

# The Physics of Racing, Part 10: Grip Angle

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In many ways, tyre mechanics is an unpleasant topic. It is shrouded in uncertainty, controversy, and trade secrecy. Both theoretical and experimental studies are extremely difficult and expensive. It is probably the most uncontrollable variable in racing today. As such, it is the source of many highs and lows. An improvement in modelling or design, even if it is found by lucky accident, can lead to several years of domination by one tyre company, as with BFGoodrich in autocrossing now. An unfortunate choice of tyre by a competitor can lead to frustration and a disastrous hole in the budget.

This month, we investigate the physics of tyre adhesion a little more deeply than in the past. In Parts 2, 4, and 7, we used the simple friction model given by  $F \leq \mu W$ , where  $F$  is the maximum traction force available from a tyre;  $\mu$ , assumed constant, is the coefficient of friction; and  $W$  is the instantaneous vertical load, or weight, on a tyre. While this model is adequate for a rough, intuitive feel for tyre behaviour, it is grossly inadequate for quantitative use, say, for the computer program we began in Part 8 or for race car engineering and set up.

I am not a tyre engineer. As always, I try to give a fresh look at any topic from a physicist's point of view. I may write things that are heretical or even wrong, especially on such a difficult topic as tyre mechanics. I invite debate and corrections from those more knowledgeable than I. Such interaction is part of the fun of these articles for me.

I call this month's topic "grip angle." The grip angle is a quantity that captures, for many purposes, the complex and subtle mechanics of a tyre. Most writers call this quantity "slip angle." I think this name is misleading because it suggests that a tyre works by slipping and sliding. The truth is more complicated. Near maximum loads, the contact patch is partly gripping and partly slipping. The maximum net force a tyre can yield occurs at the threshold where the tyre is still gripping but is just about to give way to total slipping. Also, I have some difficulties with the analyses of slip angle in the literature. I will present these difficulties in these articles, unfortunately, probably without resolution. For these reasons, I give the quantity a new name.

A tyre is an elastic or deformable body. It delivers forces to the car by stretching, compressing, and twisting. It is thus a very complex sort of spring with several different ways, or *modes*, of deformation. The hypothetical tyre implied by

$F \leq \mu W$  with constant  $\mu$  would be a non-elastic tyre. Anyone who has driven hard tyres on ice knows that non-elastic tyres are basically uncontrollable, not just because  $\mu$  is small but because regular tyres on ice do not twist appreciably.

The first and most obvious mode of deformation is radial. This deformation is along the radius of the tyre, the line from the centre to the tread. It is easily visible as a bulge in the sidewall near the contact patch, where the tyre touches the ground. Thus, radial compression varies around the circumference.

Second is circumferential deformation. This is most easily visible as wrinkling of the sidewalls of drag tyres. These tyres are intentionally set up to deform dramatically in the circumferential direction.

Third is axial deformation. This is a deflection that tends to pull the tyre off the (non-elastic) wheel or rim.

Last, and most important for cornering, is *torsional* deformation. This is a difference in axial deflection from the front to the back of the contact patch. Fundamentally, radial, circumferential, and axial deformation furnish a complete description of a tyre. But it is very useful to consider the differences in these deflections around the circumference.

Let us examine exactly how a tyre delivers cornering force to the car. We can get a good intuition into the physics with a pencil eraser. Get a block eraser, of the rectangular kind like “Pink Pearl” or “Magic Rub.” Stand it up on a table or desk and think of it as a little segment of the circumference of a tyre. Think of the part touching the desk as the contact patch. Grab the top of the eraser and think of your hand as the wheel or rim, which is going to push, pull, and twist on the segment of tyre circumference as we go along the following analysis.

Consider a car travelling at speed  $v$  in a straight line. Let us turn the steering wheel slightly to the right (twist the top of the eraser to the right). At the instant we begin turning, the rim (your hand on the eraser), at a circumferential position just behind the contact patch, pushes slightly leftward on the bead of the tyre. Just ahead of the contact patch, likewise, the rim pulls the bead a little to the right. The push and pull together are called a *force couple*. This couple delivers a torsional, clockwise stress to the inner part of the tyre carcass, near the bead. This stress is communicated to the contact patch by the elastic material in the sidewalls (or the main body of the eraser). As a result of turning the steering wheel, therefore, the rim twists the contact patch clockwise.

