`Tech 04

Steer angles, Ackerman and Tire Slip angles

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Understanding what it takes to turn your race car as you enter and continue through the turn is critical to improving your lap times. This technical article will discuss this fairly complex concept by methodically going over the issues involved. Tires obviously are a key component in getting your race car to turn and the understanding of tire slip angles is important and will be presented. The mechanical design of the steering system to produce correct toe-out in the turn will also be discussed.

Tire Characteristics

Tire friction and traction

The first thing a tire must do is generate a force at the tire footprint which serves to accelerate, stop and turn your race car. How much force the tire generates to do these things is a function of the tire construction, the rubber compound and the suspension design which should ideally maximize the tires capabilities. To understand forces the tire can generate you must have an understanding of friction forces and the coefficient of friction.

The coefficient of friction is a simple concept that defines the ratio of the vertical force on the tire to the force required to slide the tire. If a known amount of weight (W) sits on top of a block that can slide on the pavement and the force (F) is measured to slide the block as shown in Figure 1 the coefficient of friction can be determined.

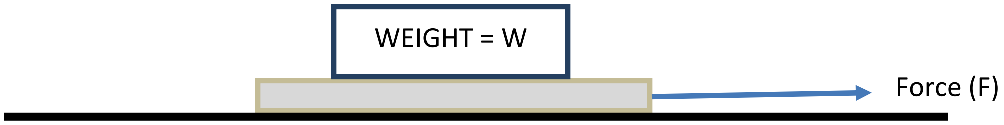


Figure 1: Determining the coefficient of friction

The coefficient of friction (f) is simply the force required to move the block (F) divided by the weight sitting on top of the block (W) as shown in Equation 1.

$$f = \frac{F}{W} \qquad \text{Equation 1}$$

For a tire, the coefficient of friction (f) is directly related to the tire compound. In general the softer the tire compound the higher the coefficient of friction. The coefficient of friction on a tire is much more complicated as the tire actually interacts with the track surface and the track tends to shear the rubber as it slides. This combination is why temperature makes a big difference, as well as the rubber on the track, on the traction available. This in itself does not generate the traction force that is needed; you also need the proper weight or vertical force on a tire as rearranging the above equation shows in Equation 2.

$$F = f \times W \qquad \text{Equation 2}$$

Equation 2 shows that as the weight on the tire increases, or the coefficient of friction increases, the ability to gain traction force (F) increases. Since there is only so much downforce available on the race car, which includes the weight AND the aerodynamic force, putting the proper force on each tire, at the proper time, optimizes the acceleration and cornering forces. A friction circle is a simple way to show how these forces interact. The circle in Figure 2 shows the limits of traction. It is a circle because sliding is sliding and, whether it is sideways or wheel lock-up, it is close to the same value (there are some differences but not enough to mention here). So what this shows is when you are accelerating you take away some of the ability to corner. When you are cornering hard you can only have a small acceleration capability. However, if all tires on the car are not at the limits of their individual friction circles, suspension and steering tuning helps you enter deeper, maintain greater speed through the turn and pick-up the throttle where others may not be able to.

Remember transverse weight transfer from Article 3 where we spoke about the dynamic wedge. That was when, as you build engine torque, it plants the left rear moving it toward its friction limit, increasing its traction force, while moving the right rear away from its friction limit, decreasing its traction force tightening the rear, rather than loosening it (this will loosen it if you are close to the friction limits with the left rear). If the right front is near its friction limit, it can't take any more from the left rear and the car will develop a late turn, or throttle push.

