Drexel University Formula SAE:

Design and Optimization of a Racecar Suspension

Senior Design Team MEM-03
AY0203

Members:

ABC

DEF

GHI

Submitted to:

Senior Design Project Committee

Department of Mechanical Engineering and Mechanics

Drexel University

On

November 26th, 2002

ABSTRACT

Every year, the Society of Automotive Engineers (SAE) sponsors a competition in which teams from universities around the world design, fabricate, and race single-seat, open cockpit, formula-style cars powered by four-stroke gasoline engines with mass production costs of less than $25,000. Judged on vehicle performance, design efficiency, and budget considerations, the students are challenged to use skills learned during their engineering curriculum, as well as techniques and considerations that are important for product development. The 2003 Drexel University Formula SAE Team is broken into three groups. The suspension group is responsible for developing the steering system, and for controlling the weight transfer to maximize lateral acceleration. The design process involves first identifying the general suspension type to analyze. After this is selected, the vehicle track width, tire and rim size, and suspension geometry is established. These parameters are analyzed using a specialized software program. The individual components are then modeled and assembled in Pro/Engineer. Using ADAMS/Car, the vehicle suspension is analyzed through dynamic simulations. The results of these simulations are used to modify the parameters until the desired dynamic characteristics are determined. Following simulation, the components are manufactured and assembled to the Formula SAE Chassis. At this point, the suspension is fine tuned and optimized. Driver training is another key aspect. The finalized suspension design will provide the driver with consistent, reliable, and dependable handling characteristics.

TABLE OF CONTENTS

INTRODUCTION

On any car, the only parts intended to be in contact with the ground are the tires, and their reactions alone determine the direction of motion of the vehicle. Therefore, the primary responsibility of a vehicle suspension is to maximize the tire contact patch with the ground at all times, thus ensuring maximum grip. Steering, body roll, and weight transfer must be managed in such a way that the lateral and longitudinal forces acting on the tires do not exceed their road-holding abilities. Taking into account track conditions such as radii of turns, bumps and dips, and temperature, as well as vehicle velocity and driver input, the designers are challenged to optimize the suspension parameters to allow the swiftest and safest completion of each event at the annual Formula SAE competition.

Secondary suspension requirements involve connecting the driver to the road. The best-designed suspension is still only a tool that the driver can use; therefore it is critical that the suspension set-up transmits enough feedback to him such that he is aware of the instantaneous track conditions. He must know if a wheel begins to slip due to loose gravel or if a bump causes one wheel to develop slightly less traction than expected, so he can apply the appropriate compensating actions. Though the stability of the vehicle is critical, it is equally important that the driver feels in complete control. The suspension must provide him with accurate input information so he can make the correct output action.

By tailoring the suspension such that weight transfer, body roll, and tire contact patch are controlled in a predictable fashion, it is possible to create a car with dynamic properties matched precisely to the characteristics of the events encountered at the competition.

PROBLEM STATEMENT

The Society of Automotive Engineers (SAE) holds an annual collegiate competition involving the design and production of a formula racecar. The car, while having a maximum mass production cost of no more than $25,000, must comply with a comprehensive set of rules established to ensure fair competition and safety. For the 2003 Drexel University LandDragon, this team will be designing and manufacturing the suspension, steering, and braking systems, while working closely with other teams to ensure the high quality of the integrated vehicle.

There will be a straight-line acceleration event, in which a specified distance must be covered as quickly as possible. Secondly, a skid pad test, involving circular right and left turns, will test the vehicle's lateral grip. The autocross event incorporates a series of variable radii turns and straight-line accelerations to be traversed in the fastest achievable time, and is intended to test the car's dynamic characteristics as well as driver skill. Finally, there will be an endurance test, during which the driver must complete a long-distance race with a limited amount of fuel.

Specifically, we will concentrate on the purchase or fabrication of the a-arms, springs and dampers, uprights, wheels, tires, anti-roll bars, steering rack, brake rotors, and calipers. To develop the physical shape and properties of these components, we must optimize the following design parameters: camber, castor, kingpin inclination angle, toe, track, spring rates, and damping coefficients. All of these parameters can be individually tuned to benefit the handling characteristics of the vehicle, but sometimes at the expense of another parameter. A properly designed suspension is a system where the trade-offs of each parameter will be at a minimum, and the sum of their contributions enhances the overall dynamic abilities of the vehicle.

