the part is made. Supports are also made as it prints which later much be dissolved in solvent to leave just the ABS part that was created. The model was scaled to a 1:16 size and preparations had to be made to the model which included making sure all sheet metal sections would print at least 1/16 of an inch when scaled to print. Hollow sections of the model must also be made solid to increase the strength of the part due to its small size. The resulting model is seen in figure 56, and has also been painted with colors matching the stress plots of the actual FEA model.
**Actual Fabrication**

The fabrication of the Cage is seen in the succession of the following figures: 57-65.

---

Figure 56-Abs Rapid Prototype

Figure 57-Install of rear plates
Figure 58- Rear main hoop and diagonal

Figure 59- Front down tubes and lower window bar
Figure 60-Rear down tubes

Figure 61-Passenger side door bar
Figure 62-Petty Bar

Figure 63-Upper window bar and rear diagonal
Figure 64-Driver’s side door bar

Figure 65-Front shock tubes
As seen in the figures a few tubes have been left out for future installation as the car becomes more complete. The car will be worked on to prepare it for the 2012 race season.

TESTING

**TESTING OF FABRICATED CHASSIS DESIGN:**

After fabrication of the final chassis design was completed a test method was developed in order to understand the effectiveness of the chassis enhancements. Since it was impossible to test the chassis under the same conditions that were specified in the computer analysis; the testing modified so that the results could be analyzed comparatively to the computer data.

The first step in the testing was to position the chassis over four jack stands. The jack stand located under the rear of passenger side was lowered from the chassis leaving a gap of 0.75in (the gap was precisely set using a set of high quality calipers). The figure below shows 0.75in gap, while the other three jacks remained in contact with the chassis.

![Figure 66: Testing - Gap under Rear Passenger Side Jack Stand](image)

After we set the gap to 0.75inches, Greg Brown (the customer), stood on the rear of the car while I stood on the front (see Figure 66). It was necessary for me to stand on the front of the chassis while Greg stood on the back so that the gap created between the chassis and jack stand would not close completely. Dial calipers were used to measure the amount of deflection as Greg applied his body weight of 200lbs to the rear of the car (see Figure 67). Dial calipers were used to measure the amount of deflection (see Figure 68). We recorded an approximate deflection value of 0.007in.
Comparing Deflection Values - (Fabricated Design Vs Computer Model (FEA)):

In the front end research of the chassis design a computer model of the Optimized Chassis was tested and analyzed using software analysis called Finite Element Analysis (FEA). The original FEA test conditions were setup in a manner that fixed the rear of the chassis, while an upward force of 750lbs was applied to the passenger side, and a downward force of 750lbs was applied to the driver side. The resulting deflection was measured at the top of the front shock towers (see Table 7).

Unfortunately, the actual fabricated chassis was not able to be tested under the same conditions as the “original” FEA. As a result an entirely new FEA study was developed to reflect the exact same conditions that were applied during the testing of the fabricated model (see Figure 69 on next page). The modified FEA analysis which applied a 200lb load to the rear of the chassis resulted in a deflection of 0.004in.

Understand that the modified testing was developed in order to address the issue that multiple front support members were not able to be included in the fabrication. The customer (Greg) chose to hold off on fabrication of the front members since the car has not received its engine placement, which will most likely set dimensional limitations.

<table>
<thead>
<tr>
<th>Final Chassis Design</th>
<th>0.043</th>
<th>0.208</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uy: Driver Side (in)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uy: Passenger Side (in)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 Testing - Deflection Value on Passenger Side
After finding the comparable deflection from the model, percent error from the FEA model to the real chassis can be calculated.

- Deflection (Fabricated model “Experimental”) = 0.007in
- Deflection (Computer model “Theoretical”) = 0.004in

\[
\frac{0.007 - 0.004}{0.004} \times 100 = 75\% \text{ error in the fabricated model compared to the FEA}
\]

In conclusion, the fabricated model yields a 75% greater deflection than the FEA. One likely factor that caused greater deflection in the fabricated model is the fact that the front reinforcement members were not fully installed. Also, since a 200lb force was applied to the front section of the chassis in order to keep the chassis planted on the jack stands, the applied force may have resulted in additional torsion (which may also cause increased deflection). Although the percent error seems relatively high, it seems feasible to believe that if all test conditions were equal the results would be much closer.