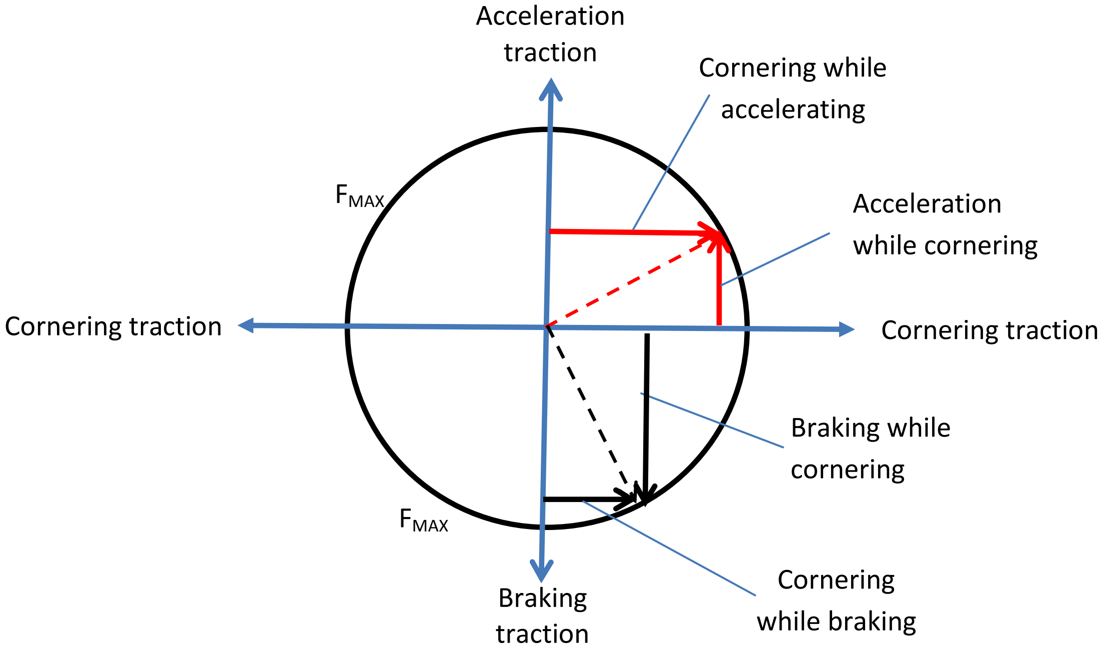


Figure 2: Friction circle for understanding traction limits

The friction circle helps us understand what goes into the tire limits and how acceleration and cornering forces combine to establish the tire limit. We will now move into a more exacting behavior of tires which is the understanding of *tire slip angles*. The friction circle shows tire behavior sort of as a switch, you are either inside the circle not at the limits of the tire, or outside going sideways. It is not quite as drastic as that because a tire builds cornering force as it begins to slip, not spin, slip. In cornering then there is a direction the tire is pointed (steer angle) and there is a direction it is traveling (heading direction). The difference is the slip angle.

Tire slip angles

Critical to your understanding of steer is your understanding of tire slip angles. A tire can only generate a turning force if it has an angle between the centerline of the tire and its ***heading direction***. This difference in the two angles is called the ***slip angle.*** The heading direction is always less than the steer angle you put in. As the slip angle increases, the cornering force increases up to the point where the tire can no longer support the side load and then it will slide sideways.

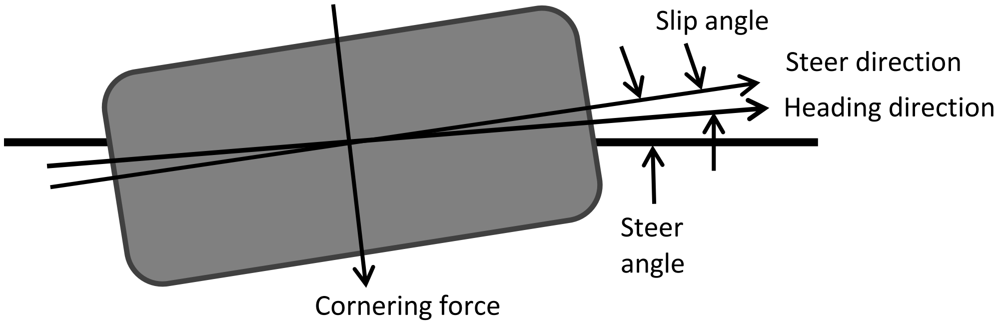


Figure 3: Front tire slip angle and steer angle in a left turn

What the tire slip angle in Figure 3 shows is that to get cornering force out of a tire, a slip angle is required. Since the rear tires are also required to generate a cornering force, the rear tires have a slip angle as well, as shown in Figure 4. When the front and rear slip angles are examined an understanding of car handling begins.

