Design and Optimization of a Formula SAE Racecar Chassis and Suspension

by

Reid F. Allen

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Signature of Author:________________
Department of Mechanical Engineering
May 12th, 2009

Certified by :________________
Daniel D. Frey
Associate Professor of Mechanical Engineering and Engineering Systems
Thesis Supervisor

Accepted by:________________
John H. Lienhard V
Collins Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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Abstract

Designing and constructing a chassis and suspension system for a Formula SAE racecar is a highly complex task involving the interaction of hundreds of parts that all perform an essential function. This thesis examines the critical factors in designing and implementing a Formula SAE chassis from the ground up, with a focus on the performance and optimization of the vehicle as an entire system rather than a collection of individual parts. Analysis includes examining the stiffness, strength, and weight of each part, as well as design verification. The thesis will serve as a summary of the knowledge that I have accumulated over four years of personally designing and overseeing the manufacturing of the MIT Motorsports suspension, provide insight into the design of the MY2009 vehicle, and act as a guide for future chassis designers.

Thesis Supervisor: Daniel D. Frey

Title: Associate Professor of Mechanical Engineering and Engineering Systems

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1. Introduction to Formula SAE

Formula SAE is a series of collegiate engineering competitions run by the Society of Automotive Engineers (SAE) in which students must conceive, design, and build a small, open cockpit formula-style racecar. The premise of the competition is that each student team represents a small start-up company, which is designing and building a prototype racecar to sell to weekend autocross racers for less than $25,000. The competition pits the teams against each other in a bid to "sell" the design to a company that wishes to manufacture it on a large scale. Therefore, the cars are judged not only on engineering design and performance, but also on cost, manufacturability, marketing, and reliability. In comparison to many other racing series, the rules for Formula SAE are very open, allowing for a maximum of student creativity in mechanical design. The majority of the rules are intended to ensure that the vehicles built will be safe to operate, not only for the driver, but also for any spectators or team members.

Figure 1 below shows the point breakdown and weighting for each event. It is important to note the high standards that each team is held to in the judging for each event and the attention to detail that is required. Event judges are experts in the industry, usually with a minimum of 20 years of experience in their specific area of expertise. Every design flaw is scrutinized, and each compromise and design choice made must be justified with detailed analysis. During the dynamic events, the cars must exhibit a very high level of performance, while also being durable and reliable enough to withstand the very demanding racing conditions over a long period of time.

Static Events:		
	Presentation	75
	Engineering Design	150
	Cost Analysis	100
Dynamic Events		
	Acceleration	75
	Skid-Pad	50
	Autocross	150
	Fuel Economy	100
	Endurance	300
Total Points		1,000

Figure 1. *2009 Formula SAE points breakdown.*

1.1 Static Events Judging

Static events judging begins with a thorough technical inspection of the vehicle which is not scored. There are three parts to the inspection, successful completion of which earns the team a sticker. All three stickers are required to be displayed prominently on the body of the car in order to be allowed to compete in any dynamic events. The first part of the inspection is a thorough scrutineering of the vehicle, ensuring it complies with the rules. The second part is a tilt test where the car is fitted to a platform that is first inclined to an angle of 45 degrees where it is held and checked for leaks. Then the angle is increased to 60 degrees, which tests the rollover stability of the car, as the angle corresponds roughly to a 1.7g lateral acceleration. After the tilt test, the car must pass the brake, noise and kill switch test. First, the car is turned on, and both of the cars emergency electrical system kill switches are tested. Next, the car must pass the noise test in which the sound level is measured at a 45-degree angle 0.5 meters from the engine exhaust outlet, and must not exceed 110 dB. Once the car has passed both the noise and kill switch tests, it must pass the brake test. A small distance is given where the car must accelerate from a stop, abruptly apply the brakes, and successfully lock all four wheels. If the car fails any of the above inspections, it must return to the paddock area, affect any repairs, and reattempt the test. It is extremely important to come to competition with a well-prepared and tested car, as it often takes more than one try, and sometimes several, in order to successfully pass all of the technical inspection requirements. This can sometimes take an entire day or more of the competition, and delay or prevent the team from competing in dynamic events.

The first scored event is the Presentation event. The judges of this event are considered "investors" and the team must pitch their business case including market analysis, cost, manufacturing, and profitability analysis. The team that was deemed to have given the best presentation wins the event.

The Cost event includes three parts. The first part is prepared and submitted by the team in advance and includes a comprehensive cost report and analysis. Every nut, bolt, and minute of labor used to manufacture the car must be recorded on the Bill of Materials and submitted. The second part involves the judges inspecting the car, and making sure that the report submitted accurately reflects actual parts and processes used to make the car. The third part is a challenge in which students must respond to a challenge question related to manufacturing on the spot.

The most important static event both from a points and also a prestige perspective is the Design event. This consists of six judges scrutinizing the mechanical design of the car and evaluating the engineering effort put in by the students. During this event, the judges are very critical, and often push team members to the limit of their knowledge in order to find out the lengths that students have gone to in designing their parts or systems and selecting components. The first round of design judging lasts only ten minutes, after which the top 10 percent of teams are called back for design semi-finals, and given additional time to show off their designs and their expertise. From here, the top five teams are selected for the finals. It is considered very prestigious to make it past the first round of design due to the high level of competition and the ever-increasing level of quality of the cars.

1.2 Dynamic Events Judging

During the five dynamic events, the actual performance of the cars is tested. The acceleration event tests the car's driveline and traction in a straight line drag race from stopped to a distance of 75 meters. The event is worth 75 points, awarded according to a scoring formula that weights your time against the fastest time from the event. In general, each dynamic event is scored in this way. Each team gets two runs for each of two drivers, totaling four opportunities.

The skid pad event tests the performance of the car's suspension and chassis by measuring its maximum cornering grip in a constant radius turn on flat ground. The cars must traverse a figure-8 style course, insuring that the teams do not optimize the car set up for turning in one direction. Figure 2 below shows a diagram of the course layout.

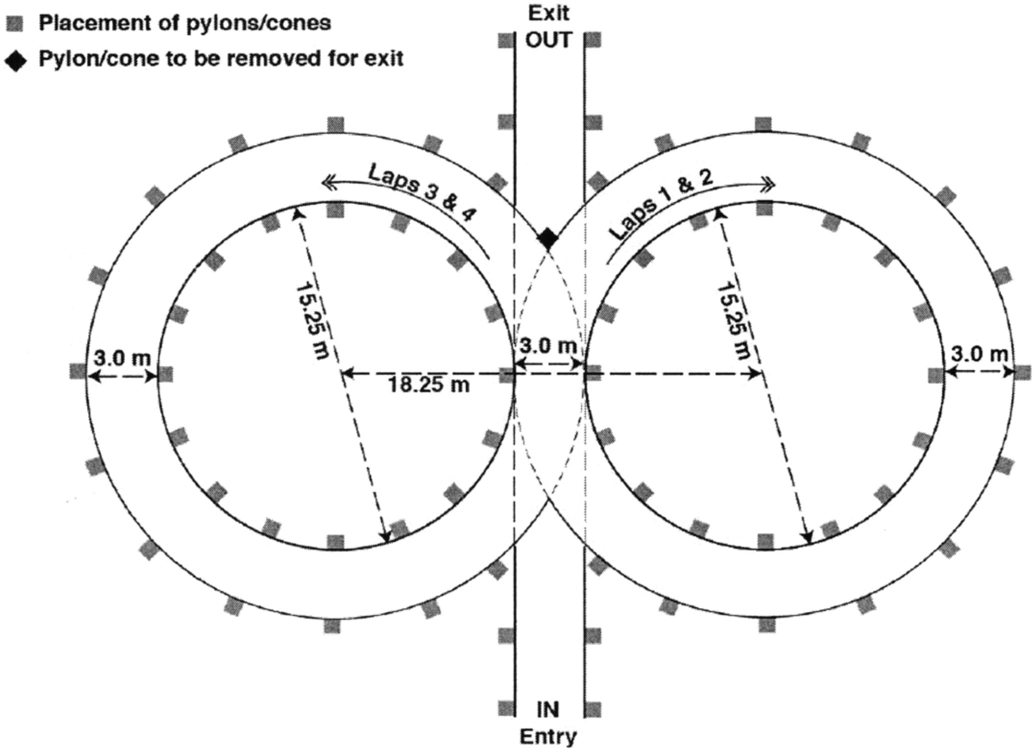


Figure 2. *Diagram of skid pad event layout*

The autocross event consists of a course with both left and right hand turns of varying radii to test the overall performance of the car over a short distance usually no more than 800 meters. The cars are run one at a time, and their times recorded.

The culmination of each competition is the endurance and fuel economy event, where the car must perform over 22 km of racing without suffering a mechanical failure, or having a single drop of fluid escape the vehicle. The courses are usually more open than the autocross event, allowing higher average and top speeds. The course designers aim for an average speed of 35 miles per hour with top speeds reaching roughly 65 miles per hour. Half way through the 22 km distance, the car is signaled into the pit lane, and a driver change must occur. The engine must be shut off, and the team is given three minutes to effect the driver change, during which time no work can be performed on the car, and event staff look over the vehicle and check to ensure that no fluids are leaking and the car is still in good mechanical order. After the change is completed, the car must be restarted by the driver, with no external aid. It is during this period that many teams are disqualified. Because of the high points value of endurance, and the low number of teams that successfully complete it each year (only about 35% of teams), it is considered a great accomplishment, and the ultimate goal for any team. Regardless of any of the other events, if the car completes the endurance, the competition is considered a success. The fuel economy event consists of measuring the fuel put into the car at the start of endurance, and measuring the remainder of fuel left in the tank at the end, and ranking the teams in order of least consumption.

2. Design Constraints

At the beginning of each year as the team sets out to design and build a brand new Formula SAE racecar, it is important to have a clear and concrete list of design criteria and keep these in mind throughout the entire design process. For a Formula SAE car, the main constraints in general order of importance are:

1) Compliance with rules

2) Meeting functional requirements

2) Stiffness/strength/durability

3) Weight

Each component of the chassis and suspension can be judged by these criteria, though naturally they differ slightly for each application. The focus of this thesis is the combined design of the frame and suspension as an entire system, so less emphasis will be placed on the details of the design of specific components.

2.1 Rule Compliance

The Formula SAE Rules Committee releases a new version of the rules governing the competitions each year. The document has grown over time to over 100 pages, nearly 40 pages of which govern the technical regulations of the cars themselves. The year 2009 saw some very large and controversial changes, forcing teams to adapt and change their designs.