While the maximum cost of the car has been stated, our operating cost will be significantly less, due to limited funding. Therefore, this economic constraint will force us to be more efficient in completing our tasks in order for us to stay competitive with teams from universities with significantly higher budgets.

Time will be another factor that must be taken into consideration. Every component of the car must be designed, manufactured, assembled, and tested in nine months. Time allocation to certain tasks is high priority. A thorough schedule of all responsibilities must be developed and followed closely for the project to be a success.

Finally, the delivery of a trained and skilled driver is crucial to the project. Unlike production cars, this vehicle will be specialized for racing on a particular course and it is necessary for the driver parameter to be optimized as well. He must familiarize himself completely with the vehicle dynamics through interpretations of the design characteristics and physical race simulations. Only through practice will he be able to fully understand the dynamic outputs for specific steering and throttle inputs. Following a thorough design and testing phase, the vehicle and driver will be an exceptionally well-tuned system and a strong contender for the SAE competition.

Method of Solution

To achieve the optimal suspension design according to the criteria listed above, the following procedure will be utilized.

1. Determine the general type of suspension
2. Determine the vehicle track width
3. Determine the tire size and rim diameter
4. Determine the suspension geometry
5. Design Uprights
6. Perform Simulations
7. Make Iterations
8. Manufacture Parts
9. Assemble Vehicle
10. Test/tune/optimize the vehicle with the driver

First, the general type of suspension must be established. By considering the many design parameters and constraints, it was determined that a non-parallel, unequal length a-arm configuration is the best suspension type. Also termed the short-long-a-arm suspension (or SLA for short), this type allows for the greatest degree of adjustability, and provides the desired behavior under dynamic conditions.

After determining the suspension type, the track of the vehicle must be established. The track is defined as the distance between the centers of the front or rear tire contact patches. The track may be different for the front and the rear. To determine the optimal track, several factors were considered. The suspension dynamics are affected by the track width. A wider track will control the weight transfer more effectively, thus improving lateral stability. However, a larger factor in determining the vehicle track is the competition events. The minimum width of the course is specified as 11.5 feet, and this width is fairly constant throughout. Therefore, a wide track will make it difficult to maneuver on such a tight course. By analyzing the results from the previous years, it was determined that a narrow track yields better results at the competition.

After determining the optimal track width, the tires and rims must be selected. The only constraint on the wheel selection is that they must be 8 inches or more in diameter. Several factors affect this decision. A smaller wheel is lighter and generally less expensive to buy. A larger wheel is much easier to assemble with the brake rotors and calipers. For this application, the best size was determined to be a 13 inch diameter wheel. This is a common size, and therefore easy to purchase. Also, they provide adequate clearance to package the brake rotor and caliper inside the envelope of the rim.

The most important factors in maximizing the dynamic stability of the vehicle are the tires. To obtain the greatest traction forces, it is imperative that the largest available surface area of the tire be in contact with the ground at all times. Therefore, the suspension can be characterized as a tool for managing the forces and directions of the tires so that they provide the driver with maximum accelerating and cornering traction. By analyzing the published data on various tire compounds and brands, the optimal tires will be determined and purchased.

The next step in designing the suspension system is to determine the geometry. This includes the mounting location of the suspension to the chassis, and the length and inclination of the a-arms. This fixes the roll center (instantaneous axis about which the vehicle will roll), which is an important variable, because it has an enormous impact on the vehicle handling characteristics. The design goal is to get this axis as close to the ground as possible, thus ensuring the most stable handling (See Appendix 3, Figure 1). The pitch center (instantaneous axis about which the car will pitch during braking and acceleration) is also established. The location of this axis affects the weight transfer during maneuvers and thus the vertical load over each tire. The suspension geometry will be determined using a software program written by William Mitchell, "Racing by the Numbers." This software models the geometry, and outputs the dynamic response to vehicle roll, as well as compression and rebound. This design phase is an iterative process. A base geometry will be selected, based on previous year's designs. Small changes, or iterations, will be made to the geometry, and the results will be compared. By repeating this process, an optimized geometry will be achieved, which will specify roll and pitch axes.

