

The Suspension System of the 2009 Cooper Union FSAE Vehicle: A Comprehensive Design Review

2010-01-0311

Published
04/12/2010Dennis Robertson and George J. Delagrammatikas
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ABSTRACT

This work details the process employed to design the 2009 Cooper Union FSAE® suspension system, spanning the overarching design philosophy, configuration selection, analysis, fabrication, and implementation, while offering recommendations to those especially new to the field. The design methodology illustrated here provides a systematic approach to suspension geometry, material selection, packaging, and construction. Though this paper serves as a starting point for FSAE® suspension designers, it provides a succinct overview for those interested in general suspension design fundamentals.

The design process began with the selection of a suspension configuration, geometries, and kinematics, which were driven in part by tire data, desired bulk vehicle dynamics characteristics, and overall geometric variability. The springs and adjustable dampers were then selected as the front and rear anti-roll bar properties were concurrently designed. The uprights were defined by reconciling a series of mutually-conflicting constraints imposed by their overall geometry, the A-arm locations and kinematics, wheel hubs, bearing selection, tie rods (front), the drive axles (rear), toe adjustment rods (rear), manufacturability, and mechanical properties.

INTRODUCTION

Since 1981, SAE® International's Formula SAE® competition has successfully trained engineers for technical and leadership positions in engineering fields. The SAE® Collegiate Design Series has also been heralded by the National Science Board in 2008 for its longstanding efforts to immerse aspiring engineers in rigorous, real-world math and science applications.

Among the many challenges that Formula SAE® students are tasked to undertake is that of designing their vehicle's myriad physical systems and electronics components. The suspension system contributes greatly to the vehicle's performance, specifically through isolation from vibration and shock, predictable vehicle control during maneuvers, and road holding ability.^[1,2] These characteristics are especially true for a race car, where high speeds and accelerations in both straight-line and angular directions dictate the vehicle's dynamic competitiveness.

Numerous texts and publications from well-known experts in vehicle dynamics are used by FSAE® teams worldwide with continued success; several of these are referenced herein. More advanced teams with a solid understanding of suspension geometry can further refine their designs with the aid of suspension analysis software. OptimumK® (OptimumG®), WinGeo3® (Wm. C. Mitchell Software®), and CarSim® (Mechanical Simulation Corporation®) are widely available and often used in FSAE®.

This paper describes the process utilized for the 2009 Cooper Motorsports suspension design and attempts to distill the information in these texts into a generalized procedure easily understandable by the suspension novice. It includes the rationale behind the selection of a general configuration, the development of suspension kinematics, and the mechanical design of the wheel-end assembly. This design review assumes a basic knowledge of vehicle and suspension nomenclature found widely in the open literature and is summarized briefly at the end of this work.

THE GOAL

The design objectives, defined by the team at the beginning of the design cycle, were to build a vehicle with exceptional maneuverability without sacrificing predictability and driver

confidence. Though the general configuration could involve a level of complexity in design, manufacture, and implementation for which experience on the team did not exist, the system could only utilize the fabrication tools at the team's disposal.

FUNDAMENTAL KNOWLEDGE

TIRE DYNAMICS

The tire is the single most important component on any land vehicle. The engine does not drive the car, the brakes do not stop the car, and the steering system does not turn the car; the tires perform all of these functions. Because all the forces transmitted by the car to the road travel through the tires, understanding how tires work is of critical importance to the suspension engineer. This subsection describes the fundamentals of tire dynamics; the information of which is discussed in more detail in [3].

Several FSAE® tires are experimentally characterized at the Calspan Tire Research Facility (TIRF), a program organized by the Formula SAE® Tire Test Consortium (FSAE® TTC). The data illustrated in this subsection were of the Hoosier 20.0×7.0-13 tire at 12 psi with zero camber (for simplicity) on a high grip belt at operating temperature. The Hoosier 20.0×7.0-13 tire was selected due to previous experience and since a proper comparison using tire data could not be performed in the available time for the prescribed design cycle.