2.1.1 Frame

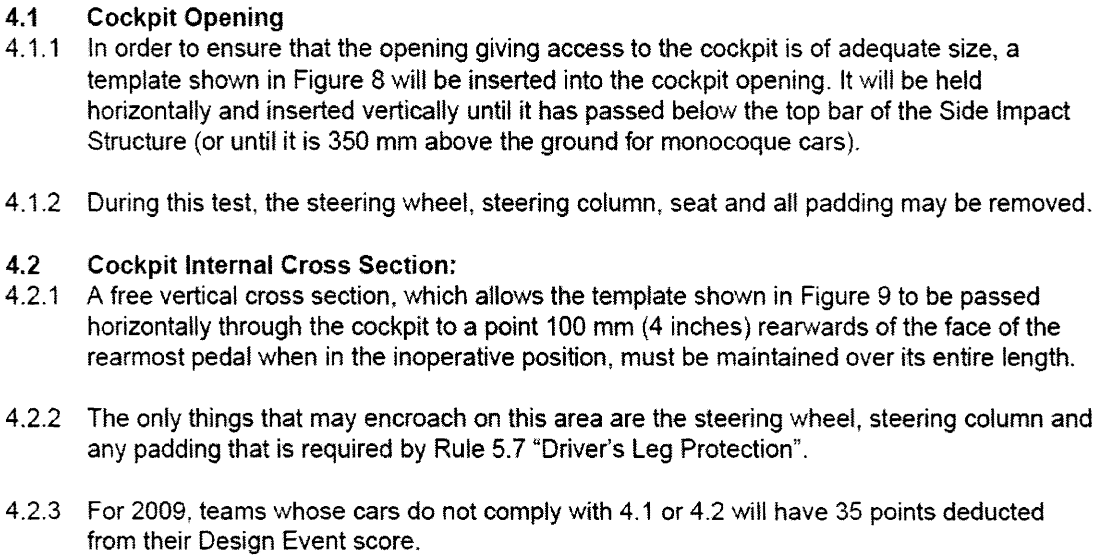
The rules pertaining to the frame are lengthy and sometimes difficult to understand, but for the year 2009 Formula SAE competitions, several major rule changes were made, precipitating large changes to the frame design. In this area, the rules deal entirely with safety and ensuring that teams build structures that can withstand an impact from both the front and side with the driver sustaining minimal injuries. The structure for the front and main roll hoops, front bulkhead, and supporting braces are all specified in the rules as to their general location and minimum material strength. Figure 3 below shows the requirements for each of these 'Primary Structure' items.

ITEM or APPLICATION	OUTSIDE DIAMETER X WALL THICKNESS
Main & Front Hoops, Shoulder Harness Mounting Bar	1.0 inch (25.4 mm) x 0.095 inch (2.4 mm) or 25.0 mm x 2.50 mm metric
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment (except as noted above)	1.0 inch (25.4 mm) x 0.065 inch (1.65 mm) or 25.0 mm x 1.75 mm metric or 25.4 mm x 1.60 mm metric
Front Bulkhead Support	1.0 inch (25.4 mm) x 0.049 inch (1.25 mm) or 25.0 mm x 1.5 mm metric or 26.0 mm x 1.2 mm metric

Figure 3. *Table of Minimum Material Requirements for the Primary Structure*

If any deviations are made from these materials, an SEF, or Structural Equivalency Form must be submitted with calculations showing that the substitute is as strong as or stronger than the minimum in both bending and buckling. In addition to specifying material minimums, the rules also specify the geometry of the main and front roll hoops that protect the driver in the event of a rollover. Bracing and load paths must be direct and intersect with major joints, or 'nodes' on the frame. Despite the depth and breadth of the rules in this area, innovation is still possible, and many good solutions exist. Optimizing the frame in terms of packaging and interdependencies with other systems and components is what separates a good frame from a great frame, and is the major focus of this thesis.

New for the year 2009, are rules governing the driver's cell and cockpit area. These rules mandate that large templates be able to be passed horizontally through the front of the frame, where the driver's lower body would be, and vertically through the cockpit opening. The rules were designed to improve the safety of the vehicles and make them more comfortable for larger people to drive. Because there is no minimum weight in Formula SAE, there is a large incentive to make the frames as small and light as possible and push the envelope in terms of driver comfort and safety. Figure 4 shows the text outlining the new regulations. While the rules will have the desired effect of increased safety, they were met with stiff resistance from students and teams. Some teams have been using the same general designs for several years, and the new rules forced teams to start over with a new frame design. In addition, because of the increase in size of the frames, some teams affectionately named the new rules the "Formula Bus" rules because of the change in the appearance of the cars.



4.1 Cockpit Opening

4.1.1 In order to ensure that the opening giving access to the cockpit is of adequate size, a template shown in Figure 8 will be inserted into the cockpit opening. It will be held horizontally and inserted vertically until it has passed below the top bar of the Side Impact Structure (or until it is 350 mm above the ground for monocoque cars).

4.1.2 During this test, the steering wheel, steering column, seat and all padding may be removed.

4.2 Cockpit Internal Cross Section:

4.2.1 A free vertical cross section, which allows the template shown in Figure 9 to be passed horizontally through the cockpit to a point 100 mm (4 inches) rearwards of the face of the rearmost pedal when in the inoperative position, must be maintained over its entire length.

4.2.2 The only things that may encroach on this area are the steering wheel, steering column and any padding that is required by Rule 5.7 "Driver's Leg Protection".

4.2.3 For 2009, teams whose cars do not comply with 4.1 or 4.2 will have 35 points deducted from their Design Event score.

Figure 4. *New rules governing cockpit size.*

To illustrate the large changes necessary to the MIT MY2009 vehicle, Figure 5 below depicts the MIT Motorsports MY2008 frame design from the side and top view with solid models of the new templates required superimposed in red.

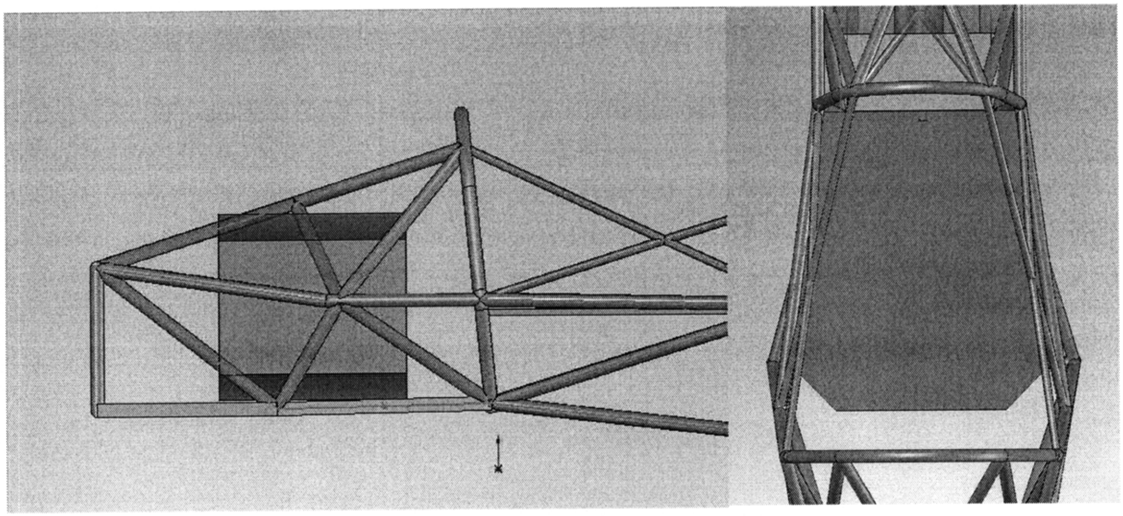


Figure 5. *Solidworks model of MY2008 Frame showing interference with new 2009 mandated templates.*

It is easy to see the front most template intersect the frame in several places. Most notably, the two diagonal braces for the upper bulkhead supports cross directly through the red zone. These braces are crucial for proper bracing of suspension loads and presented a significant challenge in the redesign of the frame. From the top view, the cockpit-opening template intersects with almost the entire upper cockpit bracing, in addition to the steering column support, which is not pictured in the above model.

2.1.2 Suspension

The rules governing the design of everything between the frame and tire contact patch of the ground is much more open than that of the frame, as there are less safety issues involved. In general, there are only three main restrictions on the design of the suspension. It must have a minimum of 50.4 mm of useable travel, 25.4 mm in each direction, have 25.4 mm or 1 inch of ground clearance at all times, and the wheels must be a minimum of 203.2 mm or 8 inches in diameter. While the rules are quite open, because of the heavy interdependencies that exist with the frame, the frame rules place large design constraints on the performance of the suspension as will be detailed in a later section.

2.2 Meeting Functional Requirements

Each component of any large assembly must have its functional requirements and interdependencies identified very early in the design process so that problem areas and complications can be identified early and mitigated. In designing a frame for Formula SAE, the most important design constraint besides meeting the rules is the mounting of the suspension links, anti-roll bars, rockers, and coil-over shocks and springs. The kinematics of the suspension has the single largest effect on the vehicles dynamics and handling, and it is crucial that the motions of the wheel and tire assembly throughout the ride travel be optimized according to data provided by the tire manufacturer. Therefore, frame design must be determined largely by the design of the suspension. In itself, the suspension comprises the highest part count of any system on the car and requires the most time to fabricate. It must connect the wheel and tire with the chassis through the wishbones, support the braking system, and be easily adjustable to be able to tune the dynamics of the car for different situations.

The next largest part that must incorporate into the frame is the engine. Besides the driver, the engine is the single largest mass of any part of the car, weighing roughly 110 lbs. That means it should be mounted as low in the car as possible to lower the center of gravity, and in the proper place longitudinally, depending on the desired weight distribution of the car, the wheelbase, and the angle of the back of the driver seat. Packaging of the intake, exhaust, and fuel tank must also be given consideration when designing the engine mounts. Being made of a very stiff block of aluminum, the engine can also be used to increase the torsional rigidity of the frame, and provide a stiff location to mount suspension pivot points.

Because it is advantageous to start frame and suspension construction as soon as possible, the design of other systems is usually not yet finalized and these systems must be designed around the frame. This includes many of the powertrain ancillary systems such as electronics, cooling, oiling, and fueling.

