SAE Mini Baja

Frame Sub-team

John Rankin

Richie Lonzaga

Koali'i Ladao

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Project Sponsor: SAE at NAU, Gore, etc.

Faculty Advisor: Mr. Willy

Sponsor Mentor: Dr. Tester

Instructor: Dr. Trevas

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

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1 BACKGROUND

1.1 Introduction

The SAE Mini Baja competition is held each year to test and develop undergraduate mechanical engineers. Teams from around the world compete against each other in the hill climb, agility, braking and 4-hour endurance tests. It is imperative that competing teams create a vehicle that will succeed in each of these tests so they can score well in each and ultimately win the competition. The sponsors of the event are helping build their new work force by giving undergraduate students a real-world project. In which they see that having a work force who is experienced in large scale project development is beneficial to their industry.

1.2 Project Description

The 2017-2018 SAE Baja project entails the design and creation of an off-road vehicle capable of enduring large obstacles over extended periods of time. To complete this project, the frame team is tasked with creating a light and durable frame that passes all safety standards. To complete this task, the team will utilize CAD and FEA programs to develop a well-researched and tested frame before building. Using dynamic testing in the FEA program ANSYS will allow for the team to realize locations of stress concentration points and adapt the design to minimize stress concentration over the entire frame. Following is the original project description provided by the sponsor,

> "Baja SAE® consists of competitions that simulate real-world engineering design projects and their related challenges. Engineering students are tasked to design and build an off-road vehicle that will survive the severe punishment of rough terrain. Each team's goal is to design and build a single-seat, all-terrain, sporting vehicle whose structure contains the driver. The vehicle is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle which serves a recreational user market.
>
> The object of the competition is to provide SAE student members with a challenging project that involves the design, planning and manufacturing tasks found when introducing a new product to the consumer industrial market. Teams compete against one another to have their design accepted for manufacture by a fictitious firm. Students must function as a team to not only design, build, test, promote, and race a vehicle within the limits of the rules, but also to generate financial support for their project and manage their educational priorities.
>
> All vehicles are powered by a ten-horsepower Intek Model 19 engine donated by Briggs & Stratton Corporation. For over forty years, the generosity of Briggs & Stratton has enabled SAE to provide each team with a dependable engine free of charge. Use of the same engine by all the teams creates a more challenging engineering design test."

Pursuit of this project will begin will collecting all engineering and customer requirements and then continues by initiating the dynamic FEA testing on a frame created in SolidWorks.

1.3 Original System

This project involved the design of a completely new Baja Mini Vehicle. There was no original system when this project began.

2 REQUIREMENTS

For the following project, the team was tasked with deciphering and implementing the entirety of the SAE Baja 2018 rule book, into a frame design. SAE heavily regulates frame design and manufacturing, due to safety concerns and if the rules are not followed explicitly the ability to compete may be placed at risk. The following sections goes over the entirety of the SAE Baja 2018 rule book as well as various insights that have been discovered.

2.1 Customer Requirements (CRs)

In terms of customer needs Mr. David Willy, our project advisor, is the project's client. Given that the SAE Mini Baja capstone project is a national competition the needs that he has supplied to the team is based off the SAE Baja 2018 rule book with an emphasis on being competitive. Due to the considerable volume of rules designated solely for frame design, the rules are instead listed in Appendix A.1 in the back of our report. These rules represent our customer requirements.

2.2 Engineering Requirements (ERs)

In terms of Engineering Requirements, the team decided what would be the goals and parameters for the frame for the design to be competitive. It was decided to use 4130 Chromoly Steel as the material for the frame due to its strength per weight ratio. It was also decided that the frame weight should be around 70lb based off advice from Gauged CVT, our transmission supplier, and the low weight of 4130 Chrome moly steel tubing should allow for this goal to be reached. This weight in theory would give the most reliability and durability while still being light. Based off the SolidWorks designs the team has mapped out the frame area to be approximately 6200 square inches which would be the best use of material to maximize durability. It was decided to design the truss members to not exceed 508 kpsi which is the yield strength of 4130 Chromoly Steel. The use of 20 frame members in the design was decided because it is the minimum number of members that are needed based off the rules. In terms of driver ergonomics, the design gives the driver 20 inches of room reaching the best ratio of driver comfort to material used. The estimated the time to build the entire frame is around two weeks based off the proficiency of the team and the resources that are available in the machine shop. The estimate for the overall cost of the frame is $700 based off the cost per length of tube of 4130 Chrome moly steel.

