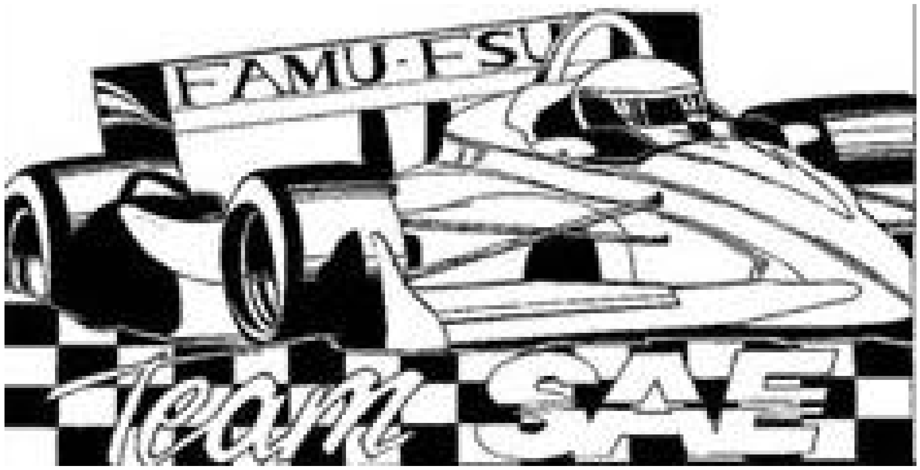
FAMU-FSU Formula SAE



Senior Design
Suspension and Chassis

Final Design Report
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Executive Summary

The purpose of this project is to design the suspension and chassis for the 2002-2003 model FAMU/FSU Formula SAE racecar. The main objectives are to reduce the overall weight of the car and at the same time increase the stiffness and strength of the vehicle components. The other main criteria for this project is to increase overall performance of the car. The 2003 FSAE design consists of a four-wheel independent suspension system and utilizes a composite monocoque chassis.

1.0 Introduction

1.1 SAE Competition Background

Our team was assembled for the purpose of designing the suspension and chassis for the Formula SAE racecar. Formula SAE is a student group sponsored by the Society of Automotive Engineers (SAE), which holds an annual competition involving the design and performance of a formula style racecar. The competition is designed for college level engineering students emphasizing on the aspects of design, team work, project management, and finances; much like the projects they may face in industry. The competition includes both static and dynamic events. The static events include the cost analysis, sales presentation, and engineering design. The performance in the static events can earn the team up to 35% of the possible total points. The dynamic events consist of the 15.25 m diameter skid-pad, 100 m acceleration event, the 0.8 km autocross, 44 km endurance race, and the fuel economy. I list of all of these events as well as the points breakdown is shown in table 1.1.1.

Table 1.1.1

Event Breakdown		
Static Events		Points
Safety and Technical Inspection		None
Cost and Manufacturing Analysis		100
Presentation		75
Design		150
	Total from Static	325
Dynamic Events		
Acceleration		75
Skid Pad		50
Autocross		150
Fuel Economy		50
Endurance		300
	Total from Dynamic	625
	Total	950

1.2 Purpose of Suspension and Chassis

Maintaining the handling of the vehicle throughout corning and other race conditions is the sole purpose of a suspension system. The suspension system affects the handling of the vehicle because it controls how the tires maintain contact with the track. The suspension controls the tire's complete dynamic motion throughout five different degrees of freedom and must do so in a manor that the car remains very stable throughout all wheel and vehicle motions. Understanding how the tires react with the ground throughout the range of suspension travel plays an important role in the design of a suspension system.

Similar to the suspension system, the chassis plays a large role in the handling of the vehicle. The chassis must be designed to connect both the front and rear suspensions as well as provide all attachment points for other systems in the car. It must also be rigid enough to resist bending and torsional deflection. In addition to being this, the chassis design must also incorporate the packaging of the rest of the system components that are necessary for a car. This is also done with the purpose of having everything be serviceable at the track very quickly.

