Making Suspension Geometry work

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Caster, **Camber**, and **Steering Axis Inclination** (SAI) are some of the basic geometry angles used to improve stability and handling and improve the work and life you get from the tires. When you move from a static environment, such as measuring these angles on the shop floor, to a dynamic environment such as entering and/or exiting a turn, the interaction of these geometric variables becomes more important. In a dynamic environment **camber gain, caster gain, effective camber, camber thrust, weight jacking and driver feel** become important. In this tutorial I will attempt to explain some of these relationships as well as how you might measure and optimize them for improved performance. The first step will be to explain the individual angles. This should be old hat to most but for clarity I am explaining them in my terms.

Caster Angle Basics

Caster is the inclination of the wheel pivot axis, or steering axis, as viewed from the side. In a solid axle car with kingpins, it is the inclination of the kingpin viewed from the side as shown in Figure 1a. In a ball joint independent suspension it is the inclination of a line drawn through the two ball joints as viewed from the side, as shown in Figure 1b. Caster is most often associated with steering effort and stability; however, it also affects camber as the wheels are steered.
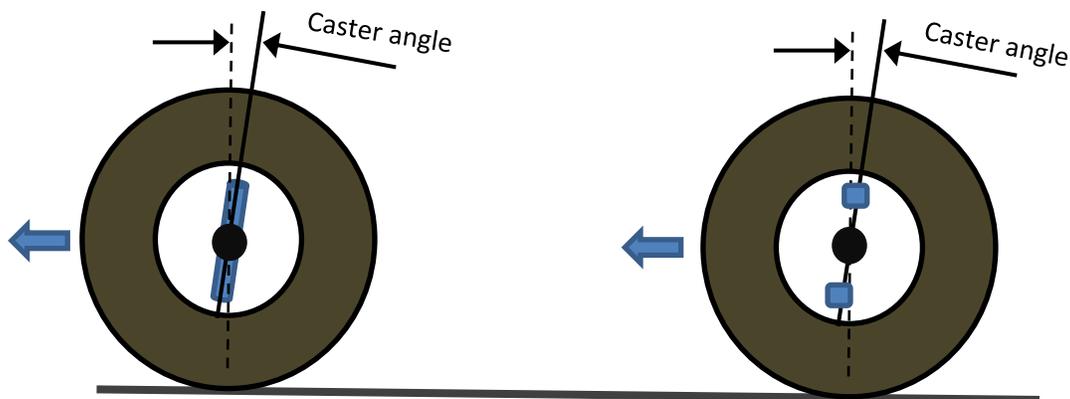

Figure 1a: King pin system   **Figure 1b: Ball joint system**

The key to understanding how caster affects steering effort and stability is understanding caster lead. If a line through the king pin or ball joint centerline is extended to the ground and the line strikes the ground in front of the center of the tire, the axle is set with positive caster (top tilted back). Because most race cars use positive caster, this will be the focus of this discussion. Notice that Figure 2a has less caster than Figure 2b. Figure 2b indicates that the distance between the extended axis and the center of the tire is increased over Figure 2a due to the increased caster. This distance is the caster lead which increases directly with caster angle. Also note that caster lead, for the same caster angle, increases as the rolling radius of the tire increases.
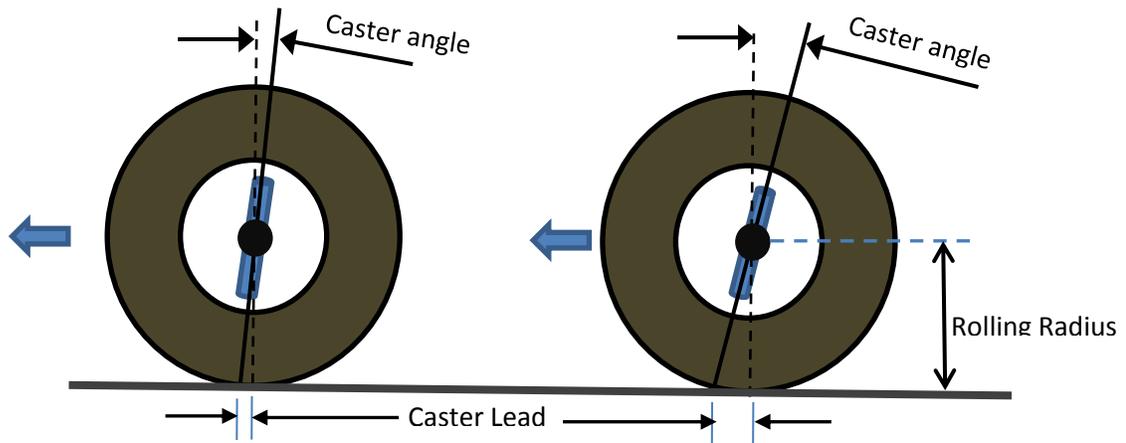
Figure 2: Less caster, less caster lead   Figure 2b: Greater caster, greater caster lead