Once the geometry is established, the uprights must be designed. The uprights are the elements which connect the suspension arms (A-arms) to the wheel. In the front of the vehicle, the uprights are also an integral part of the steering system, allowing the wheels to turn for maneuvering. They will be designed for strength and durability to withstand the stresses and loads that will be imposed upon them; however they must also be light to reduce the overall weight of the vehicle. Their design will be examined using finite element analysis to determine the stress flows and deflections resulting in manufactured components that represent a perfect balance of strength and weight. They must be able to withstand the bending, tensile, and torsional forces exerted on them during competition and must also be designed with a provision for tuning. In designing the upright, two more important suspension parameters are established. The kingpin axis is formed by a line connecting the upper and lower ball joint when looking at the wheel from the front (See Appendix 3, Figure 4). This affects the dynamic characteristics of the wheel motion. A larger kingpin angle will cause a greater positive camber gain as the suspension is compressed. However, a larger kingpin angle will provide a lower scrub radius, which causes less friction. Caster is another parameter built into the upright. This is the axis formed by connecting the upper and lower ball joint in the side view (See Appendix 3, Figure 3). A larger caster angle will cause more negative camber change as the suspension is compressed. However, a large caster angle causes the wheel to lift the chassis as the wheel is steered, which increases the force required to steer. The optimal selection of kingpin and caster is determined through iterations using ADAMS/Car software.

The ADAMS/Car software package is an important tool in suspension design. This software package is a dynamic program that models the entire vehicle and describes output effects for independent and conditional input parameters. It accounts for geometry, mass properties, and spring/damper properties in both the shock absorbers and the tires. The software can perform dynamic simulations, then calculate and plot the results for numerous parameters, including camber gain, slip angles, scrub radius, steering effort, wheel motion, body roll, and various other characteristics. The simulations include constant radius turns, parallel wheel travel, lane changes, and other scenarios that simulate the suspension behavior. By changing certain model parameters and performing simulations, the optimal suspension design can be achieved and tested.

The next step in the design and analysis of the suspension is manufacturing. This process is made much easier by the use of solid modeling. Pro/Engineer solid modeling software will be employed. This allows for the complete assembly of the suspension components to check for proper fit and clearance. Once the assembly is approved, the parts can be exported into a program called MasterCAM. This program takes the geometry of the part and creates a CNC code. This code is entered into a CNC machine, and the part is precision machined. Once all of the parts are manufactured, they will be assembled onto the chassis.

After the initial assembly is completed and the vehicle is operational, fine tuning will take place. This post-assembly analysis is needed due to the inaccuracies of the manufacturing process and is regarded by the automotive community as imperative and irreplaceable. Manufacturing tolerances are inevitable, which limits the precise correlation between the model and the physical system. Therefore, the physical system needs to be adjusted to obtain the desired characteristics. This also allows for the tuning of the car to meet the specific style of the driver. The driver must feel comfortable with the vehicle. The driver must be able to anticipate the response that the suspension has to his inputs. This will allow the driver to push the car to its limit, and produce much faster lap times. The only way to provide this relationship between the driver and the vehicle is to practice, and get as much time in the seat as possible. Therefore the suspension design must be completed in a timely fashion to provide the maximum testing time.

ENVIRONMENTAL AND SOCIAL IMPACT

All of the components will be designed to minimize weight without compromising strength and rigidity with the aid of a solid modeling program. They will then be tested using a finite element analysis program to ensure proper stress distribution. The use of solid modeling allows the designer to reduce the amount of material without actually producing a part. Many design iterations can be done and compared before any material is used. This saves on raw materials by only manufacturing one optimized part.

Another environmental consideration is that the components in the suspension system can be recycled. Whether they are made of steel, aluminum, plastic or rubber, all of these materials can be recycled for future applications. Also, the components such as brake calipers and shock dampers can all be rebuilt, rather than replaced. This again reduces the amount of waste.

Another reason for a fine tuned suspension is for the safety of the driver and others on the track. If the suspension system were to fail, the safety of everyone could be in jeopardy. An example of a precaution is the dual master cylinder in the braking system. If one of the cylinders were to fail, the other would be able to carry the load and allow the driver to stop safely. There is also a safety switch which will turn off the vehicle if the brake pedal travels too far. This increases the level of safety, and minimizes potential harm.