The car is still going straight, just for an instant. How are we going to explain a net rightward force from the road on the contact patch? This net force must be there, otherwise the tyre and the car would continue in a straight line by Newton’s First Law.

Consider the piece of road just under the contact patch at the instant the turn begins. The rubber particles on the left side of the patch are going a little bit faster with respect to the road than the rest of the car and the rubber particles on the right side of the patch are going a little bit slower than the rest of the car. As a result, the left side of the patch grips a little bit less than the right. The rubber particles on the left are

more likely to slide and the ones on the right are more likely to grip. Thus, the left edge of the patch “walks” a little bit upward, resulting in a net clockwise twisting motion of the patch. The torsional stress becomes a torsional motion. As this motion is repeated from one instant to the next, the tyre (and the eraser-I hope you are still following along with the eraser) walks continuously to the right.

The better grip on the right hand side of the contact patch adds up to a net rightward force on the tyre, which is transmitted back through the sidewall to the car. The chassis of the car begins to yaw to the right, changing the direction of the rear wheels. A torsional stress on the rear contact patches results, and the rear tyres commence a similar “walking” motion.

The wheel (your hand) is twisted more away from the direction of the car than is the contact patch. The angular difference between the direction the wheel is pointed and the direction the tyre walks is the grip angle. All quantities of interest in tyre mechanics-forces, friction coefficients, *etc.*, are conventionally expressed as functions of grip angle.

In steady state cornering, as in sweepers, an understeering car has larger grip angles in front, and an oversteering car has larger grip angles in the rear. How to control grip angles statically with wheel alignment and dynamically with four-wheel steering are subjects for later treatment.

The greater the grip angle, the larger the cornering force becomes, up to a point. After this point, greater grip angle delivers less force. This point is analogous to the idealized adhesive limit mentioned earlier in this series. Thus, a real tyre behaves qualitatively like an ideal tyre, which grips until the adhesive limit is exceeded and then slides. A real tyre, however, grips gradually better as cornering force increases, and then grips gradually worse as the limit is exceeded.

The walking motion of the contact patch is not entirely smooth, or in other words, somewhat *discrete*. Individual blocks of rubber alternately grip and slide at high frequency, thousands of times per second. Under hard cornering, the rubber blocks vibrating on the road make an audible squalling sound. Beyond the adhesive limit, squealing becomes a lower frequency sound, “squalling,” as the point of optimum efficiency of the walking process is bypassed.

There is a lot more to say on this subject, and I admit that my first attempts at a mathematical analysis of grip angle and contact patch mechanics got bogged down. However, I think we now have an intuitive, conceptual basis for better modelling in the future.

Speaking of the future, summarizing briefly the past of and plans for the *Physics of Racing* series. The following overlapping threads run through it:

#### Tyre Physics

concerns adhesion, grip angle, and elastic modelling. This has been covered in Parts 2, 4, 7, and 10, and will be covered in several later parts.

### Car Dynamics

concerns handling, suspension movement, and motion of a car around a course; has been covered in Parts 1, 4, 5, and 8 and will continue.

### Drive Line Physics

concerns modelling of engine performance and acceleration. Has been covered in Parts 3, 6, and 9 and will also continue.

### Computer Simulation

concerns the design of a working program that captures all the physics. This is the ultimate goal of the series. It was begun in Part 8 and will eventually dominate discussion.

The following is a list of articles that have appeared so far:

1. Weight Transfer
2. Keeping Your Tyres Stuck to the Ground
3. Basic Calculations
4. There is No Such Thing as Centrifugal Force
5. Introduction to the Racing Line
6. Speed and Horsepower
7. The Circle of Traction
8. Simulating Car Dynamics with a Computer Program
9. Straights
10. Grip Angle

and the following is a tentative list of articles I have planned for the near future (naturally, this list is “subject to change without notice”):

### Springs and Dampers,

presenting a detailed model of suspension movement (suggested by Bob Mosso)

### Transients,

presenting the dynamics of entering and leaving corners, chicanes, and slaloms (this one suggested by Karen Babb)

### Stability,

explaining why spins and other losses of control occur

### Smoothness,

exploring what, exactly, is meant by smoothness

### Modelling Car Data

in a computer program; in several articles

### Modelling Course Data

in a computer program; also in several articles

In practice, I try to keep the lengths of articles about the same, so if a topic is getting too long (and grip angle definitely did), I break it up in to several articles.