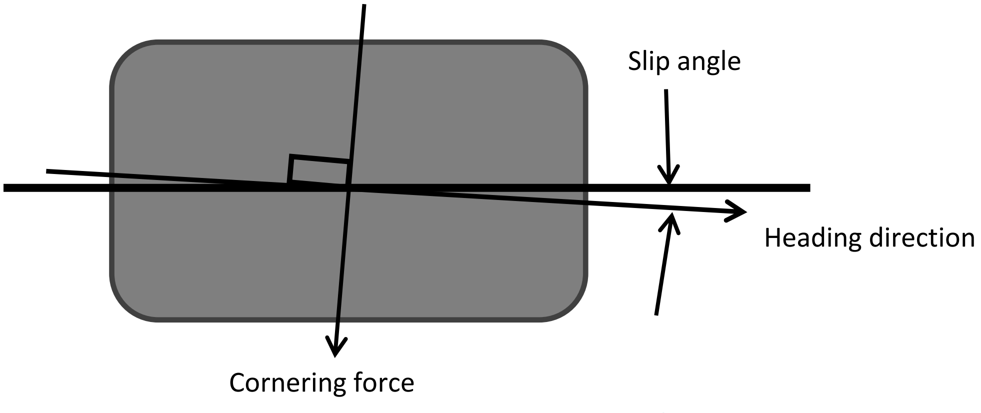


Figure 4: Rear tire slip angle in a left turn

It is important to understand that when looking at Figure 3 you see that front tire slip angle increases the front steer angle required while rear tire slip angle, Figure 4, decreases the front steer angle required to make a turn of a specified radius. Not that it's important but, the cornering forces follow the heading direction at 90 degrees, Figure 3 and Figure 4. Since that vector is not at 90 degrees to the rotational plane of the tire, drag is introduced. This is why braking actually occurs due to the tire slip angles, slowing the car into the turn, even though brakes are not applied.

Figure 5 shows an example of what is called the cornering stiffness plot of a tire. The graph plots the slip angle of the tire against the cornering force the tire generates at that slip angle. These are plotted for three different tire loadings, as we discussed earlier the more the tire is loaded the greater the cornering force available. The line of peaks indicates that as the tire loading increases the slip angle at which the peak cornering force occurs increases. The amount of Ackermann used in the front end can change the slip angle between the inside and outside tire in a turn. On the rear end with any solid axle race car, the slip angle between the inside tire and the outside tire are essentially the same as independent steering of each wheel in the rear does not occur. The tires steer as the axle steers and the slip angles establish the available cornering force.

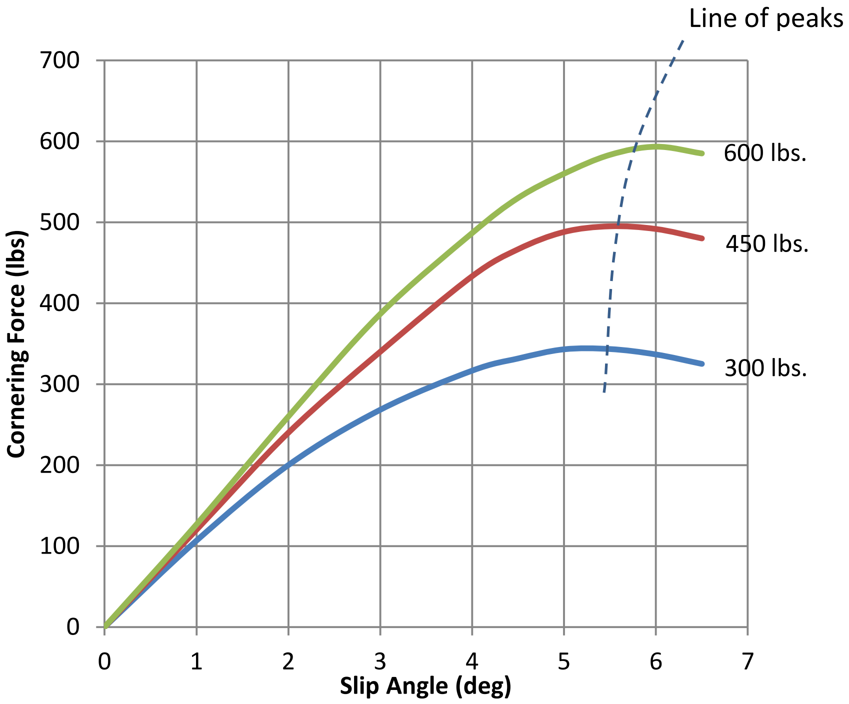


Figure 5: Example Slip angle vs. Cornering force plot

Note in Figure 5 that the line of peaks shows as the tire load increases the slip angle to produce the maximum cornering force increases. You may also note that at lighter loading the tire produces a greater cornering force for the loading. In the plot above at 300 lbs. loading the peak is about 340 lb. cornering or 340/300 = 1.13, at 600 lb. loading the peak is about 595 lb. cornering or 595/600 = 0.99. The idea is to maximize the cornering force possible out of all the tires. This takes having the proper weight transfer across the front and rear, and idealizing slip angles which, for the front end, is where Ackerman steering comes in.

Ackerman Steer Angles

As a result of track width, the tires on the inside and outside of a vehicle in a turn roll on different turn radii requiring different steer angles, Figure 6.