With a fine tuned suspension, the engine will be able to work more efficiently. The vehicle will be able to perform the way the driver desires, maintaining higher speeds without applying as much throttle as would be needed without a tuned suspension. This reduces the fuel consumption of the vehicle.

SCHEDULE

One of the most important factors in ensuring an optimal suspension is testing after assembly. The design phase is important, and determining the optimal geometry is essential. However, it is impossible to manufacture a vehicle to zero tolerances. The suspension parameters are sensitive to small changes. Also, the system has many components, and between the steering wheel and the tires, many tolerances sum together. It is necessary to adjust the suspension after the car is assembled to compensate for manufacturing. The schedule for this project reflects this need for testing and adjustment. There are two separate colors on the timeline. The red indicates the January plan timeline, which includes preliminary design and manufacture of the suspension components. The blue color indicates the competition plan, which includes extensive testing and optimization of the suspension, as well as formulating the appropriate setup for each event at competition. (See Appendix 1, Timeline)

BUDGET

The budget is broken into three categories. There is a section for required resources, which includes the computers and software needed to design and analyze the suspension. It also includes the theoretical cost of the manufacturing and assembly facilities. The second section is the cost of the individual components in the suspension. This includes the cost to either purchase the part, or the raw material to machine the part. The third section is the labor. It includes the engineering time required to design the component, as well as the manufacturing time to either machine the part, or assemble it to the vehicle. Operating overhead is already taken into account in the facilities cost, and in the engineering costs per hour, and is therefore not added at the end. This gives a total project cost of $55,807.50. However, the resources are provided at no cost to the students, and all engineering and manufacturing time is provided by the students. Therefore, the prototype costs incurred by the students are roughly $7,195. This money will come from the Formula SAE budget. Formula SAE receives an annual allocation from the Student Activity Fee Allocation Committee, as well as contributions from the Drexel University Mechanical Engineering Department, the Drexel University College of Engineering, and from several independent sponsors. (See Appendix 2, Budget)

REFERENCES

2003 Formula SAE Rules, available as PDF at http://www.sae.org/students/formula.htm

Adams, Herb. Chassis Engineering. HPBooks. New York, NY. 1993

Milliken, William F., Milliken, Douglas L. Race Car Vehicle Dynamics. SAE International, Warrendale, PA, 1995 ISBN: 1-56091-526-9

Smith, Carroll, Engineer To Win, MBI Publishing Inc.,Osceola, WI, 1984
ISBN: 0-87938-186-8

Smith, Carroll, Prepare to Win, Aero Publishers, Inc., Fallbrook, Cal., 1975

Smith, Carroll, Tune To Win, Aero Publishers, Inc. Fallbrook, CA, 1978
ISBN: 0-9651600-3-3

Van Valkenburgh, Paul, Racecar Engineering and Mechanics, Published by author, 2000
ISBN: 0-9617425-0-X

Appendix 1: Timeline

See timeline.xls for detailed schedule

Appendix 2: Budget

Drexel University Formula SAE
Suspension Group Expenses, 2003

Resources Required:

Computer	$3,000
Assembly Facilities	$24,000
Software:	
AutoCAD 2002	$2,500
"Racing By The Numbers"	$350
ProEngineer	$6,500
ADAMS/Car	$2,000
Subtotal:	**$38,350**

Prototype Cost:

Component:	Material Cost	Engineering Time (hours) ($75.00 per hour)	Manufacturing Time (hours) ($50.00 per hour)	Total Cost
A Arm tubing	$200	3	10	$925
Bell cranks	$50	5	2	$525
Brake Calipers/Pads	$450	2	0.5	$625
Brake Disks	$300	1	0.5	$400
Brake lines/fittings	$75	2	1	$275
Brake master cylinder	$150	3	1	$425
Centerlock Hubs	$1,200	12	10	$2,600
Centerlock Nut	$25	1	0.25	$113
Dampers	$1,000	6	1	$1,500
Rod Ends	$100	5	3	$625
Spherical Bearings	$400	5	12	$1,375
Springs	$250	6	1	$750
Steering column/inserts	$45	4	3	$495
Steering rack	$550	5	2	$1,025
Steering support/bearings	$100	1	2	$275
Suspension bearings	$100	1	1	$225
Tires	$400	3	1	$675
Uprights	$400	17	10	$2,175
Wheel Bearings	$200	2	2	$450
Wheels	$1,200	10	1	$2,000
Subtotal:	**$7,195**	**94**	**64.25**	**$17,458**
		($7,050)	($3,212.50)	

