Tech 03: Spring spacing, Roll Stiffness and Transverse Weight Transfer

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Understanding how your choice of spring type, spring stiffness, spring placement and spring angle influence the front and rear roll stiffness and the roll stiffness distribution is important to understanding how the weight is distributed to the tires when the race car is cornering. In this tutorial we will work primarily with helping you understand how roll stiffness is determined and how your choice of the above mentioned variables affects its value.

Just as the springs act to support the race car weight and control the vertical chassis motions, they also work to control the amount of roll the race car chassis has when cornering. This resistance to chassis roll offered by the springs is called *roll stiffness.* In addition to the roll stiffness, the front and rear roll center heights also determine how each of the suspensions transfer the cornering forces, the weight transfer and how much roll the chassis takes on during cornering. Tech 01- Springs, Shocks and your Suspension which was posted earlier is a reference for this Tech session. A quick overview of that material is included to assure you have correct suspension values with which to work.

The terminology

There are two primary angles that govern how race cars transfer weight during racing maneuvers. The first is the *roll angle* which is the angle, side-to-side, the car seeks as the turn is entered and as the car proceeds through the turn. If there is a roll angle, there MUST be a center for that rotation to occur about; that defines the *roll center*. There are two roll centers on a race car, one at the front suspension and one at the rear suspension. If a line is drawn connecting the front roll center to the rear roll center, this defines the axis about which the chassis wants to roll; this is called the *roll axis*. The ratio of the front suspension roll stiffness to the rear suspension roll stiffness is called the *roll stiffness distribution*; when worked to include the roll centers it is referred to as *roll couple distribution*.

The second angle is the *pitch angle* which is the angle, front to rear, as the car is braked or accelerated. In a Supermodified, pitch angle may be influenced by, as much as anything, aerodynamics. Just as in roll there is a roll center and roll stiffness, in pitch there is a *pitch center, a spring center* and there is *pitch stiffness*. Pitch behavior will be left to a future article.

Our discussion will include the above mentioned terms as well as a discussion of the ***"spring base"*** or the points on the frame to which the springs transfer the wheel loads. The spring base is typically narrower than the track width, from side-to-side, as the springs are located inside the tire locations. The spring base may also be shorter or longer than the wheel base as the pickup point on the frame for the wheel loads may be forward or behind the axle centerline. As you will see, the spring spacing, or span, plays a big role in the roll and pitch stiffness determination.

Spring Spacing or span

There are three important things to consider in determining the roll stiffness on the suspension. The first is the spring rate of the spring, the second is the motion ratio of the spring and the third is the spring spacing. The first to be examined will be a simple straight axle with springs of equal value and springs in a vertical orientation.

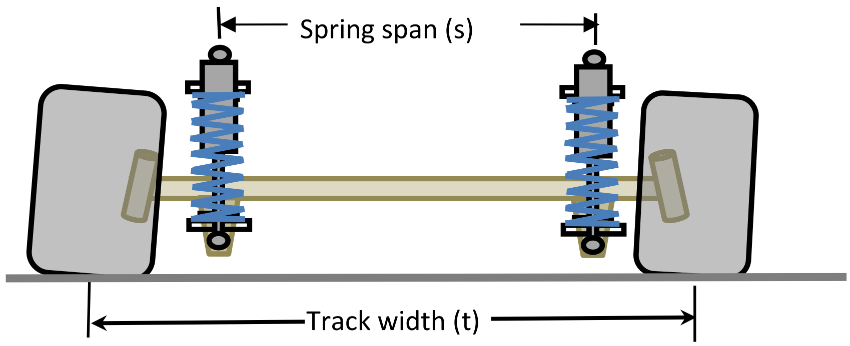

Figure 1: Solid axle suspension with track width (t) and spring spacing (s)

The formula for determining roll stiffness from the front suspension shown in Figure 1 above, with equal springs in the front is as shown in Equation 1. If for example the car is set up with a pair of 500 lb/in springs (K) and has a spring span (s) at the chassis of 48 inches the roll stiffness (RS_f) is as shown below.

$$RS_f = \frac{s^2}{1375} K \qquad \text{Equation 1}$$

$$RS_f = \frac{s^2}{1375} K = \frac{(48 * 48)}{1375} * 500 = 838 \frac{ft - lb}{deg.}$$

As shown in Equation 1, roll stiffness is the torque on the chassis to cause a certain roll angle. Roll stiffness therefore has a value in ft-lbs, as in torque, for the angle produced in degrees, or ft-lbs/deg. Now let's move the springs closer together, to a 40 inch spring span as shown in Figure 2 and calculated below.

