Chapter Four: Suspension Dynamics Overview

RIT Baja SAE

Introduction

The suspension dynamics overview is intended to address the vehicle dynamics unique to an SAE Baja car. This summary will assume that the user has a basic working knowledge of suspension dynamics and will attempt to distill the most valuable knowledge gained over the past four years of design, testing, and competition. The summary will be layered as sections of the car beginning at the front and working towards the rear to explain the most important and effective concepts. While excellent suspension design requires that all components are designed to work in unison, each of the dynamic concepts will be explained individually and weighted on a 1-5 scale of importance, 5 of utmost importance and 1 being of lesser importance.

Fig. 1: (2005-2006)SLA A- Arm Rear
**Tire Traction 5**

Tire selection is of ultimate importance. Many hours can be committed to the design and analysis of a suspension system, however, its capabilities will be observed as limited on the test track with a tire of poor quality or improper selection. To think of the tire in the most simplistic sense, one can imagine a chassis rolling around a turn on smooth dirt disregarding driveline torque inputs, suspension movement, steering inputs. This application would be similar to that of a skid pad where the car would be driven around in a circle at a very gradually increasing speed until the car could no longer hold lateral traction. In this application, the car’s maximum speed can be calculated simply from the coefficient of friction between the tires and the dirt circle. Of course, any real world situation adds an infinite number of complications, but from this thought experiment, one can easily see the utmost importance of tire selection. For the purpose of this discussion tire parameters will be limited to tread pattern and compound.
Tire Tread Pattern 5

The tire tread pattern has long been understood as a critical component of off-road vehicle dynamics. Contrary to performance road tire design, relying heavily on increasing contact patch area and the stickiness of the compound, off-road tires rely first and foremost on the tread pattern.

There are a number of factors to consider when selecting the tread pattern. Off-road tire manufacturers use features such as knobs, sharp edges, and bars for general traction, sidewall tread for sidewall protection and crawling traction, and tread draft and angle for clearing in muddy situations. Selecting the tread pattern is somewhat an art of experience, but it is important to know what the functions of these tread design features are and how they will generally effect the overall traction and handling of the car.

Historically, the team has chosen “knobby” style treads over bars to increase the lateral stability or lateral g-force capabilities of the car. The “knobby” style tread pattern will tend to “bite” more in corners and drive the car through the turn, while chevron or bar style treads tend to slide out in the turns giving an over steer effect that subtracts from the forward momentum of the car.
Tire Rubber Compound 4

Road performance cars rely heavily on tire compound as the main source of traction. This is so important that preheating the tires to increase their stickiness is a vital part of many road car race preparations. As Baja car lives its life at under 40 miles-per-hour on a dirt track, temperature has not been looked to as a significant factor of traction. The rubber compound has recently become an area of focus for Baja suspension design. A look into modified dirt track racing and ATV flat track racing have validated the significance of the using softer stickier tire compounds on dirt surfaces.

Frequently, the track of an SAE Baja competition will be similar to that of an oval style dirt track, not in the sense of flatness, but in the condition of the dirt itself. Many portions of a baja track tend to be "hard packed" or "scraped off" leaving only compacted pavement-like dirt for the tire to interact with. Under these conditions, the tire compound takes the lead roll in cornering and accelerating traction.

This concept of the rubber being the most important contributor to car traction on packed surfaces also extends to many other applications including, but not limited, to acceleration event runs on pavement, sled pull events on pavement, and the rock crawl event.

Flat Track Racing ATV with tires that rely on heavily on compound sticktion for traction on hard pack clay track.
The air pressure within a tire combined with the structure of the tire itself create the overall tire stiffness. This phenomenon creates not only a spring stiffness but also a damping effect caused by the energy lost in the deformation of the rubber. Performance parameters caused by stiffness can be tuned in a number of ways.

The first parameter that can be adjusted is traction. Decreasing the tire pressure changes the shape of the tire. This deflation of the tire causes the contact patch size of the tire to increase creating, in many situations, greater traction. This tire deflation also decreases the tire's overall stiffness allowing it to conform to rougher terrain more readily. The practice of significant tire deflation is used mainly in specific events where increased tire contact patch traction is necessary. During competition, this includes rock crawling and hill climbing. Although the increased traction over extremely rough or rocky terrain is evident and widely practiced, not much has been scientifically proven within the RIT team as to the effects of tire pressure on traction. Maintaining a record and conducting tests in this area may hold potential gains in research and testing.