Required Resources:	**$38,350.00**
Prototype Cost:	**$7,195.00**
Engineering:	**$7,050**
Manufacturing:	**$3,212.50**
Total Project Cost:	**$55,807.50**

Appendix 3: Suspension Parameters

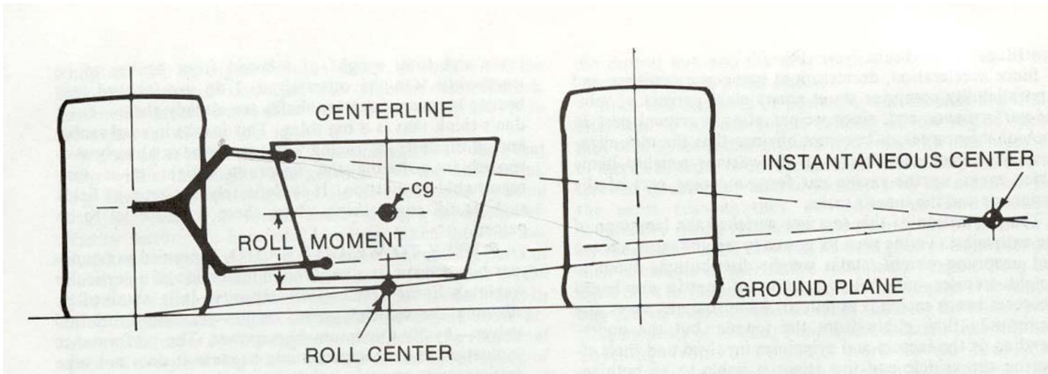

Figure 1: Roll Center