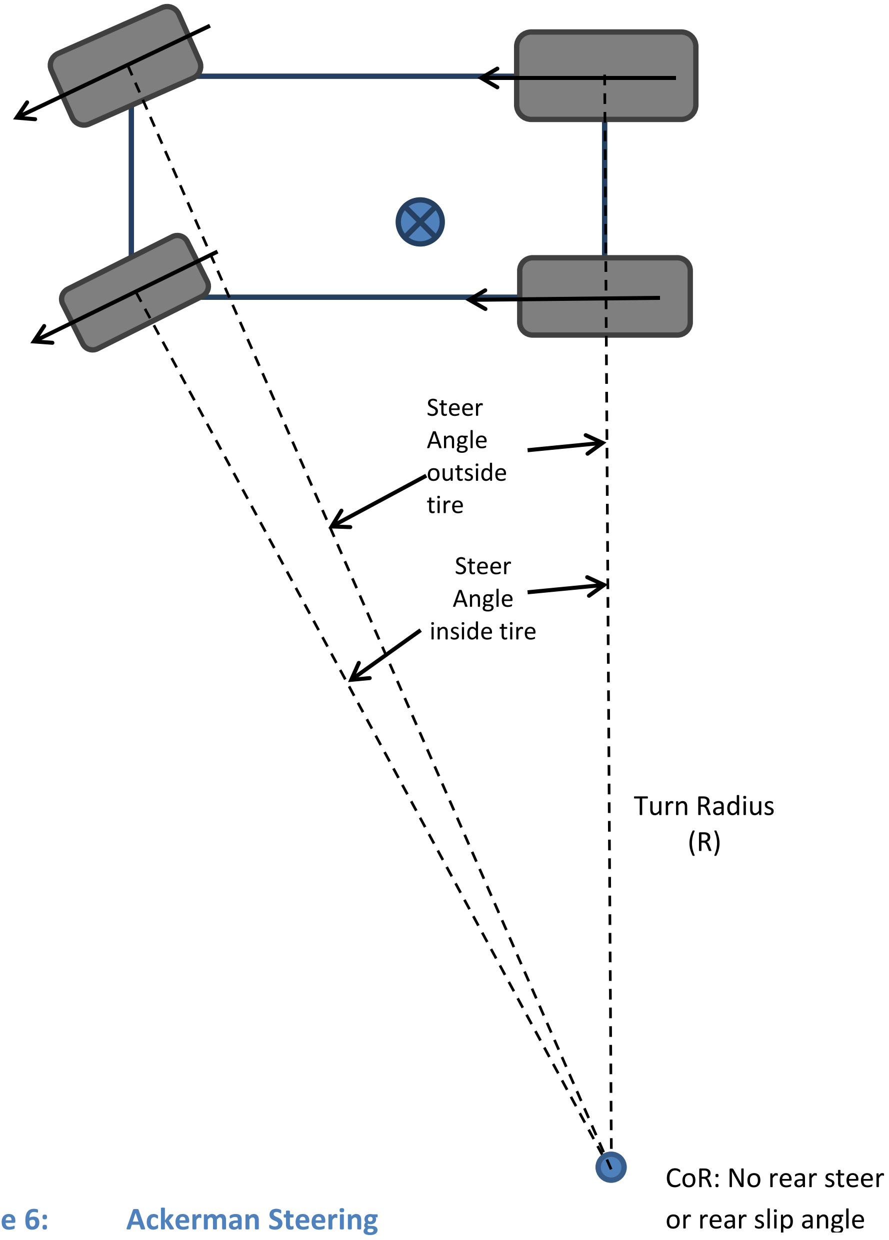


Figure 6: Ackerman Steering

A vehicle with Ackermann steering produces differing steer angles inside-to-outside with the inside tire steered at a greater angle than the outside tire. Varying amounts of Ackermann can be achieved and are typically discussed as a % of true (100%) Ackerman. If the system is designed for 100% Ackerman, the diagram of Figure 6 applies. With 100% Ackerman the race car has a common center of rotation (CoR) for all tires.

How you achieve 100% Ackerman is fairly straight forward. The only thing that needs to be considered is the length of the wheel base (L) and the distance between the kingpins or ball joints side-to-side (steering axis-PSA). The steer axis span is always close to the track width as well. The first consideration is where the steering arms are located, whether they are forward of the front axle as shown in Figure 7, or behind the front axle, Figure 8. Ackerman is much harder to achieve with the front steer arm arrangement because the wheels, rotors, and steer arms typically interfere.

Designing Ackerman into your steering system allows the steering system to produce increasing amounts of toe-out as the front wheels are steered, producing the toe-out you need at the time you need it. Although Ackerman can be achieved by having different steer arm lengths on each side, I do not think this is optimum for cars running longer tracks. On a long straightaway, a car with different length steer arms may produce toe-in, due to driver counter steer required, to offset the stagger and as a result require an instantaneous transition from toe-in to toe-out at the end of the straight as you approach corner entry. In my opinion, you are better off without Ackerman on a long track than to have that upsetting transition (toe-in to toe-out) because of different length steer arms.