2.3 House of Quality (HoQ)

As restricted as the design of this frame will be, it is imperative to still be creative with different concepts. To achieve this, an analyzation of the various aspects of how a space frame concept will react to forces, and how it will be built, was conducted. The aspects considered were the weight of the vehicle, size of the frame, yield strength of the weakest point, driver comfort, manufacturing time, primary and secondary member design, the number of member, which material, and the overall cost of the entire design.

Table 1:QFD

System QFD

Project:	SAE Baja	Frame Sub team
Date:	10/4/2017	

Correlation	
.++	Strong Positive
.+	Positive
	No Correlation
.-	Negative
.--	Strong Negative

Frame Characteristics		Weight	Frame Size	Strength	Driver Ergonomics	Manufacturing Time	Primary Member Design	Secondary Member Design	# of Members	Material Selection
Weight										
Frame Size		.++								
Strength		.++	.+							
Driver Ergonomics			.++	.+						
Manufacturing Time			.+	.++	.+					
Primary Member Design		.+	.+	.++	.+	.++				
Secondary Member Design		.+	.+	.++	.++	.++				
# of Parts		.++	.+	.++	.-	.++				
Material Selection		.++	.+	.++	.+	.+	.++	.++	.++	
Cost			.+	.+		.--	.+	.++	.+	.++

Customer Needs	Customer Weights	Weight	Frame Size	Strength	Driver Ergonomics	Manufacturing Time	Primary Member Design	Secondary Member Design	# of Members	Material Selection	Cost
		Technical Requirements									
Durable	10	4	4	10	7	7	10	10		7	
Maneuverable	4	7	10		4				4		
Reliable	10	1	1	10	1		4	4	1	7	
Maintainable	7		1		4		10	10	7	7	
Ergonomic	9	4	7		10	1	7	7	4		
Economic	9	4	7	4	7	10	4	4	7	7	10
Safety	10	1	1	10	10	7	7	7		10	
Lightweight	10	10	10	10	10		10	10	10	10	
Ease of Manufacturing	6			4	4	10	4	4	7	7	
Inexpensive	5		1	4	4	7	1	1	4	10	10
Mass Production	7	4	4	4	1	10	1	1	7	7	10
Technical Requirement Units		lb	in^2	kpsi	in	hours	in	in	#	in	$
Technical Requirement Targets		70	6200	58	20	196	1.25x0.095	1x0.095	20	4130	700
Absolute Technical Importance	4312	288	366	508	528	404	515	515	385	593	210
ATI (percent)		0.067	0.085	0.118	0.122	0.094	0.119	0.119	####	0.138	0.049
Relative Technical Importance		10	6	7	4	7	8	8	4	8	3

Using a QFD the requirements with the greatest technical importance were found to be the weight of the vehicle, yield strength of the weakest point, material selection, and member design. Through this development the focus of the design will be on these 4 aspects.

3 EXISTING DESIGNS

Through the analysis of different frame types and the benchmarking completed by the team leads at last year's competition the best competing vehicle designs have been compiled. The team used these designs to further improve and develop the frame concept.

3.1 Design Research

Team leads attended the past year's competition and recorded photos and notes of vehicles that were performing well. From these the team has been able to determine the type of frame and weight range that would be ideal for success. The top competitors at the previous year's competition used a mixture of the nosed and no-nose variants which will be ideal for both weight and driver comfort, while a frame in the range of 70-80lbs was found to have a competitive power to weight ratio.

3.2 System Level

Every competing Baja frame must fulfill the safety requirements and pass the technical inspection to compete. Since the frame is one uniform rigid body there is only one system level, and that would be the frame. There are however two distinctive designs for the frame outlined within the rule book that contain their own engineering requirements. These and the weight of the frame are the only variables when comparing differing designs.

3.2.1 Existing Design #1: NAU 2016 Mini Baja

Last year's Baja did not do well in competition yet still gave many valuable insights from its frame design. The frame was very large and unwieldy for the purpose it needed to accomplish. It could be cut down by nearly a foot and the width by a quarter of a foot while still having similar durability's. It also had a very minimalistic nose design which caused them significant issues when pitted against rough terrain. A durable nosed focused frame will mediate this issue.