When cornering, the weight and cornering g's combine to create the cornering force. The cornering force pushes on the steering axis. The greater the cornering g's, the greater the cornering force. However the force that pushes on the tire to make the car turn pushes at the center of the tire footprint. Therefore the cornering force from the race car is acting at the extended steering axis while the force exerted to keep the car on the track is at the center of the tire as shown in Figure 3 which is a top view of the right front tire in a turn. The equal and opposite forces, separated by the caster lead, create a torque that is trying to bring the wheel back straight. This is also the force that returns the wheel to straight ahead when you release your steer input at the steering wheel
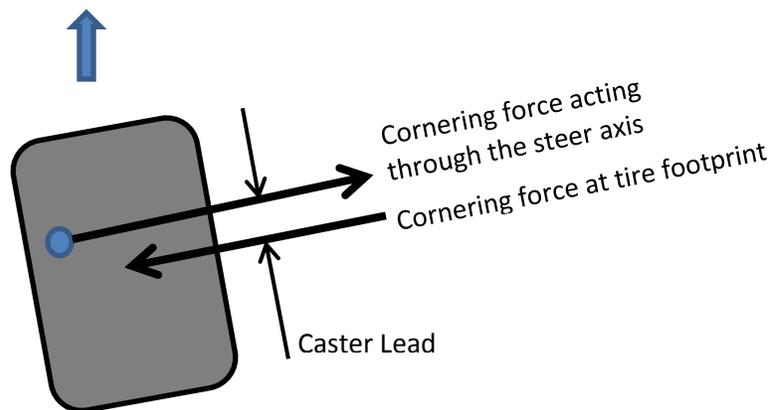

Figure 3: Caster related torque from caster lead and cornering force

With less caster comes less caster lead and hence less input torque from the driver and less returning force. Caster lead at high speed stabilizes the car. Most race cars tend to use between 4 degrees and 10 degrees of caster. Most asphalt cars use around 4 or 5 degrees. If caster is excessive a "caster shake" can occur since the steering axis moves more horizontal. As caster increases, and if the caster lead gets very large, the forces can interact to "shake" the wheel back and forth.

