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Introduction to Formula SAE® Suspension and Frame Design

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ABSTRACT

This paper is an introduction to Formula SAE® (FSAE) suspension and frame design based on the experience of the design team at UM-Rolla. The basic theories and methodologies for designing these systems are presented so that new teams will have a baseline for their first FSAE design. Examples will be given based on UM-Rolla's 1996 FSAE entry.

INTRODUCTION

Formula SAE® is a student competition, sponsored by the Society of Automotive Engineers (SAE), in which students design, build, and compete with a small formula style race car. The basis of the competition is that a fictitious company has contracted a group of engineers to build a small formula car. Since the car is intended for the weekend autocross racer, the company has set a maximum cost of $8,500. The competition rules limits the race car engine to a maximum displacement of 610cc with a single inlet restrictor. Other rules require that the car must have a suspension system with a minimum wheel travel of 50mm and a wheelbase greater than 1524mm. The car must also satisfy safety requirements such as side impact protection [1].

The competition is separated into static and dynamic events. The static events include the cost analysis, sales presentation, and engineering design. The dynamic portions of the competition are the 15.25 m diameter skid-pad, 91.44 m acceleration event, 0.8 km autocross, 44 km endurance race, and fuel economy.

The FSAE competition was established to provide an educational experience for college students that is analogous to the type of projects they will face in the work force. To participate in FSAE, student groups work with a project from the abstract design phase until it is completed. Aspects of engineering design, team work, project management, and finance have been incorporated into the basic rules of Formula SAE®.

This paper covers some of the basic concepts of suspension and frame design and also highlights the approach UM-Rolla used when designing its 1996 suspension and frame. The suspension section addresses the basic design parameters and presents specific examples. The frame section discusses how to achieve a compromise with the FSAE design constraints. Finally, the design section gives a brief overview of the design methodology used by UM-Rolla for the 1996 race car.

The 1996 team finished 12th in the engineering design event, while the overall finish was 19th out of 77 competing teams.

1 SUSPENSION GEOMETRY

The suspension geometry section concentrates on some of the basic areas of suspension design and highlights what the UM-Rolla design team selected for its 1996 race car suspension geometry.

FSAE suspensions operate in a narrow realm of vehicle dynamics mainly due to the limited cornering speeds which are governed by the racetrack size. Therefore, FSAE suspension design should focus on the constraints of the competition. For example, vehicle track width and wheelbase are factors governing the success of the car's handling characteristics. These two dimensions not only influence weight transfer, but they also affect the turning radius.

Not only does the geometry have to be considered for FSAE suspension, but the components must also be reasonably priced for the cost analysis and marketable for the sales presentation. For example, inboard suspension could be a more marketable design, while outboard suspension might cost less and be easier to manufacture.

UM-Rolla chose to use a four wheel independent suspension system with push rod actuated inboard coil-over shocks. This decision was mainly due to packaging constraints. Furthermore, the appearance of inboard suspension was considered important for both the design judging and the sales presentation because of its similarity to modern race cars.

Although this discussion is of short-long arm suspension systems, many of the concepts are valid for other suspension types.

Track Width

Track width is the distance between the right and left wheel centerlines which is illustrated in Figure 1. This dimension is important for cornering since it resists the overturning moment due to the inertia force at the center of gravity (CG) and the lateral force at the tires [2]. For the designer, track width is important since it is one component that affects the amount of lateral weight transfer [3]. Also, the designers must know the track width before kinematic analysis of the suspension geometry can begin.

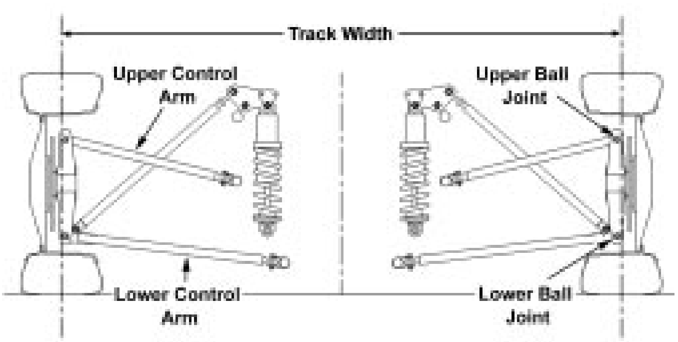

Figure 1. Track Width
(1996 Front Suspension, Front View)

When selecting the track width, the front and rear track widths do not necessarily have to be the same. For example, track width is typically wider in the front for a rear wheel drive race car. This design concept is used to increase rear traction during corner exit by reducing the amount of body roll resisted by the rear tires relative to the front tires [4]. Based on the corner speeds and horsepower-to-weight ratio of FSAE cars, this concept should be considered by the designer.

Wheelbase

The wheelbase also needs to be determined. Wheelbase is defined as the distance between the front and rear axle centerlines. It also influences weight transfer, but in the longitudinal direction. Except for anti-dive and anti-squat characteristics, the wheelbase relative to the CG location does not have a large effect on the kinematics of the suspension system. However, the wheelbase should be determined early in the design process since the wheelbase has a large influence on the packaging of components.

For track width and wheelbase starting points, the designers should research the dimensions of the opposition cars to serve as a baseline for their own calculations. FSAE car specifications for the competing teams, including track width and wheelbase, are available in the event program published by SAE.

The 1996 design team selected a 1727mm wheelbase, 1270mm front track width, and a 1219mm rear track width. This selection was based on previous UM-Rolla cars. Although this wheelbase was adequate for the FSAE competition size courses, the UM-Rolla design team has decided to increase the wheelbase for the next car to 1854.2mm. This increase in wheelbase is an attempt to improve stability for high speed corner entry at the competition.