3.2.2 Existing Design #2: Michigan Mini Baja

Michigan has consistently been a top performer in the SAE Mini Baja competition. The hope to emulate their frame's traits that seem to be successful, like the general efficiency of weight greatly increases the Baja's performance. Using FEA calculations to create a frame which stands on the very threshold of its yield point allows for reduced weight while still having a factor of safety.

3.3 Functional Decomposition

Breaking down the separate subsystems of the overall vehicle helps the frame team plan for the housing and attachment points for every component.

3.3.1 Black Box Model

To track the energy inputs and outputs of the entire vehicle a black box model was developed. Like a common combustion vehicle, the inputs and outputs of the Baja vehicle take the signal of the gas pedals push to release fuel into the engine, creating a chemical combustion reaction, then delivering this power to the Constant Variable Transmission (CVT) which then engages the gearbox, producing power into the rear axle. The outputs of this process are the forces related to the acceleration of the vehicle, such as momentum and friction, and the loss of energy through noise, unutilized fuel in the exhaust, and heat energy dissipated into the air.

Figure 1: Black Box Model

Fine tuning the CVT, gear box, and power delivery will allow the final vehicle to produce as much power from its fuel source and gain a competitive advantage. The only energy loss that can be mitigated is unutilized fuel escaping in the exhaust and this can be fixed through the fine tuning of the power system.

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Breaking each functional system down for the entire vehicle begins with the design. To have a smart designed vehicle the design must derive from the most basic yet important aspects. The FEA of the frame allows for a light but strong body for the vehicle. The brake design allows for the front and rear end teams to develop an accurate and effective spring constant for their suspension designs. The drive train calculations will allow for the rear end team to send their required specifications to the CVT client and allow for the delivery of a tuned transmission. The team will then take these developments and use them in further developments to create a smart designed final vehicle.