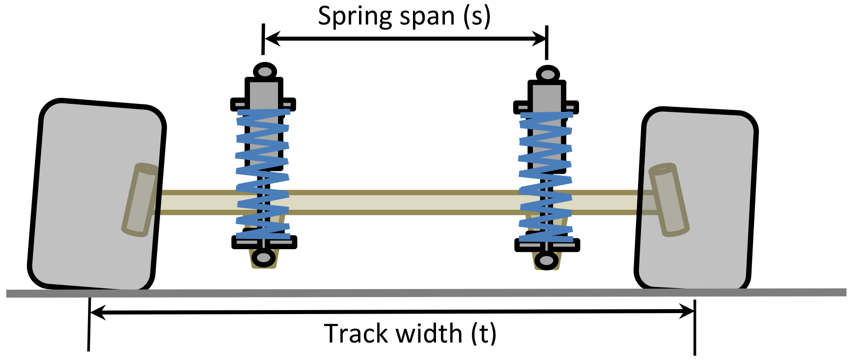

Figure 2: Solid axle suspension with track width (t) and spring spacing (s)

$$RS_f = \frac{s^2}{1375} K = \frac{(40*40)}{1375} * 500 = 582 \frac{ft-lb}{\text{deg.}}$$

To get the same roll stiffness with a 40 inch spring span as with a 48 inch spring span it would require increasing the spring stiffness to 720 lb/in.

$$RS_f = \frac{s^2}{1375} K = \frac{(40*40)}{1375} * 720 = 838 \frac{ft-lb}{\text{deg.}}$$

Roll Stiffness and spring centers with different spring rates

With that said, many race cars do not use the same springs on the left and right sides. To analyze this situation properly, you need to find the spring center. The spring center is that point between the springs where you could stand on the frame and the frame would move down equally on each side. As you stiffen a spring you move the spring center toward the stiffer spring.

As the spring center moves so does the roll center. Think about it this way: if I put a pipe in place of the left front spring, when I push the frame down it rolls around the LF spring mount. That is now the roll center position left to right with the panhard bar establishing the height of the roll center. So if you soften the RF spring you make that corner softer, which usually gives that corner more traction AND you move the roll center to the left toward the stiffer spring. Both the roll center moving left and the softer spring give the RF more travel which then typically gives the front more traction which in turn loosens the car up. By the way, softening the right front on a race car with a high torque engine will loosen the car up on the throttle as well, partly due to the *transverse weight transfer*, which we will discuss later in this article.

To find the spring center, left to right, you are going to use the equation below to identify how far off center your spring center is from the center of your spring mounts.

Spring center offset (X)

$$X = -\left(\frac{K_l - K_r}{K_l + K_r}\right) \times \frac{s}{2} \qquad \text{Equation 2}$$

So let's use the example of a 400 lb/in spring left and a 500 lb/in spring right with a 48 inch spring span.

$$X = -\left(\frac{Kl - Kr}{Kl + Kr}\right) \times \frac{s}{2} = -\left(\frac{400-500}{400+500}\right) \times \frac{48}{2} = 2.67\,inches$$

We have now found the spring center to be 2.67 inches toward the stiffer spring from the center of the chassis mounts. By taking out 100 lb/in of spring rate from the left front we lowered the roll stiffness and moved the spring center to the right.

Now you can calculate roll stiffness using Equation 3. In our example s/2 = 48/2 = 24 inch and X = 2.67 so (s/2+X) = 26.67 inch and (s/2 – X) = 21.33 inch. The total of 26.67 plus 21.33 = 48 inches, which is the span.

$$RS_f = \frac{K_l \times \left(\frac{s}{2} + X\right) \times \left(\frac{s}{2} + X\right) + K_r \times \left(\frac{s}{2} - X\right) \times \left(\frac{s}{2} - X\right)}{688} \qquad \text{Equation 3}$$

$$RS_f = \frac{(400 \times 26.67 \times 26.67) + (500 \times 21.33 \times 21.33)}{688} = 745 \frac{ft-lb}{\deg}$$

Now you know the true story the car we just did has the spring center at 26.67 inches from the left spring mount and has a front roll stiffness of 745 ft-lb/deg. Having fun yet!!