Camber Angle Basics

Camber is the inclination of the tire, from the vertical, when it is viewed from the front as shown in Figure 4. By tradition a positive camber angle is when the top of the tire leans outward. Shown in Figure 4 is a negative camber angle on the right front and positive camber on the left front. Oval track race cars typically use Negative camber on the right front and positive camber on the left front. Also shown in Figure 4 is the Steering Axis Inclination angle (SAI) sometimes called the King Pin Inclination angle (KPI). Note that the line through the king pin axis, when extended to the ground, commonly falls short of the center of the tire. The distance between the extended SAI line and the center of the tire is called the scrub radius (I have seen this called the scuff radius also). The amount of scrub radius is dependent upon KPI and wheel offset.
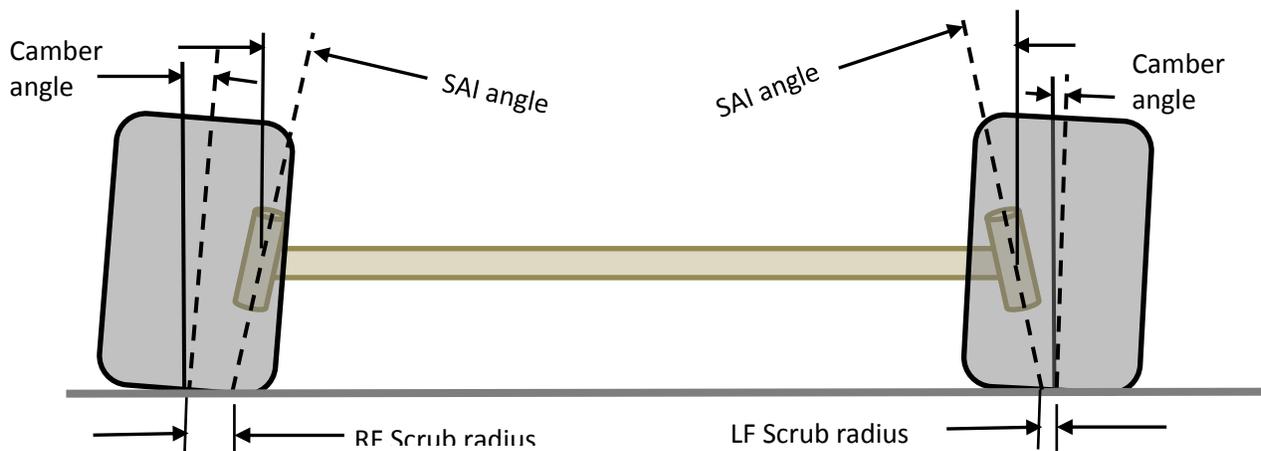

Figure 4: Camber, SAI and Scrub (Front view)

Steer Axis Inclination (SAI) Basics

Steer axis inclination (SAI) is based on the included angle which is the angle between the line drawn through the king pin and the line drawn through the center of the spindle as shown in Figure 5. The amount of SAI is defined as the angle between the vertical line to the road surface and the king pin (or ball joint) inclination when the tire is set to zero camber. The SAI for a spindle can be measured by placing the spindle in a vice and adjusting the angular position until the spindle pin angle is exactly zero. The king pin is then placed in the spindle (or a rod positioned to center in the two ball joint stud holes) and the angle of the king pin is measured from the vertical. Please note that 90 degrees is a perfect right triangle so the angle measured may be ninety degrees more than the actual SAI. If the angle measured is 8 degrees, (or 98 degrees) it is an 8 degree spindle. If it measures 12 degrees (or 102 degrees) it is a 12 degree spindle.
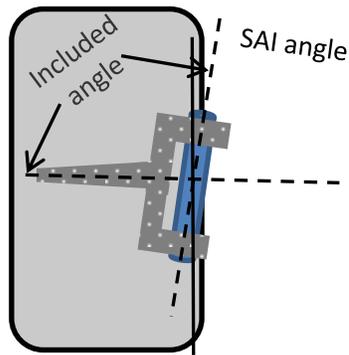
Figure 5: Included angle and SAI

The steering axis inclination causes the spindle pin to point downward on the end as the wheel is steered. If the right front wheel on a car with caster = 0, static camber = 0 and SAI = 8 degrees were turned 90 degrees the tire would take on camber equal to the SAI or 8 degrees. The problem is, on the right front the 8 degrees is with the top tilted out or positive camber, exactly what you do not want on the outside tire in a turn. Obviously the tire is not steered 90 degrees but no matter what amount the RF is steered to the inside it is losing the initial static negative camber due to the arc the outer spindle follows with SAI. So SAI on the RF spindle decreases the amount of negative camber that the car has as the wheel is steered into the turn and throughout the turn. Interestingly, the left front tire which is also steering into the turn is gaining the positive camber it needs due to the SAI on the LF. **SAI therefore adds to the camber on the left front and takes away from the camber needed on the right front** when the tires are steered toward the inside of the track. This is one reason why camber stagger, left to right, may be beneficial. SAI can also introduce dynamic weight jacking when the wheels are steered.