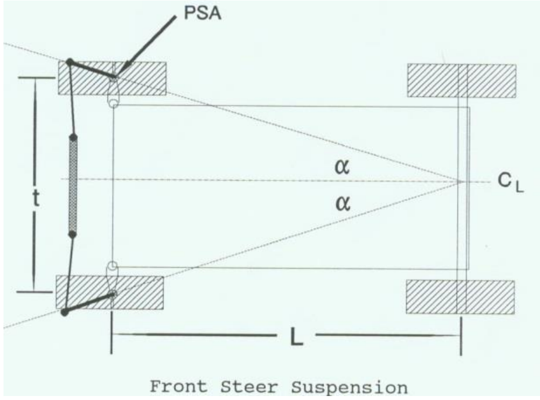


Figure 7: Steering system with the steer arms in front of the front axle

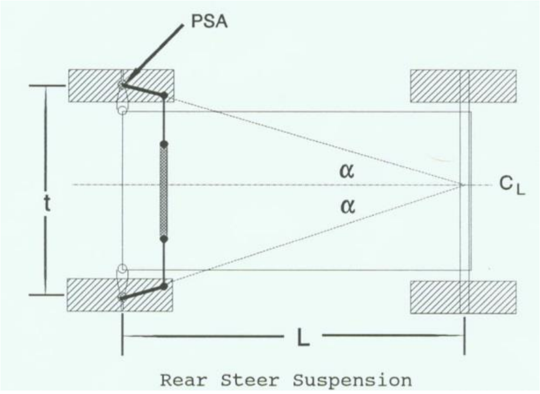


Figure 8: Steering system with the steer arms to the rear of the front axle

Steering arm angle (SAA)

The steer arm angle, especially with a rear steer car, is one of the primary ways to achieve Ackerman. In theory if the steering rack is positioned so the tie rods are parallel with the axle, the steer arms should point toward the center of the rear axle. You will find that if the tie rods are different lengths, because the rack is not in the center of the axle, you still end up with toe-out in both steer directions but it will be a lesser value in one direction because the shorter tie rod puts Ackerman in slower as it gains angle to the steering rack than the longer tie rod.

$$SAA = \operatorname{atan}\left(\frac{t}{2 \times L}\right)$$ **Equation 3**

Where t = track (center to center between wheel pivots) and L = wheelbase length

(If you are using a spreadsheet tool such as Excel you may have to multiply the answer above by 57.3 to get the answer in degrees. This is because those programs calculate the answer in radians, which is mathematically related to degrees by 57.3.)

This brings up the 2nd way to get Ackerman which is to move the steering rack. If you notice in Figure 7 there is an angle between the tie rod and the steer arm. Moving the rack back allows you to keep the same angle while reducing the steer arm angle; this provides Ackerman as well.

Table 1 shows the calculated steering arm angle for 100% Ackerman steering with the steering rack behind the axle (rear steer) and a wide variety of wheel base and track width combinations. If you use this approach always check the actual Ackerman after as tie rod angles alter the results. On a front steer suspension this can be used as a guide. By getting as much as possible out of the steer arms and positioning the rack properly some gains can be made toward true Ackerman.

	Wheelbase length (in)						
Front KP Span or track (in)	94	95	96	97	98	99	100
	Inward angle (deg.) of the steer arms (KP-Heim attachment bolt) with steer arms behind the axle centerline						
70	20.4	20.2	20.0	19.8	19.7	19.5	19.3
68	19.9	19.7	19.5	19.3	19.1	19.0	18.8
66	19.3	19.2	19.0	18.8	18.6	18.4	18.3
64	18.8	18.6	18.4	18.3	18.1	17.9	17.7
62	18.3	18.1	17.9	17.7	17.6	17.4	17.2
60	17.7	17.5	17.4	17.2	17.0	16.9	16.7
58	17.1	17.0	16.8	16.6	16.5	16.3	16.2

Table 1: Steering arm angle producing Ackerman with a rear steer front axle

Tire steer angle and toe-out.

To check the amount of Ackerman you actually have, you will need to turn the wheels to some steer angle and either measure the steer angle of each tire or measure the toe-out. If Ackerman is properly set the car should gain toe-out as the wheels are turned. The steer angle (SA) needed can be determined by knowing the radius of the turn (R) and the wheel base (L) and can be calculated with Equation 4, the results of which are shown in Table 2. *(As earlier mentioned if you are using a spreadsheet tool such as Excel you may have to multiply the answer by 57.3 to get the answer in degrees.)*

The steer angle (SA) required to make a turn with no consideration for tire slip angle is shown in Equation 4. If you use the equation the different steer angle inside and outside are calculated by simply increasing the radius (R) by the track width (t) for the outside wheel.