Tire and Wheel

After track width and wheelbase considerations have been addressed, the next step in the design process is tire and wheel selection. Since the tire is important to the handling of the vehicle, the design team should thoroughly investigate the tire sizes and compounds available. The tire size is important at this stage of the design since the height of the tire must be known before the suspension geometry can be determined. For example, the tire height for a given wheel diameter determines how close the lower ball joint can be to the ground if packaged inside the wheel.

<u>Tire Size</u> **-** The designers should be aware that the number of tire sizes offered for a given wheel diameter is limited. Therefore, considering the importance of the tire to handling, the tire selection process should be methodical. Since the amount of tire on the ground has a large influence on grip, it is sometimes desirable to use wide tires for increased traction. However, it is important to remember that wide tires add rotating mass which must be accelerated by a restricted FSAE engine. This added mass might be more detrimental to the overall performance than the increase in traction from the wider tires. Not only does a wider tire add mass, but it also increases the amount of rubber that must be heated. Since racing tires are designed to operate most efficiently in a specific temperature range, this added material may prevent the tires from reaching the optimum temperature range [3]. The UM-Rolla team used tires for the 1996 competition that were designed to work most efficiently at a minimum of 71^{o} C.

During the selection process the designers must consider how the tires will influence the performance of the entire package. For example, the weather conditions for the FSAE dynamic events might determine which tire compound and tire size should be used for the competition. Another important consideration is the price of the tires, since the cost can be a large portion of a team’s budget.

For the 1996 competition, UM-Rolla selected a 20 by 6–13 racing tire for both the front and rear of the car. Because of the low vehicle mass, a narrow tire was selected so that tire temperatures would be greater than previous UM-Rolla designs. This tire selection increased the operating temperature from 48° to 60° C. For the competition, the weather was predicted to be cool, so the team brought sets of hard and soft compound tires. The team chose to use the harder compound since the weather for the endurance was predicted to be clear and warm.

Wheel Selection - Once a decision has been made as to which tire sizes to use, the wheel selection should be next. Usually, the wheel dimensions are fixed and allow for little modification. Therefore, it is important to have some design goals in mind before investing in wheels. Generally, the upright, brake caliper, and rotor are placed inside the wheel which requires wheel offset for clearance. It is usually easier to design the suspension geometry if the wheel profile is known. For example, the ball joint location is limited to the area defined by the wheel profile.

Other considerations for wheel selection include: cost, availability, bolt circle, and weight. For example, three-piece rims, although expensive, have the distinct advantage of offering many offsets and profiles that can be changed during the design process [3].

UM-Rolla designed the 1996 suspension geometry around a wheel profile from a previous car and then acquired a set of three-piece rims to meet the design specifications. All four wheels selected for the 1996 competition were size 6 by 13. This wheel selection allowed for tire rotations, reduced cost, and a wide selection of tire sizes, compounds, and manufacturers.

Geometry

The designer can now set some desired parameters for the suspension system. These usually include camber gain, roll center placement, and scrub radius. The choice of these parameters should be based on how the vehicle is expected to perform. By visualizing the attitude of the car in a corner, the suspension can be designed to keep as much tire on the ground as possible. For example, the body roll and suspension travel on the skid pad determines, to a certain extent, how much camber gain is required for optimum cornering. The amount of chassis roll can be determined from roll stiffness while the amount of suspension travel is a function of weight transfer and wheel rates.

Once a decision has been made about these basic parameters, the suspension must be modeled to obtain the desired effects. Before the modeling can begin, the ball joint locations, inner control arm pivot points, and track width must be known.

The easiest way to model the geometry is with a kinematics computer program since the point locations can be easily modified for immediate inspection of their influence on the geometry. Should a dedicated kinematics computer program not be available, then a CAD program can be used simply by redrawing the suspension as the points are moved.

When designing the geometry, it is important to keep in mind that designing is an iterative process and that compromises will be inevitable. For instance, the desired scrub radius might not be possible because of packaging constraints. When modeling the suspension, the designers should not aimlessly modify points without first thinking through the results. For example, the designer should visualize how the wheel will camber relative to the chassis when making the lower A-arm four times longer than the upper A-arm. One method that can be used to visualize the results is the instant center location for the wheel relative to the chassis. Another method is to use the arcs that the ball joints circumscribe relative to the chassis. For a complete explanation about determining suspension point locations from instant center locations refer to Milliken [4].

Scrub Radius, Kingpin Inclination, and Caster - The scrub radius, or kingpin offset, is the distance between the centerline of the wheel and the intersection of the line defined by the ball joints, or the steering axis, with the ground plane which is illustrated in Figure 2. Scrub radius is considered positive when the steering axis intersects the ground to the inside of the wheel centerline. The amount of scrub radius should be kept small since it can cause excessive steering forces [5]. However, some positive scrub radius is desirable since it will provide feedback through the steering wheel for the driver [5].