Figure 6 below shows a 10 degree spindle, positioned straight ahead and set with caster = 0 deg. and camber set at 1 deg. negative (top in). Figure 7 shows the same setup with the spindle turned in approximately 30 degrees. The camber now reads 3.7 degrees positive. This is a camber change of 1.0 +3.7 or 4.7 degrees.

Figure 8 and Figure 9 show the spindle steered approximately 10 degrees in and 10 degree out respectively (more like what happens on the race track). Note that in each case the camber changed from 1.0 degree negative to 0.3 degree negative, a change of 0.7 degrees. On the right front the loss in camber is going to heat the outside edge of the tire, which could introduce push, which heats the outside edge more …, You get the picture.

Since caster introduces negative camber when the tire is turned in, now you need to introduce positive caster (top tilted back) to correct for the camber loss due to SAI on the right front. Remember the SAI on the left front already is increasing the positive camber on the left front which is what you want. The question is how much caster.
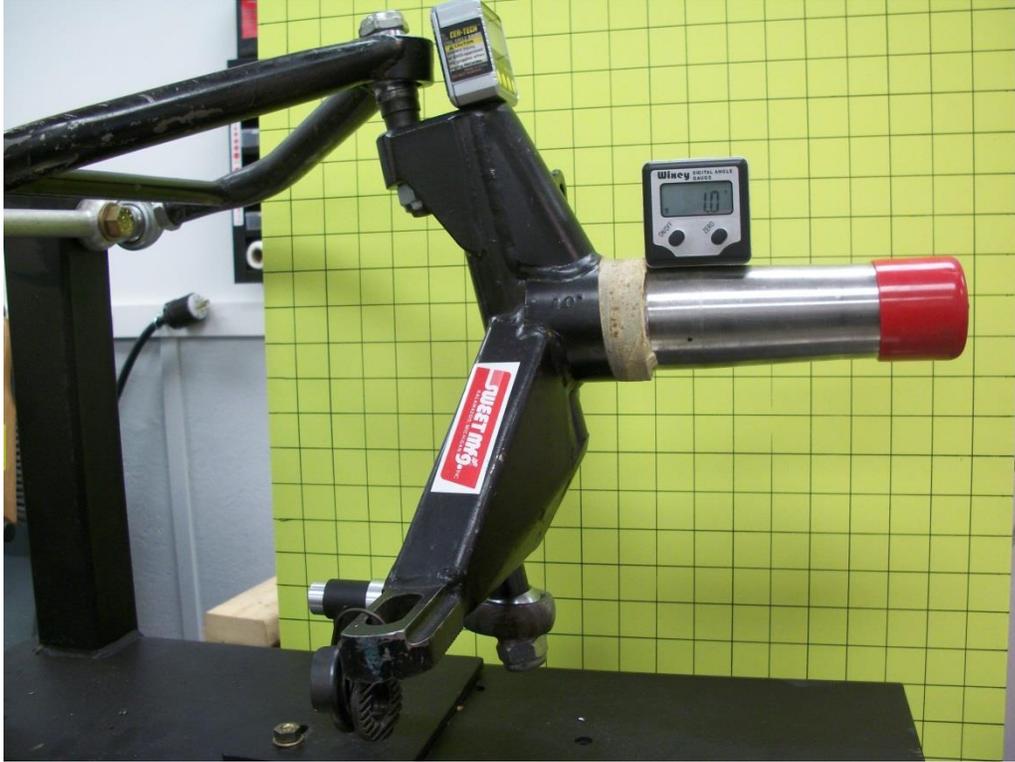
Figure 6: 10 degree RF Spindle pointed straight, caster @ 0 deg., camber @ 1 degree negative.