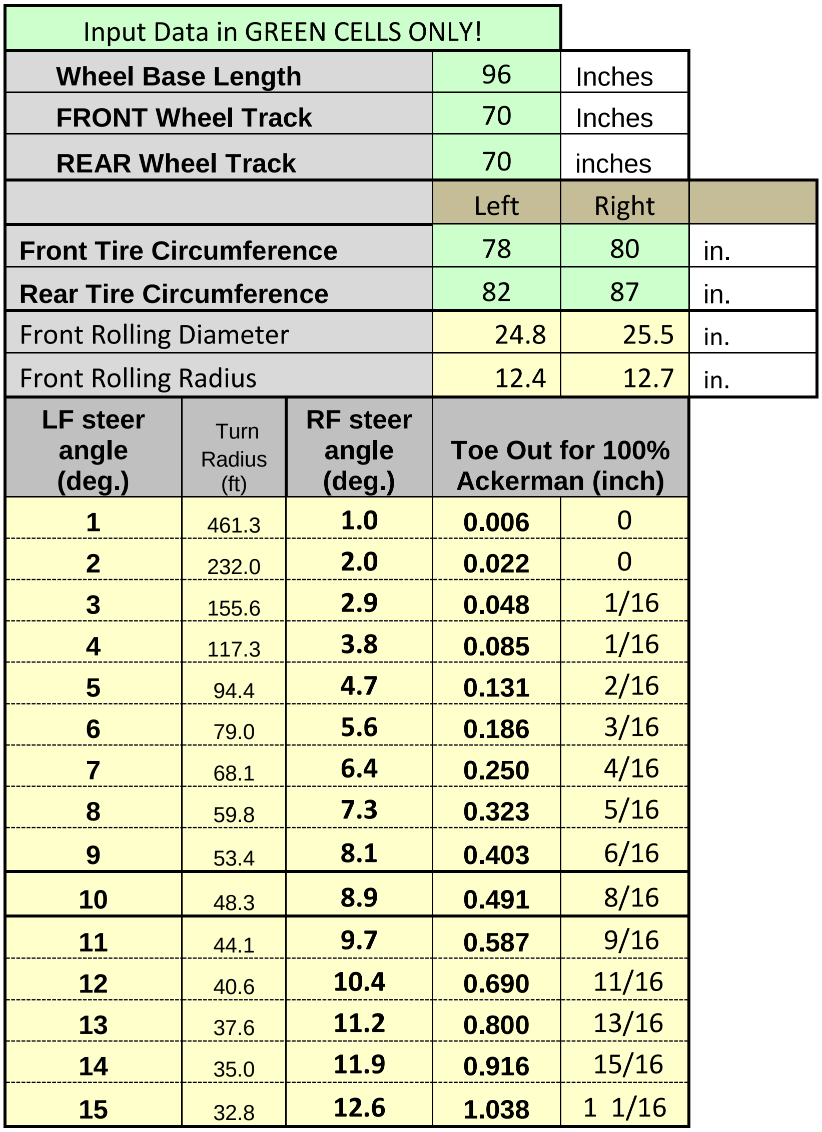
$$SA = \operatorname{atan} \frac{L}{R} \qquad \textbf{Equation 4}$$

	Wheelbase length (in)						
	94	95	96	97	98	99	100
	Front track width				70	in	
	Estimated tire slip angle (deg)				4	deg	
Turn Radius (ft)	Degrees of steer of the inside (LF) tire with slip angle considered						
50	13.45	13.55	13.64	13.74	13.84	13.94	14.04
75	10.20	10.27	10.33	10.40	10.46	10.53	10.60
100	8.61	8.66	8.71	8.76	8.81	8.86	8.91
125	7.67	7.71	7.75	7.79	7.83	7.87	7.91
100	8.61	8.66	8.71	8.76	8.81	8.86	8.91
125	7.67	7.71	7.75	7.79	7.83	7.87	7.91
150	7.05	7.08	7.11	7.15	7.18	7.21	7.24
175	6.61	6.63	6.66	6.69	6.72	6.74	6.77
200	6.28	6.30	6.32	6.35	6.37	6.40	6.42

Table 2: Steer angle for various wheelbase lengths and turn radii with 4 degrees of tire slip angle

In Table 2, I added a 4 degree slip angle to the calculation as front slip angle increases the required steer input and decreases the radius of the turn. Note from the values of Table 2 that as the wheelbase length of the race car is increased, the amount of Ackerman needed increases.