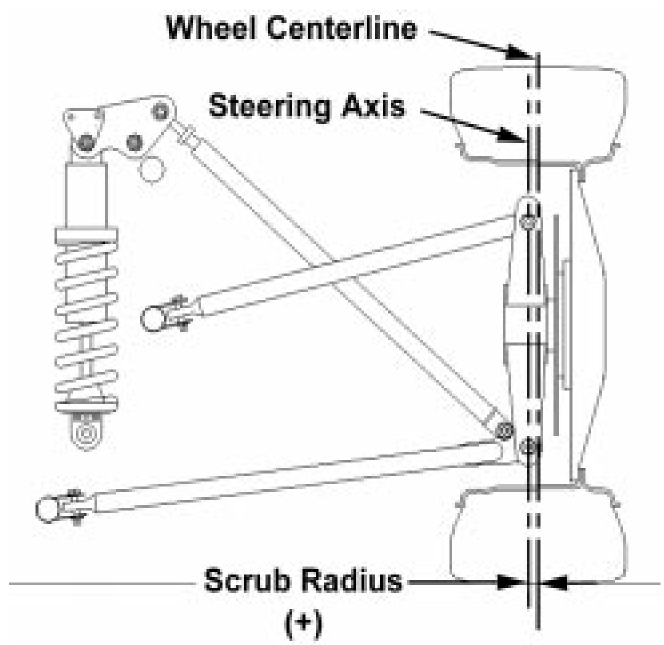

Figure 2. Scrub Radius

Kingpin inclination (KPI) is viewed from the front of the vehicle and is the angle between the steering axis and the wheel centerline [4]. To reduce scrub radius, KPI can be incorporated into the suspension design if packaging of the ball joints near the centerline of the wheel is not feasible. Scrub radius can be reduced with KPI by designing the steering axis so that it will intersect the ground plane closer to the wheel centerline. The drawback of excessive KPI, however, is that the outside wheel, when turned, cambers positively thereby pulling part of the tire off of the ground.

However, static camber or positive caster can be used to counteract the positive camber gain associated with KPI.

Caster is the angle of the steering axis when viewed from the side of the car and is considered positive when the steering axis is tilted towards the rear of the vehicle [4]. With positive caster, the outside wheel in a corner will camber negatively thereby helping to offset the positive camber associated with KPI and body roll. Caster also causes the wheels to rise or fall as the wheel rotates about the steering axis which transfers weight diagonally across the chassis [3]. Caster angle is also beneficial since it will provide feedback to the driver about cornering forces [3].

The UM-Rolla suspension design team chose a scrub radius of 9.5mm, zero degrees of KPI, and 4 degrees of caster. This design required the ball joints to be placed near the centerline of the wheel, which required numerous clearance checks in the solid modeling program.

Roll Center **-** Once the basic parameters have been determined, the kinematics of the system can be resolved. Kinematic analysis includes instant center analysis for both sets of wheels relative to the chassis and also for the chassis relative to the ground as shown in Figure 3. The points labeled IC are the instant centers for the wheels relative to the chassis. The other instant center in Figure 3, the roll center, is the point that the chassis pivots about relative to the ground [6]. The front and rear roll centers define an axis that the chassis will pivot around during cornering. Since the CG is above the roll axis for most race cars, the inertia force associated with cornering creates a torque about the roll center. This torque causes the chassis to roll towards the outside of the corner. Ideally, the amount of chassis roll would be small so that the springs and anti-roll bars used could be a lower stiffness for added tire compliance [3,4]. However, for a small overturning moment, the CG must be close to the roll axis. This placement would indicate that the roll center would have to be relatively high to be near the CG. Unfortunately, if the roll center is anywhere above or below the ground plane, a "jacking" force will be applied to the chassis during cornering [3,4]. For example, if the roll center is above ground, this "jacking" force causes the suspension to drop relative to the chassis. Suspension droop is usually undesirable since, depending on the suspension design, it can cause positive camber which can reduce the amount of tire on the ground. Conversely, if the roll center is below the ground plane, the suspension goes into bump, or raises relative to the chassis, when lateral forces are applied to the tires. Therefore, it is more desirable to have the roll center close to the ground plane to reduce the amount of chassis vertical movement due to lateral forces [3].

Since the roll center is an instant center, it is important to remember that the roll center will move with suspension travel. Therefore, the design team must check the migration of the roll center to ensure that the "jacking" forces and overturning moments follow a relatively linear path for predictable handling [3]. For example, if the roll center crosses the ground plane for any reason during cornering, then the wheels will raise or drop relative to the chassis which might cause inconsistent handling.

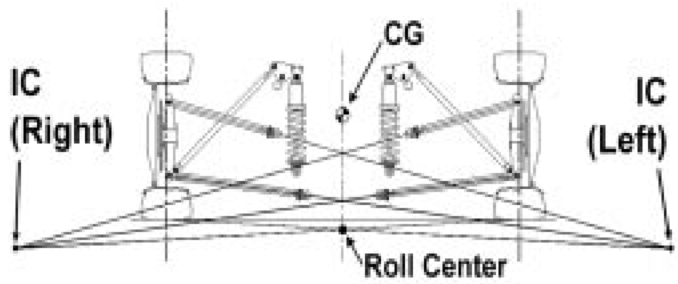

Figure 3. Front Roll Center

The roll center is 35.6mm below ground in the front and 35.6mm above ground in the rear for the 1996 UM-Rolla car. Since none of the previous UM-Rolla cars had below ground roll centers, the selection of the 1996 points was basically a test to understand how the below ground roll center affected the handling. Because of the large roll moment, the team designed enough camber gain into the suspension to compensate for body roll associated with soft springs and no anti-roll bar. The team was very happy with the handling but decided, for the next car, to have both roll centers above ground for a direct comparison between both designs.

Camber **-** Camber is the angle of the wheel plane from the vertical and is considered to be a negative angle when the top of the wheel is tilted towards the centerline of the vehicle. Camber is adjusted by tilting the steering axis from the vertical which is usually done by adjusting the ball joint locations. Because the amount of tire on the ground is affected by camber angle, camber should be easily adjustable so that the suspension can be tuned for maximum cornering. For example, the amount of camber needed for the small skid pad might not be the same for the sweeping corners in the endurance event.