In this example, let's make the assumption your car has a right front with the coil-over inclined 20 degrees to the center which gives your race car a spring span that is smaller. Due to the motion ratio of the spring and chassis, the spring rate, supporting the chassis, actually is softer.

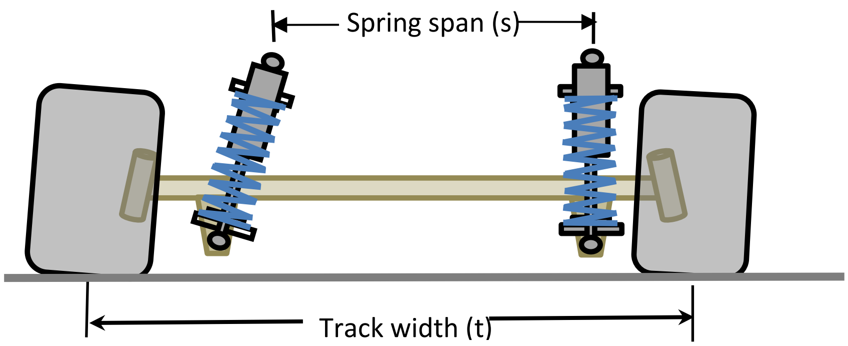

Figure 3: Solid front axle with the RF inclined toward the center

ANGLE (α)	Cosine(α)	Cosine^2	ANGLE (α)	Cosine(α)	Cosine^2
0	1.00	1.0	25	0.906	.82
5	0.996	.99	30	0.866	.75
10	0.985	.97	35	0.819	.67
15	0.966	.93	40	0.766	.59
20	0.940	.88	45	0.707	.50

Table 1: the effect of angle on spring rate

$$Spring\ rate_{frame} = \text{Cosine}^2 \times Spring\ rate \qquad \text{Equation 4}$$

$$Spring\ rate_{frame} = .88 \times 500 = 440 lb/in$$

Let's also say that to get the angle we moved the RF coil-over in 3 inches. Now you have a spring span of 45 inches. Using equation 2 and equation 3 with a 400 lb/in left front spring the roll stiffness is calculated.

$$X = -\left(\frac{K_l - K_r}{K_l + K_r}\right) \times \frac{s}{2} = -\left(\frac{400-440}{400+440}\right) \times \frac{45}{2} = 1.07\, inches$$

$$\frac{s}{2} + X = 23.57 \quad \frac{s}{2} - X = 21.43$$

$$RS_f = \frac{(400 \times 23.57 \times 23.57) + (440 \times 21.43 \times 21.43)}{688} = 617 \frac{ft-lb}{\deg}$$

This indicates a reduction in front roll stiffness of 17% (745 to 617), which is a significant change. You also moved the spring center closer to the LF because you softened the RF and this itself produces more roll angle.

Now, just to confuse you further, let's talk about a race car that uses a rocker (cantilever) in the front end as shown in Figure 4.