The second practice that employs tire stiffness reduction is the decreasing of the effective radius of the tire for more available torque. Tire deformation that occurs during low tire stiffness not only increases the contact patch size but also decreases the effective radius of the tire providing the car with a slightly lower overall drive ratio. This technique comes into play mainly during the sled pull event. During this event, the car will stop pulling for one of two main reasons: a loss of traction or torque. Pulling torque is somewhat increased by a shorter effective tire radius that gained by decreasing tire stiffness. Increased contact patch size distributes the stresses caused by tire torque over a larger area and aids traction in "loose" or "soft" terrain situations. Overall this theory lacks documented testing or research, but it has been standard over the past 4 years to run atmospheric pressure (0 psi) in the rear tires during a sled pull event. The only danger in using this technique is that ground clearance must be maintained in the rear to keep from transferring weight from the tires to the frame when it contacts the ground.

The most common use of tuning to the tire stiffness is to adjust the roll stiffness of the front or rear of the car. Roll stiffness characteristics are designed and
controlled by the spring rates, sway-bar rates and the low speed damping in the shock. Tire stiffness tuning can also significantly change the handling characteristics and feel of the car. Changing tire stiffness by increasing rear tire pressure or decreasing front tire pressure provides a subtle change that can be employed in between the runs of an event to give the driver a slightly increased turning ability. During the practice of using tire pressure to tune roll stiffness, the changes in tire pressure should be done to both front tires or both rear tires. Conventionally, increased tire pressure and stiffness are not desirable for driver comfort or traction. In practice, front tire pressure may be dropped 2-3psi resulting in decreased overall front roll stiffness creating greater front end roll, increased outside rear traction, decreased inside rear traction, and earlier and greater incurred yaw moment. The standard baseline setup for the past few years has been 7psi front, 10 psi rear.
King Pin Inclination 4

Kin pin inclination is a key concept in the dynamics of the suspension system. Making this more complex than the previous concepts is that king pin cannot be easily separated from other dynamic systems, nor can it alone account for any one handling characteristic. The king pin inclination is a key part of camber control in both suspension compression and extension and also during transient turning.

During compression and extension, the king pin axis, upper and lower a-arms, and the line connecting the upper and lower inboard suspension points can be simplified to a 2 dimensional quadrilateral looked a from a front view. It is the geometry of this simplified quadrilateral that mainly controls the camber of the wheel during suspension movement. It is here that the designer is able to trade off position of the 4 corners of this quadrilateral to create different dynamic camber changes.

The second critical function of the kingpin inclination is how it works together with caster to create camber gains during turning. The caster angle and the king pin inclination fully define the axis about which the wheel pivots during turning. The end result of this dynamic during wheel turning is that the wheel will gain or lose camber. This is traditionally setup to incur a negative camber on the front outside wheel and positive camber on the inside front wheel. Here, camber gain will negate and balance out the camber changes during body roll and create a more favorable contact patch as well as incur a diagonal weight transfer. This can be used very effectively in the baja suspension application.
Caster Angle and Mechanical Trail

Like king pin inclination, caster is also a very integral concept that cannot be easily segregated from other dynamic suspension concepts. The main function of the caster angle works in conjunction with the king pin inclination to define the wheel turning axis in space and creates the noted camber changes and resulting incurred suspension dynamics.

The second distinguishing function of the caster angle is to create mechanical trail. This concept is best visualized by the front wheel of a grocery store shopping cart, or the front of a motorcycle. The king pin axis looked at in a side view intersects the ground at a point somewhere in front of the contact patch center. The distance between these two points is known as the mechanical trail, termed for the "trailing" behind of the contact patch. This action creates the self centering action similar to the shopping cart and also determines how much the steering system "shifts" the front end of the car during wheel turn. The caster angle in creating mechanical trail becomes a lever arm through which the driver controls the contact patch. Together, these concepts are effective in creating a necessary weight transfer. While little is known within the team about this weight transfer, it is a key component of some of the "hard" or un-tunable suspension design parameters.