The maximum cornering force that the tire can produce will occur at some negative camber angle [3,4]. However, camber angle can change as the wheel moves through suspension travel and as the wheel turns about the steering axis. Because of this change, the suspension system must be designed to compensate or complement the camber angle change associated with chassis and wheel movements so that maximum cornering forces are produced.

The amount of camber compensation or gain for vertical wheel movement is determined by the control arm configuration. Camber gain is usually obtained by having different length upper and lower control arms. Different length control arms will cause the ball joints to move through different arcs relative to the chassis. The angle of the control arms relative to each other also influence the amount of camber gain. Because camber gain is a function of link geometry, the amount of gain does not have to be the same for both droop and bump. For example, the suspension design might require the wheels to camber one degree per 25mm of droop versus negative two degrees per 25mm of bump.

Static camber can be added to compensate for body roll, however, the added camber might be detrimental to other aspects of handling. For example, too much static camber can reduce the amount of tire on the ground, thereby affecting straight line braking and accelerating. Similarly, too much camber gain during suspension travel can cause part of the tire to loose contact with the ground.

Caster angle also adds to the overall camber gain when the wheels are turned. For positive caster, the outside wheel in a turn will camber negatively, while the inside wheel cambers positively. The amount of camber gain caused by caster is minimal if the wheels only turn a few degrees. However, FSAE cars can use caster angle to increase the camber gain for the tight corners at the FSAE competition.

UM-Rolla designed for a relatively large amount of camber gain since anti-roll bars were not used in the 1996 suspension design. The use of low wheel rates with a large roll moment required the suspension to compensate for the positive camber induced by chassis roll and suspension travel. The camber gain for UM-Rolla's 1996 car was from both the caster angle and the control arm configuration.

Steering System

The steering geometry has a large influence on the handling characteristics of the vehicle. For example, if the system is not properly designed, then the wheels will toe in or out during suspension travel. This toe change is referred to as bump steer which is described in detail in both references [3,4]. Bump steer is basically undesirable since the car changes direction when the driver does not expect a change [4].

Ackermann steering must also be considered during the design process. Ackermann steering occurs when the outside wheel turns less than the inside wheel. This is possible since the amount of steering angle for each wheel is determined by the steering geometry. Reverse or anti-Ackermann occurs when the outside wheel turns more than the inside wheel during cornering [3,4].

During a turn, the inside wheel travels around a smaller geometric radius than the outside wheel. Ackermann steering can be used so that the wheels travel about their corresponding radii, theoretically, eliminating tire scrub. However, designing for precise Ackermann steering might not provide the best handling since tire slip angles influence the actual turning radius [9]. The designer must decide, based on the requirements, if the steering system design will include Ackermann geometry.

UM-Rolla placed the rack and pinion in front of the axle centerline near the lower control arms because of packaging constraints. This placement required extra room in the frame design since the driver had to straddle the steering column. After building a test car that was hard to steer because of a half a turn lock to lock system, the 1996 steering system was designed to be one turn lock to lock. This was accomplished by changing the rack and pinion ratio instead of increasing the steering arm length because of packaging constraints. The system specifications for the 1996 car are: 76mm steering arms, 250mm diameter steering wheel, and 51mm of rack travel per one pinion revolution. These specifications were retained for the next race car design because the resulting handling characteristics were thought to be satisfactory. The 1996 UM-Rolla design has a small amount of anti-Ackermann because of packaging.

Conclusion

FSAE suspension designs not only have to be competitive on the racetrack, but the suspensions must also perform well in the static events. For the dynamic events, the designers should concentrate on the geometry so that most of the tire will stay in contact with the ground for all normal driving situations: braking, accelerating, and cornering. The suspension system must also be designed so that it is easy to manufacture and is reasonably priced for the cost analysis. To reduce the cost and complexity of the 1996 race car, UM-Rolla designed the system so that the wheels, hubs, and bearings were the same for each corner of the car.

Designing the suspension geometry is only a small part of building a vehicle. A well engineered suspension system does not automatically make a fast race car. Although this paper has concentrated on the design aspect, development is just as important to the success of the package. Because the design process must take place within a given time constraint, the first suspension design might not provide the best handling. It is not uncommon to make design changes after the car is completed. It is more important for FSAE teams to compromise on the overall design so that the car can be completed and tested prior to competition.

2 FRAME

The purpose of the frame is to rigidly connect the front and rear suspension while providing attachment points for the different systems of the car [8]. Relative motion between the front and rear suspension attachment points can cause inconsistent handling [4]. The frame must also provide attachment points which will not yield within the car's performance envelope.

There are many different styles of frames; space frame, monocoque, and ladder are examples of race car frames. The most popular style for FSAE is the tubular space frame. Space frames are a series of tubes which are joined together to form a structure that connects all of the necessary components together. However, most of the concepts and theories can be applied to other chassis designs.

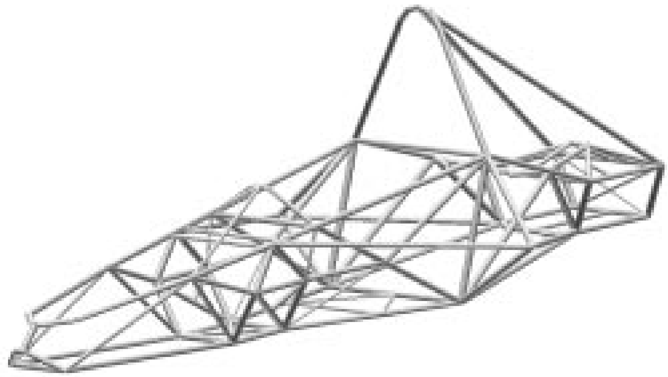

Figure 4. UM-Rolla's 1996 Frame Design

Stiffness

The suspension is designed with the goal of keeping all four tires flat on the ground throughout the performance range of the vehicle. Generally, suspension systems are designed under the assumption that the frame is a rigid body. For example, undesirable changes in camber and toe can occur if the frame lacks stiffness. An image of a frame subjected to a torsional load is superimposed on an undeflected frame in Figure 5.