2.3 Stiffness, Strength and Durability

In addition to complying with the rules and fulfilling its functional requirement, each part of the frame and suspension must meet a certain structural target. For the frame, the most common metric to measure stiffness is its torsional rigidity. This is because as the car enters a corner, the suspension on the outside of the corner will transmit loads horizontally through suspension wishbones and vertically through the push rod, which actuates the shock and spring. For the race engineer, whose job entails diagnosing handling problems and tuning the car for different track or weather conditions, a vehicle that is easy to analyze and adjust is much easier to work with. If the chassis is sufficiently stiff, the engineer can essentially make the assumption of the frame as a rigid body. That means that the coil springs at each corner of the car are the only springs in the equations of motion that govern the dynamics of the vehicle except the tires. The engineer can then be certain that when he or she makes a decision to stiffen the front springs to reduce the oversteer of the car, that changing the springs will have the desired effect of reducing the load transfer at the rear of the car, reducing the loads at the contact patch of the tire, and increasing the amount of tractive effort available to the rear tires. If the frame is too soft either overall or locally at the suspension mounts, then it must be modeled as having several springs in series, and changing the coil springs will not have the desired effect.

In terms of the design of suspension components, stiffness is equally as important. As mentioned previously, controlling the interaction between the tire and the road surface is extremely important to maintain the optimal conditions for the tire under all circumstances. This includes the camber angle of the tire, the toe or slip angle that the tire assumes in relation to its direction of travel, and location of the roll center. The roll center is the point about which the chassis rolls when a side force is applied, or in other words it is the point where if a side load were applied, no roll of the chassis would occur. Determining the appropriate stiffness of suspension components is much more complicated than that of the frame. Rather than just being stiff enough to be ignored, the stiffness, or compliance of each component must be known to ensure that the suspension remains within an acceptable range of the optimal under all conditions. This will help to avoid many problems in tuning the car later on. For example, the toe of the rear wheels in relation to the straight-ahead position is crucial for vehicle stability. If the rear wheels are toed-out, where the front of the wheels are further apart than the back, it can lead to a very unstable car that sometimes results in sudden and severe oversteer. If the car is aligned to have toe-in, but the suspension uprights are not stiff enough, compliance could cause the rear wheels to toe-out under heavy cornering load. The toe of the wheel would change as the driver turned into the corner, and would suddenly become unstable, resulting in a car that is unpredictable and difficult to drive.

Strength and fatigue life of these components that are subjected to oscillating cyclic loading is also extremely important. In general, if one is designing for stiffness, the part will be inherently strong enough assuming proper material selection. However, care must still be taken to minimize stress concentrations and take extreme care in preparing parts that must be welded.

2.4 Weight

Keeping the weight to a minimum is essential to every aspect of the performance of any racecar. Not only does additional weight translate into slower acceleration, but it means that the brakes must be designed to decelerate that mass as well. More weight is also extremely detrimental to the handling and cornering performance of the car due to the load sensitive nature of modern pneumatic tires. The coefficient of friction between the contact patch of the tire and the road surface falls off dramatically as the load on the tire is increased. Increased weight also raises the center of mass of the car, which incurs more body roll and the car will have less stability in cornering. In addition, the polar moment of inertia of the vehicle will be greater, resulting in slower yaw response of the car to steering input and slower direction changes, which is a huge disadvantage on the tight autocross courses, which often include one or more slaloms.

To this end, the entire vehicle must be optimized and communication between designers is paramount. It is easy to make very stiff components that are heavy. Diligent and clever designers can make parts that fulfill all of their functional requirements, hit their stiffness and strength targets, and still use material as efficiently as possible to keep weight to a minimum.

3. Design Methodology

3.1 Material selection

For the frame, the material for the primary structure is mandated to be mild or alloy steel tubing with the dimensions specified above in Figure 3. Construction of the entire frame from steel tubing is the most common method in Formula SAE because of the minimum of tools and equipment required and the low cost of materials. A small handful of teams attempt alternative constructions such as a carbon fiber monocoque or aluminum construction, however history has shown no distinct and clear advantage of one type of chassis over another in the context of Formula SAE. A well-designed steel tube frame should weigh less than 60 lbs and be sufficiently stiff. Because of the higher level of analysis required for the alternate constructions, they are often not optimized and many weigh more than and are less stiff than a good steel frame. Once the decision is made to use a steel frame, the only choice left to make is the specific alloy and tubing sizes. Chrome-Moly steel, or SAE 4130, is a steel alloy that includes higher amounts of Chromium and Molybdenum. It is stronger than mild steel, has excellent welding properties, and is available in a very wide range of tubing and sheet sizes due to its wide use in the aircraft industry. These make it an easy choice for building a Formula SAE steel space frame.

3.2 Suspension Packaging and Kinematics Analysis

Because the inboard suspension mounting points determine the location of the major frame structures, simultaneous design is required. In the past, the frame and suspension were designed by two separate people, each using a different software package. This meant that every week, the frame designer would receive a new set of suspension mounting points from the suspension designer, and would have to update his design accordingly. This leads to a slower design process, more redesigns, and complications keeping track of revisions. This year, a combined kinematics and frame model was produced, which allowed some basic level kinematics design to be done in Solidworks alongside the frame model, with frame structures being driven in the model directly from the suspension points. Figure 6 below depicts the Solidworks model of the kinematics used to drive thee frame model.

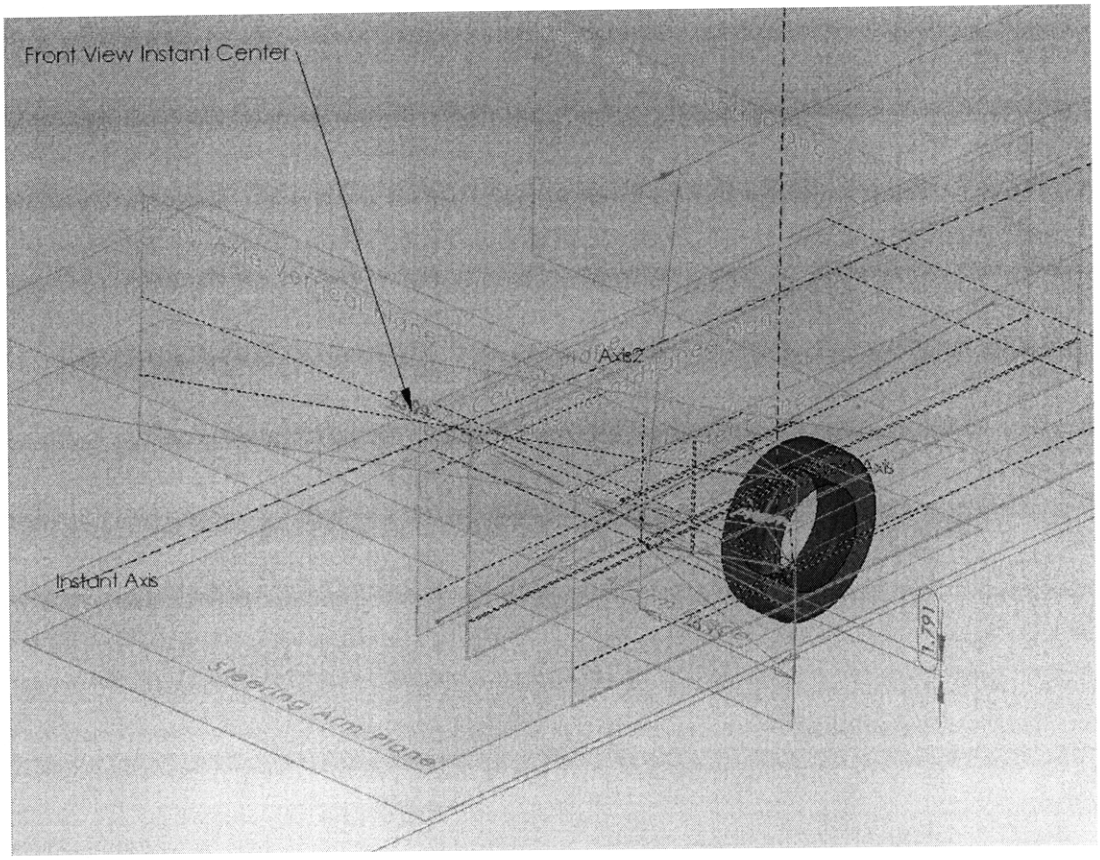


__Figure 6.__ Student generated kinematics analysis model.

Once the basic layout of the frame and suspension analysis was completed, a more thorough study of the geometry could be done to fine tune the performance of the suspension and look at transient effects such as camber gain, bump steer, roll steer, and track change. This was done using a simple and inexpensive program called WinGeo3. It is a geometric solver with parameterized models of many different types of suspension layouts that can be modified to suit almost any need. As both the front and rear suspension on the car are dual-wishbone and push-rod actuated, geometric analysis is straightforward. Figure 7 below shows a screen shot of the MY2009 front suspension in WinGeo3. A dual-wishbone set up was chosen over other designs as it is allows the designer the greatest degree of flexibility in choosing the kinematics with the fewest compromises. On road cars, many compromises have to be made for cost and packaging reasons, especially in front-wheel drive cars with transversely mounted engines, as they leave the least amount of room for mounting of the suspension.