**Testing for Driver Clearance**

One of the largest factors in the entire project was safety. Keeping the body away from tubing as much as possible allows the prevention of contact with roll cage tubing. Typically the closest spot in the car is between the driver and the door bar. In this case the door bar was extended outwards into the door itself to allow for over 7 inches of clearance between the seat and the door bar. This is seen in the following figures 70 and 71.
WELD INTEGRITY TESTING

Quality of the welding process is very important to not only the safety of the driver but as well as the torsional rigidity of the cage itself. Poor welding processes can lead to stress cracks from fatigue due to porosity as well as problems due to welding a lower setting than required. Poor weld penetration can allow the welds to crack as well when the cage becomes loaded in turns. A way to test this is using a ASME test used in the Baha racing leagues which requires two samples be made. One sample being a 90 degree while the other a 35 degree joint. The test samples are then to be welded used the same machine on the same settings as used on the cage install. Once cooled the two samples are then held using a fixture while a lead pipe is inserted into the other part and a torque is applied till failure. The key to look for is that the base metal fails prior to the weld indicating that the weld is far stronger than the base metal. If the weld fails, signs of poor penetration or porosity should be addressed prior to welding the cage to the car. Some samples of this test are seen in the following figures 72 and 73.
Figure 72 - Weld Test Rig

Figure 73 - Tested weld sample
BUDGET AND SCHEDULING

BUDGET

As with any project, the budget becomes a very important aspect of a project. In table 8, an estimated proposed budget was developed. This estimate however can vary greatly depending on final material decision and tooling used to produce it. Standard “Drawn Over Mandrel” (DOM) roll cage tubing was used for the estimate and was roughly figured using a 20 ft section cost. All tooling costs are a very rough estimate and they may be null if the work is done at the sponsors shop. Installation quote was for a pre bent cage to be welded in a standard two door vehicle and was given by Rob Lewis at Rigid Race Cars (3). Tubing cost as seen in table 9, came in $30.00 over the estimate due to ordering an extra length for a just in case event during installation and bending. Installation would still cost the same but since it was self performed it was not included in the actual total.

<table>
<thead>
<tr>
<th>Materials, Components, or Labor</th>
<th>Forecasted Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 7/8 Dom Tubing</td>
<td>$450.00</td>
</tr>
<tr>
<td>Welding Materials</td>
<td>$250.00</td>
</tr>
<tr>
<td>Tube Notching</td>
<td>$500.00</td>
</tr>
<tr>
<td>CNC Tube bending</td>
<td>$500.00</td>
</tr>
<tr>
<td>Installation (welding of Cage)</td>
<td>$550.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,250.00</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material, Components, and Labor</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubing (1.75” DOM x 0.095” wall thickness)</td>
<td>$480.00</td>
</tr>
<tr>
<td>Sheet Metal (10” x 6”, 1/8” thick)</td>
<td>$50.00</td>
</tr>
<tr>
<td>Welding Material</td>
<td>$20.00</td>
</tr>
<tr>
<td>Tubing Notcher (Borrowed)</td>
<td>N/A</td>
</tr>
<tr>
<td>Installation (Self Performed)</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$550.00</strong></td>
</tr>
</tbody>
</table>

Modular Depot will supply all of the materials and tools needed to complete the chassis fabrication on the 2009 Mustang Road race car. This will include but not be limited to tubing, welding supplies, grinding disks and the facility to do the work.

Greg Brown
513-200-4077
**SCHEDULING**

During the Preliminary Design through the final report, there are many Important due dates to keep the project on schedule. These due dates are laid out as shown in table 10.

Table 10-Important Due Dates Part 1 and 2

<table>
<thead>
<tr>
<th>Milestone Date</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January</td>
<td>February</td>
</tr>
<tr>
<td>Weighted Objective Method</td>
<td>3-8</td>
<td>3-15</td>
</tr>
<tr>
<td>Record Dimensions of car</td>
<td>1-12</td>
<td>1-17</td>
</tr>
<tr>
<td>Proof of Design Statement</td>
<td>1-12</td>
<td>1-17</td>
</tr>
<tr>
<td>Proof of Design Agreement</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Perform Design Calculations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Sub-Frame Connectors in CAD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collaborate with Race Team</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consider Design Changes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Freeze</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Order Parts for Assembly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work on Draft/Presentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral Design Report</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Finalize Design Report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Report Due</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Milestone Date</th>
<th>Winter Quarter</th>
<th>Spring Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January</td>
<td>February</td>
</tr>
<tr>
<td>Assemble and Mount Sub-Frame Connectors</td>
<td>3-8</td>
<td>3-15</td>
</tr>
<tr>
<td>Test and Consider Improvements</td>
<td>1-12</td>
<td>1-17</td>
</tr>
<tr>
<td>Implement Changes/Improvements if needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Data Collection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demo to Adviser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demo to Faculty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete Oral Presentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral Presentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete Final Report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Report</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES

2. Rehagen Racing Koni cage for Mustang. Rehagen Racing. [Online] [Cited: July 20, 2010.]
7. Cages, Izzys Custom. Izzys Custom Cages. [Online] [Cited: September 2010, 5.]
APPENDIX A - RESEARCH

- Information gathered via surveys and discussions on November 20 and 21, 2010.
- Interviewees were Greg Brown, Dave Blundell, Ken Bjonnes, and Chris Richards.
- The interviews for everyone took place at Modular Depot - 8025 Action Blvd., Florence, Kentucky, 41042
- All interviewees agree that certain race standards must be met according to the class in which the car will race.
- All interviewees agreed that durability is essential to a roll cage's safety.
- Ken Bjonnes – Entry and exit are very important to the driver and many cages do not account for this.
- Greg Brown – Removing body sheet metal and replacing it with roll cage tubing is a great way to save weight and meet the rules.

Typical 2005 Ford Mustang Interior

Includes carpet and all amenities of a standard car


Standard Interior

- Comfortable
- Does not meet race standards
- Allowable Body flex
- Does not protect driver for racing

Appendix A1
## Rehagen Racing Koni Cage for Mustang

Cost $2849

- Structural tubes are 1.75" x 0.120" DOM mild steel
- Tubing is cut, notched, and substantially pre-welded to save installation time
- Major sections are CNC-bent and jig-welded
- Includes rear close-out panel, pass-through plates, rear shock tower reinforcements, base plates, window net mounts, body tie-in brackets, and a shut-off switch mount
- "NASCAR-style" driver's side door bars, and dual straight door bars on the passenger side for added safety
- Main hoop features a complete "X" and a harness bar across the entire hoop for safety
- Legal for NASA, SCCA, and Grand-Am

<table>
<thead>
<tr>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expensive to purchase</td>
</tr>
<tr>
<td>Very Standard setup</td>
</tr>
<tr>
<td>No weight reduction</td>
</tr>
<tr>
<td>Easy weld in installation</td>
</tr>
<tr>
<td>Doesn’t utilize frame rails</td>
</tr>
</tbody>
</table>

http://www.rehagenracingproducts.com/product.sc?productId=1697 Rehagen Cage
Bolt-In Roll Cage-Cost $832.15
It's designed to quickly and easily transform your street car into a race legal competition car. This cage closely conforms to your car's interior, allowing quick entry & exiting. It uses precision fit, 6 mounting point, slip-tube and bolt-in design. This cage is approved by SCCA and NASA for open road racing and drifting events.

- Top of the line in fit and construction.
- These cages are made to order, allowing for tube size and type to be selected.
- Diagonal cross brace and horizontal brace are a permanent weld-in design.
- Autopower will select tube size and type for your needs.
- All necessary installation and mounting hardware with back-up plates is included.
- Most Bolt-In Cages are made of 1.50 or 1.750 x .120 DOM mild steel tube.
<table>
<thead>
<tr>
<th>Custom built to order-Cost Varies</th>
<th>Professional shop that offers any cage the customer could possibly want. Motto is: “Why spend lots of money for a cage that doesn't even fit your car? Get a custom cage.” Located in Akron Ohio</th>
</tr>
</thead>
</table>
|                                  | Expensive  
|                                  | Time consuming  
|                                  | Allows design freedom  
|                                  | Long wait time…3 Month Backup period  
|                                  | Installation Included  |

| Custom built to order-Cost Varies | Our basic cage pricing is easy. $14.00-17.00 per foot of tubing, $65.00 per attachment point and $25.00 per bend, Gussets Extra  
|----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                  | Expensive  
|                                  | Time consuming  
|                                  | Allows design freedom  
|                                  | Long wait time…Booked through end of the year  
|                                  | Installation Included  |
2005 weld in Mustang Cage-Cost $499.95

1-3/4 x .120" wall DOM tubing 10 point cage
Pre Bent, Pre Notched
Generic base plates included

SW Racecars Cage

- Cheaper
- Generic Tube Placement
- Does not meet race standards
- Tube size incorrect
- Easy to install
# APPENDIX B – SURVEY

## Race car cage/chassis Design

### Customer Survey

Please follow the instructions below and fill out this survey concerning a race car cage/chassis design. The survey will be used to help describe customer needs, and the importance of product features.