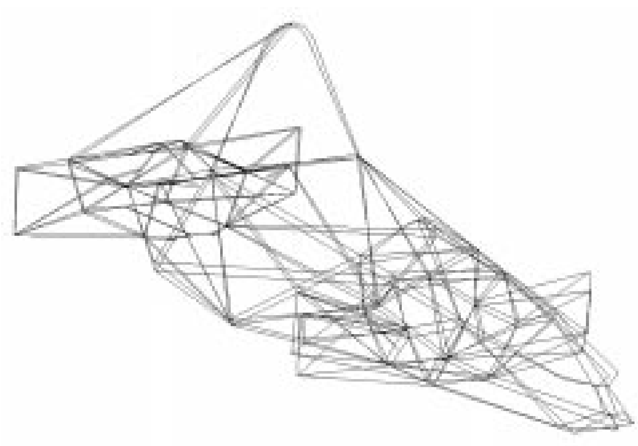

Figure 5. Chassis Deflection

UM-Rolla has found that in most cases, a chassis that is stiff enough for competition will not yield. However, some care should be taken to ensure that the attachment points of the frame do not yield when subjected to design loads. For example, the engine mounts should be made stiff enough to reduce the possibility of failure.

Torsional Stiffness - Torsional stiffness is the resistance of the frame to torsional loads [4]. UM-Rolla used FEA to analyze the torsional stiffness of the 1996 chassis. The solution of the simple rod and beam element model for the frame showed that the torsional rigidity was roughly 2900 Newton meters per degree of deflection. The mass of the 1996 frame is approximately 27kg, which UM-Rolla believes is heavier than needed for a two day racing series. However, some extra structure was added to the frame to increase its safety. Also, the drivetrain mounts were significantly strengthened so that the car would be able to serve as a driver training tool for several semesters.

As the 1996 frame evolved, the stiffness to weight ratios of different designs were compared. A chassis can be made extremely stiff by adding significant amounts of material to the frame. However, this additional material might degrade the performance of the car because of the added mass.

Obviously, torsional rigidity is not the only measurement for analyzing the stiffness of a chassis. Bending stiffness can also be used to analyze the efficiency of a frame design. However, bending stiffness is not as important as torsional stiffness because deflection due to bending will not affect wheel loads [4]. Because the design time is severely limited in FSAE, UM-Rolla's team used a torsional analysis to determine the relative stiffness of different frame designs.

Triangulation - Triangulation can be used to increase the torsional stiffness of a frame, since a triangle is the simplest form which is always a structure and not a mechanism. Obviously, a frame which is a structure will be torsionally stiffer than a mechanism [7]. Therefore, an effort should be made to triangulate the chassis as much as possible.

Visualizing the frame as a collection of rods which are connected by pin joints can help frame designers locate the mechanisms in a design [8]. Designers can also evaluate their frame by checking to see if each pin jointed node contains at least three rods which complement the load path.

UM-Rolla chose to use thin wall steel tubing for the 1996 frame design. This required significant triangulation of the frame, since thin wall tubing performs very well in tension and compression but poorly in bending. The components which produce significant amounts of force, for example the engine and suspension, were attached to the frame at triangulated points.

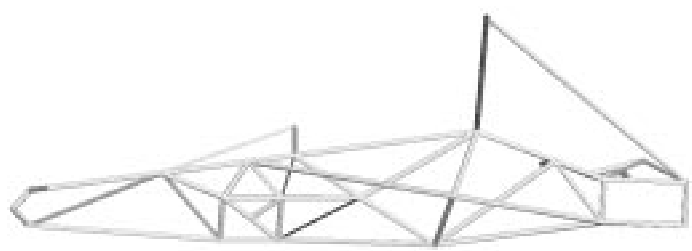

Figure 6. Frame Triangulation
(Frame, Side View)

Previous UM-Rolla frames have lacked adequate triangulation for highly loaded components. These components were attached to the frame with load bearing tabs which were welded at the midpoint of a single section of tubing. As expected, this tube bent like a simply supported beam and caused unwanted movement of the attached component. Although these designs worked for the duration of the competition, they invariably failed by fracturing the tube or breaking the tab. For the 1996 car, all of the highly loaded components were attached to triangulated points.

Area Moment of Inertia - The area moment of inertia has a large influence on the stiffness of a structure. Therefore, the farther material is from the axis of twist the stiffer the frame will be in bending and torsion. This concept is implemented by adding structural side pods to the basic frame.

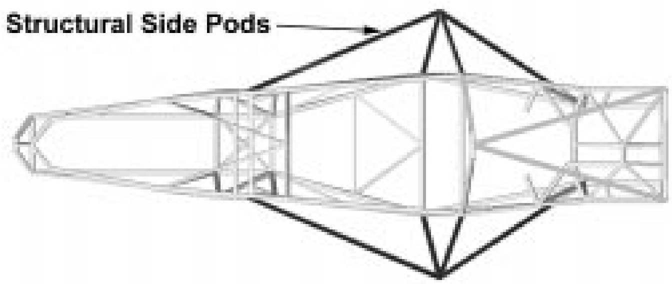

Figure 7. Structural Sidepods (Frame Top View)

Figure 7 shows the triangulated side pods which were used to increase the torsional rigidity of the 1996 frame. This material also increased the side impact protection. The sidepods add structure as far from the centerline of the chassis as possible which increases the area moment of inertia between the front and rear suspensions. Most of the successful FSAE cars have structural side pods for safety and increased torsional stiffness.