Figure 7: Same spindle as above with the wheel steered approximately 30 degrees (just to show effect) showing camber change. Note camber is now positive (out at the top).

Figure 8: Same spindle as above caster=0, initial camber=1 negative, steered 10 degrees to left, camber now showing 0.3 degrees (although still negative) it lost 1.0-.3 or .7 degrees in steering.

Figure 9: Same spindle as above caster=0, initial camber=1 negative, steered 10 degrees to right, camber now showing 0.3 degrees (still negative) it lost 1.0-.3 or .7 degrees in steering.
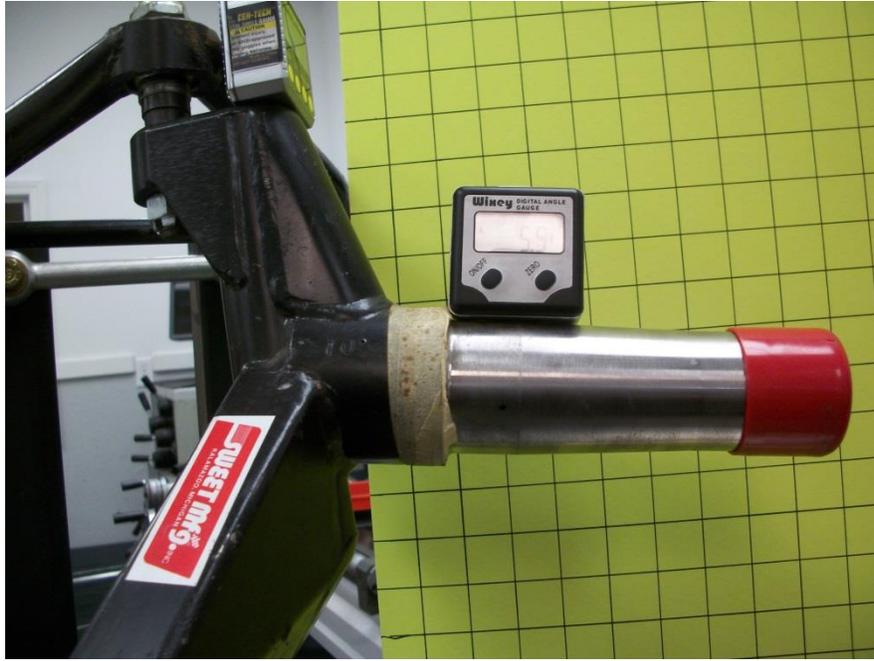
Figure 10: Spindle turned at approximately 45 degrees showing how spindle end points downward.

Figure 10 Shows the spindle turned the maximum amount I could get which is about 45 degrees. The camber gage reads 5.5 degrees which means a 6.5 degree camber change. It is visibly obvious the spindle is pointed downward by viewing against the grid in the background. This is what tends to push the corner up as it is steered, the spindle end moving down. The amount it is pushed up depends on the SAI and also the caster setting and the scrub radius. (If I could have continued to turn the spindle to 90 degrees, it would have read 9 degrees, then by adding the 1.0 degree negative camber you would have the spindle pin inclination of 10 degrees.)

Scrub Radius basics

Scrub radius results from the steer axis inclination and the hubs, spindle, and wheel offset used, as shown in Figure 4. Everything that moves the centerline of the tire away from the kingpin or ball joint centerline increases scrub radius.   Scrub radius, when combined with **caster and SAI affect the weight distribution on the tires when the front tires are steered from straight ahead.** If weight distribution is changed on the front end of the car it is also changed at the rear axle. It was shown in Figure 6 and Figure 7 how steering the spindle causes the outer end of the spindle to move downward, attempting to push the tire into the road surface and raising that corner of the car. The amount it moves downward and raises the chassis is directly related to the scrub radius which is affected by SAI. It is usually desirable to have the king pin (or ball joint) centerline, when extended to the ground, inside the tire footprint as shown in Figure 4. In my opinion it is never good to have the ball joint centerline intersect with the road outside the tire foot print because the track forces, braking forces and (hopefully not) impact forces are not dampened by the tire footprint. Just remember the greater the scrub radius the

greater the steer angle jacking forces and the greater the loads on the steering system. Some choose zero scrub when building a car to reduce the effects of weight jacking and to reduce steering system loads.