Figure 9 and Table 3 present the actual toe-out and steer angle for 100% Ackerman. I did the calculation for a fairly standard wheelbase of 96 inches and front track of 70 inches. I find measuring at either 8 degrees or 10 degrees of left front steer angle is about the best to help reduce the error in the measurement. As always measuring toe-out in steps as you move toward 8 or 10 is best because tie rod angles can affect the actual toe-out obtained. It is also suggested that you measure it both for left turn and right turn to make sure nothing is out-of-normal either way. With proper Ackerman you should gain toe-out in both directions. Usually the measurement you get in a left hand turn and those in a right hand turn are different due to unequal tie rod lengths of most race cars. Of course the focus should be on left hand turns for circle track cars. Just make sure the right hand turn does not produce toe-in.



Input Data in GREEN CELLS ONLY!			
Wheel Base Length	96	Inches	
FRONT Wheel Track	70	Inches	
REAR Wheel Track	70	inches	
	Left	Right	
Front Tire Circumference	78	80	in.
Rear Tire Circumference	82	87	in.
Front Rolling Diameter	24.8	25.5	in.
Front Rolling Radius	12.4	12.7	in.

LF steer angle (deg.)	Turn Radius (ft)	**RF steer angle (deg.)**	**Toe Out for 100% Ackerman (inch)**	
1	461.3	**1.0**	**0.006**	0
2	232.0	**2.0**	**0.022**	0
3	155.6	**2.9**	**0.048**	1/16
4	117.3	**3.8**	**0.085**	1/16
5	94.4	**4.7**	**0.131**	2/16
6	79.0	**5.6**	**0.186**	3/16
7	68.1	**6.4**	**0.250**	4/16
8	59.8	**7.3**	**0.323**	5/16
9	53.4	**8.1**	**0.403**	6/16
10	48.3	**8.9**	**0.491**	8/16
11	44.1	**9.7**	**0.587**	9/16
12	40.6	**10.4**	**0.690**	11/16
13	37.6	**11.2**	**0.800**	13/16
14	35.0	**11.9**	**0.916**	15/16
15	32.8	**12.6**	**1.038**	1 1/16

Table 3: Toe-out and Steer angles for 100% Ackerman

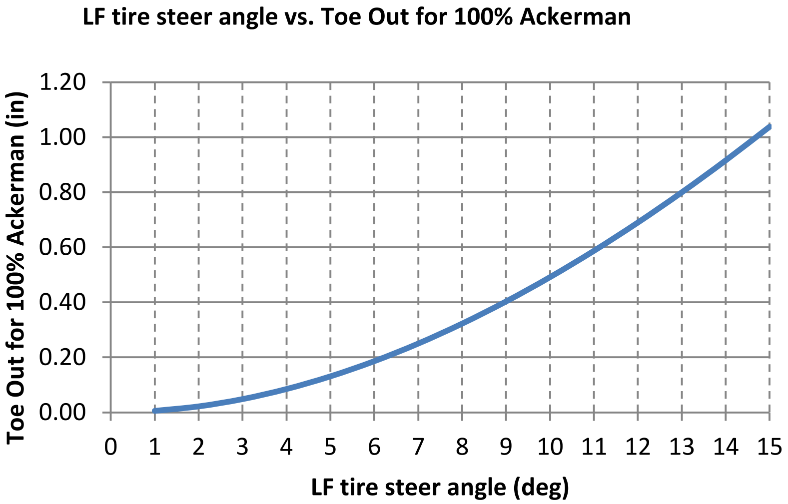


Figure 9: **Toe-out for 100% Ackerman for the car of Table 3.**

Steer with slip angles and/or rear steer

Figure 10 presents a view of a race car with Ackerman steering in a turn producing front and rear slip angles. As the car begins to produce rear slip angle, note that the center of rotation (CoR) moves forward. As the CoR moves forward it moves closer to the center of gravity (CG) line. If the CG and the center of rotation move to the same line there is no requirement for the center of gravity to be "pushed" sideways by the front steer tires, hence only rotation of the CG occurs and the entire vehicle rotates about the center of rotation. This means better rotation of the entire vehicle and quicker response times.