In addition to using the sidepods to increase the stiffness of the chassis, 1996 entry used the roll hoop and down tubes to increase the rigidity of the frame. The 1997 FSAE rules state that the tubes from the top of the roll hoops to the base of the frame have to be 0.049" wall when fabricated from 4130 steel [1]. Because these tubes are stiffer than 0.035" wall tubing, the frame stiffness can be substantially increased by properly placing the roll hoop tubes.

Load Path

During the design process, it is important to consider how loads are passed into the frame. A load path describes the path through which forces are dissipated into the frame. For example, Figure 8 shows how the vertical load generated by the weight on the wheel will travel through the upright, push rod, rocker, coil-over shock and into the structure of the frame. Of course, to properly investigate the forces involved, a freebody diagram for each component must be drawn. Nevertheless, this concept can be used by the designers to visualize how the frame should be constructed.

Crash Worthiness

In the interest of safety, the Formula SAE® Rules Committee has written very specific rules to protect the driver from frontal, side, and roll-over crash situations.

While designing the 1996 entry, the UM-Rolla team found that if the FSAE rules were followed and the frame was optimized for stiffness, it was obvious that the car would be adequate for most possible crash situations. Due to the possibility of a head on collision, more structure was placed in the nose of the frame than was necessary for the 1996 rules. Based on past experiences, the team believed that the probability of the vehicle running into a solid object, such as a curb or loading dock, was high. Therefore, considerable thought was given to the safety of the drivers feet during a frontal impact.

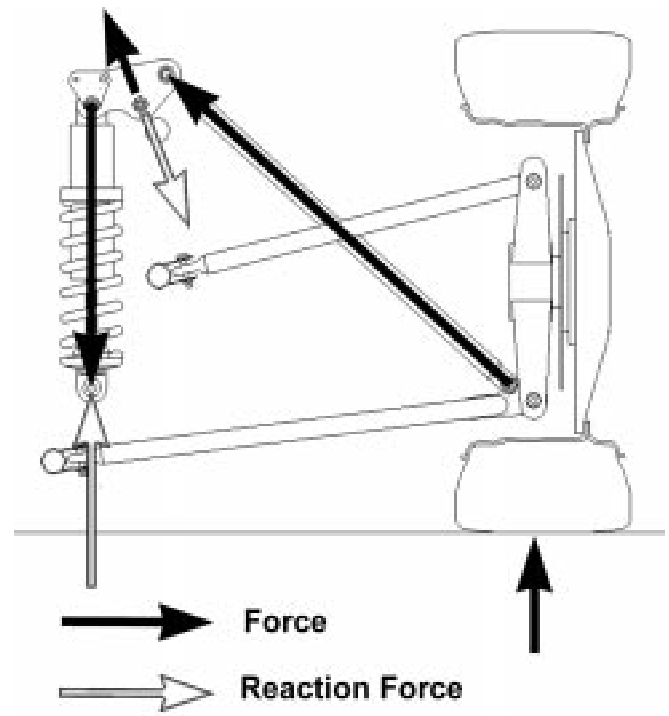

Figure 8. Load Path for Front Inboard Suspension

Packaging

Each of the systems of a FSAE car must be packaged within the frame. The placement of these components limits the available paths for tubes, which is usually detrimental to the chassis stiffness [8]. For example, the driver occupies a section of the frame which could be used to significantly increase the stiffness of the frame.

Suspension - Packaging of the suspension to the frame is generally not an interference problem since most of the components are exterior to the frame. However, it is especially important to attach the suspension components to stiff portions of the chassis to correctly distribute the loads that will be passed through these components [8].

Designing the frame so the control arms are attached to a stiff portion of the chassis can sometimes be very difficult. UM-Rolla found that changing the distance between the control arm pivot points can help to optimize the load path for the control arms. This distance can be changed because it will not affect the suspension geometry, since the rotational axis of the control arm is not affected. However, decreasing the span of the control arms will reduce the arm's ability to react to the forces which are generated by accelerating or braking.

UM-Rolla found that the suspension should be designed concurrently with the frame. This allows the designer to concentrate on the load paths from the push rods and rockers so that the frame can efficiently react to the loads.

Drivetrain - Correctly attaching the components of the drivetrain to the frame is very important for extended frame life. The relative stiffness between the engine, differential, and frame is not as critical as when attaching the suspension. This is due to the fact that most FSAE chassis layouts have short distances between the drivetrain components. The main design point is to ensure that the frame does not break during an incorrect downshift or a violent release of the clutch. Most of the frame failures which the UM-Rolla cars have experienced were due to fractures in the engine mounts or differential mounts.

When designing the frame around the motor and differential on chain driven designs, sufficient clearance must exist so that several front and rear sprockets can be used. This clearance allows a wide selection of final drive ratios. Several UM-Rolla entries have been built with the inability to change the final drive ratio. This inability has proven to be a drawback when trying to drive the race car in the confined space of the FSAE competition and the more open spaces of autocrosses.

Ease of maintenance is also an important design consideration when designing the frame around the drivetrain. UM-Rolla has found that providing clearance for direct removal of the engine will reduce the amount of mechanic's stress involved with engine changes. It has also been found advantageous to provide simple access to all covers on the motor such as the clutch, alternator, and valve cover.