- **How important is each feature to you concerning the design of a race car cage design?**

Please circle the appropriate answer.  

<table>
<thead>
<tr>
<th>Feature</th>
<th>1 = low importance</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>N/A</th>
</tr>
</thead>
</table>
| Safety                       | 1                  | 2 | 3 | 4 (1) | 5 (9) | N/A | 4.9  
| Affordability                | 1                  | 2 | (8) | 3 | 1 | 4 | 1 | 5 | N/A | 2.3  
| Ease of manufacturing        | 1 (7) | 2 (2) | 3 (1) | 4 | 5 | N/A | 1.4  
| Ease of installation         | 1 (8) | 2 (1) | 3 (1) | 4 | 5 | N/A | 1.3  
| Ease to Enter/Exit           | 1                  | 2 | 3 | 1 | (8) | 4 | 5 | (1) | N/A | 4.0  
| Weight                       | 1                  | 2 | (6) | 3 (3) | 4 (1) | 5 | N/A | 2.5  
| Appearance                   | 1 (1) | 2 (7) | 3 (2) | 4 | 5 | N/A | 2.1  
| Durability                   | 1                  | 2 | 3 | 4 (2) | 5 | (8) | N/A | 4.8  
| Compliance with standards    | 1                  | 2 | 3 | 4 | 5 | (10) | N/A | 5.0  
| Maneuverability              | 1                  | 2 | (1) | 3 (7) | 4 | (2) | 5 | N/A | 3.1  

Appendix B1
- **How satisfied are you with currently available race car cage design?**

Please circle the appropriate answer.  

<table>
<thead>
<tr>
<th>Category</th>
<th>1 = Not Satisfied</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 = Satisfied</th>
<th>N/A</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>1</td>
<td>2</td>
<td>3 (7)</td>
<td>4 (2)</td>
<td>5 (1)</td>
<td>N/A</td>
<td>3.4</td>
</tr>
<tr>
<td>Affordability</td>
<td>1</td>
<td>2 (3)</td>
<td>3 (6)</td>
<td>4 (1)</td>
<td>5</td>
<td>N/A</td>
<td>2.8</td>
</tr>
<tr>
<td>Ease of manufacturing</td>
<td>1</td>
<td>2 (1)</td>
<td>3 (8)</td>
<td>4 (1)</td>
<td>5</td>
<td>N/A</td>
<td>3.0</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>1</td>
<td>2 (8)</td>
<td>3 (2)</td>
<td>4</td>
<td>5</td>
<td>N/A</td>
<td>2.2</td>
</tr>
<tr>
<td>Ease to Enter/Exit</td>
<td>1 (1)</td>
<td>2 (6)</td>
<td>3 (3)</td>
<td>4</td>
<td>5</td>
<td>N/A</td>
<td>2.2</td>
</tr>
<tr>
<td>Weight</td>
<td>1</td>
<td>2 (7)</td>
<td>3 (1)</td>
<td>4 (1)</td>
<td>5 (1)</td>
<td>N/A</td>
<td>2.6</td>
</tr>
<tr>
<td>Appearance</td>
<td>1 (1)</td>
<td>2 (9)</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>N/A</td>
<td>1.9</td>
</tr>
<tr>
<td>Durability</td>
<td>1</td>
<td>2</td>
<td>3 (8)</td>
<td>4 (2)</td>
<td>5</td>
<td>N/A</td>
<td>3.2</td>
</tr>
<tr>
<td>Compliance with standards</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5 (10)</td>
<td>N/A</td>
<td>5.0</td>
</tr>
<tr>
<td>Maneuverability</td>
<td>1</td>
<td>2 (3)</td>
<td>3 (6)</td>
<td>4 (1)</td>
<td>5</td>
<td>N/A</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Thank you for your time.**
## APPENDIX C – QFD