The data generated from the FSAE® TTC represents the full potential of the tire on an idealized roadway. No real road surface offers such a high grip potential as the Calspan TIRF belt, so a road surface coefficient must be introduced. This coefficient represents the fraction of the full potential that a tire is likely to see for a given real road surface. Millikan Associates suggests a value of 0.6 for the road surface coefficient for FSAE®.

Generating Grip

All tire forces are generated at the interface between the tire and the ground (called the contact patch). This force, termed 'grip', is produced in three major ways: adhesion, deformation, and tearing, and commonly modeled using the frictional force equation here:

$$F_f = \mu_s N \quad (1)$$

F_f is the frictional force at the contact patch, μ_s is the coefficient of static friction, and N is the normal force on the tire. The static friction coefficient is appropriate here because a non-slipping tire does not slide against the ground in any significant way. A sliding tire would require the kinetic friction coefficient, a lower value. To illustrate the difference

between these conditions, consider two sets of situations: 1) sliding through a curve, locking the wheels under braking, or spinning the driven wheels under acceleration, as opposed to 2) cornering, braking, or acceleration without the tires sliding. Case 1) will yield a slower time.

A tire in contact with a smooth surface will generate friction by adhesion (molecular attraction), though deformation as well plays a key role on asphalt. A rubber tire will conform to the rough surface of the ground, effectively interlocking itself with the ground. As a tire slides over this rough asphalt, high local stresses can cause tearing, a phenomenon which yields greater frictional loss through energy absorption.

Load Sensitivity

In a simple model, the coefficient of friction is considered constant, but empirical data suggest otherwise for a pneumatic tire. A distinct drop-off in the frictional coefficient occurs as normal load increases. Termed load sensitivity, the consequences of this decrease in friction are profound.

If one assumes insignificant aerodynamic loads, maximum overall grip requires that all four tires have as low a normal load as possible. This condition implies that the vehicle's weight should be as evenly distributed as possible under all conditions. The vehicle's anti-roll bar, detailed later, exploits this phenomenon to adjust the balance of the racecar accordingly.

Figure 1 represents the maximum coefficient of friction for each of the normal loads experienced by the Hoosier 20.0×7.0-13 tires used on the Cooper Union racecar.

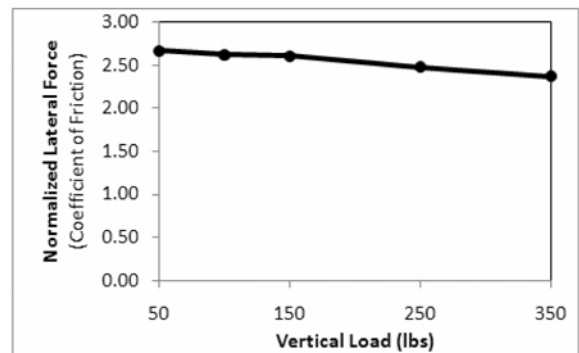


Figure 1. Normalized lateral force (coefficient of friction) versus normal force (FSAE® TTC).

For this tire, the coefficient of friction decreases by about 0.3 or 11% from the minimum to the maximum loads. For 100 lbs additional weight per tire (400 lbs additional weight for the entire car), there is at most a 5% decrease in tire effectiveness. The tires, therefore, do not exhibit a load

sensitivity that justifies a serious redesign of any other related vehicle attribute.

Slip Angle

Consider a race car traveling along a curved path. Examining any one of the four tires, two quantities can be determined: the direction the tire is pointed, and the direction the tire travels. The angle between them is termed the slip angle (Fig. 2) and is always non-zero when sustaining lateral force due to the elastic nature of a pneumatic rubber tire.