1.3 Project Scope

The FSAE competition includes many factors relevant to the engineering process. The design of the car should be geared towards the weekend race enthusiasts. Costs must be kept to a minimum while still maintaining a high degree of performance. Aesthetics, comfort, and the use of common parts should also be considered in order to increase the car's marketability. The car is to be designed for a production number of four cars per day, all at a price of less than $25,000. The final product should be profitable at the said production number, including tooling costs and labor.

The project was divided into two main stages. The first stage included the design of the suspension and chassis of the 2003 Formula SAE racecar. Included in this stage were the research of existing designs, determination and analysis of the specifications from the customer needs, the work break down structure and scheduling of the project and the actual design.

The second stage of the project includes the machining of components and the assembling of the car itself. Analysis of the performance of the car, and the needed adjustments and modifications are also part of this stage. At this point we will further compare the theoretical performance results from Adams modeling with the actual performance data taken from the car.

1.4 Initial Desired Performance Specifications

The initial design specifications for the 2003 car are listed below in Table 1.4. The respective rules governing the particular specification is listed in the far right column.

Specification	Minimum Value	Maximum Value	2003 Formula SAE Rules Section
CHASSIS			
Wheelbase	60 “	NA*	3.1.2
Torsional Deflection	0	TBD	
Bending Deflection	0	TBD	
Total Vehicle Mass (including drive train)	0	500 lbs	
Ground Clearance (with 220lb driver)	2”	NA*	3.2.1
SUSPENSION			
Wheel Travel	2”	3”	3.2.3
Vehicle Track Width (Front)	NA*	NA*	
Vehicle Track Width (Rear)	75% of front track width	75% of front track width	3.1.3
Wheels Diameter	13”	NA*	3.2.2
Lateral Acceleration (g=acceleration due to gravity)	0.9g	8g (max for human before health issues)	
COST			
Overall Cost of Vehicle	$0	$25000.00	4.3.3

Table 1.4 Initial desired performance specifications.

*NA means there are no restrictions governing this particular specification.

2.0 Design Criteria and Methods

2.1 System Modeling

Mathematical modeling or dynamic modeling implies the description of the important system characteristics by a set of differential equations that describe the dynamic behavior of the system. The results obtained from the model are only accurate to the extent the model approximates a given system. In reality, no mathematical model can represent any system exactly. The procedure for obtaining a mathematical model for a system can be summarized as follows:

1. *Draw Schematic diagram of the system, and define variables*
2. *Using Physical laws, write equations for each component, combine them according to system diagram.*
3. *To verify the validity of the model, the results obtained by solving the equations of motion are compared with experimental results. The process is repeated until a satisfactory agreement is obtained between prediction and experimental results.*

We will wait until a prototype is built to obtain experimental results. In order to simplify the complicated system that is a racecar, a quarter car model was used to analyze the dynamics and determine the stability of the suspension.

Dynamic Model Analysis: Suspension System

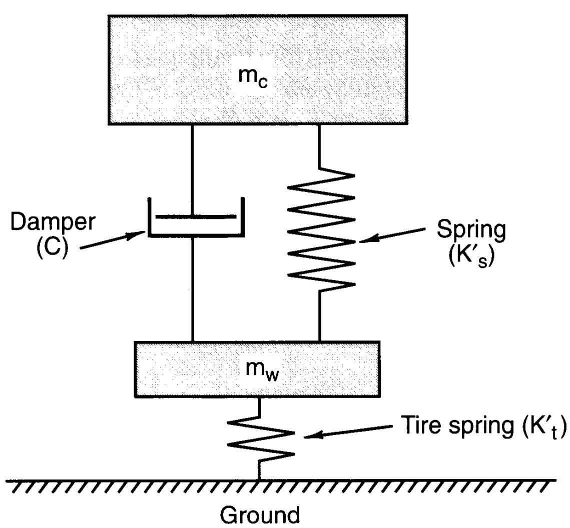

Figure 2.1 Free-body diagram of the quarter-car model

The model is for a car with quarter mass m_c (assuming equal weight distribution), wheel of mass m_w, coil spring with spring constant k_s, shock absorber with damping constant c, and tire with spring constant k_t. The system input is provided by the road surface or the inertial reference, r. System outputs include the position of the wheel, x, and the position of the car, y.