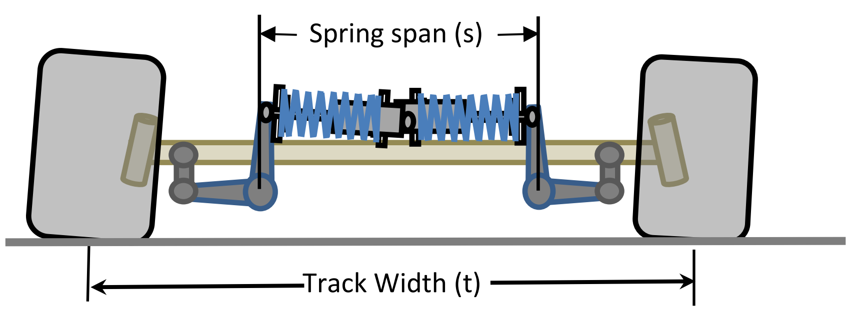

Figure 4: A simple rocker arm (cantilever) suspension

The roll stiffness is calculated using the spring spacing just as before. Some builders want to use a different length arm on the horizontal part of the cantilever than on the vertical part *(Don't ask me why because it hurts your shocks speeds as discussed in Tech 01 that was posted on this site).* This then gives you a motion ratio that has to be applied to the spring rate. Let's say cool car builder Joe uses a lower arm length of 12 inches and a vertical arm (connected to the shock) of 10 inches. By the time Joe puts it all together with the maximum width rule he now only has a spring span of 29 inches because he has 26 inches of tires plus 2 inches of clearance on each side and 24 inches of rocker length. Then Joe puts a motion ratio of 10/12 = 0.83:1. Recall now to get the spring ratio the motion ratio is multiplied by itself so the spring ratio is 0.83 x 0.83 or 0.689:1. Therefore, due to motion ratio, a 1000 lb/in spring is acting as a 689 lb/in spring. Note if the arms were the same length and the spring acts straight to the arm, the motion ratio is 1:1.

For fictitious Joe, his car has a roll stiffness of 297 ft-lb/degree, as shown below, even though we bumped the spring rate to a 700 lb/in rate. So this car has a high spring rate, giving you a high wheel rate with a low front roll stiffness. We will examine this further as we talk about transverse weight transfer.

$$RS_f = \frac{s^2}{1375} K = \frac{(29 \times 29)}{1375} \times \left(\frac{10}{12}\right) \times \left(\frac{10}{12}\right) \times 700 = 297 \frac{ft-lb}{\text{deg.}}$$

Joe's design might be a design where you would consider an anti-roll bar to add to the roll stiffness if desired. I hope this discussion thus far has given you some insight into spring rates, spring spacing and roll stiffness.

Rear Roll Stiffness, Total Roll Stiffness and Roll Stiffness distribution:

All the work and understanding we have done thus far for the front suspension applies to the rear suspension as well. In most cases in the rear the greatest span you can achieve is about 48 to 50 inches due to the width of the tires and the ISMA, or other governing body's, width restrictions. To understand the complete picture you must look at total roll stiffness and roll stiffness distribution. Let's compare a couple of different configurations.

Case 1: This case uses the previously examined car with a 48 inch spring span with a 400 lb/in spring in the left front and a 500 lb/in spring in the right front. The front roll stiffness was calculated, as shown below, to be 745 ft-lb/deg.

$$RS_f = \frac{(400 \times 26.67 \times 26.67) + (500 \times 21.33 \times 21.33)}{688} = 745 \frac{ft-lb}{\text{deg}}$$

Let's use the rear roll stiffness we just calculated of 417 ft-lb/deg.

$$RS_r = \frac{s^2}{1375} K = \frac{(48 * 48)}{1375} * 250 = 417 \frac{ft-lb}{\text{deg.}}$$

The total roll stiffness is the addition of the front and rear roll stiffness. The total is then 745 plus 417 or 1162 ft-lb/deg. The percentage of the roll stiffness that is in the front is 745/1162 = 64%. Shown below are the calculations.

$$RS_{total} = RS_f + RS_r = 745 + 417 = 1162 \ ft-lb/\text{deg}$$

$$\% \ F = \frac{RS_f}{RS_{total}} = \frac{745}{1162} = 0.64 = 64\%$$

Case 2: If the same rear suspension is used but we compare it now to our rocker arm (cantilever) suspension with the lower roll stiffness as shown below.

$$RS_f = \frac{s^2}{1375}K = \frac{(29\times 29)}{1375}\times\left(\frac{10}{12}\right)\times\left(\frac{10}{12}\right)\times 700 = 297\frac{ft-lb}{\text{deg.}}$$

$$RS_{total} = RS_f + RS_r = 297 + 417 = 714\ \ ft-lb/\text{deg}$$

$$\%\ F = \frac{RS_f}{RS_{total}} = \frac{297}{714} = 0.41 = 41\%$$

This shows a front roll stiffness proportion reduction of about 30% (64 vs. 41%). The higher the percentage of front roll stiffness the more nose aerodynamics you will probably need to turn it in the center, depending on your weight distribution and a number of other factors. The next article I plan to write will address weight distribution in a turn which will use the roll stiffness as a key element. Let's now look at how roll stiffness distribution affects acceleration off the turn.

Transverse weight transfer

Transverse weight transfer is not anything as fancy as it may sound. All cars which have the engine mounted to the frame and springs separating the drive axle and the frame will have transverse weight transfer because the drive shaft applies torque to drive axle which is only resisted by the springs and the tires on the track. The quick illustration shows the drive shaft torque (T_d) twisting the rear end and the reaction torque (T_r) resisting that motion, Figure 5.