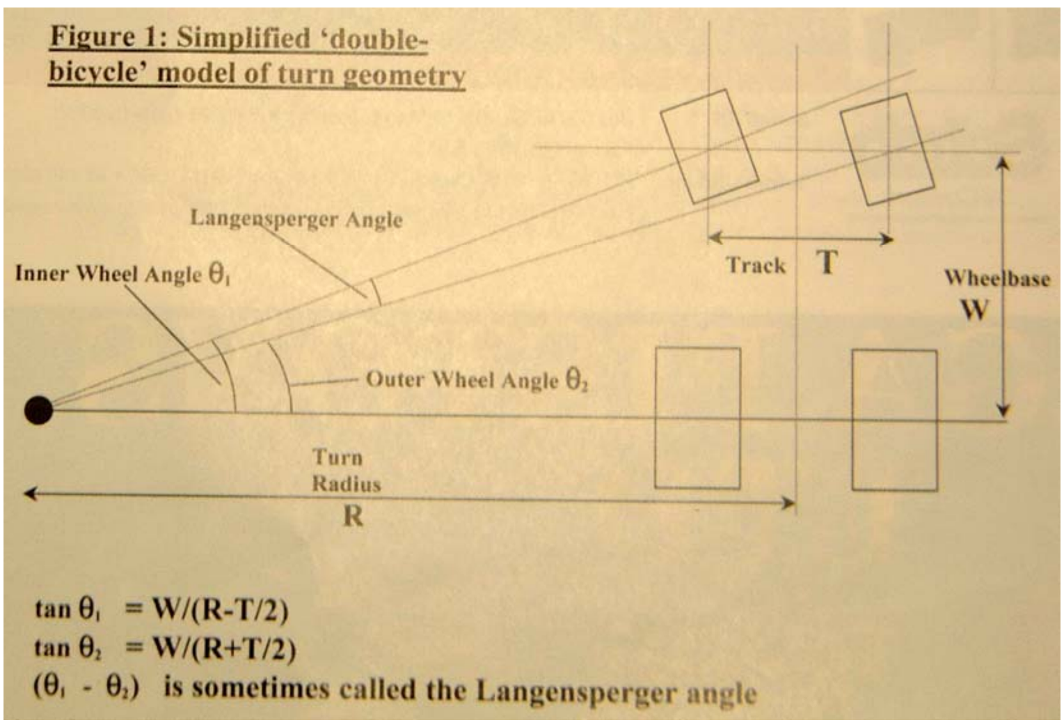

Figure 2: Steering considerations

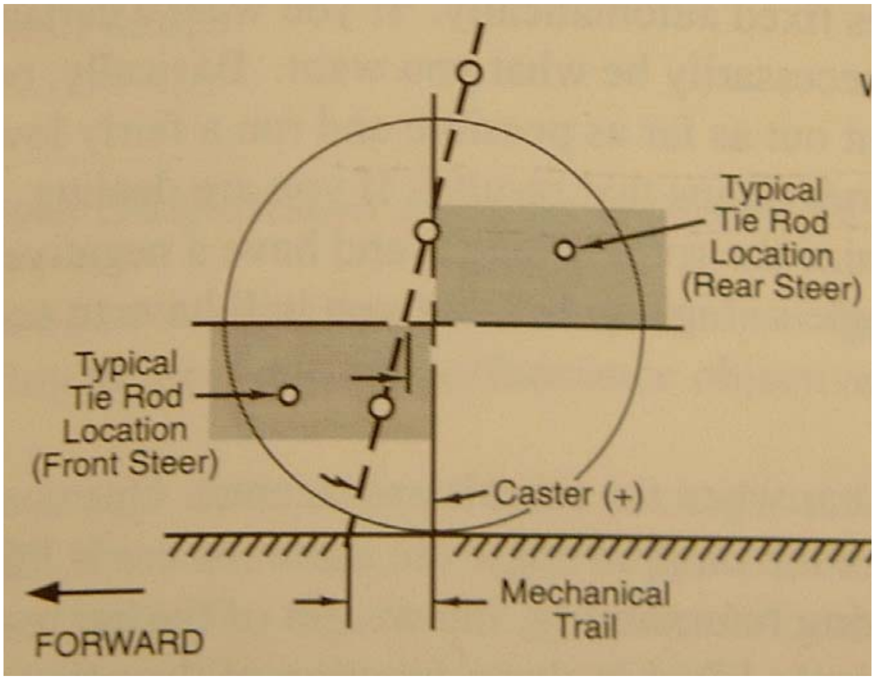

Figure 3: Caster and Mechanical Trail

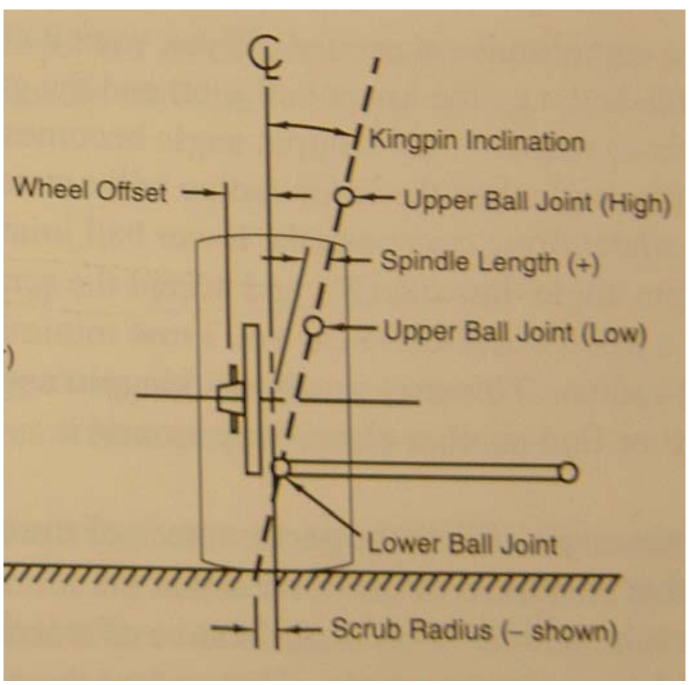

Figure 4: Kingpin Angle and Scrub Radius

Appendix 4: Team Members' Qualifications