The resulting equations from free body diagram are:

$$\ddot{x} + \frac{b}{m_1} \cdot (\dot{x} - \dot{y}) + \frac{k_s}{m_1} \cdot (x - y) + \frac{k_w}{m_1} \cdot x = \frac{k_w}{m_1} \cdot r \ ,$$

$$\ddot{y} + \frac{b}{m_2} \cdot (\dot{y} - \dot{x}) + \frac{k_s}{m_2}(y - x) = 0$$

Taking the Laplace transform of the dynamic equations gives:

$$(1) \quad s^2 \cdot X(s) + s \cdot \frac{b}{m_1} \cdot (X(s) - Y(s)) + \frac{k_s}{m_1} \cdot (X(s) - Y(s)) + \frac{k_w}{m_1} \cdot X(s) = \frac{k_w}{m_1} \cdot R(s)$$

$$(2) \quad s^2 \cdot Y(s) + s \cdot \frac{b}{m_2}(Y(s) - X(s)) + \frac{k_s}{m_2}(Y(s) - X(s)) = 0$$

Solving equation (2) above for X(s) then, substituting into equation (1) and rearranging results in the transfer function, G(s), which compares the output Y to the input R.

$$G(s) = \frac{Y(s)}{R(s)} = \frac{\frac{k_w b}{m_1 m_2} \cdot \left(s + \frac{k_s}{b} \right)}{s^4 + \left(\frac{b}{m_1} + \frac{b}{m_2} \right) \cdot s^3 + \left(\frac{k_s}{m_1} + \frac{k_s}{m_2} + \frac{k_s}{m_1} \right) \cdot s^2 + \left(\frac{k_w b}{m_1 m_2} \right) \cdot s + \frac{k_w k_s}{m_1 m_2}}$$

The spring constant for the coil spring, k_s, is known from the choice of the spring, and the manufacturer of the tire normally supplies the spring constant of the tire, k_w. Choosing adjustable damping shocks allows the user to tune the shock absorber to their own performance needs.

Table 2.1 The applicable values for the constants are summarized in the table below.

Variable	**Value**	**Units**
¼mass of car, m_c	105	lbs.
Wheel mass, m_w	5	lbs.
Spring constant, k_s	400	lb/in
Spring constant, k_t	1027	lb/in
Damping coefficient, c	0 - ∞ (adjustable)	lb*s*in

2.2 Suspension Geometry

The main specification of the suspension system as required by FSAE (2003 FSAE Rules Section 3.2.3) is that there must be a minimum of 2 inches of wheel travel. This must to include one-inch travel in jounce and one-inch travel in rebound with the driver seated.

The wheelbase and track width of the vehicle need to be considered first in the design of a suspension system, as they affect the turning radius and the weight transfer of the car. Track conditions and the rules of competition will help to determine these dimensions. In addition to kinematics, the cost of the components also needs to be considered as to ensure the car will be marketable and to fulfill the cost analysis portion of the competition.

The FAMU-FSU FSAE team chose to proceed with a short-long arm four-wheel independent suspension for the 2003 FSAE racecar for its ability to meet the performance objectives.

2.2.1 Track Width and Wheelbase

Track width is defined as the distance between the left and right wheel centerlines. The track width is important to suspension design because it is one of the components that affect the load transfer during cornering. The front and rear track widths do not always have to have the same dimensions. The front track width front is generally larger than that of the rear, for a rear wheel drive racecar. This design concept is used to increase rear traction during cornering exit by reducing the amount of body roll resisted by the rear tires relative to the front tires [Milliken].

The wheelbase is another dimension that needs to be determined and is defined as the distance between the front and rear axle centerlines. The wheelbase affects load transfer in the longitudinal direction; however it has a small affect on the kinematics of the suspension. However, it is important to determine the wheelbase early in the design process because it does play a major role in the packaging of the components.