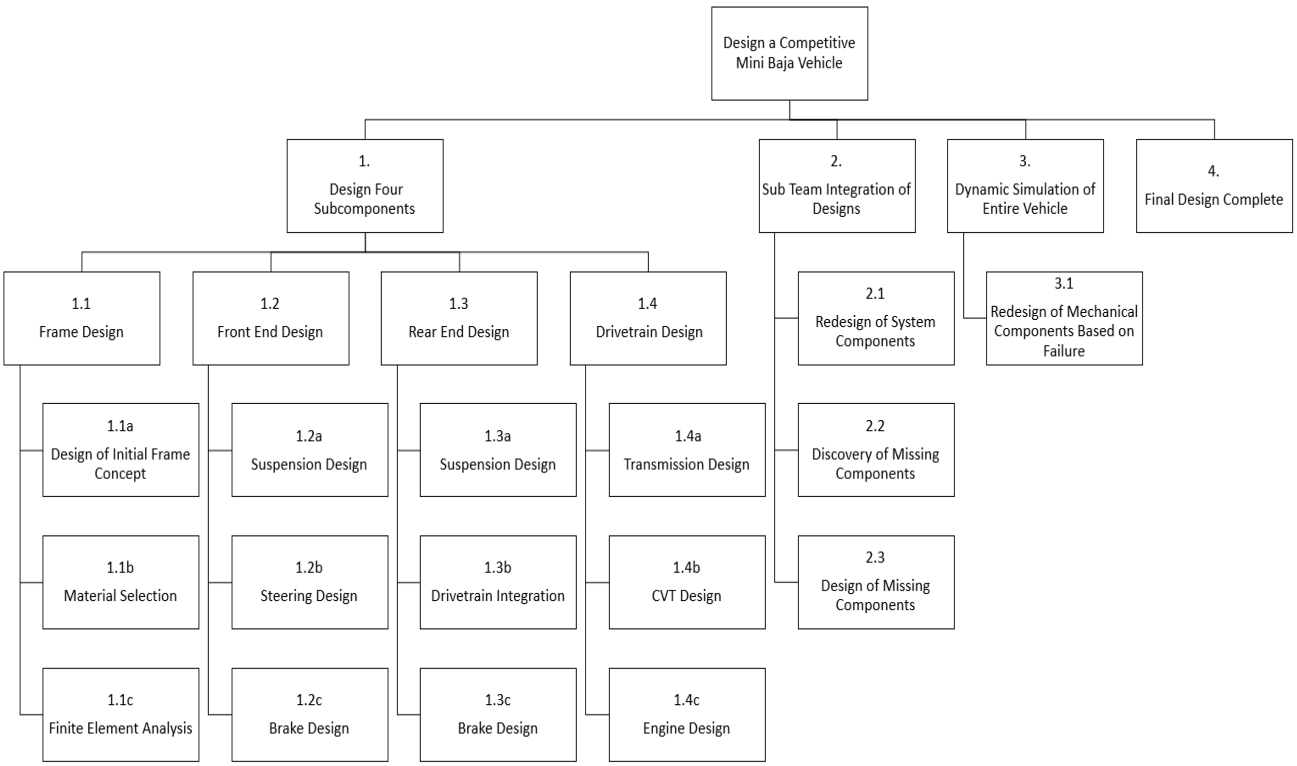


Figure 2: Functional Model

For the frame sub team, the focus was to create a frame which was intelligently designed. Starting with a bare frame, testing in FEA was conducted to highlight the stress concentrations within the frame when subjected to equivalent forces of a 45-degree impact from a 4-foot fall going at 30 miles per hour. Adapting the design to compensate for these stresses by seeing which location of a support member produced the largest difference in strength. Through many iterations a final frame design will be developed and be able to disperse the forces encountered during the impacts of overcoming a large obstacle. The process in Figure 3 is shown to be a continuous cycle that is only completed when the requirements for the design are met to a satisfactory level.

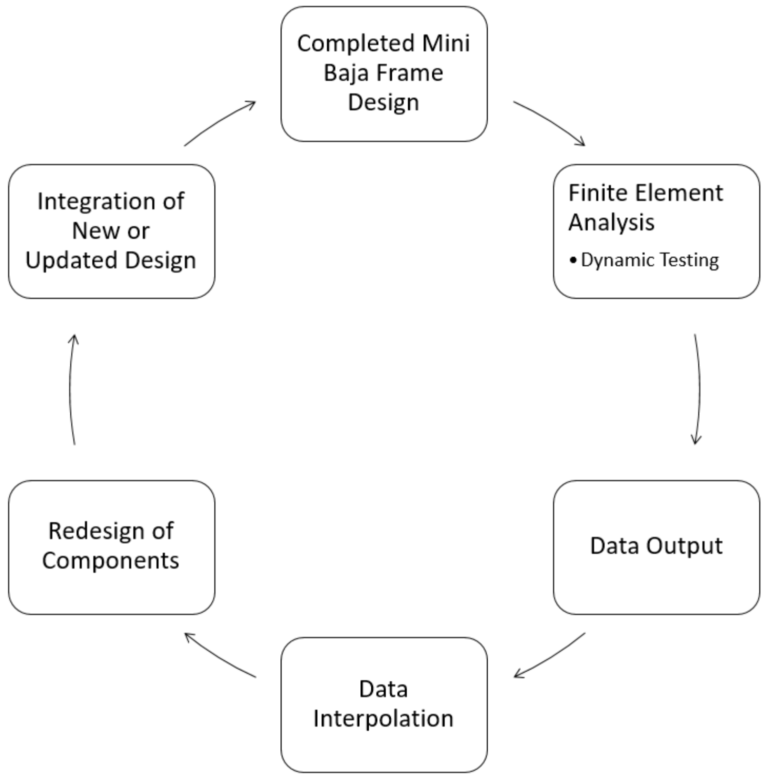


Figure 3: Work Process Model

Using this design cycle, the team will develop the best frame concept possible in a reliable and proven method. A well-designed frame will allow for a competitive outcome at competition.

3.4 Subsystem Level

Subsystems are non-applicable to the frame as it is one uniform rigid body.

4 DESIGNS CONSIDERED

Since frame design is heavily regulated by SAE, the amount of freedom in terms of frame design is very limited. Many of the ideas in the beginning have become non-applicable due to safety reasons. The amount of unique designs that are physically capable of achieving are less than ten due to project constraints.

4.1 Design #1: Support Gusset Frame

The frame design process our team has been focused on creating is the most durable frame for the least amount of weight. The supporting gusset design idea is consideration in which would gain durability by sacrificing a small gain in weight. The design includes adding gussets to the overhead members for better stress distribution.