Ergonomics

Properly incorporating the driver into a FSAE frame design can be very difficult because of wide variations in driver sizes. Each driver interface has to be designed so that it is comfortable for a wide variety of drivers. UM-Rolla's 1996 entry is able to accommodate drivers who range in height from 1.58m to 1.90m.

Controls - Designing the frame around the controls, such as the steering wheel and pedals, is a matter of ensuring that the structure of the frame does not interfere with the driver's task. Also, the controls must be adequately supported by the frame so that the attachment points do not yield while the car is being driven.

The frame should not interfere with the drivers as they move through the full range of motion which is required to drive the car. The driver's arms are a particular problem in this area. In the past, UM-Rolla has designed cars in which it was very difficult for large drivers to keep their arms inside the cockpit. Fortunately, this was remedied on the 1996 chassis by increasing the cockpit cross sectional area.

The frame designers should look beyond the structural considerations of the frame when designing it so major oversights are reduced. For example, a previous team encountered a packaging issue for their chassis when they placed the steering wheel directly over the rack and pinion. This was a design error because the universal joint between the steering wheel and the rack and pinion was not able to bend 90^{o}.

Safety Harness - Most importantly, the attachment points of the harness must be strong enough to ensure that they will not fail during a crash. They also must be positioned so that the buckles will not bind when the harness is tightened [9]. This has been a problem for UM-Rolla in the past when trying to place the attachment points for both large and small drivers.

Egress - Rapid egress is very important since the 1997 rules mandate that the driver must exit the vehicle within five seconds [1]. Past UM-Rolla cars had a difficult time with the egress requirement. These race cars were designed with structural tubes that left an area only 165mm high for the drivers feet and legs to fit through. This was a situation in which the designers compromised ergonomics for chassis stiffness.

Conclusion

It is obvious that frame design is a compromise between stiffness, weight, and packaging. The stiffness of the frame is important because it affects the overall performance of the vehicle. If too much material is added to the frame in the quest for stiffness, the performance of the vehicle will be degraded because of the added mass. Not only must the frame be stiff and light, it must also package all of the vehicle systems. Therefore, the design of the frame will require many iterations to achieve a balance. The timeline of the competition will limit the number of iterations possible so that the car can be built and tested. If the basic design concepts have been applied to the frame and some thought has been given to the integration of each sub-system, the end result will be a sound foundation for a FSAE car.

3 UM-ROLLA'S 1996 DESIGN METHODOLOGY

Although it is simple to design a single part or system, it is more difficult to incorporate all of the parts and systems into a single package, such as a race car. The design team for each system or part must keep in mind how its design will affect the overall package. For example, the suspension design team must leave enough room for the driver's legs between the left and right control arm pivot points.

This section explains the basic design sequence that UM-Rolla used for the 1996 car. This sequence is not the only avenue for the design of a vehicle. However, UM-Rolla has found that this is a logical sequence for the design of its FSAE cars.

Layout

The 1996 design was initiated by determining the track width and wheel base dimensions of the vehicle. Once this was completed, the driver and engine placement was sketched into the design for an estimation of weight distribution. Some thought was given to the placement of other important or hard-to-package systems. For example, the fuel system had to be packaged near the center of gravity to reduce the effects of its varying mass during the race.

Suspension Geometry

After the track width and wheelbase had been determined, the team made a preliminary decision on tire and wheel size. The design team settled on some basic suspension parameters: camber gain, caster, KPI, scrub radius, and roll center height. These were needed so that the design team could model the suspension geometry.

A suspension modeling program was used to analyze camber change and roll center movement. The suspension was modeled with 0^o of static camber, because static camber could be optimized during testing. During the modeling of the suspension, the team looked at vertical and lateral roll center movement and camber change as the chassis went through ∀25mm of vertical travel and ∀2^o of roll. It was necessary to perform several iterations before a satisfactory geometry was obtained.

After the suspension design had been determined, the steering system was designed based on the probable location of the frame rails and steering arms. The suspension modeling program was also used to reduce bump steer.

Solid Modeling

Once the preliminary suspension design was complete, the next step was to enter the suspension points into a 3-D computer model. Then the preliminary mechanical designs of the suspension components were drawn. The suspension was moved through its range of motion in a solid modeling package to check for interference between the control arms, tie rods, uprights, and wheels.

After the suspension system had been checked for interference problems, the next step was to start designing the frame. UM-Rolla used a CAE package to model the frame structure. The major components, such as engine and differential, were drawn into the model. To simplify this process only mounting points or rough sketches were entered. Also, sufficient room was designed into the frame for the systems that had not been completed. For instance, ample room was left for the controls needed for various driver sizes.

After the major components had been modeled, the first roll hoop design was placed into the model. This was needed because it represents a major component of the frame which is defined by the FSAE rules. Figure 9 represents this early frame model.

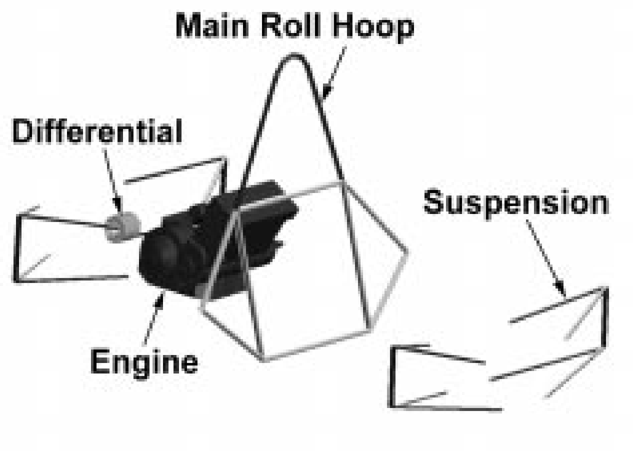

Figure 9. Major Frame Components

At this point, the inboard suspension system had not been designed. However, some preliminary designs for the inboard suspension allowed a load path analysis to drive the design of the structure.