Moving from shop (static) settings to what is happening on the race track (dynamic)

The larger the scrub radius, and the greater the SAI, the greater the weight jacking during steer that is possible. However if all things are equal left front to right front (scrub radius, caster, steer angle and SAI) then the left front may rise more than the right front as the wheels are steered. This would be due to the fact that SAI and caster are moving the spindle down on the left front while caster is moving it up and SAI is moving it down on the right front. In most race cars wheel offset, Caster stagger, and Ackerman steer make the geometry different left to right and, as a result, weight jacking as the car is steered occurs. The goal is to make the weight jacking due to steer improve the cars speed through the corners. Moving weight to the right rear during corner entry will usually help tighten the car up.

Camber is highly dependent upon the steer angle of the tire because both caster angle and steering axis inclination cause the camber to change as the wheels are steered. First looking at SAI, the camber changes as the wheels are steered. If you use spindles with an inclination of 8 degrees, the included angle as shown in Figure 5 is 90 degrees plus 8 degrees or 98 degrees. The SAI reduces the camber on the RF (usually not good) and increases the camber on the left front (usually good) as the wheels are steered. Caster also affects tire camber. As the front wheels are steered into the turn, caster on the outside tire tends to tilt the outside tire in at the top increasing the amount of negative camber (good). Caster on the inside tire tilts the tire out at the top, increasing the amount of positive camber on the left front tire (also good). This is addressed further in this article.

Caster also affects weight distribution as the wheels are steered. The amount of weight distribution change is a function of the steer angle of the tires, the amount of caster, the amount of wheel offset and the steering axis inclination (SAI). In a hypothetical case if a race car had SAI = 5 degrees, caster = 5 degrees and camber =0 on the right front and that wheel were turned 90 degrees to the inside the camber would remain at zero and the weight jacking would be negligible. If the same set-up were used on the left front and the tire was turned to the inside, the camber would increase due to SAI and it would increase due to caster and, depending on the amount to scrub radius would raise that corner of the car and jack weight onto the right rear. We know that it is only in a crash when the wheels get turned 90 degrees but any amount of steer angle will produce these same effects. If a 10 degree spindle is used on the right front with caster angle at 5 degrees and zero static camber the car would have 5 degrees of positive camber (you want negative on the RF) when turning to the inside a full 90 degrees. The left front would, at the impossible 90 degrees, would have 15 degrees of positive camber as it turned to the inside. The amount of steer angle weight jacking would depend upon the scrub radius used left to right in this case.

Now let's steer it more like would happen on the track which is more like 10 degrees. Let's use a pair of 8 degree spindles, set caster = + 4 degrees on the right front and +2 degrees on the left front. Let's set camber on the RF to 2 degrees negative and on the LEFT FRONT set camber to 0 degree positive, and

lets only turn left. These are only examples, these are NOT recommendations. Table 1 shows the things that are happening as the car is steered to the left with the settings discussed.

When steering Left, the net effects of steering geometry			
Static setting		What happens	result
RF caster	+4	Adds negative camber	good
RF camber	-2	Increases negative camber	good
RF SAI	8 deg.	1) Takes away negative camber, 2) pushes down on the tire, up on the chassis (amount dependent upon Scrub) Tends to add wedge.	1) Not good, 2) May be good or bad ?
RF Scrub radius	6 in	Affects the amount of LR weight and wedge in steer	May be good or bad?
LF caster	+2	1)Adds positive camber, 2) decreases wedge depending on scrub radius	1)good 2) may be good or bad
LF camber	0	positive camber increases	good
LF SAI	8 deg	1) Adds positive camber, 2) Tends to take away wedge.	1) Good, 2) May be good or bad?
LF Scrub radius	2 in	Affects the amount of RR weight jacking	May be good or bad?