<table>
<thead>
<tr>
<th>Ryan Carter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Race Car Roll Cage</td>
</tr>
<tr>
<td>9 = Strong</td>
</tr>
<tr>
<td>3 = Moderate</td>
</tr>
<tr>
<td>1 = Weak</td>
</tr>
</tbody>
</table>

| Risk Factors                  | Cage Tube Size | Weld Integrity | Weight in Lbs | Material | Paint/Epoxy coat quality | Tube Notch Fit | Door Bar Height | Manufacturability | NASA Standards | Leg Movement in Degrees | Arm Movement in Degrees | Drive Style allowable | Customer importance | Designer’s Multiplier | Current Satisfaction | Planned Satisfaction | Improvement ratio | Modified Importance | Modified Rel. weight | Relative weight % |
|------------------------------|----------------|----------------|---------------|-----------|--------------------------|----------------|-----------------|------------------|---------------|-----------------------|----------------------|----------------------|-----------------------|---------------------|----------------------|---------------------|---------------------|------------------|---------------------|----------------------|--------------------|
| Safety                       | 9              | 9              | 3             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 4.9                  | 1.1                   | 3.4                 | 4.5                 | 1.3                 | 7.1                | 0.17               | 17%                |
| Affordability                | 9              | 9              | 9             | 3         | 3                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 2.3                  | 1.1                   | 2.8                 | 2.8                 | 1.0                 | 2.3                | 0.05               | 5%                 |
| Ease of Manufacturing        | 3              | 9              | 9             | 3         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 1.4                  | 1.1                   | 3.3                 | 3                  | 1.0                 | 1.4                | 0.03               | 3%                 |
| Ease of Installation         | 3              | 3              | 9             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 1.3                  | 1.1                   | 2.2                 | 2                  | 0.9                 | 1.2                | 0.03               | 3%                 |
| Ease of Entry/Exit           | 3              | 9              | 9             | 3         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 4.1                  | 2.2                   | 4.1                 | 1.9                 | 8.2                 | 0.19               | 19%                |
| Weight                       | 9              | 9              | 9             | 3         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 2.5                  | 1.1                   | 2.6                 | 2.6                 | 1.0                 | 2.8                | 0.06               | 6%                 |
| Appearance                   | 3              | 3              | 3             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 2.1                  | 1.9                   | 2.2                 | 2                  | 1.1                 | 2.2                | 0.05               | 5%                 |
| Durability                   | 9              | 9              | 3             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 4.8                  | 1.1                   | 3.2                 | 5                  | 1.6                 | 8.3                | 0.19               | 19%                |
| Compliance with Standards    | 9              | 9              | 9             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 5.5                  | 1.1                   | 5                  | 5                  | 1.0                 | 5.5                | 0.13               | 13%                |
| Maneuverability              | 3              | 9              | 3             | 9         | 9                       | 9              | 9               | 9                | 9             | 9                     | 9                    | 3.1                  | 1.1                   | 2.8                 | 3                  | 1.1                 | 3.7                | 0.09               | 9%                 |
| Abs. importance              | 6.08           | 4.57           | 1.75          | 6.02      | 2.37                     | 2.72           | 5.18            | 0.88             | 5.18         | 5.18                   | 4.40                 | 47.8                 | 42.6                  |                     |                     |                     | 47.8               | 42.6               |
| Rel. importance              | 0.13           | 0.10           | 0.04          | 0.13      | 0.05                     | 0.06           | 0.11            | 0.02             | 0.07         | 0.11                   | 0.09                 | 0.13                 | 0.10                  | 0.04               | 0.13               | 0.05              | 0.11               | 0.02           | 0.07               | 0.11               | 0.09               |

Appendix C1
APPENDIX D – PROJECT OBJECTIVES

Race Car Roll Cage

The following is a list of product objectives and how they will be obtained or measured to ensure that the goal of the project was met. The product objectives will focus on a race car roll cage in a 2005 Ford Mustang. The car that was selected is intended for racing in the American Iron Extreme race class.