4.2 Design #2: Bent Front Primary Members Frame

Another frame design that was considered is using bent members for the front primary members of the Baja. This design would give a larger area in the driver cockpit for the same amount of material. The use of this design includes front primary members that would be subject to the rules regarding bent members because of it being a bit less durable in instances of front impacts.

4.3 Design #3: Nosed Frame

This frame variant extends the pedal assembly forward from the roll hoop and allows for more room for the driver. It adds an unnecessary length to the vehicle and adds weight. The extended wheel base reduces the turning radius and clearance of the vehicle.

4.4 Design #4: No-nose Frame

This frame variant completes the rolling hoop without extending forward. This reduces the overall size of the vehicle, reducing weight, but restricts the room for the driver. The short wheel base of this design allows for a smaller turning radius but reduces the stability of the vehicle while impacting after a jump.

4.5 Design #4: Nosed and No-nose combination

Design #4 is a combination of the nosed frame and the no-nosed frame. Through research the team found that this combination frame has success in the competition due to its high ratio between weight and durability. It is slightly heavier than the no-nose frame, yet it is much more structurally reliable, and while it is less durable than the nosed frame it is durable enough and light enough to fulfill all the engineering requirements affectively.

5 DESIGN SELECTED – First Semester

The design that has been selected moving forward is a mixture of a no-nose and nosed space concept frame. The use of FEA and SolidWorks simulations will allow for a final advanced design to be developed.

5.1 Rationale for Design Selection

Using ANSYS, SolidWorks Simulation, technical research, benchmarking, and the SAE Mini Baja rule book the team derived a minimalistic frame concept that is a variation of both current variations. Through research it was found that teams who competed well had a frame that was a balanced combination of a no-nose and nosed frame, this allows for more room within the vehicle for the driver while maintaining an overall smaller volume, allowing for a lighter frame. Using ANSYS during development allowed for a minimalistic but efficient frame to be built out of a rough design. ANSYS showed where the rough frame would be most susceptible to failure and allowed for the team to implement a support at that location. Over several iterations a strong yet light frame concept was conceived and the regulation design created.

Table 2: Pugh Chart

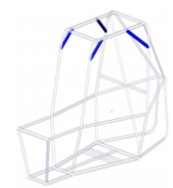
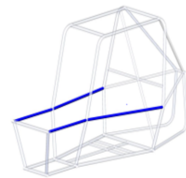
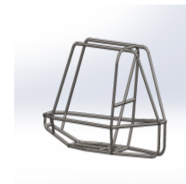
Description		Support Gusset	Nosed Frame	No-nosed Frame	Bent Forward Members Frame	Combined Nosed and No-nosed Frame
Sketch						
Criteria	Weight	Design 1	Datum	Design 2	Design 3	Design 4
Durability	3	+	0	-	-	0
Wieght	3	-	0	+	0	+
Driver Ergonimcs	1	0	0	-	+	0
Manufacturing Time	1	-	0	+	-	-
Strength	2	+	0	-	0	0
+		5	0	4	1	3
0		1	10	0	5	6
-		4	0	6	4	1
Net		1	0	-2	-3	2

Table 3: Decision Matrix

Decision Matrix						
	Criteria					
Stategies	Durability 10	Weight 10	Driver Ergonomics 3	Manufacturing Time 5	Strength 8	Total
Nosed Frame	5__10 = 50	7__10 = 70	5__3 = 15	7__5 = 35	4__8 = 32	202
No-nosed Frame	8__10 = 80	5__10 = 50	6__3 = 18	4__5 = 20	7__8 = 56	224
Support Gusset Frame	6__10 = 60	4__10 = 40	6__3 = 18	3__5 = 15	8__8 = 64	197
Bent Forward Members	4__10 = 40	5__10 = 50	9__3 = 27	4__5 = 20	3__8 = 24	161
Combined Nosed and No-nosed Frame	7__10 = 70	6__10 = 60	6__3 = 18	6__5 = 30	6__8 = 48	226

The results from Tables 3 & 4 represent that statistically the mixture of the two variants is the most efficient design choice. The team has selected to continue with this design moving forward.

6 CONCLUSIONS

The team has been able to create a functional method to creating a competitive space frame concept. The combination of the two current variations allows for a balance between a stable and sturdy frame and a more agile and light frame. From this variation the team developed a rough and unstructured frame for FEA testing development. Through this process a final and efficient frame will be developed, furthering the chances of success at competition.