Diagram of Caster and Mechanical Trail
**Spindle Offset**

Commonly, the spindle axis is located so that it intersects the kingpin axis. This allows the suspension uprights to be side independent and also aids in the simplicity of manufacturing. In the 2004-2005 design cycle, the team experimented with offsetting the spindle from the kingpin axis in the front suspension. No substantial evidence of this design shift has been collected comparing this design to previous or later ones, however, the results of this design change have been said to be favorable. The following analysis of the spindle offset is only a logical analysis of the design parameter and has not been scientifically proven and would benefit from further research and testing.

There are two key components of the spindle offset, the first is in conjunction with the caster angle. These two work in conjunction to create the overall mechanical trail as termed previously and will have governance of the lever arm through which the driver has control over the contact patch and also the amount of lateral shift of the front end of the car during steering input.

The second key point of the spindle offset is how it works in conjunction with the kingpin inclination angle. If the spindle is offset toward the front end of the car from the kingpin axis, during turning the outside spindle (and the wheel center) position will move closer to the ground. Conversely the inside spindle and wheel center will move upward away from the ground. This combined action of the turning wheels causes a “lean” effect of the chassis that may be beneficial in turning and stability.
Bumpsteer 3

Any multi-link suspension is a very complex dynamic system. When optimizing the motion control of all six degrees of freedom of a wheel there will always be trade-offs in desired wheel motion. One of the most common parameters that requires many iterations of kinematic simulation as well as discretionary trade off is the steering geometry. The long travel application of a Baja car suspension causes many of the small undesired motions of the wheel to be exaggerated near the limits of travel. Many iterations of computer simulation as well as a significant portion of design time is normally allotted to analyzing the bumpsteer or wheel turn angle due to suspension travel in a front suspension design. Although bumpsteer dynamics can be beneficial if applied in very specific ways, such as adjustable rear wheel bumpsteer creating a dynamic similar to 4 wheel steer, for the most part it is understood that the steer angle of the front wheels should be under complete driver control to create stability, predictability, and consistency.

The ideal situation for minimizing bumpsteer is as follows:

1. Consider the car at standard ride height with steering rack centered and no wheel turn angle

2. In the top view, the steering rack bar should be inline (axial) with the tie-rod wheel the rack is centered. This will also minimize radial loading of the rack bar due to steering loads.

3. In the front view, the extended tie-rod line should intersect the instantaneous center of the controlled wheel (the intersection point of the extended a-arm lines).

4. The inboard tie-rod point should lie on the plane created by the corresponding four inboard a-arm points.
Bumpsteer (continued)

This is an effective starting point but will require considerable time for optimization and trade off due to driver compartment restraints as well as other interrelated desired wheel motion. For further minimization the extended tie-rod line should continue to intersect the instantaneous center of the controlled wheel throughout the entire travel.

Bumpsteer should be taken into consideration not only in the zero turn angle or straight driving situation but is especially important during high steering angle turning situations. In the turning situation the outside wheel will compress while the inside wheels will extend due to body roll. During turning the car also frequently encounters bumps and obstacles that can cause bumpsteering as well. There are some resources that may state that a slight increase in wheel turn angle with turn progression and body roll can be favorable, but due to the unpredictability of the terrain traveled stable bumpsteer characteristics are usually favored. This is especially critical on the outside since more weight, traction, and turning force is shifted to it during turn progression. Typically with no wheel turn angle over 12 inches of travel the wheel will bumpsteer 1-2 degrees.

Diagram of Bumpsteering
Traditional Ackerman geometry is considered in low speed "parking lot" style maneuvering to minimize wheel scrub and was originally invented to keep horse drawn carriages from disturbing gravel driveways. Because of this, many high speed race cars do not consider Ackerman to be a vital part of steering geometry and many times will run parallel steer. The Baja application however holds a slightly different use for this steering parameter, both during high and low speed maneuvering.

In the low speed tight radius turn the benefits of Ackerman geometry are somewhat conventional and obvious. The wheels being turned to different steer angles reduces energy loss from wheel scrub and keep the front wheel from "fighting" each other. In the higher speed applications the benefits may not be as obvious.

When maneuvering on dirt, the wheels are generally running at a significant slip angles. At high speeds, turning the inside wheel slightly more during turn initiation will cause its slip angle to be greater than that of the outside wheel. While initiating the turn this inside wheel will scrub more than the outside and cause a desired yaw moment to pull the chassis into the turn. Although these high speed benefits are believed to be true little has been done to test the hypothesis scientifically and create supporting data. Also, it should be acknowledged that this yaw moment effect will decrease as the turn progresses and as weight is transferred to the outside of the turn.
Camber gain during Compression 2

Although many of the tires used by the RIT team have a round knobby profile and are designed to have good side traction, the a-arms and semi-trailing arms are designed to gain negative camber during compression and conversely gain positive camber during extension.