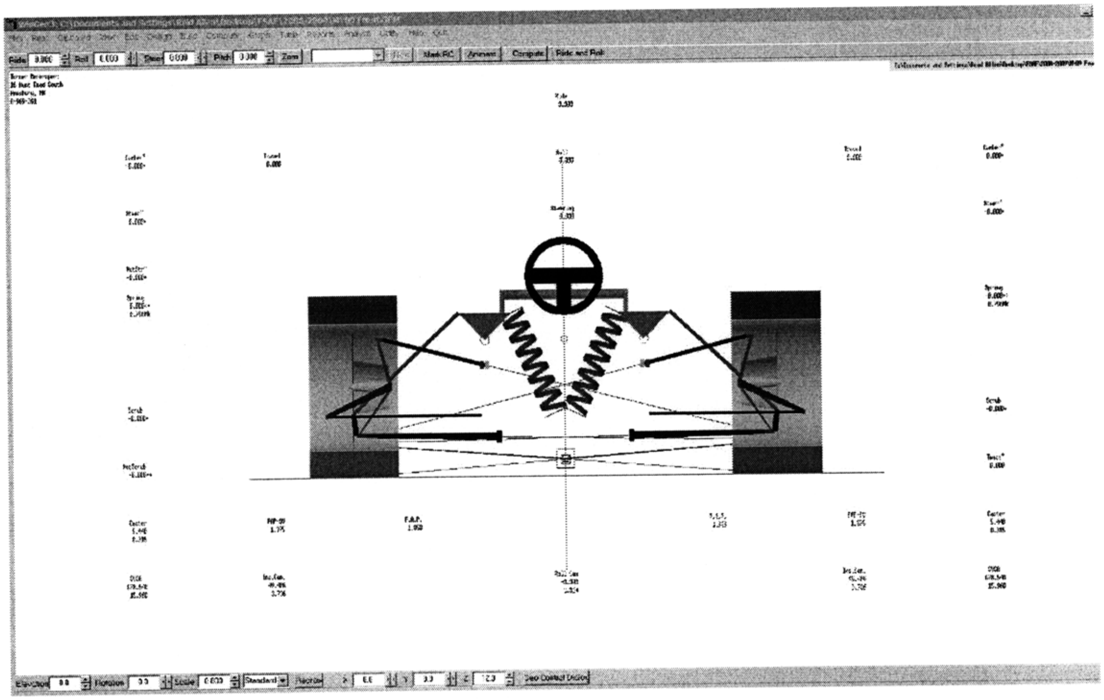


Figure 7. *WinGeo3 analysis of the front suspension kinematics.*

The best suspension modeling software in the world will not get you very far however if you do not know what targets you are trying to hit. That is why the field of tire modeling and tire testing has grown substantially in the last several decades as vehicle dynamics models have grown more complex. A modern pneumatic racing tire produces varying amounts of side force or traction under different operating conditions. Large tire testing machines exists which vary all parameters relevant to tire operation and record the performance of the tire. This data can then be used to extract specific pieces of information, or to create a more general mathematical model for the tire. Parameters affecting the maximum grip of the tire are its slip angle, or angle between the direction of heading of the tire and the trajectory of the vehicle, the camber of the tire, and the load on the tire, the inflation pressure, and the temperature of the rubber. It is the job of the suspension designer to make sure that the tire operates as close to its optimal point at all times. This requires complex knowledge of the types of courses the car will be running on with typical cornering radii, the weight of the vehicle, and the location of the center of mass.

3.3 Vehicle Dynamics Modeling

In addition to optimizing the kinematics for maximum tire potential, significant effort needs to be applied to modeling the dynamics of the vehicle as a whole. As stated previously, the load transfer from the inside wheel to the outside wheel in cornering is the driving physical phenomenon. Because only a certain amount of traction is available at the tire, in order to maximize the overall cornering ability of the vehicle, the usable traction should be spread over each of the four tires as evenly as possible. In general, the traction available at the tire is available for any combination of braking, turning, or accelerating. A graphical depiction of this is commonly known as the 'traction circle' where the radius of the circle is the maximum coefficient of friction available. Figure 8 shows a typical traction circle.

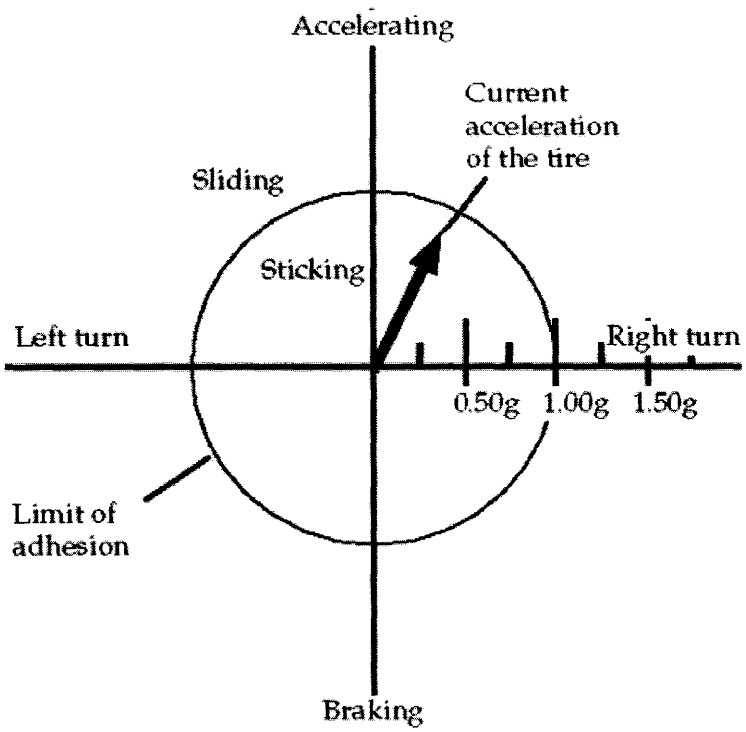


Figure 8. *A typical traction circle.*

Because of this phenomenon, the front tires are often tasked with doing more of the turning work so that more traction is available at the rear tires for accelerating the car well out of the corner, which is essential to overall speed of the car.

In order to calculate just how much roll stiffness each end of the car should provide, Milliken's *Race Car Vehicle Dynamics*, or *RCVD* as it is commonly referred to, was an excellent reference. RCVD is colloquially known as the 'Bible' on vehicle dynamics. Chapter 5 on simplified steady-state stability and control and Chapter 16 on ride and roll rate calculation are the two most important chapters for developing most of the vehicle dynamics analysis required for a racecar at this level of competition.

4. Manufacturing

4.1 Timeline

Tasking a group of students to design and build a new racecar from scratch within the timeframe of two semesters is a very ambitious goal and requires precise scheduling and a clear timeline to ensure that the car is completed with enough time for testing and repair of any unforeseen issues. A trade-off must be made between leaving enough time for thorough design, and leaving enough time for thorough testing and verification. This year the team has opted out of the normal Virginia and Michigan competitions in favor of the California competition for this reason. The Michigan competition is in May each year, and always conflicts directly with MIT final examinations. The California competition takes place in late June, giving an extra month to work on the car without the burden of schoolwork. Before being incorporated into the curriculum this year through the sophomore 2.007 design class, each member of the team worked strictly as a volunteer, receiving no class credit. Other challenges unique to college organizations include very high turnover of people and difficulty with continuity.

4.2 Frame Manufacturing

Because it provides the main structure for the entire vehicle, the frame must be built as early and as quickly as possible. In addition, it is a great opportunity for new members to get involved, become familiar with the team and the car, and become comfortable with the machine tools. In previous years, this team has usually started frame construction no later than October 1. However, this year the team was severely handicapped as we were forced to move out of our old facility and could not move into our current workshop location until after January 1. This meant we had to start construction of the new car with a three-month deficit, meaning quick construction was more important than ever. See figure 9 below for a diagram of the MY2009 frame with important structures labeled.

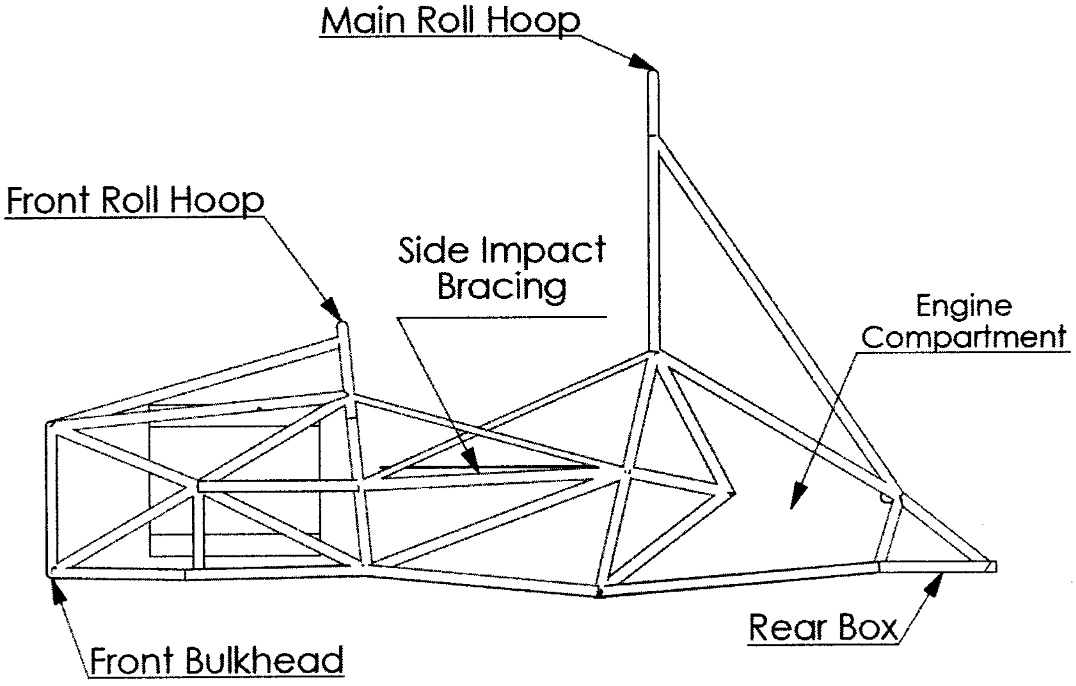


Figure 9. *Labeled frame diagram.*

4.3 Roll hoop bending

Each year the construction of the frame begins with bending the radii for the front and main roll hoops. The most efficient design of the roll hoops requires large bend radii, usually greater than 200 mm or 8 inches. No machine exists on MIT campus to bend tubing with such large geometry, so custom dies had to be built. A full-size plot of the each roll hoop was made and traced onto sheets of ¾" marine-grade plywood. The contours were then carefully cut out, allowing for the thickness of a strip of metal to act as a heat shield, and checked against the plots for accuracy. The metal strip makes sure the red-hot tube does not burn the wood as it is pulled and stretched against the die. It is essential that the tube maintains its profile throughout the bend and no buckling or kinking of the tube occurs which will ruin its strength and be unable to pass the technical inspection. Therefore, the ends of each length of tube are sealed with wood after it is filled with fine sand. The metal is heated gradually section by section to a dull cherry-red color with an oxy-acetylene torch to reduce the force required to bend it and increase the ductility of the metal. It is important not to overheat the metal, and to heat the tube uniformly. This process takes some time and requires a minimum of four people, as the tube must be removed from the jig after each section is bent in order to heat the next section. Quick placement and securing of the tube in the jig is necessary so the tube does not cool down too much before it can be bent. The person on the end of the tube should be careful to pull the tube as well as bend it to make sure it stays in contact with the jig, does not kink or wrinkle, and stays in plane.