Table 1:Effects of Caster, SAI and Scrub

Getting Caster and SAI to work together

Previously we talked about how, on the RF tire, SAI tends to remove static camber when the tires are steered to the inside and tends to add to static camber of the left front tire in the same turn. The trick on the RF is to get the caster set so the positive effect of caster on camber offset the negative effect of SAI on camber. The real challenge is that camber change due to SAI is non-linear while camber change due to caster is linear. The camber change due to SAI starts out very slow and as you steer it produces a change in camber at an increasing rate. The camber change due to caster is linear which means every degree you steer it brings on an equal amount of camber change.

I have found that a good starting point for the RF is to set static caster at ½ of the value of the SAI. In other words, if you use a 10 degree spindle on the RF, set the caster to 5 degrees. If you use a 8 degree spindle on the RF then you might use a static caster of 4 degrees. Usually this will produce a slightly increasing negative camber in the early part of the turn and then continued steer will decrease the camber gain until your original camber setting is reached. This is shown in Figure 11 where I took a 10 degree spindle, set 5 degrees of static caster and 1 degree of camber. I then turned the spindle to the left and observed the camber increase, then start to decrease and when it reached the original camber (1 degree negative) I stopped steering. Figure 12 shows a top view of the steer angle where the camber became equal to the static setting.

Figure 11: A 10 degree spindle with caster = 5 degrees positive, static camber = 1 degree negative and turned to the inside until the camber reached 1 degree negative (the static setting)

Figure 12: A top view to show the steering angle where camber returned to the original 1 degree as the wheel was turned left with a 5 degree caster setting.

Note: This setup was with static caster at ½ the value of the SAI angle. At a lesser steer than shown, the negative camber was slightly higher than what was set statically which is better than having the camber go away as soon as you start to steer. Slightly less than ½ the SAI angle for the RF can work but it does reduce the steer angle at which camber starts to go away. Remember on the LEFT FRONT the camber due to SAI and the camber due to caster are both adding together so you might consider setting caster

at less than ½ of the SAI angle on the LF. This example, I hope, demonstrates why an 8 degree spindle and a 10 degree spindle should have different caster on the right front. Remember as the caster changes the caster lead changes as well.

Usually you would set the caster on the LF 1-2 degrees less as SAI is helping on the Left front already. The caster setting on the left front is driven by the LF SAI as well. The more SAI used on the LF, the lesser amount of caster needed on the LF because SAI is adding favorable camber and the caster trail is not as important. These settings will give a slight gain in camber change on the RF and a larger camber gain on the LF at normal steer angles.

Getting the proper balance on the suspension geometry variables tends to produce a more consistent handling race car. Once you have your suspension set, place a pair of greased plates under each front tire while the car is on the scales. Weigh the car and record the diagonal weight. Steer the car to the left the amount you would normally steer in the center of the turn and re-read the scales and the diagonal %. While you are there measure the camber as well. Now you have the true picture. Happy race preparation. Hope this article gave you something to think about.

Disclaimer

I hope this discussion helps with your understanding of how geometry settings affect your race car handling. This is provided as information to ISMA members and is not claimed to be used as recommendations for designs or setups.

If you felt this article was informative, or you want to discuss it further, drop me a line at Richard@HSDesignandPrototype or Richard.Hathaway@wmich.edu. If you did not like the article I obviously would prefer you keep it to yourself (only kidding). If you have other areas you would like me to write on please contact me at my email address. I would like to hear from you. My plan is to do some more in suspension, steering and possibly one on Aerodynamics. Any priority?   "Doc"