Connecting the Points

Once the main points of the frame were defined in the model, the “connect the dots” phase could begin. By using the concepts of triangulation and area moment of inertia, the defined points were connected with tubes. Connecting the dots simply consists of attaching the front suspension to the rear suspension while providing attachment points for the systems of the car. Refer to Figure 10 for the final 1996 frame design.

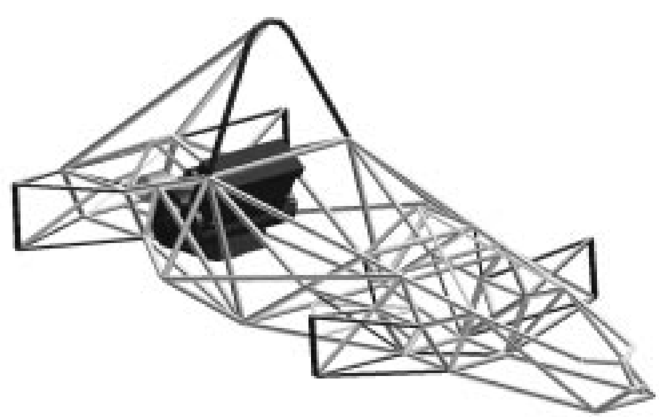

Figure 10. Connecting the Dots

Analysis

Once all of the points had been connected, the frame was ready for finite element analysis. This analysis was performed on a commercially available CAD/FEA software package. Beam elements were used for the major frame structure while rod elements were used for the suspension as illustrated in Figure 11. A more representative load could be applied by using a model with the suspension attached. Since accurately modeling a welded joint is beyond the undergraduate level, this model was strictly for determining if the frame was a satisfactory structure.

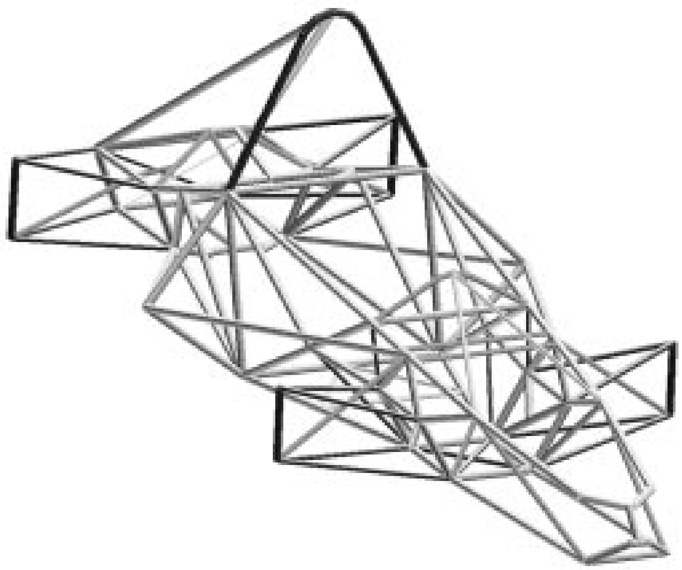

Figure 11. FEA Model

After the model was solved, the results could be viewed as an animation to expose any weak links. This approach allowed for quick "what ifs." For example, if an area appeared to be over-stressed, a different geometry for that joint could be substituted and modeled. Also, the UM-Rolla designers found that tubes with long versus short spans between joints should have a larger area moment of inertia to increase the stiffness.

To reduce the cost of the race car, only a small selection of tube sizes were used, which made the modeling simpler since wall thickness optimization was limited. The UM-Rolla team used the following 4130 tubing sizes to construct the structure of the 1996 chassis:

- **1" x 0.065" (Roll Hoop Material)**
- **1" x 0.035"**
- **3/4" x 0.035"**
- **5/8" x 0.035"**

To simplify the complexity of the frame construction, the number of tubes which had bends in more than one plane was reduced to only two.

Although this is not the only sequence for designing a FSAE car, UM-Rolla has successfully used this basic method for the past three designs.

CONCLUSION

Unlike the school environment, there are no right or wrong answers in the FSAE competition. The designers can make successive iterations on their designs until a satisfactory compromise has been reached. Constructing FSAE cars imparts to college students the knowledge of how to function in real world design groups while also introducing them to the entire design process involved in a product's development.

During the design process, the team must achieve a compromise between cost, manufacturing, performance, and design time so that their car will be competitive in all aspects of the FSAE competition. The timeline of the competition, combined with the rigorous schedule of college, limits the number of iterations for each design. However, the team should understand that it will take several iterations to converge on a satisfactory design. The amount of time used for the design process subtracts from the time available for manufacturing and testing. Although this paper has concentrated on design, it is very important to test the car so that any design oversights will be highlighted before competition.

A poorly engineered vehicle may not perform well at the competition. Conversely, a highly engineered car may not perform well unless there is time to manufacture and test. For the inexperienced FSAE team, concentrating on complex engineering techniques can be too time consuming for the amount of performance gained. Therefore, FSAE teams should use basic engineering concepts to design their car. This will simplify the design process and allow the team to finish the car as early as possible to allow for testing and redesign. Teams which finish their car and compete will gain the most knowledge and experience from Formula SAE®.

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