The 2003 design team selected a wheelbase of 72 inches, a front track width of 52 inches and a rear track width of 48 inches. These dimensions were selected after researching the specifications of the previous year's competitors and slightly modified for packaging purposes.

2.2.2 Tire and Wheel Size

Determination of the wheel and tire size is the next step in the design process. The largest possible tire should be selected in order to maximize the contact patch between the tire and the track surface. However, the restrictions on engine size influence will influence tire size, as a larger rotating mass will require more power. A large tire will require a large rim, which will increase the total weight of the car, and will also increase the amount of rubber that needs to be heated. Racing tires are designed to operate most effectively in a specific temperature range. The added mass and lower operating temperature for the tire may not be as beneficial as the increase in the contact patch, so a compromise must be made.

The selection of the wheel must be made in accordance to the desired tire size. The upright, brake rotor and caliper must also be considered, as they must be packaged within the wheel. Knowing the wheel profile will aid in the design of the suspension geometry. The locations of the ball joints and the maximum kingpin length will be limited to the area defined by the wheel profile.

The 2003 design team decided to use wheels from a previous car in an effort to reduce costs. The front wheel size is 13”x6” and the rear wheel size is 13”x7”. The tire selected for the 2003 competition is the Goodyear d3419 racing tire. The front tire size is 20”x6.5”-13” and the rear tire size is 20”x8”-13”. The optimum operating temperature range of this tire is 150 F.

2.2.3 Kingpin Length and Inclination

The next step in the design process is the design of the upright, which determines the kingpin length and angle, and where the upper and lower ball joints will be located. The kingpin angle, scrub radius and spindle length, are all interrelated and each one must be considered and a compromise made (see Figure 2.2.3). The kingpin length is distance between the upper and lower ball joints, and should be made as long as possible to reduce the load on the control arms and other components.

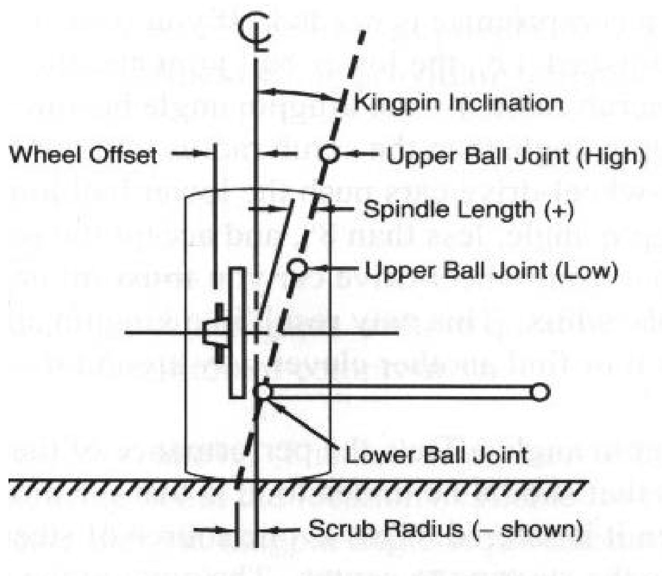

Figure 2.2.3 Front suspension packaging. (Courtesy of Milliken and Milliken).

The kingpin angle affects the handling of the car as it is steered. The larger the kingpin angle the more the car is lifted when it is steered. The spindle length also determines the amount the car is lifted as it is steered. This helps to return the steering to center but may introduce the need for large steering forces. The scrub radius is the distance between the centerline of the wheel and the intersection of the line defined by the ball joints with the ground plane. There is a tradeoff between the scrub radius and kingpin angle and a compromise is needed. The kingpin angle also affects the camber change of the wheels as the car is steered. Caster is the angle of the steering axis when viewed from the side view of the car. Caster is considered positive when the steering axis is tilted towards the rear of the car. The addition of positive caster will introduce negative camber, which can offset the positive camber due to the kingpin inclination. Caster also causes vertical deflection of the wheels as it is steered and provides steering feedback to the driver, similar to the kingpin angle.