Equation 5 shows that the front tire slip angle adds to the steer angle (SA) needed at the front tires while the rear tire slip angle decreases the steer angle required. Note also in Figure 10 the amount of Ackerman steer needed is also reduced as the CoR moves forward along the wheelbase length. You may also find the amount of rear stagger can be reduced as the CoR moves closer to the CG line.

$$SA = \operatorname{atan}\left(\frac{L}{R}\right) + \left(\text{slip angle}_{\mathrm{F}} - \text{slip angle}_{\mathrm{R}}\right) \quad \textbf{Equation 5}$$

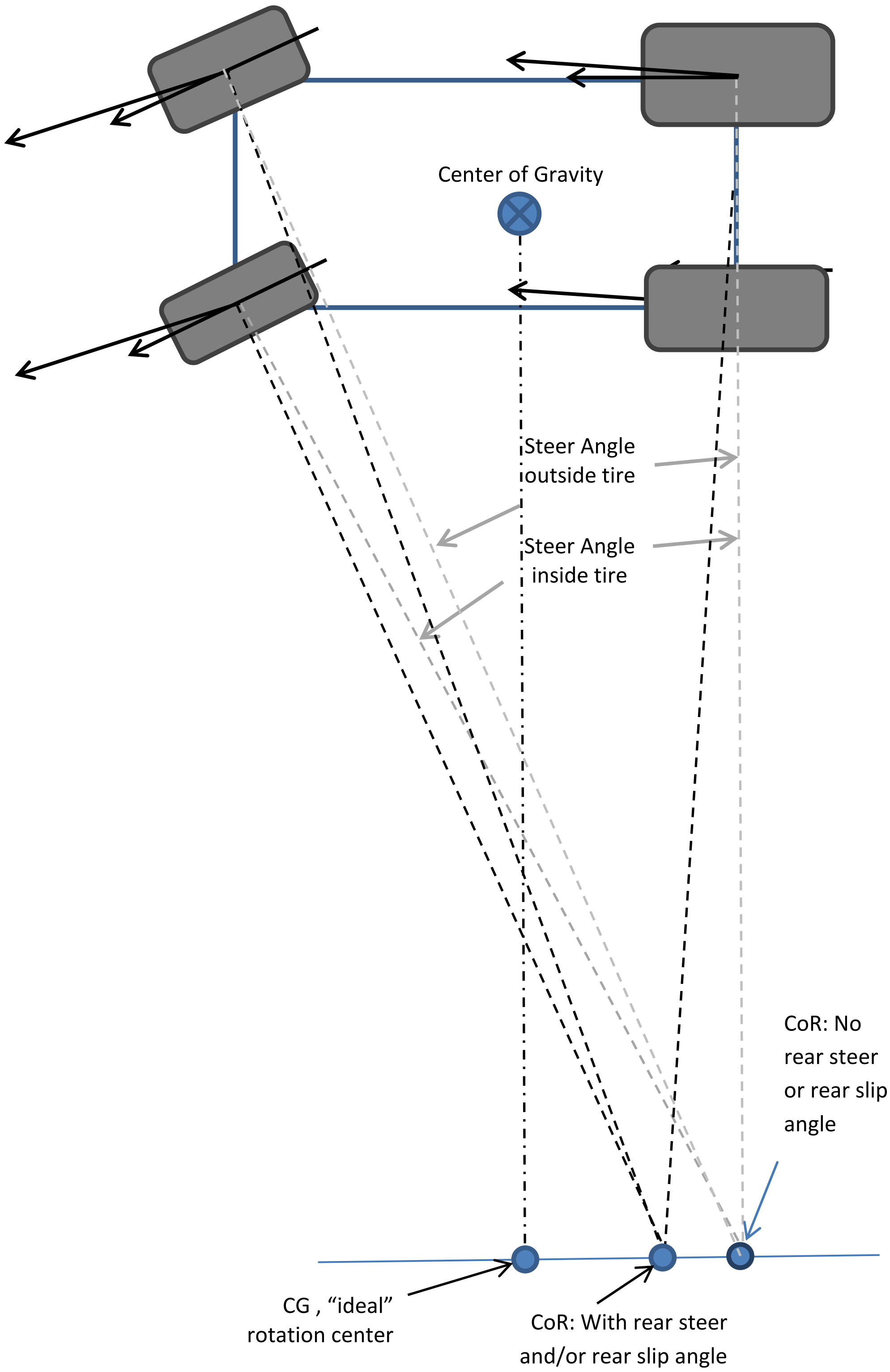


Figure 10: Steer with rear slip angles and/or rear steer

In summary, track width and wheel base length, from a design point, are the fundamental vehicle variables in determining the Ackermann. Ackermann is achieved through steering arm angles, tie rod angles and selected other variables. Front steer vehicles (steering in front of the axle) tend to have greater restriction on the availability for Ackermann correction. Slip angles, tire loadings and cornering forces are helpful in understanding basic dynamic behavior and steer requirements. Tire selection and vehicle goals may determine final Ackerman goals.

Disclaimer

I hope this discussion helps with your understanding of tire behavior and Ackerman steer and how each 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. “Doc”