4.4 Tube Preparation and Jigging

Besides the two roll hoops, each of the other frame members are straight and need only to be cut to length and have their ends cut to the correct profiles. Last year each joint was modeled and the correct profile was cut using a CNC laser cutter by an outside contractor. Each of the frame members then only needed minimal preparation before being welded into place. Several problems were encountered with the method that were determined to be detrimental enough for it not to be used again this year. The first was the large initial time commitment required in preparing the CAD model and extracting each of the tube profiles in a form readable by the CNC machine. The second was that it took almost a month of lead-time after this before we had the tubes in the shop and could commence building the frame. Because our construction timeline was truncated with a later start time, the extra development time could not be justified. In addition, because the design of the frame was significantly different for this year over last year, it was advantageous to retain flexibility and the ability to make last minute adjustments if the cockpit templates did not fit.

This means that each of the tubes had to be either cut using a one-inch hole saw for simple fits, and hand ground on a bench grinder for more complex joints. This might seem more time consuming, but with each tube made confidence and skill increases, and so does productivity. In addition, once one tube is made, the profile can easily be mirrored by making a paper template and copying it over to the equivalent tube for the other side of the car.

Jigging is the term used to describe the method by which frame members are held in place before and during welding. Jigging can be accomplished by many different methods, each differing in cost, time, and accuracy. In general, more accuracy is paid for with more money and more time. Taking into account that a Formula SAE team builds only one car each year, and time is a crucial factor, a balance is struck between accuracy and speed. A full-size plot of the frame is made and secured to an ultra-flat granite table on which the frame is built. Any sections of the frame that involve a structure that is in-plane are built first as they are the easiest to make accurately. Wooden blocks are screwed down to the table on top of the plot to place the tubing accurately, and they are clamped in place as they are welded. The front bulkhead and the rear box are made in this way. After these two sections are made, the front bulkhead can be connected with the front roll hoop. A digital level accurate to 0.1 degrees is used to set the angle of the bulkhead and roll hoop, and the bottom of the roll hoop is placed using the frame plot. Supporting struts are then tack welded in place to hold the two sections fixed while other frame members can be placed. The frame members in between need only to "connect the dots" and precise jigging is not required.

The frame members which are the most crucial to place accurately are the suspension runners. Any slight variation in the height or width of these runners from side to side would change the location of suspension mounting points and could cause the car to handle differently in right and left hand turns, which is highly undesirable for an autocross car. Therefore, precise jigs are manufactured from steel tubing, welded, and faced to a precise height using a milling machine. These jigs are used to set the height of these runners in relation to the rest of the frame, which is crucial to the roll center location. Likewise, similar jigs are made to accurately set the width of these runners in relation to the centerline of the car.

Next, the main roll hoop is jigged in place in a similar manner to the front roll hoop. The bottoms of the tubes are located using the plot, and the angle is set using a digital level. The side impact and upper cockpit bracing can then be easily fit in place and welded. The rear box is then put in place and connected to the main roll hoop via the main roll hoop braces. The engine mounts are the last major part of the frame to be completed. An empty engine block is placed on the plot according to the design and specifications of the powertrain and secured in place. The engine mount tubes are then ground to fit and welded in place. It is important to make aluminum spacers to fit between the engine block and the frame mounts to allow side-to-side movement of the engine that greatly simplifies the task of removing and replacing the engine later on. Once this is done, the frame is largely completed, with only minor braces and mounting tabs left. This year with the help of several excellent new members, a dedicated welder and a lot of caffeine, the frame was completed to this stage in only 13 days, which is a new record for this organization.

4.5 Welding

Each weld on any component on the car is done using a TIG, or Tungsten-Inert-Gas welding process. It uses a Tungsten electrode that is shielded with Argon gas to heat the metal using electric current. Filler material is added separately by hand. TIG welding is much preferred over other methods because of the quality of welds produced. Because of the highly focused electrode, shielding gas, and the large degree of control the welder has over the heat intensity, very strong and consistent welds can be produced. Unfortunately, this method takes a long time to master and takes significantly longer than other methods. Care must also be taken to clean, debur, and degrease each of the pieces to be welded to minimize the amount of contaminants in the weld and reduce the amount of smoke created which can increase the fatigue of the welder.

4.6 Finishing

In order to provide a frame, which is clean in appearance and protected from the elements, dirt, and grease, the bare metal must be finished in some way. Powder coating is typically the paint of choice because of its extreme durability. The frame must first be cleaned of all dirt, grease or oxidation, and then is charged electro statically. The powder, which is typically a thermoset or thermoplastic polymer, is attracted to the charged frame and clings to it. The frame is then placed in an oven and baked at temperatures of roughly 200 degrees Celsius. The powder melts and 'flows' forming a very smooth and tough coating.

4.7 Suspension Manufacturing

The A-arms are typically the first parts of the suspension to be fabricated, as they are very time intensive to make. Functionally, the A-arms are very simple and must connect the outboard suspension pivot point with the inboard mounts on the frame. A typical suspension A-arm or wishbone consists of a bearing pocket on the outboard side, two steel tubes welded to the bearing pocket, two threaded inserts welded to the ends of each tube, and rod-ends installed in the threaded inserts. A spherical bearing is installed in the outboard bearing pocket via a process called V-groove staking. In order to increase the stiffness and strength of the A-arms, slight deviations were made in part design and manufacturing. In 2008, a cylindrical bearing pocket was turned on a lathe and the tubes had to be deformed on the ends and ground to fit up to the circular bearing pocket as seen below in Figure 10.

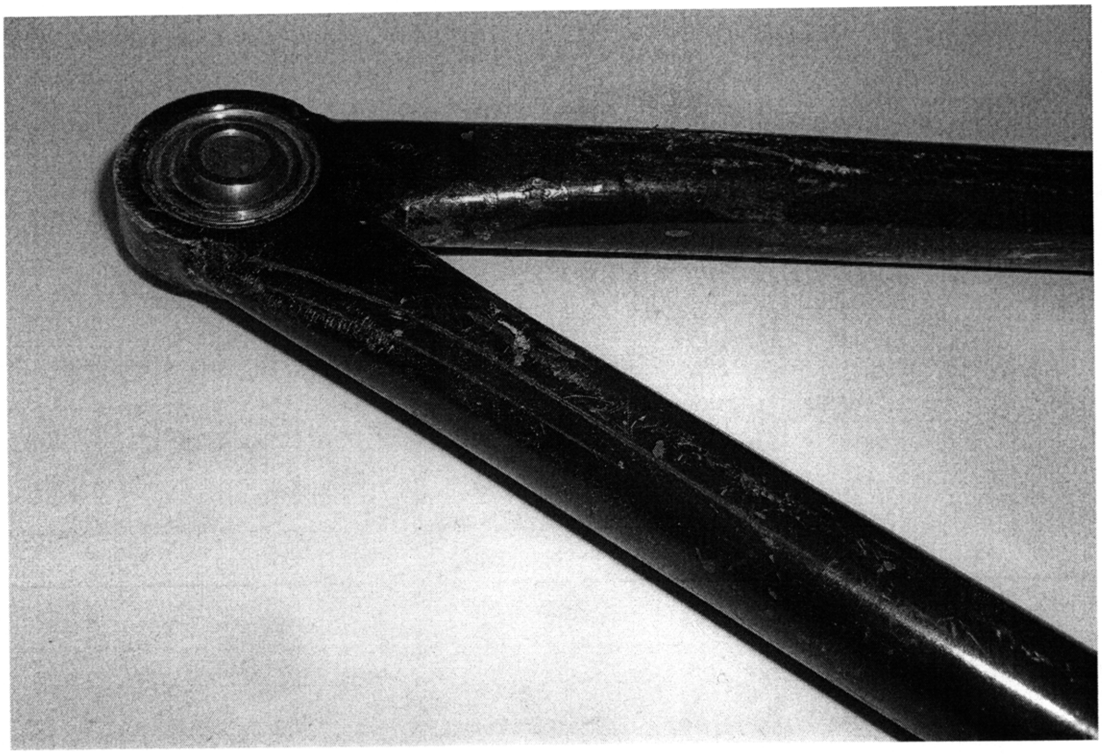


Figure 10. *Completed front upper A-arm from the MY2008 vehicle.*

There are several problems with this design. The first is that jigging to make sure the bearing pocket stays in plane with the tubes throughout final welding is very difficult. The second is that there is a minimum of weld area between the tubes and the bearing pocket that could lead to a catastrophic fatigue failure, most likely to occur under heavy braking. For MY2009, bearing pockets were cut on a CNC OMAX water jet machine from steel plate stock. This allowed the geometry to extend several inches into the tube, providing a much stiffer and stronger connection for the bearing pocket, and quadrupling the weld area. Rather than being hand ground, simple slots were cut in the tubes using the proper size end-mill on a milling machine. Figures 11 and 12 below show a bearing pocket before final machining and a new completed A-arm. The raw bearing pocket is marked "BAD" as the plate stock was not properly secured, and it shifted during cutting resulting in an unusable part. Luckily, two simple clamps fixed the problem and new pockets were cut very quickly. Each pocket was then fly-cut on a milling machine to the correct thickness, and the ends were then ground round on a belt sander. The final inner diameter of the bearing pocket itself was left undersized, as final reaming must be done after all welding is completed and any deformation due to uneven heating and cooling has occurred, which makes sure the bearing fit will be as good as possible.