The 2003 FAMU-FSU FSAE design team selected a kingpin length of 10 inches, a kingpin angle of 8 , a scrub radius of 0.75 inches, and zero degrees of caster for the front suspension. The rear suspension was designed to have a kingpin length of 10 inches, a kingpin inclination of 0 , zero degrees of caster, and no scrub radius. The limited packaging area and wheel offset were considered in this selection of these parameters.

2.2.4 Control Arm Construction

The geometry of the control arms plays an important role in the handling of the vehicle. The control arms determine the location of the instant centers, the location of the roll center and the change in wheel camber due to suspension travel. The configuration of the control arms also determines how the forces will be distributed throughout the suspension system.

2.2.4.1 Instant Centers

The term instant center refers to the pivot point of a linkage at that particular instant. The instant center can be determined by projecting a line along the upper and lower control arms until they intersect at some point as shown in Figure 2.2.4.1. The two instant centers labeled in Figure 2.2.4.1 are the instant center of the tires relative to the chassis. The instant center can be thought of as the pivot point of the tire affecting the camber change of the wheel as it is lifted. Instant centers also control force and motion factors as a result of accelerations, and the tire lateral scrub. The instant centers of the wheels determine the location of the roll center.

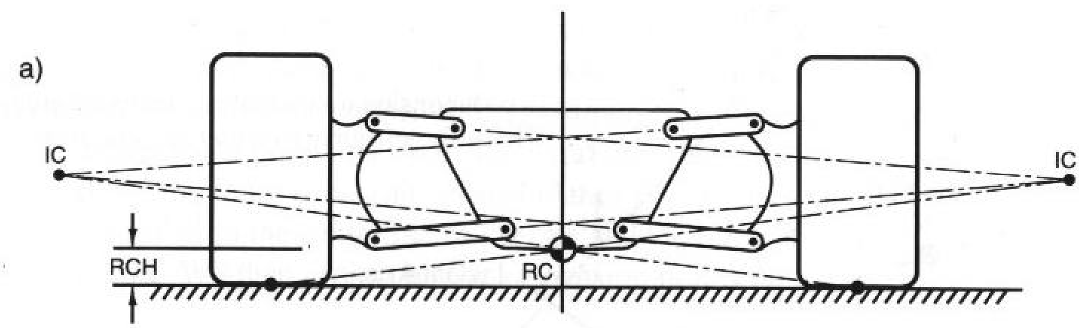

Figure 2.2.4.1 Instant center and roll center construction. (Milliken and Milliken)

2.2.4.2 Roll Center

The roll center is an instant center and is the pivot point of the chassis relative to the ground. The model of the system as shown in Section 2.1, describes the car as a coupled system. The roll center determines the force coupling point between the sprung and unsprung masses. Drawing a line from each tire centerline at the ground level and extending them to the respective instant center as shown in Figure 2.2.4.1 locates the roll center. The intersection of these two lines determines the height of the roll center. The front and rear roll centers determine the axis of rotation for the chassis. The main consideration in determining the desired roll center height is jacking. As the car is steered, the lateral force from the tire creates a moment about the instant center and pushes the wheel down and lifts the mass up. If the roll center is located below ground level the opposite occurs and the sprung mass is pushed down. There are no jacking forces when the roll center is located at ground level.

The 2003 design team decided to use a double A-arm suspension. One of the control arms was chosen to mount straight across with the other arm splayed at a 30 . The roll center of the 2003 car is located at one inch above ground level and at the centerline of the car. This was achieved with an upper control arm length of 7.25 inches mounted at an angle of negative 5.5 degrees with respect to ground level, and a lower control arm length of 11.5 inches mounted at an angle of negative one degree with respect to ground level.

2.3 Spring and Damping Rates

The 2003 team decided use the Vanilla RC coil-over manufactured by Fox Racing Shox, with a pull rod configuration, because of its small size and lightweight. The coil-overs were reused from the previous year's car in an attempt to minimize costs. The Vanilla RC has a spring rate of 400lb/in with adjustable damping. The adjustable damping was an important specification of the coil-over, as it will enable fine-tuning of the suspension system.