This concept is mainly used to control the contact patch area during turning. During turning the centrifugal force acting at the chassis center of gravity will cause the body to roll to the outside of the turn. This "leaning" of the body will cause the wheels to lean to the outside of the turn also. The dynamic camber gains designed into the suspension are created to balance out the body roll and keep the contact patch stable and on a favorable area of the tire.

Another dynamic which camber gain during compression creates is essentially an extension of track width during compression. Since the bottom of the wheel is angled outward in compression the distance between the contact patches can essential increase depending on the amount of negative camber gained.
Progressiveness 4

Off-road suspensions are generally designed to become stiffer as the suspension compresses. This allows smaller high frequency bumps to be absorbed by the less stiff region of the travel and the high amplitude, low frequency bumps to be mitigated by the stiffer regions of suspension travel. This dynamic is designed to create a smooth ride, control and traction, while minimizing speed scrubbing and potentially damaging bottom-outs. A progressive geometry can usually be visually characterized by the shock being at an acute angle to the link it is governing. The progressiveness is a characteristic of the related rates of the triangle created by the upper shock point, lower shock point, and the link pivot. Progressiveness can also be a function of the selected springs, multi rate spring pack, or the air shock used.
**Jounce Bumper 3**

The jounce bumper is a small simple part of off road suspension that is often overlooked. The jounce bumper can be a simple compressible rubber disk or a slightly more complicated air chamber design, but the function of the jounce bumper is the same. It is the last line of defense between the frame and the ground. Just before the spring is fully compressed the shock will engage the jounce bumper which adds an additional compressive spring rate to the pack, stiffening the system even further before all suspension travel is used. Although little attention is paid to this component during design and shock selection, the energy storage or dissipation it provides can be vital in protecting suspension components in very hard impacts.

In tuning it has been designated a rule of thumb or baseline that the damping settings chosen by the suspension tuner and the driver should allow the car to slightly bottom out at least once on the track to verify full use of available suspension travel.
Damping 5

In the traditional sense, the term damping is used to describe any medium or method through which energy is dissipated or damped. In the off-road application, suspension components, driver, and chassis alike receive frequent and significant high energy impulses. It can be arguably stated that controlling these high energy impulses is one of the most base functions of an off-road suspension system. This makes damping design, control and tuning important aspects of Baja suspension design. Historically the RIT Baja team has focused much of its design emphasis on the importance of shock absorber selection and tuning, but the team is currently realizing the importance of energy dissipation throughout the entire design mainly for durability in the extreme impact loading resulting from suspension and traction course style obstacles as well as driver error and crash scenarios. The following paragraphs will address both categories of damping.

Most current offroad shock absorber technology employs similar technology. Shock absorber selection and tuning has existed as a somewhat black art on the team for a number of years. Earlier in our team history we had employed Penske racing dirt track shock, and have currently moved our selection process towards better application match of performance ATV coilover shock absorbers, successfully competing for 3 years with Performance Engineered Product (PEP) shocks and shifting to experimentation with Fox Float Evol shock during the 2008-2009 season.

The PEP shock features triple rate selectable springs, adjustable shim style crossovers, adjustable spring preload, and adjustable compression and rebound damping circuits. The triple rate springs create a dynamic spring rate (abiding by the equations for springs in series) allowing the suspension to become stiffer as it compresses as force is distributed across fewer springs in the series. The spring pack will create three distinct rates, switching when the cross over shims are contacted and the respective spring is rendered inactive functionally removing it from the system. This "progressive" stiffness allows the flexibility to mitigate high frequency, low amplitude bumps with softer suspension characteristic, and prevent bottom out during lower frequency, high amplitude obstacle situations with stiffer suspension characteristics.
Motion Ratio 4

Since the coil over is never directly connected to the wheel itself, the spring acts on the wheel through the a lever arm. This lever arm through which both spring and damping forces act on the wheel, can be described as the motion ratio. During suspension travel the motion of the geometry causes these motion ratios to change. Ideally, in an off road suspension, this motion ratio will be progressive allowing the springs and dampers increasing leverage on the wheel during compression. Typically packaging issues can limit the progressiveness of motion ratio dynamics, and motion ratios that are very high (shock has very little leverage on wheel) will increase the needed spring rates, overall shock output force and also increase the bending stress in the link carrying the shock absorber load. This high motion ratio will also require more force to be absorbed by the fluid damper, increasing damper heat and decreasing performance.