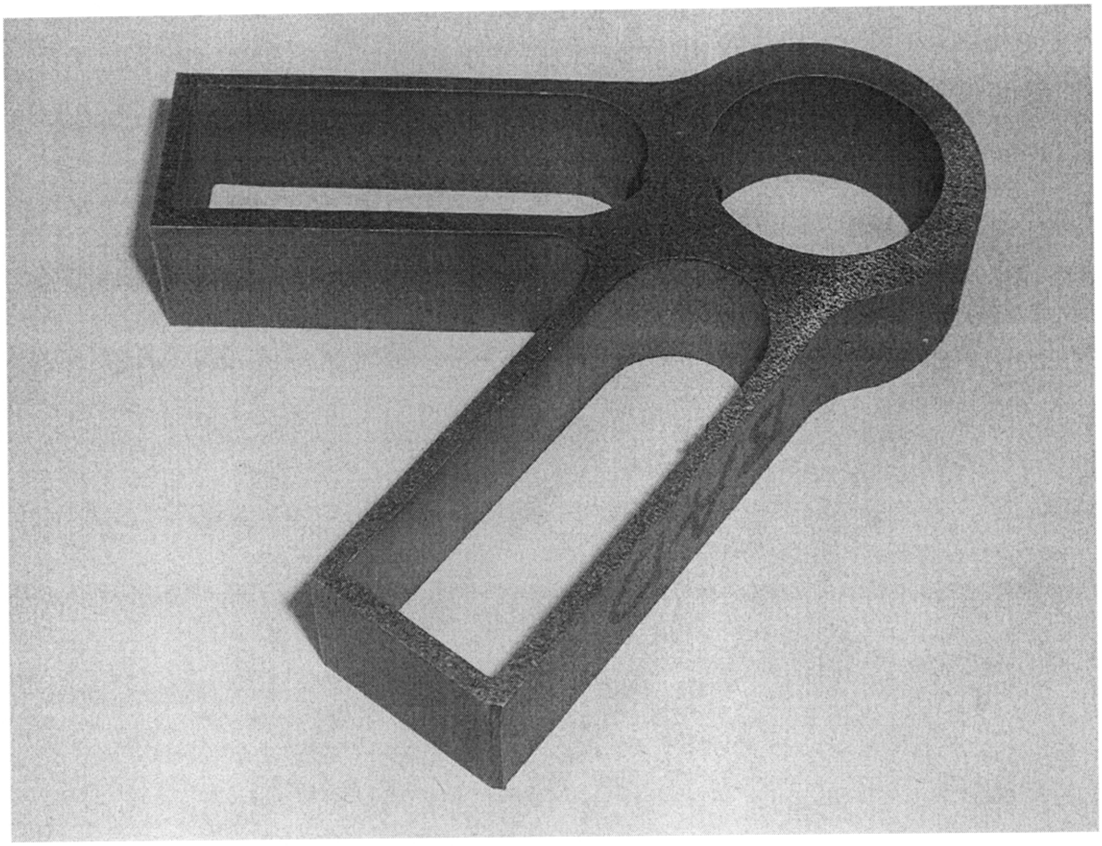


Figure 11. Waterjet cut A-arm bearing pocket.

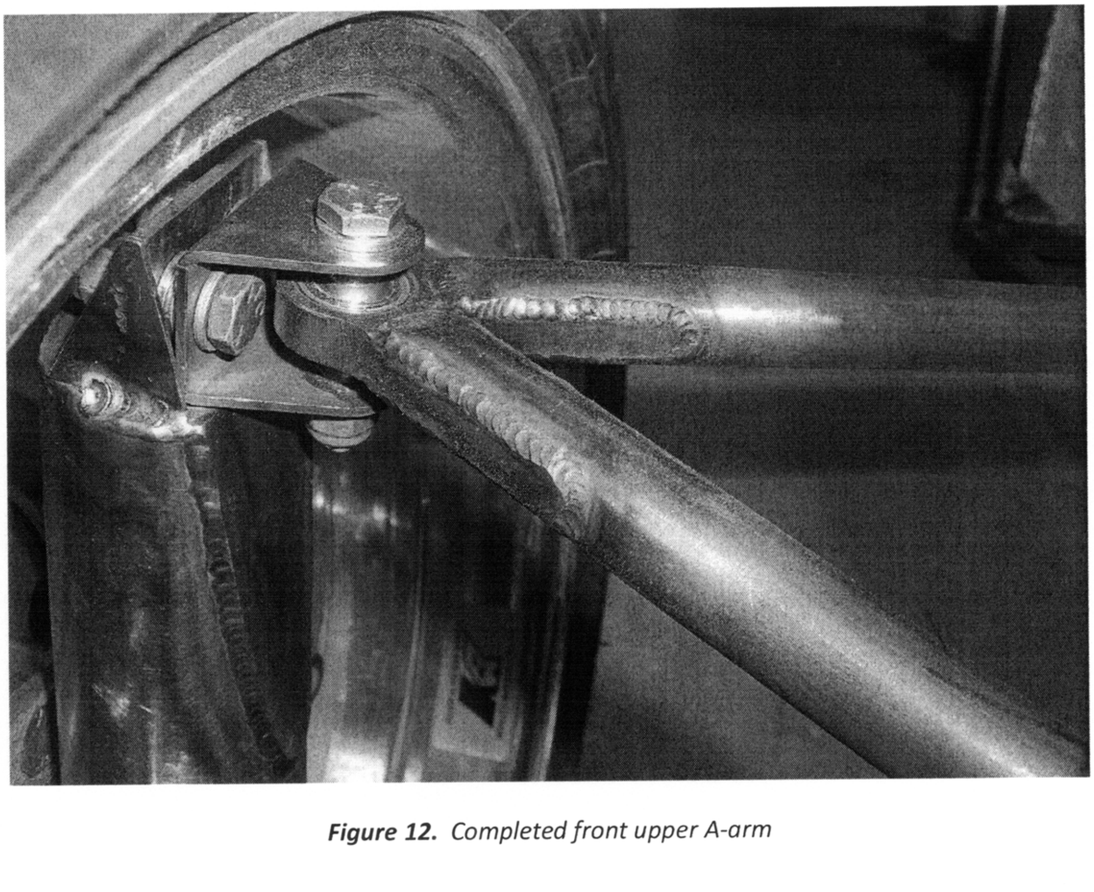


Figure 12. Completed front upper A-arm

New Hampshire Ball Bearings graciously supplied the spherical bearings used on the outboard of the A-arms to the team. Each bearing has a small V-groove in each side, which must be swaged or staked into a corresponding chamfer in the bearing pocket using a specific die. Figure 13 below shows a diagram of the staking set-up. The staking force must be precisely applied to ensure that the bearing is not too loose or becomes bound up due to excessive force. The bearings were installed using an Instron machine in one of MIT's materials processing labs where the force could be measured exactly. Using bearings of this type is advantageous because it eliminates the need for snap rings or other methods of bearing retention, which allows the bearing pockets to be made smaller, further simplifying upright design.

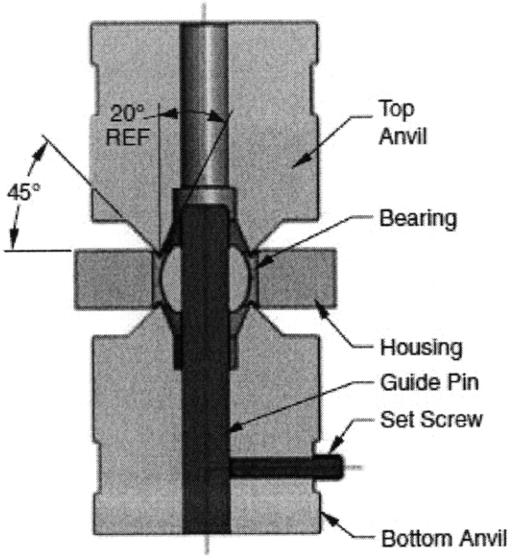


Figure 13. *Diagram of V-groove staking procedure.*

The rockers or bell cranks were designed such that they could be rapidly produced. For the front rockers, which had to use a two-piece design for packaging reasons, the structure of the rocker (for which four identical pieces were required) was simply cut on a water jet machine. Four identical bearing pockets were turned on a lathe, and then the two pieces could be welded together. The most time consuming process involved setting up the welded pieces in the lathe using a four-jaw chuck so that the final diameter on the bearing pocket could be machined. The same process was repeated for the rear rockers, except that the rear rockers were designed to be one piece, and only two bearing pockets needed to be machined.

Because of the uprights new design utilizing tubular 4130 steel rather than sheet, manufacturing was simplified greatly. Previous methods required cutting large amount of steel sheet on a water jet, which then needed to be bent into shape on a sheet metal break. This created problems with imperfect fit-up and difficulties in precise jigging. This year, the spindles for the front uprights and the bearing pockets for the rear uprights were machined on a Hass CNC lathe. Next, the tubing that makes up the main structure of the uprights was cut using an EZ-Trak milling machine to cut the final profile to be certain of perfect fit up which will increase the strength of the welded joints. The machined parts were then carefully fit together and bolted down before welding. See figure 14 below for pictures of the completed and assembled front and rear uprights.

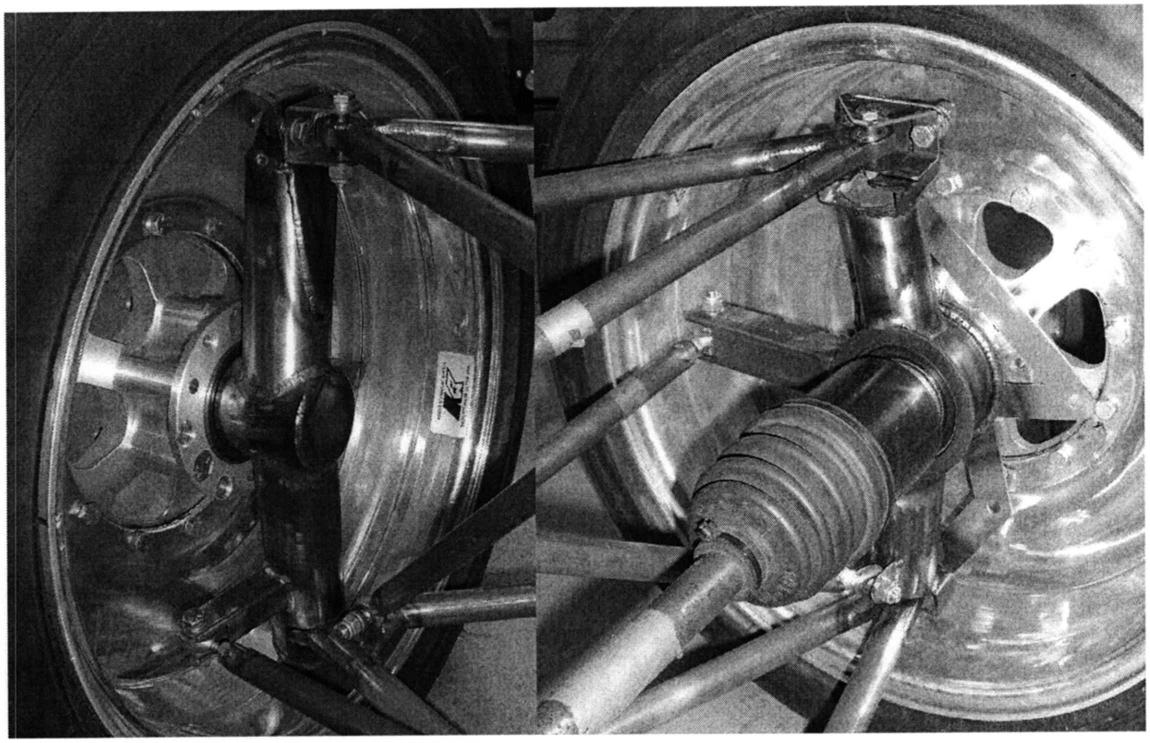


Figure 14. Completed front and rear uprights.