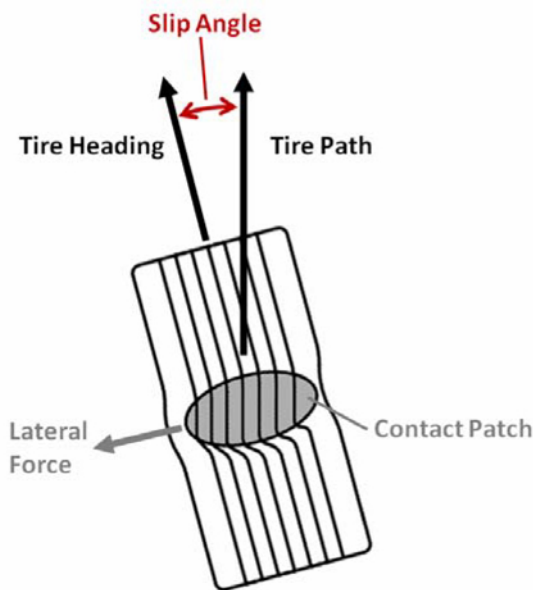


Figure 2. Slip angle.

Since lateral force is dependent on slip angle, it is necessary to experimentally determine the functional relationship between these factors. Figure 3 illustrates the function between lateral force and slip angle at a vertical load of 250 lb.

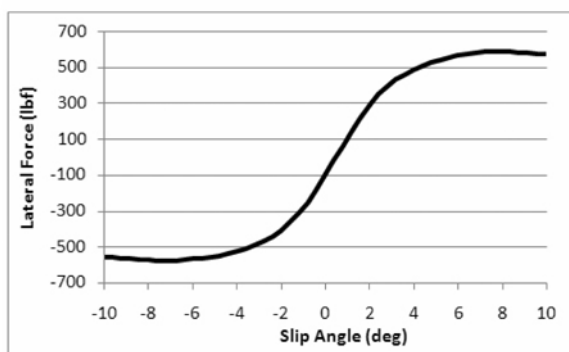


Figure 3. Lateral force vs. slip angle (FSAE® TTC).

This graph indicates that the maximum lateral force is generated with 6-8 degrees of slip angle. These slip angles offer the highest possible lateral force, although as slip angle increases the mechanical drag of the tire also increases. It may be that a driver at 4 or 5 degrees slip angle can achieve a lower time with the lower drag, despite the lower lateral force.

Camber

Closely related to lateral force is the ability for a tire to supply 'camber thrust' - the phenomenon that generates lateral load solely from camber. As shown in Fig. 4, camber is the angle a centerline of the tire makes relative to the vertical when viewed from the front, where negative camber exists when the tops of the tires point toward the vehicle, and vice versa. Excessive camber, however, can lead to undesirable levels of tire wear and decreased grip.

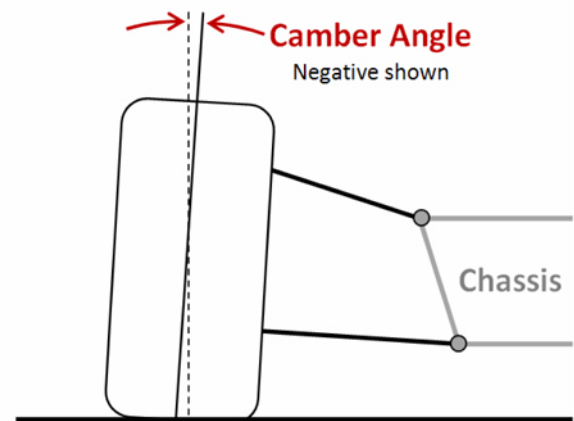


Figure 4. Camber angle depicted from a front view of the right front corner.

SUSPENSION TYPES

Research of the functional requirements and constraints imposed on the suspension by the competition rules and foreseeable loading conditions is the next step. Considerations include typical maximum speeds, accelerations, braking times, powertrain loads, chassis reaction forces, geometric compatibility with other subsystems, serviceability, and safety requirements.

A dual wishbone (dual A-arm) suspension was selected because it generally offers broad design freedom for suspension kinematics and the most facile packaging for an FSAE® space frame chassis.

VEHICLE DESIGN

With the fundamental principles governing suspension design understood, the design of the vehicle can begin. The order

followed in this paper reflects the order followed in the design of the vehicle. Each concept of vehicle suspension design will begin with a short definition and description of its effects, followed by the design choice and rationale behind this decision. Locating the tires with respect to each other is the first step in designing the vehicle.