Durability (19%)
5) Chosen materials able to withstand repeated suspension loads due to fatigue on a smooth race track.
6) A recommended top coat to prevent rust and corrosion
7) Tube bending will be addressed and the proper way to bend seam welded tubing.
8) ASME welding standards will be applied to the installation of the roll cage

Ease of entry/exit (19%)
2) Car will be possible to get in and out of with the cage applying human standards for a normal to larger than normal human size

Safety (17%)
1) Use Cosmos to simulate loading the roll cage in race conditions.
2) Standard roll cage foam wrap will be used to protect driver in case of contact with roll cage tubes to prevent possible injuries

Compliance with race standards (13%)
2) Must conform to American Iron Extreme class rules and regulation

Maneuverability (9%)
3) Driver is able to easily move around inside the car
   c) Legs able to move 15 degrees each way while seated
   d) Arms able to move 45 degrees each way while seated
4) Able to accommodate a human factors 75th percentile male +/- 20%

Weight (6%)
2) Cage will not add more than 250lbs to the car

Affordability (5%)
2) Cage will cost less than $2500.00 to purchase

Appearance (5%)
2) Cage will contour the inside body of the car
Ease of manufacturing (3%)
2) Cage can be made with standard fabrication tools
   d) Machining for tube notches
   e) Milling for tube lengths
   f) Hydraulic tube bending for precise angles and bends

Ease of installation (3%)
3) Cage can be installed with multiple welding processes
   c) Mig Welding
   d) Tig Welding
4) No unusual tools needed for installation
   d) Tubes will be pre bent
   e) Tubes will be pre notched
   f) Tubes will require no cutting
## APPENDIX E – BUDGET

<table>
<thead>
<tr>
<th>Materials, Components, or Labor</th>
<th>Forecasted Amount</th>
<th>Actual Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 7/8 Dom Tubing</td>
<td>$450.00</td>
<td></td>
</tr>
<tr>
<td>Welding Materials</td>
<td>$250.00</td>
<td></td>
</tr>
<tr>
<td>Tube Notching</td>
<td>$500.00</td>
<td></td>
</tr>
<tr>
<td>CNC Tube bending</td>
<td>$500.00</td>
<td></td>
</tr>
<tr>
<td>Installation (welding of Cage)</td>
<td>$550.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,250.00</strong></td>
<td></td>
</tr>
</tbody>
</table>
## APPENDIX F – SCHEDULE

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TASK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proof of Design</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubing Placement Options</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choose Best tubing placement</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SolidWorks Drawings for Cage Layout</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Cage Design</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Front Tubing Optimization</td>
<td></td>
<td></td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Rear Tubing Optimization</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Door Bar Optimization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Joint Gusset Optimization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Body attachment points</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Finite Analysis of complete cage</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Freeze</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Cage Design Drawings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Order Cage Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component Fabrication</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Measurements for Comparison</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Modifications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Final Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Demo to advisor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Demo to faculty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Oral Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Final Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Appendix F1
APPENDIX G – ROLL CAGE DATA