7 REFERENCES

[1] bajasae.net. (2017). *2018 Mini Baja Competition Rules*. [online] Available at: http://bajasae.net/content/2018-BAJA-RULES-FINAL-2017-08-30.pdf [Accessed 6 Oct. 2017].

8 APPENDICES

8.1 Appendix A.1: Frame Rules and Requirement

Rule Section	Description
B.3.2.1 - Roll Cage Objective	"The purpose of the role cage is to provide a minimum space around the driver."
B.3.2 - Roll Cage Structure	"The following section outlines the requirements of the physical members and joining methods of the roll cage."
B.3.2.1 - Member Requirements	"Roll cage members must be made of steel tube, and may be straight or bent. Straight members may not extend longer than 1016 mm (40 in.) between Named Points. Bent members may not have a bend 24 greater than 30 deg."
B.3.2.2 - Primary Members	"The roll cage must be a space frame of tubular steel. "
B.3.2.3 - Secondary Members	"Secondary members must be steel tubes having a minimum wall thickness of 0.89 mm (0.035 in) and a minimum outside diameter of 25.4 mm (1.0 in)"
B3.2.4 – B Additional Support Members	"For bent or straight Roll Cage Members that exceed the maximum allowable length, additional support members may be added. For straight members, a single secondary member should connect from the mid-point (+/- 127 mm or 5 in.) to a Named Point. For bent members, a single secondary member should connect from between the tangents of the bend to a Named Point. At no time may a bent member have a bend greater than 30°."
B3.2.5 - Lateral Cross Member	"Lateral cross members cannot be less than 203.5 mm (8 in.) long. LC's cannot have a bend; however, they can be a part of a larger, bent tube system, provided the minimum length is met between bend tangents."
B3.2.6 - Roll Hoop	"The RRH is a planar structure behind the driver's back, and defines the boundary between the front-half (fore) and rear-half (aft) of the roll cage. The driver and seat must be entirely forward of this panel. The

	RRH is substantially vertical, but may incline by up to 20 deg. from vertical. The minimum width of the RRH, measured at a point 686 mm (27 in.) above the inside seat bottom, is 736 mm (29 in.). The vertical members of the RRH may be straight or bent, and are defined as beginning and ending where they intersect the top and bottom horizontal planes (points AR and AL, and BR and BL in Figure B-8). The vertical members must be continuous tubes (i.e. not multiple segments joined by welding). The vertical members must be joined by ALC and BLC members at the bottom and top. ALC and BLC members must be continuous tubes or adhere to B.3.2.14 - Butt Joints. ALC, BLC, RRH members, LDB and the shoulder belt tube must all be coplanar."
B3.2.7 - Lateral Diagonal Bracing	"The RRH must be diagonally braced. The diagonal brace(s) must extend from one RRH vertical member to the other. The top and bottom intersections of the LDB members and the RRH vertical members must be no more than 127 mm (5 in.) from points A and B. The angle between the LDB members and the RRH vertical members must be greater than or equal to 20 deg. Lateral bracing may consist of more than one member."
B3.2.8 - Roll Hoop Overhead Members	"The aft (rearward) ends of the RHO members intersect the RRH and define Points BR and BL (joined by BLC). The forward ends of the RHO members (intersection with the CLC) define points CR and CL (Figure B-7). CLC, BLC and RHO members must all be coplanar and bends at the aft (rearward) ends of the RHO members are not permitted. Points CR and CL must be between at least 305 mm (12 in.) forward of a point, in the vehicle's side view, defined by the intersection of the RHO members and a vertical line rising from the aft end of the seat bottom. This point on the seat is defined by the seat bottom intersection with a 101 mm (4 in.) radius circle which touches the seat bottom and the seat back. The top edge of the template is exactly horizontal with respect to gravity. "
B3.2.8.1 - Gussets for RHO and RRH	"If a gusset is used to brace the RHO and RRH to achieve the Lateral Clearance in Rule B.3.3.1 - Lateral Space the added tubes must be a primary member (B.3.2.16 - Roll