WHEELBASE AND TRACK

A short wheelbase carries with it increased maneuverability, but at the cost of high-speed stability. Given the nature of the circuits and the speeds observed in winning vehicles in the past, high-speed instability was a lesser concern, making increased maneuverability paramount. Because the competition regulations mandated a lower bound on the wheelbase of 60 inches, the suspension designer selected a 60.25" wheelbase to ensure it was higher than the strict minimum.

As an outline of this car's suspension system is beginning to take shape, it is necessary to next consider the car's fore/aft weight distribution. The other team designers would then use this information to appropriately locate their subsystems in a concurrent fashion.

A slight rearward weight distribution is advantageous for FSAE® vehicles.^[4] It offers 1) trivial oversteer in steady-state cornering (in line with the team's initial design goal of high maneuverability), 2) a more evenly-balanced car under braking for greater overall braking force, and 3) added traction to the rear tires under acceleration. These advantages led to the selection of a 45% front, 55% rear weight distribution target. Predicting the final weight distribution requires a complete CAD model (the more complete the model, the more accurate the prediction). The resources needed to obtain a sufficiently accurate CAD model exceeded the available resources, so an approximate weight distribution was used.

Track not only affects the physical width of the car, it affects the lateral weight transfer as well. A vehicle with a narrow track may more easily navigate corners thereby generally increasing lap times. However, this narrow track creates a larger weight transfer, which (due to load sensitivity of the tires) compromises cornering performance. The relationship between track and weight transfer can be found in [Eq. \(2\)](#).^[5]

$$WT = \frac{a \times W_s \times h_{CG}}{t} \quad (2)$$

where WT is weight transfer, a is lateral acceleration (in g units), W_s is sprung weight, h_{CG} is the CG height, and t is track. This equation can be applied to the front, the rear, or the combined weight transfers.

Resolving the above mutually-conflicting constraints, a front track of 46 inches and a rear track of 44 inches was selected. These are typical values for both our team's previous vehicles and other FSAE® teams. The CG height carries significant uncertainty early in the design phase, for the same reason listed in predicting the final weight distribution, therefore the designer chose a relatively high (i.e. potentially safer) track selection.

The ratio of wheelbase to track is a concise metric in understanding the relative stability of wheel configurations. Typical values for FSAE® range from 1.2 to 1.6, where the lower the ratio, the more unstable (i.e. maneuverable) the vehicle is. The ratio of wheelbase to track for the 2009 Cooper Union FSAE® car was not selected as the driving factor. Rather, the wheelbase and track were selected, then the ratio of the two was compared to typical values and was deemed acceptable.

SUSPENSION KINEMATICS

Suspension kinematics defines the motion of the suspension during maneuvers and over any road surface geometry. Optimal contact with the road is crucial in maximizing the vehicle's acceleratory response.

This subsection details the design considerations needed to create a properly functioning vehicle. Since the goal of suspension kinematics is to maximize use of the tires, the analysis begins with wheel geometry, and then builds upon that to describe how the location and orientation of the various suspension links affect the forces and moments from the tire on the vehicle. The design process detailed here describes the effect each concept has and the rationale behind the chosen values. Further details on suspension geometry and its effects on vehicle dynamics can be found in [\[5\]](#).

Wheel Geometry

Camber has one of the most substantial effects on vehicle performance. As such, the suspension design must strive to keep the camber of all four tires at the optimum value. From tire data, 2 degrees of negative camber generated the most lateral force. The suspension geometry was designed to maintain this value over all operating points taking into account chassis roll and suspension compliance. The static value of camber was -1.5 degrees on the front tires and -1 degree on the rears. Note that a higher value of static camber will reduce traction on the rear tires under acceleration, so the designer must strike a conscientious balance.

While camber describes the angle of the tire from a front view, toe describes the angle from a top view. As seen in [Fig. 5](#), toe is the angle a centerline of the tire makes relative to the vehicle centerline when viewed from the top.