2.4 Chassis Stiffness, Materials and Geometry

Stiffness, packaging requirements, and weight must all be considered in the chassis design of a racecar. The two most popular styles of frames in the FSAE competition are the space frame and the composite monocoque. The space frame is a series of steel or aluminum tubes that are connected together to form the structure for which the system components can be attached. Our composite monocoque chassis is made from sheets composite material joined together with carbon fiber tape. The composite chassis is lighter and more rigid, but the price paid with all added performance is added cost.

The chassis must be designed to withstand both torsional and bending deflection. The performance of the suspension system will be affected if the chassis lacks the adequate torsional stiffness. Bending stiffness is not as important as torsional stiffness because torsional deflection affects the wheel loads. Here is an example where a suspension design being limited by the integrity of the chassis to which it is attached.

All of the systems of the FSAE car must be packaged within the frame. The connection of the suspension components to the chassis usually does not produce packaging problems, but they must be attached to stiff portions of the chassis. Special attention should be made in the connection of the control arms to the chassis as they transfer the majority of the forces between the suspension and chassis. The packaging of the engine and drive train must also be considered in the design of the frame. A compromise between the mounting and the ease of maintenance of these components must be examined.

The 2003 design team chooses to use a composite monocoque chassis for the 2003 race car because of its lighter weight and superior stiffness.

The composite material selected for the chassis is aluminum 5052 aerospace grade honeycomb core faced with carbon fiber in a quad-axial orientation. Although the composite monocoque is more expensive than the tubular space frame it was determined that the lighter weight and increased stiffness outweighed the increased costs of the material.

3.0 Results and Discussion

3.1 Design (Engineering) Specifications

The car is still being analyzed using Algor, Pro/Mechanica, and Adams Model. While the design is finished, the full analysis has not been completed. Despite hours worth of help from Dr. Patrick Hollis we are still facing difficulties analyzing the chassis in Algor to find the amount of torsional and bending deflection in the chassis. The same difficulties are faced with using Adams Model which is a dynamic modeling software that the school has obtained just in the past few months and the learning curve is still quite steep. All of these computer models will be completed by the first of January to ensure that our design is the best that it can be before we assume construction. The final design specifications can be found below in Table 3.1

Specifications	**Values**
CHASSIS	
Wheelbase	72”
Torsional Deflection	TBD
Bending Deflection	TBD
Total Vehicle Mass (including drive train)	450 est.
Ground Clearance (with 220lb driver)	2.5”
SUSPENSION	
Wheel Travel	2”
Vehicle Track Width (Front)	52”
Vehicle Track Width (Rear)	48”
Wheel Diameter, (tire)	13”, (20”)
Lateral Acceleration (g=acceleration due to gravity)	TBD

Table 3.1 *Final Design Specifications*

3.2 Final Design Package

3.2.1 Pro-E Model

The final design of the 2003 FSAE racecar can be seen below in Figure 3.2.1. The model was created using the computer aided design software Pro-Engineer.