<table>
<thead>
<tr>
<th>Modification Upgrade</th>
<th>Uy: Driver Side (in)</th>
<th>Uy: Passenger Side (in)</th>
<th>Uy: Average (in)</th>
<th>Rigidity Increase (%)</th>
<th>Kc (ft-lbs/deg)</th>
<th>Cage Weight (lb)</th>
<th>Upgrade Weight (lb)</th>
<th>Rigidity Increase (%)</th>
<th>Rigidity Increase Over Previous (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 base model</strong></td>
<td>1.166</td>
<td>1.126</td>
<td>1.146</td>
<td>2.638</td>
<td>14,156.71</td>
<td>104.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2 add lower hor x tube</strong></td>
<td>1.143</td>
<td>1.116</td>
<td>1.130</td>
<td>1.5%</td>
<td>14,363.52</td>
<td>118.07</td>
<td>13.89</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td><strong>3 add lower window</strong></td>
<td>0.910</td>
<td>0.897</td>
<td>0.904</td>
<td>26.8%</td>
<td>17,956.39</td>
<td>126.11</td>
<td>8.04</td>
<td>26.8%</td>
<td>25.0%</td>
</tr>
<tr>
<td><strong>4 add upper shock</strong></td>
<td>0.568</td>
<td>0.575</td>
<td>0.572</td>
<td>100.5%</td>
<td>28,387.17</td>
<td>131.53</td>
<td>5.42</td>
<td>100.5%</td>
<td>58.1%</td>
</tr>
<tr>
<td><strong>5 add upper shock mount</strong></td>
<td>0.745</td>
<td>0.732</td>
<td>0.739</td>
<td>55.2%</td>
<td>21,968.31</td>
<td>140.46</td>
<td>8.93</td>
<td>55.2%</td>
<td>22.6%</td>
</tr>
<tr>
<td><strong>6 just drivers side upright</strong></td>
<td>0.742</td>
<td>0.726</td>
<td>0.734</td>
<td>56.1%</td>
<td>22,102.99</td>
<td>150.52</td>
<td>10.06</td>
<td>56.1%</td>
<td>0.6%</td>
</tr>
<tr>
<td><strong>7 add Vertical Uprights</strong></td>
<td>0.733</td>
<td>0.725</td>
<td>0.729</td>
<td>57.2%</td>
<td>22,254.59</td>
<td>155.55</td>
<td>5.03</td>
<td>57.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>8 add rear diag</strong></td>
<td>0.296</td>
<td>0.267</td>
<td>0.282</td>
<td>307.1%</td>
<td>57,632.66</td>
<td>163.78</td>
<td>8.23</td>
<td>307.1%</td>
<td>159.0%</td>
</tr>
<tr>
<td><strong>9 make x in rear diag</strong></td>
<td>0.260</td>
<td>0.274</td>
<td>0.267</td>
<td>329.2%</td>
<td>60,762.53</td>
<td>171.83</td>
<td>8.05</td>
<td>329.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td><strong>10 add main hoop diag</strong></td>
<td>0.245</td>
<td>0.250</td>
<td>0.248</td>
<td>363.0%</td>
<td>65,549.88</td>
<td>180.23</td>
<td>8.40</td>
<td>363.0%</td>
<td>7.9%</td>
</tr>
<tr>
<td><strong>11 add roof cluster</strong></td>
<td>0.194</td>
<td>0.197</td>
<td>0.196</td>
<td>486.2%</td>
<td>82,985.14</td>
<td>197.68</td>
<td>17.45</td>
<td>486.2%</td>
<td>26.6%</td>
</tr>
<tr>
<td><strong>12 add petty bar</strong></td>
<td>0.092</td>
<td>0.233</td>
<td>0.163</td>
<td>605.2%</td>
<td>99,837.51</td>
<td>212.03</td>
<td>14.35</td>
<td>605.2%</td>
<td>20.3%</td>
</tr>
<tr>
<td><strong>13 add window bar</strong></td>
<td>0.095</td>
<td>0.197</td>
<td>0.146</td>
<td>684.9%</td>
<td>111,120.51</td>
<td>220.14</td>
<td>8.11</td>
<td>684.9%</td>
<td>11.3%</td>
</tr>
<tr>
<td><strong>14 add strut bar</strong></td>
<td>0.093</td>
<td>0.190</td>
<td>0.142</td>
<td>709.9%</td>
<td>114,654.38</td>
<td>226.04</td>
<td>5.90</td>
<td>709.9%</td>
<td>3.2%</td>
</tr>
<tr>
<td><strong>15 add only short front diag</strong></td>
<td>0.086</td>
<td>0.170</td>
<td>0.128</td>
<td>795.3%</td>
<td>126,746.84</td>
<td>235.27</td>
<td>9.23</td>
<td>795.3%</td>
<td>10.5%</td>
</tr>
<tr>
<td><strong>16 add only long front diag</strong></td>
<td>0.077</td>
<td>0.147</td>
<td>0.112</td>
<td>923.2%</td>
<td>144,853.53</td>
<td>239.87</td>
<td>4.60</td>
<td>923.2%</td>
<td>14.3%</td>
</tr>
<tr>
<td><strong>17 both diag no x bottom</strong></td>
<td>0.077</td>
<td>0.144</td>
<td>0.111</td>
<td>937.1%</td>
<td>146,819.86</td>
<td>253.70</td>
<td>13.83</td>
<td>937.1%</td>
<td>1.4%</td>
</tr>
<tr>
<td><strong>18 add x on bottom</strong></td>
<td>0.070</td>
<td>0.124</td>
<td>0.097</td>
<td>1081.4%</td>
<td>167,253.56</td>
<td>303.70</td>
<td>50.00</td>
<td>1081.4%</td>
<td>13.9%</td>
</tr>
<tr>
<td><strong>Fully Optimized</strong></td>
<td>0.043</td>
<td>0.208</td>
<td>0.126</td>
<td>813.1%</td>
<td>129,271.67</td>
<td>197.22</td>
<td></td>
<td>813.1%</td>
<td></td>
</tr>
</tbody>
</table>