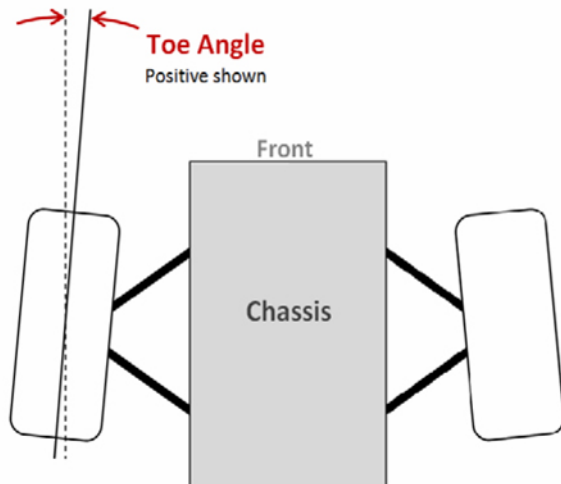


Figure 5. Toe angle depicted from a top view of the front wheels.

Toe out (negative toe) on the front wheels gives the front end of the car more maneuverability, assisting turn-in, while toe in on the rear offers rear-end stability. From previous experience, 1 degree toe out at the front and 0.5 degree toe in at the rear offered a good balance between maneuverability, stability, and wear.

An important consideration for upright design and packaging is kingpin inclination (KPI). As shown in [Fig. 6](#), kingpin inclination is the angle a steering axis makes relative to the vertical when viewed from the front, where positive kingpin inclination is when the top of the steering axis points towards the vehicle, and vice versa.

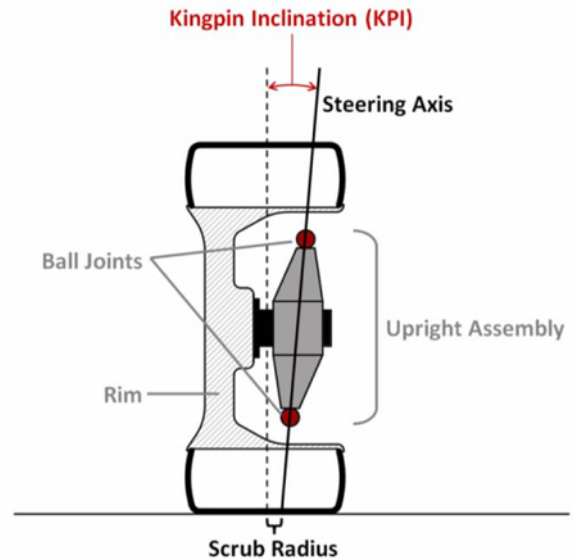


Figure 6. Front view of right front wheel depicting kingpin inclination and scrub radius.

The distance between the intersection of the steering axis with the ground and the center of the tire when viewed from the front is called the scrub radius, also depicted in [Fig. 6](#). Scrub radius is positive if it lies inboard of the center of the tire.

The scrub radius provides feedback to the driver when the braking limit is about to be reached. Since the braking force is perpendicular to the scrub radius, a torque about the steering axis proportional to the scrub radius is generated. Under normal conditions the torques from both wheels would cancel each other out. However, near the limit of total traction, one tire will approach its limit sooner (since the conditions for each tire are not identical), creating an imbalance of these torques, which would generate a net torque about the steering axis. This net torque can be felt at the steering wheel and indicates to the driver that the wheels are about to lock up. Conversely, too much scrub radius increases the steering effort.

The packaging constraints of the rim and upright assembly limited the range of possible scrub radii to a minimum of 1.25". The minimum was selected since it offered sufficient feedback without an excessive required steering effort, from previous team experience. The scrub radius for the rear is kinematically irrelevant, but is critical in generating force in the toe link which contributes generally in counteracting the steering torque in the rear tires caused by from braking/driving forces.

Analogous to kingpin inclination and scrub radius in front view, are caster and mechanical trail in side-view. As shown in [Fig. 7](#), caster is the angle a steering axis makes relative to