	Cage Materials); completely welded around the circumference of both ends of the gusset tube."
B3.2.9 - Low Frame Side Members	"The two Lower Frame Side members define the lower right and left edges of the roll cage. These members are joined to the bottom of the RRH at Point A and extend generally forward, at least as far as a point forward of every driver's heels, when seated in normal driving position. The forward ends of the LFS members are joined by a lateral cross member, FLC (Figure B-7). The intersection of the LFS members and the FLC define the points FR and FL. In 'Nose' designs, as shown in Figure B-14, the LFS extends forward to Point E, and is joined by a lateral cross member FLC and ELC (Figure B-7)."
B3.2.10 - Side Impact Members	"The two Side Impact Members (SIM) define a horizontal mid-plane within the roll cage. These members are joined to the RRH, defining Point S, and extend generally forward, at least as far as a point forward of every driver's toes, when seated in normal driving position. The forward ends of the SIM members are joined by a lateral cross member, DLC. The intersection of the SIM and DLC define the points DR and DL. The SIM members must be between 203 mm (8 in.) and 356 mm (14 in.) above the inside seat bottom (Figure B-11) at all positions between points S and D. In 'Nose' designs, as shown in Figure B-15, the SIM extends forward to Point G, and is joined by a lateral cross member GLC (Figure B-7). In this case, DLC may be omitted if GLC provides adequate protection for the driver's toes as noted below."
B3.2.11 - Under Seat Member	"The USM must be positioned in such a way to prevent the driver from passing through the plane of the LFS in the event of seat failure. Two options are given for the USM member: 1) The two LFS members must be joined by the Under-Seat Members. The USM must pass directly below the driver where the template in Figure B-11 intersects the seat bottom. 2) The ALC and FLC members must be joined longitudinally by the Under-Seat Member. The USM must and pass directly below the driver where the template in Figure B-11 intersects the seat bottom. "

B3.2.12 - Front Bracing Members	"Front Bracing Members must join the RHO, the SIM and the LFS (Figure B-17) at Points C, D and F. The upper Front Bracing Members (FBMUP) must join points C on the RHO to point D on the SIM. The lower Front Bracing Members (FBMLOW) must join point D to point F. The FBM must be continuous tubes. The angle between the FBMUP and the vertical must be less than or equal to 45 deg. If Front FAB, per Rule B.3.2.13.1 - Front Bracing, is used there is no angle requirement between FBM and vertical."
B.3.2.12.1 - Gussets for RHO and FBM	Front Bracing Members must join the RHO, the SIM and the LFS (Figure B-17) at Points C, D and F. The upper Front Bracing Members (FBMUP) must join points C on the RHO to point D on the SIM. The lower Front Bracing Members (FBMLOW) must join point D to point F. The FBM must be continuous tubes. The angle between the FBMUP and the vertical must be less than or equal to 45 deg. If Front FAB, per Rule B.3.2.13.1 - Front Bracing, is used there is no angle requirement between FBM and vertical.
B3.2.13 - FAB – Fore - Aft Bracing	The RRH must be restrained from rotation and bending in the side view by a system of triangulated bracing. Bracing must either be front bracing or rear bracing: • Rear Bracing - directly restrain both points B from longitudinal displacement in the event of failure of the joints at points C; or • Front Bracing - restrain both points C from longitudinal and vertical displacement, thus supporting points B through the RHO members. A better design will result if both front and rear bracing are incorporated. 38 Members used in the FAB systems must not exceed 1016 mm (40 in.) in unsupported length. Triangulation angles (projected to the side view) must be at least 20 deg. between members.
B.3.2.13.1 - Front Bracing	Front systems of FAB must connect the FBMUP members to the SIM members (on the same sides). The intersection with the FBMUP members must be within 127 mm (5 in.) measured as a straight-line distance from centerline to centerline of point C. The intersection with the SIM members (defined at Point P) must be vertically supported by further members connecting the SIM members to the LFS members (defined at

	Point Q).
B.3.2.14 - Rear Bracing	Rear systems of FAB must create a structural triangle, in the side view, on each side of the vehicle. Each triangle must be aft of the RRH, include the RRH vertical side as a member, and have one vertex at Point B and one vertex at either Point S or Point A. The tubes forming this structural triangle must be continuous members; but bends of less than 30 deg. are allowable. The third (aft) vertex of each rear bracing triangle, Point R (Figure B-18), must additionally be structurally connected to whichever Point, S or A, is not part of the structural triangle. This additional connection is considered part of the FAB system, and is subject to B.3.2.1 - Member Requirements, but may be formed using multiple joined members, and this assembly of tubes, from endpoint to endpoint, may encompass a bend of greater than 30 deg.