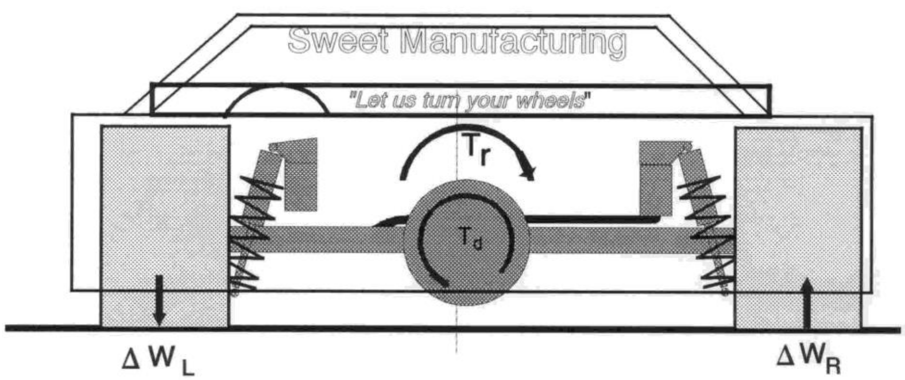

Figure 5: Transverse late model race car example

Transverse weight transfer occurs because the driveshaft torque (Td) reacts between the frame-mounted engine and the drive axle. The axle has to resist the torque at the tire foot print. It is important to realize that *transverse weight transfer adds cross weight during acceleration* and removes cross weight during deceleration. The cross weight change during deceleration is much less than during acceleration because the only drive shaft torque is that due to decelerating the car. The cross weight that is added during acceleration depends on the roll stiffness distribution, the engine torque and the rear track width. On a Supermodified, drive shaft torque and engine torque are the same so the formula is as shown in Equation 5, with $W_{transverse}$ indicating the transverse weight transfer. Let's use an engine with 650 ft-lbs of torque as an example and compare the two suspension systems of Case 1 and Case 2, above.

For Case 1:

$$W_{transverse} = \frac{T_{engine}}{\text{track width}} \times \frac{RS_f}{RS_{total}} \qquad \text{Equation 5}$$

$$W_{transverse} = \frac{650 \times 12}{58\,\text{in}} \times \frac{745}{1162} = 86\ lb$$

By the way this is why drag race cars always lift the left front first as the transverse weight comes off the left front and adds to the right front. The other thing is that a drag race car launches in first gear which multiples the engine torque by about 3 times so it has a high transverse weight transfer unless you use almost no front roll stiffness.

In reality with the offset of the center section, the weight added to the left rear and right front during acceleration can be as high as 3 times that calculated. For simplicity let's use 2 times because of the common spring splits that are used front and rear affect how much is added to the left rear and how much is removed from the right rear. At two times it makes it about 172 lbs. of transverse weight. The 172 lbs. is added to the left rear and to the right front adding 344 lb. to the cross. It removes the same amount from the left front and the right rear. If the car was scaled at 50% cross the simple numbers would show it going up to 68% during acceleration, which I refer to as dynamic wedge.

For Case 2:

$$W_{transverse} = \frac{650 \times 12}{58\,\text{in}} \times \frac{297}{714} = 55\ lb$$

For Case 2, using our same multiplier due to center section offset and spring splits we added 110 lbs. to the left rear and right front, a total of 220 lbs. to the cross. If the car was scaled at 50% cross the simple numbers would show it going up to 62% during acceleration. So the Case 1 race car is most likely to be tighter in the apex due to the higher front roll stiffness and tends to be tighter off because of the increased transverse weight transfer which gave it a higher cross weight when accelerating out of the turn. The Case 2 race car is freer in the apex and freer off the corner.

It is obvious you can change the front roll stiffness number and the transverse weight transfer number by adding an anti-roll bar. If it is added to the front it increases the roll stiffness of the front suspension and increases the dynamic wedge, which is the increase in cross due to engine torque.

In summary, with suspension small changes can yield big results. In a future article I will show how roll stiffness and roll centers can be used to establish a basic set-up for your race car.

Disclaimer

I hope this discussion helps with your understanding of how spring positioning and roll stiffness 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.

I have had two requests for information and I will be working on those articles in the future. One request is for information regarding rear steer. The second request is regarding aero tubing and its benefits other than helping empty your wallet.

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. "Doc"