In a traditionally linked suspension (no bellcrank/push or pullrod) the challenge to minimize link bending loads while achieving desired travel distance.

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Yaw Moment

Yaw moment is an broad term that encompasses any torques generated to cause a turning motion of the car. These torques or moments are forces generated at the wheels acting on the center of gravity of the car.

The most obvious driver controlled yaw moment is that generated by front wheel traction during turning. The second and less obvious source of the essential yaw moment is in the driving rear wheels. This dynamic happens when power is transferred to the outside rear wheel. The force generated by this wheel acting about the center of gravity creates the moment that actively "drives" the car through the corner.

In traditional vehicle dynamic situations this power transfer to the outside wheel is controlled by the differential. Many times in the Baja car application differentials can be heavy, complicated and can cause the loss of vital traction, so a spooled rear end is used. In this case, the yaw dynamics of the vehicle have a twofold challenge to overcome.

First, with no difference in rear wheel speed the two tires actually "bind" or "scrub" during turning causing a detrimental yaw damping effect. Second, there is no mechanically governed transfer of power to the outside wheel and effectively no yaw moment incurred by the driving wheel. To overcome this handling issue, body roll is used to transfer load, traction, and torque to the outside rear wheel and slightly "lift" or decrease the traction of the inside rear tire. In this way, the yaw moment and likewise the handling of the baja car becomes very much depended on turning speed, body roll, rolling moment, and front–rear roll stiffness bias.
Being a measure of the roll angle of the car usually during cornering, body roll serves two main purposes. Body roll, first and foremost, is a dynamic parameter effecting the stability and traction of the car during cornering. Body roll effects contact patch and camber angles, all the way through the suspension system to wheel loads creating the yaw moments explained previously. The second function of body roll is a feedback device to the driver. The angle of the chassis which the driver senses with his or her internal gyroscope is a strong signal of the car's cornering limitations and when they are being reached.
Roll Stiffness

The roll stiffness is a measure of the chassis's resistance to body roll. The suspension geometry in conjunction with the spring rates of the shocks, tires, and anti sway bars, create the combined torsional spring rate of the chassis.
Rolling Moment/ Body Roll Dependent Handling

In the yaw moment portion of this chapter we discussed the handling of a spooled rear axle Baja car is extremely body roll dependent. The rolling moment is a critical factor in creating body roll dynamics and therefore a large factor in handling attributes of the Baja car. The rolling moment is a simple concept that can have very dramatic handling, stability, and diver feedback characteristics of the car. The rolling moment is defined as the cornering force applied at the center of gravity multiplied by the distance from the CG to the roll center of the suspension. By controlling the height of the CG and the roll center during design and setup, the roll characteristics and therefore the handling can be dramatically affected.

The standard for RIT Baja suspension design is to design different roll center heights for the front and the rear. By lowering the front roll center to approximately ground level the large CG to roll center distance causes a large rolling moment value and gives the front end a tendency to "roll" rather that "tip" onto the outside wheel. Raising the rear roll center closer to the CG will give the rear suspension a tendency not to comply during body roll and "tip", lifting the inside rear to create a favorable yaw moment.

The SLA A-arm setup offers superior rolling moment control over a trailing arm suspension. By adjusting the link angles in the front view the suspension designer can create a number of different rolling moment scenarios and handling characteristics. The rolling moment is also a factor to be taken into account when designing the sway bars and selecting roll stiffness's. Overall the body roll characteristics of the car can be most completely described by the torque provided by the rolling moment and the resistive stiffness provided by the overall roll stiffness.
Body Roll Dependent Handling

Top View

Load Transfer to Outside due to $F$

$M_1$

$F = \frac{mv^2}{r}$

F, Traction Force

$M_1$, Imbalance Causes

Rear View

Rolling Moment

$M_{rolling} = F_{cent.} \times L$

C.G.

$F_{centrifugal}$

Instantaneous Center