5. Testing and Verification

5.1 Frame

Physical torsion testing can be done to validate the calculations made with FEA. The torsion tester should be designed such that it mimics the real-world loading conditions as much as possible so a good understanding of where and how much the frame flex is occurring can be achieved. This means that the shock/spring assembly should be replaced by a rigid link, and the loads should be applied through the wheels or hubs, through the suspension, and transmitted to the frame through the A-arm mounting points and the shock and spring mount. The opposite end of the car should then be fixed rigidly so it cannot be rotated, and the degree of twist measured at the loaded end. Because of the use of COSMOSWorks for the FEA of the frame, perfectly realistic loading of the frame was not possible in the model due to the limitations of the software. Each frame member is considered a beam element, and analysis of the entire suspension at once is not possible. The frame was then loaded in a manner similar to real world, and the analysis was used to provide relative comparisons between different frame configurations. Figures 15 and 16 show the meshing of the frame model and the subsequent results of the FEA.

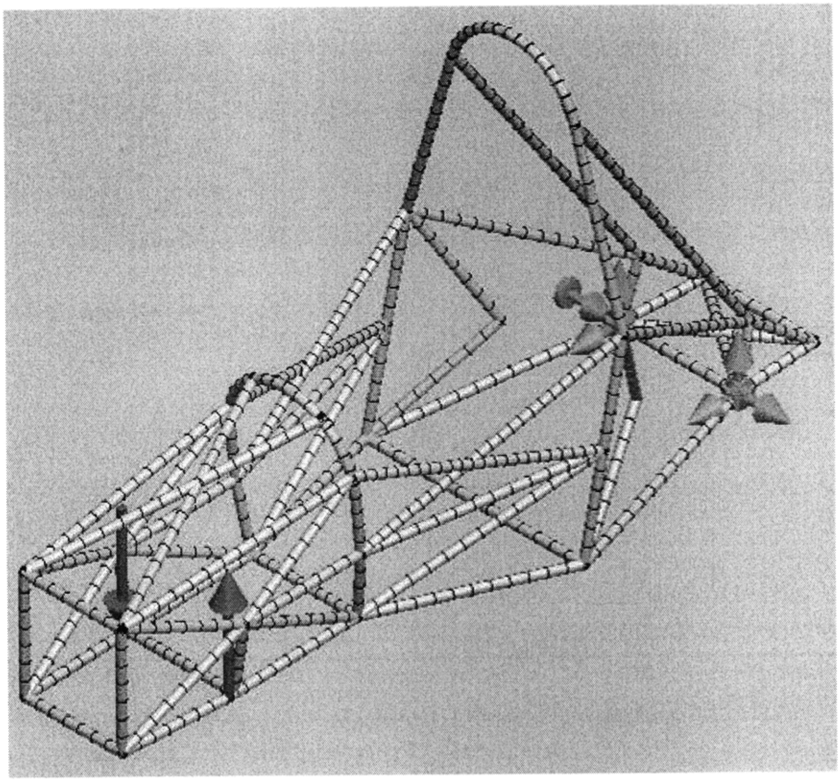


Figure 15. *Meshing of the frame model in COSMOSWorks.*

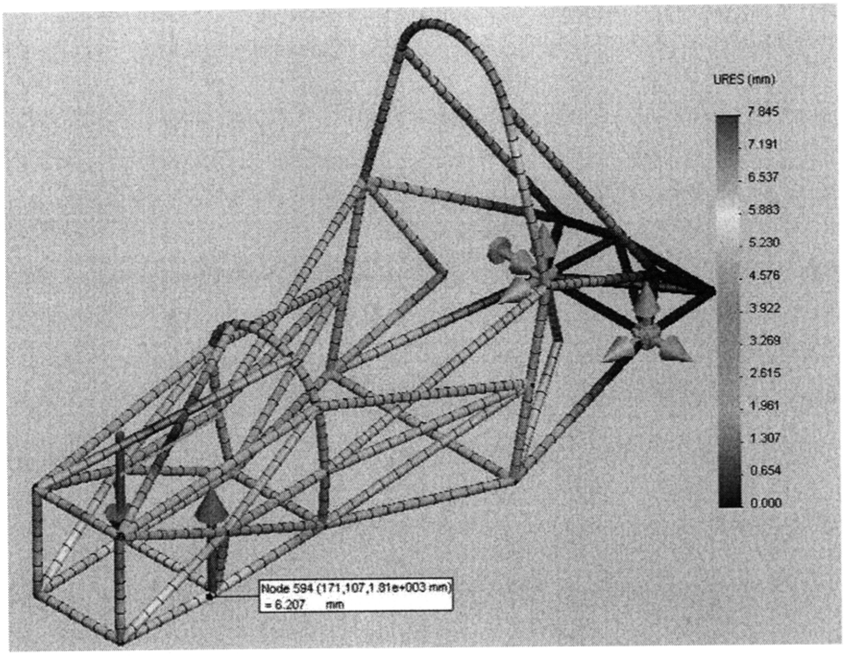


Figure 16. *Color-coded plot of displacement in the frame model.*

It was determined that the next best course of action for physical testing was to try to replicate the COSMOSWorks as close as possible to get a feel for how well the FEA correlated to the actual frame. Figure 17 below shows a picture of this year's torsion tester fixed to the frame. You can see the mounts fixed rigidly to the rear, and a pivoting beam attached rigidly to the front of the frame.

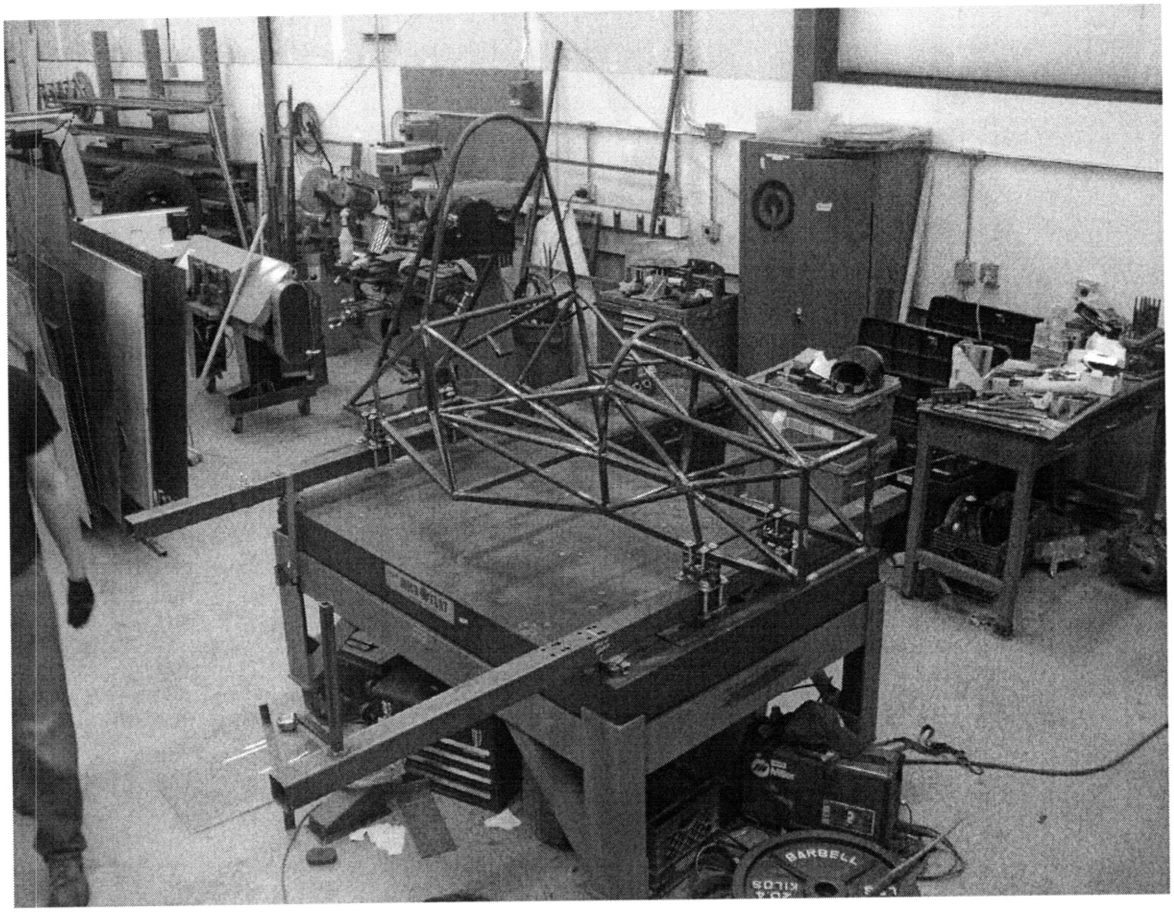


Figure 17. Frame torsion testing apparatus.

45-pound weights were subsequently added to the lever arm on the front pivoting beam and the angle of torsion was measured with a digital level. Figure 18 shows a plot of the results comparing the physical frame with and without the engine in place and the FEA prediction.

