The Physics of Racing, Part 2: Keeping Your Tires Stuck to the Ground

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In last month's article, we explained the physics behind weight transfer. That is, we explained why braking shifts weight to the front of the car, accelerating shifts weight to the rear, and cornering shifts weight to the outside of a curve. Weight transfer is a side-effect of the tires keeping the car from flipping over during maneuvers. We found out that a one G braking maneuver in our 3200 pound example car causes 640 pounds to transfer from the rear tires to the front tires. The explanations were given directly in terms of Newton's fundamental laws of Nature.

This month, we investigate what causes tires to stay stuck and what causes them to break away and slide. We will find out that you can make a tire slide either by pushing too hard on it or by causing weight to transfer off the tire by your control inputs of throttle, brakes, and steering. Conversely, you can cause a sliding tire to stick again by pushing less hard on it or by tranferring weight to it. The rest of this article explains all this in term of (you guessed it) physics.

This knowledge, coupled with a good 'instinct' for weight transfer, can help a driver predict the consequences of all his or her actions and develop good instincts for staying out of trouble, getting out of trouble when it comes, and driving consistently at ten tenths. It is said of Tazio Nuvolari, one of the greatest racing drivers ever, that he knew at all times while driving the weight on each of the four tires to within a few pounds. He could think, while driving, how the loads would change if he lifted off the throttle or turned the wheel a little more, for example. His knowledge of the physics of racing enabled him to make tiny, accurate adjustments to suit every circumstance, and perhaps to make these adjustments better than his competitors. Of course, he had a very fast brain and phenomenal reflexes, too.

I am going to ask you to do a few physics "lab" experiments with me to investigate tire adhesion. You can actually do them, or you can just follow along in your imagination. First, get a tire and wheel off your car. If you are a serious autocrosser, you probably have a few loose sets in your garage. You can do the experiments with a heavy box or some object that is easier to handle than a tire, but the numbers you get won't apply directly to tires, although the principles we investigate will apply.

Weigh yourself both holding the wheel and not holding it on a bathroom scale. The difference is the weight of the tire and wheel assembly. In my case, it is 50 pounds (it would be a lot less if I had those $3000 Jongbloed wheels! Any sponsors reading?). Now put the wheel on the ground or on a table and push sideways with your hand against the tire until it slides. When you push it, push down low near the point where the tire touches the ground so it doesn't tip over.

The question is, how hard did you have to push to make the tire slide? You can find out by putting the bathroom scale between your hand and the tire when you push. This procedure doesn't give a very accurate reading of the force you need to make the tire slide, but it gives a rough estimate. In my case, on the concrete walkway in front of my house, I had to push with 85 pounds of force (my neighbors don't bother staring at me any more; they're used to my strange antics). On my linoleum kitchen floor, I only had to push with 60 pounds (but my wife does stare at me when I do this stuff in the house). What do these numbers mean?

They mean that, on concrete, my tire gave me $85/50 = 1.70$ gees of sideways resistance before sliding. On a linoleum race course (ahem!), I would only be able to get $60/50 = 1.20G$. We have directly experienced the physics of grip with our bare hands. The fact that the tire resists sliding, up to a point, is called the *grip phenomenon.* If you could view the interface between the ground and the tire with a microscope, you would see complex interactions between long-chain rubber molecules bending, stretching, and locking into concrete molecules creating the grip. Tire researchers look into the detailed workings of tires at these levels of detail.

Now, I'm not getting too excited about being able to achieve $1.70G$ cornering in an autocross. Before I performed this experiment, I frankly expected to see a number below $1G$. This rather unbelievable number of $1.70G$ would certainly not be attainable under driving conditions, but is still a testimony to the rather unbelievable state of tire technology nowadays. Thirty years ago, engineers believed that one G was theoretically impossible from a tire. This had all kinds of consequences. It implied, for example, that dragsters could not possibly go faster than 200 miles per hour in a quarter mile: you can go $\sqrt{2ax} = 198.48\,\text{mph}$ if you can keep $1G$ acceleration all the way down the track. Nowadays, drag racing safety watchdogs are working hard to keep the cars under 300 mph; top fuel dragsters launch at more than 3 gees.

For the second experiment, try weighing down your tire with some ballast. I used a couple of dumbells slung through the center of the wheel with rope to give me a total weight of 90 pounds. Now, I had to push with 150 pounds of force to move the tire sideways on concrete. Still about $1.70G$. We observe the fundamental law of adhesion: the force required to slide a tire is proportional to the weight supported by the tire. When your tire is on the car, weighed down with the car, you cannot push it sideways simply because you can't push hard enough.

The force required to slide a tire is called the *adhesive limit* of the tire, or sometimes the *stiction*, which is a slang combination of "stick" and "friction." This law, in mathematical form, is

$$F \leq \mu W$$

where F is the force with which the tire resists sliding; μ is the *coefficient of static friction* or *coefficient of adhesion*; and W is the weight or vertical load on the tire contact patch. Both F and W have the units of force (remember that weight is the force of gravity), so μ is just a number, a proportionality constant. This equation states that the sideways force a tire can withstand before sliding is less than or equal to μ times W. Thus, μW is the maximum sideways force the tire can withstand and is equal to the stiction. We often like to speak of the sideways acceleration the car can achieve, and we can convert the stiction force into acceleration in gees by dividing by W, the weight of the car. μ can thus be measured in gees.

The coefficient of static friction is not exactly a constant. Under driving conditions, many effects come into play that reduce the stiction of a good autocross tire to somewhere around $1.10G$. These effects are deflection of the tire, suspension movement, temperature, inflation pressure, and so on. But the proportionality law still holds reasonably true under these conditions. Now you can see that if you are cornering, braking, or accelerating at the limit, which means at the adhesive limit of the tires, any weight transfer will cause the tires unloaded by the weight transfer to pass from sticking into sliding.

Actually, the transition from sticking 'mode' to sliding mode should not be very abrupt in a well-designed tire. When one speaks of a "forgiving" tire, one means a tire that breaks away slowly as it gets more and more force or less and less weight, giving the driver time to correct. Old, hard tires are, generally speaking, less forgiving than new, soft tires. Low-profile tires are less forgiving than high-profile tires. Slicks are less forgiving than DOT tires. But these are very broad generalities and tires must be judged individually, usually by getting some word-of-mouth recommendations or just by trying them out in an autocross. Some tires are so unforgiving that they break away virtually without warning, leading to driver dramatics usually resulting in a spin. Forgiving tires are much easier to control and much more fun to drive with.

"Driving by the seat of your pants" means sensing the slight changes in cornering, braking, and acceleration forces that signal that one or more tires are about to slide. You can sense these change literally in your seat, but you can also feel changes in steering resistance and in the sounds the tires make. Generally, tires 'squeak' when they are nearing the limit, 'squeal' at the limit, and 'squall' over the limit. I find tire sounds very informative and always listen to them while driving.

So, to keep your tires stuck to the ground, be aware that accelerating gives the front tires less stiction and the rear tires more, that braking gives the front tire more stiction and the rear tires less, and that cornering gives the inside tires less stiction and the outside tires more. These facts are due to the combination of weight transfer and the grip phenomenon. Finally, drive smoothly, that is, translate your awareness into gentle control inputs that always keep appropriate tires stuck at the right times. This is the essential knowledge required for car control, and, of course, is much easier said than done. Later articles will use the knowledge we have accumulated so far to explain understeer, oversteer, and chassis set-up.