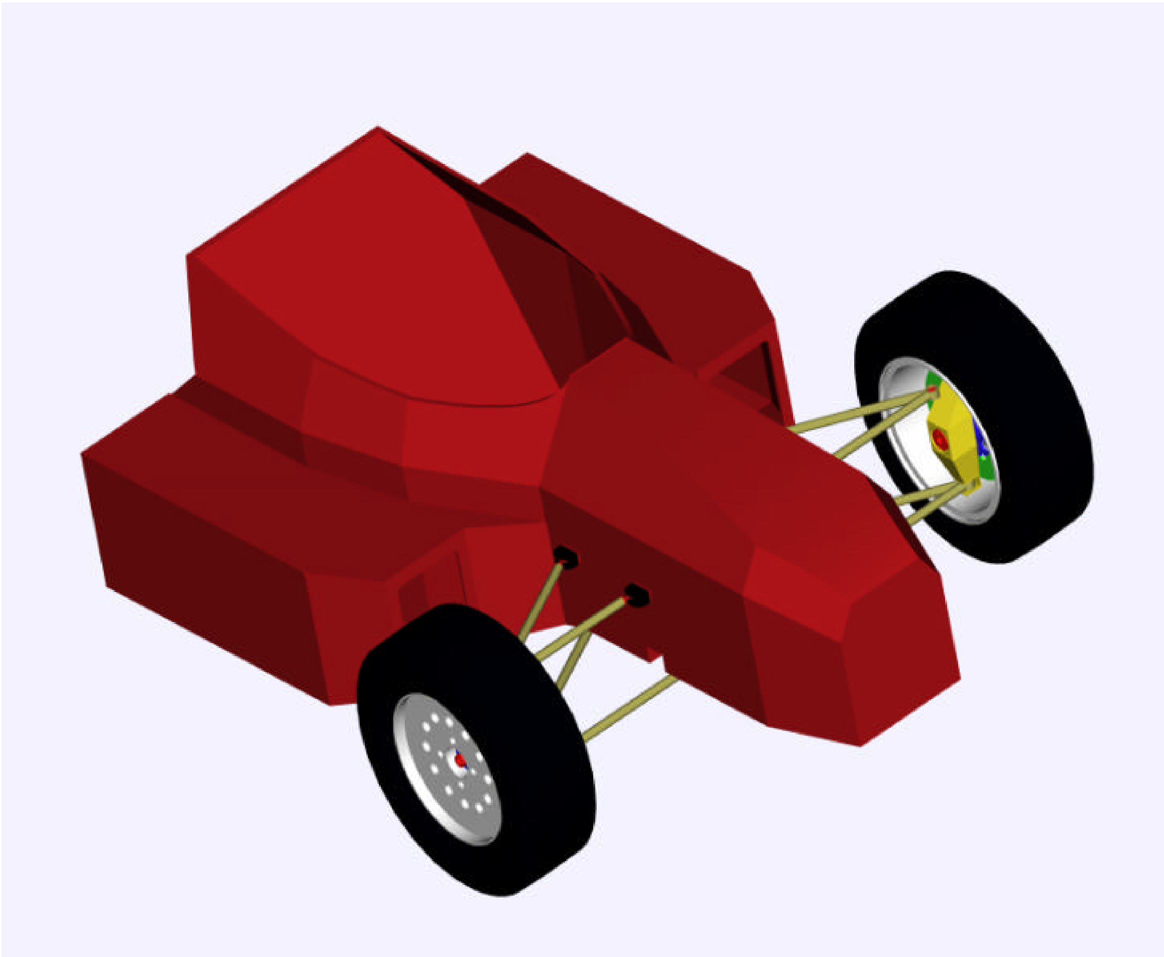

Figure 3.2.1 Pro/E Assembly of Chassis and front Suspension

3.3 Cost Analysis

The cost of the suspension system and chassis can be found below in Table 3.2.3. Systems and components related to suspension are included, as they had to be considered in the design process for packaging reasons.

Table 3.3 Cost analysis 2003 FSAE suspension and chassis.

System or Category	Cost
Brake system	$ 608.85
Steering system	$ 379.88
Wheels, Tires & Hubs	$ 1,080.00
Suspension	$1,743.74
Chassis	$2,500.00
Total Costs	$6,312.47

4.0 Conclusion

Suspension systems designed to compete in the FSAE competition needs to be designed to perform well on the racetrack and in the static events. An emphasis on suspension geometry is important for the dynamic events, ensuring that all four tires will stay in contact with the racetrack. Manufacturability and low cost are important considerations to ensure success in the static events.

Frame design is a compromise between packaging requirements, stiffness and weight. The stiffness of the frame affects the handling of the vehicle, however if too much material is added to increase the stiffness, the added mass may compromise any effect from the increased rigidity. The frame must also incorporate the packaging of all the vehicles systems.

A compromise between performance, costs, manufacturing, and design time must be made by the design team to be successful in all portions of the FSAE competition. Proper project management will allow for iterations that are necessary to fine-tune the overall performance of the design.

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