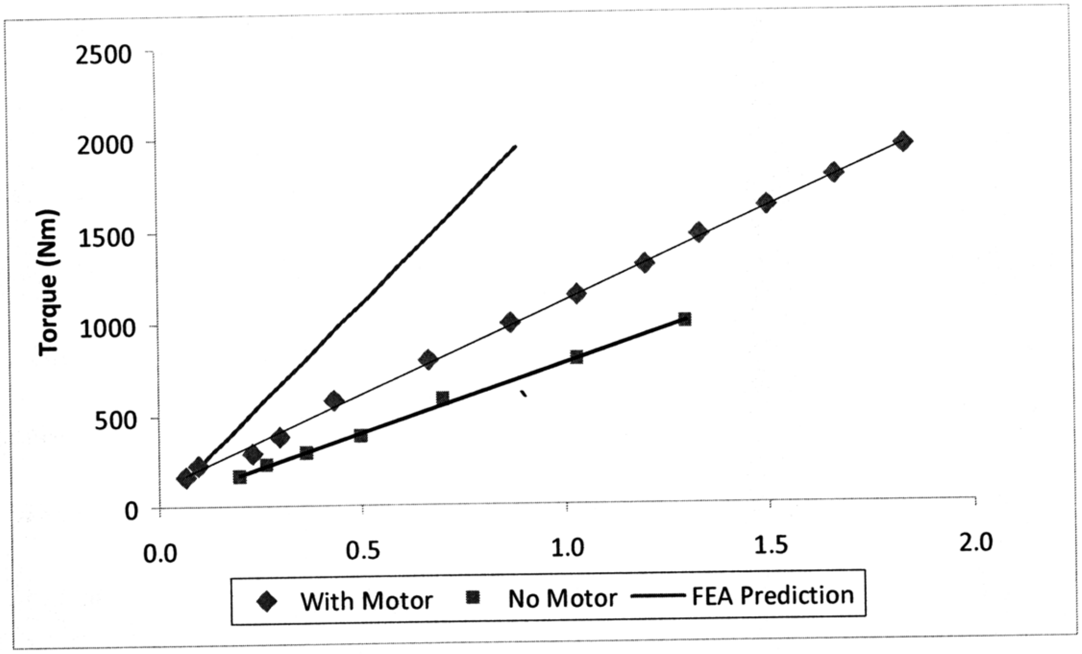


Figure 18. Results of physical torsion testing.

Because it is not possible to do FEA on the frame with the engine in place, the only way to determine its effect on the rigidity of the frame is to physically test it. As can be seen above, the engine contributed significantly to the stiffness of the frame, adding roughly 30% to its rigidity. It can also be seen that the FEA overestimates the stiffness of the frame by a large margin. This is to be expected to some degree, as the torsion testing equipment is not 100% rigid and the welded joints in the frame do not behave exactly as they do in the model. What is important is obtaining a calibration factor in order to correlate the FEA with the physical testing. This lets one design iteratively and have a sense of the actual torsional rigidity that can be expected from the real frame and choose an appropriate factor of safety.

5.2 Suspension

Ideally, the same care in physical testing taken with the frame would be taken with each component of the suspension in order to properly correlate theory with reality. However, due to time and resource constraints, and because the loading of the suspension components is much more straightforward than that of the frame and more care is taken in manufacturing to maintain tolerances, it was assumed that the FEA would correlate much better, and no physical compliance testing was done.

The suspension cannot be considered fully tested until it is run on the track and the car is pushed to its limits by the driver(s). While a huge amount of effort and analysis was put into the suspension design, there are always factors that either were overlooked or are otherwise unknown and the car is not always manufactured exactly on specification. That means that no matter who you are or how many racing cars you have designed, a new car will never ever handle perfectly right out of the box. Much time must be spent in tuning the new chassis from baseline spring and toe changes to fine-tuning of the shock absorbers. At the time of this writing, the MY2009 vehicle has not yet been driven on track. Previous vehicles have never been far off, but that cannot be used as a metric to conjecture about the performance of the new car, especially given that we are running on brand new Continental tires of a different construction with which we have no experience.

6. Future Developments and Recommendations

6.1 Technical Improvements

This year for the first time since 2006, upright design deviated from tradition and new and novel design was conceived. This involved the use of steel tubes rather than bent and welded sheet metal. The uprights were stiffer than previous uprights but there was very little measurable difference in weight. The move was made in 2006 to steel uprights from machined aluminum uprights because of the time saved in machining and the difficult access to CNC machines. With our new facility and in-house EZ-Trak machine, this problem no longer exists. Because the steel uprights rely heavily on welded joints, factors of safety must be increased due to uncertainty about the weld beads and local weakening of the metal. With proper heat-treating, this issue would be mitigated, but heat-treating is often an afterthought with the heavy time constraints. With a machined aluminum upright, FEA analysis will correlate directly with the finished product and the uncertainty is reduced or eliminated. This means that factors of safety can be reduced and a more efficient design can be produced. It is my recommendation that a thorough study be done to quantify the benefits and rewards of one design over the other and a more educated decision can be made.

Packaging of the spring and shock and rocker is always one of the most difficult parts of designing a Formula SAE car. Because these parts support the full weight of the car and large cornering forces, the load paths must be as direct as possible and feed into major structural nodes in the frame. In addition, the push or pull rod must actuate the rocker while staying as close to in-plane as possible to minimize bending loads on the rocker. For 2009, the front shocks were placed very high up on the frame and were actuated with a push rod so that an anti-roll bar could be easily packaged near the front bulkhead. While successful, this design requires that the links that actuate the anti-roll bar be placed outside of the frame. For next year, a pull rod design should be pursued which will yield many benefits. First, it will place the shocks and springs much lower on the car, reducing the center of gravity. The anti roll bar and all links could be packaged such that they do not interfere with the bodywork and provide a more aesthetic looking vehicle. While it is more complicated to design and care will have to be taken to ensure nothing interferes with the cockpit templates, the benefits are worth the extra care in design.

Because design of the suspension was completed in December of 2008 and the team's new sponsorship agreement with Continental was not concluded until February, it was not possible to optimize the car for the new tires. An intensive study of the force and moment data provided by Continental should be done followed by a thorough redesign of the suspension kinematics to make sure the tires are operating under optimal circumstances at all times.

6.2 Organizational Improvements

The team was placed under extreme circumstance during this past school year, which severely handicapped our ability to produce the best vehicle we can. Now that the move into the new shop is completed, and our access to machine tools is greater than ever before, efforts should be made to return to a normal design cycle comprising of summer design of frame and suspension, commencement of frame and suspension fabrication in September, and finalizing of all other component design before the Thanksgiving holiday break. Complete parts lists should be made listing each part of an assembly and any stock, raw materials and special tooling needed in order to manufacture it. After designs are finalized, between the Thanksgiving holiday and the Christmas break, these lists can be compiled and all orders should be placed. This would put everything in place to begin large-scale fabrication and assembly during MIT's IAP or Independent Activities Period and make an early March car completion date possible.

This year for the first time the team was successfully integrated into the Mechanical Engineering Curriculum through the 2.007 Design and Manufacturing I course. This gave the team much greater exposure to the Institute, valuable new members, and potential opportunities for more course credit. This must be pursued at all costs, as the single largest factor limiting the time available for students to work on the car is that they previously received no class credit for it.

7. Conclusions

The year 2009 was a revolutionary year for the MIT Motorsports Formula SAE team. Large challenges were met head on, including a very small number of returning members from 2008, a fall semester spent without access to a workshop, and creating and running a design course lab section while simultaneously meeting internal deadlines and keeping progress on track. In addition, the rules changes for 2009 were greater than any one-year change effected in the last 5 years. Despite these challenges, due to the hard work and dedication of its members, the team was able to develop and manufacture a vehicle that will be highly competitive when it competes at the 2009 Formula SAE West event from June 17-20. The frame is larger and heavier due to the new rules, but also stiffer than previous frames. Suspension components exhibit an attention to detail and quality of manufacturing never before seen on an MIT Motorsports vehicle. Significant room for improvement remains and the team should use the 2009 vehicle as a stepping-stone to take the program to the next level, continually increasing the quality of analysis and design and pushing them to learn more and delve deeper. The program developments that occurred this year have given MIT Motorsports the resources it needs to become one of the top-level Formula SAE programs in the country and help it to create the next generation of great engineers.

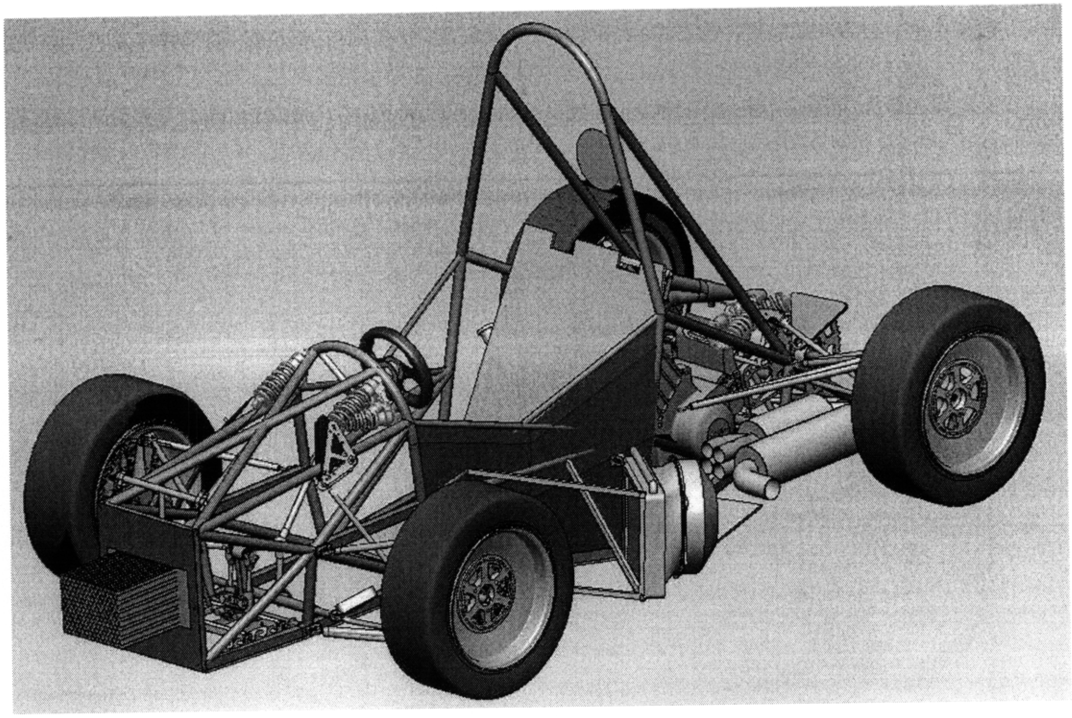


Figure 19. *Completed Full Car Assembly Model.*

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9. Suppliers

Aircraft Spruce & Specialty Co.
452 Dividend Drive
Peachtree City, GA 30269
(770) 487-2310
www.aircraftspruce.com

Continental AG
Vahrenwalder Str. 9
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www.motorsportsspares.com

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www.nhbb.com

Pegasus Auto Racing Supplies, Inc.
2475 S 179th Street
New Berlin WI 53146 USA
(800) 688-6946
www.pegasusautoracing.com

10. Acknowledgements

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