

Pi Note: The Science of Motorsports

by Professor Pi
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The FastTrack RC (FTRC) radio-controlled car may look like a simple toy, but that couldn't be farther from the truth. The 1:10 scale RC car is in many ways a small version of the real thing; with literally thousands of ways you can set it up.

Hendrick Motorsports is a leading stock car organization and has six NASCAR racing teams, including the famous Jeff Gordon, Kyle Busch and now legendary Jimmie Johnson. Hendrick hires 45 engineers that are integral to the success of these teams because properly setting cars up for each race is as important as what the driver does.

Just like car developers and motorsports teams, your FastTrack RC team will improve racing performance by applying your own ingenuity and the lessons learned from thousands of years of scientific inquiry. Start with the most basic law of motion described first by Sir Isaac Newton: **F = ma**.

This famous equation says that the force required to move something is directly proportional to its mass and indirectly proportional to the acceleration. With respect to racing, this means that a lighter car accelerates faster than a heavier, more massive car. Based on this law, you might think that light cars are best; unfortunately, the truth isn't so clear. Everything in racing is a trade-off (and that's the fun of it!).

The heavier car accelerates slower but is more stable and therefore easier to control and steer. Figuring out the best compromise between acceleration and stability is an optimization problem. The solution to this problem, as with every aspect of setting up your car, depends on the driving course and can only be figured out by collecting and evaluating data. You can't guess the right setting.

Acceleration vs. stability is only one of many questions to answer when preparing for a race. Below are some of the most important. See the FastTrack RC Team Manual and Web Site Resources for more information on each one and on how to make informed decisions about them.



$$F = ma$$

F = sum of forces,

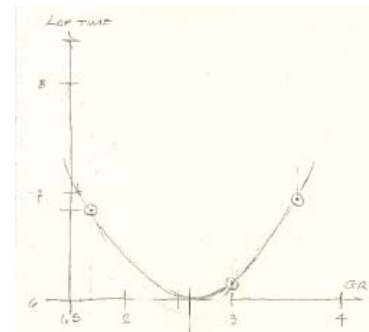
m = mass,

a = acceleration

Gear Ratio & Inverse Relationships

Most cars, especially race cars, can go a lot faster on straight-aways than they can on curves. The driver therefore has to constantly slow down into and speed up out of the curves. You want a high top speed on the straight-aways, but you want a high acceleration rate out of the corners.

The gear set includes the spur and pinion gears and determines both top speed and top acceleration rate. If you increase top speed with one gear set then you're automatically decreasing the acceleration rate and vice versa; they are inversely related. Just like on a bicycle, higher gears are easy to get started with but don't allow you to go very fast. Low gears are the opposite. Professional race teams have as many as two dozen different gear sets (ratios) for any single race car; the best teams may have as many as 50.



Everything in racing is a trade-off. Mathematically, this is represented as inverse relationships and quadratic equations. Finding the best trade-off is sometimes called a Goldilocks Problem. One is too hot, one too cold and one just right.

Overall Handling & The Chassis-Spring System

When a driver turns the steering wheel but the car doesn't turn enough, the car is "tight". It under-steers, meaning that it under rotates and the circle it's turning on has a larger radius than the one it is supposed to turn on. In an extreme scenario, the driver turns the steering wheel but the car continues ahead and crashes into the outside wall.

By contrast, if the car rotates more than expected then it is considered "loose", it over-steers. The back of the car spins around and passes the front (spin-out!). It over rotates and turns on a much smaller radius than it is supposed to.

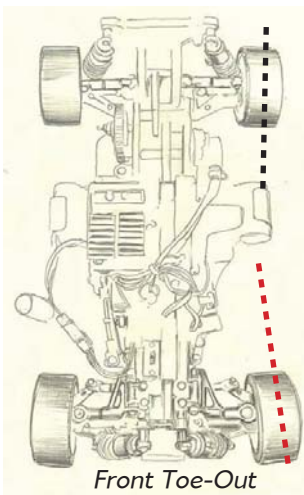
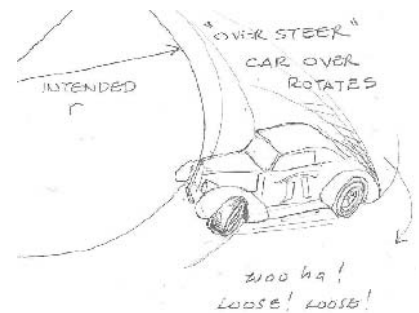
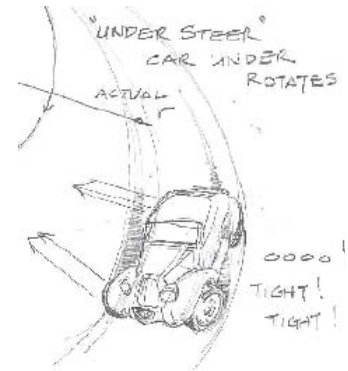
Both over-steer and under-steer can be corrected by adjustments in the chassis geometry and springs, collectively known as the chassis-spring system. This system is very complex. Just two average Formula 1 race cars may have 50 full-time engineers solving this complex optimization problem. Obviously, FTRC teams are not expected to fully understand the RC car system, but you can understand a lot about each part of the system and make informed decisions about how to set them up.

Tire Angles; Toe-In and Toe-Out

As a race car turns into a corner, it tends to "roll off" in the opposite direction, just as when you're tossed to the right when a car turns left. When a car turns left and rolls to the right, it unloads the left side wheel (more in the front than the back). You can compensate for the rolling with "toe out." This means that if you look down on the car from the top, the front wheels are turned slightly out. This looks like your own feet when you are imitating a "duck walk."

In a left turn, toe-out means that the left front wheel turns more sharply than the right wheel. This sharper turn compensates for the fact that it tends to lift from the ground in the turn. While front wheel toe-out allows you to drive faster in the curve, toe-out slows you down on the straight-away. The best setting is a compromise between speed on the corner and speed on the straight-away, but there is still another thing to consider. Excessive toe-out wears tires more quickly so that on long runs (more than 30 laps) the improved performance may be lost. There's that trade-off again.

A toe out of more than 5/16 inches across the diameter of the tire (front to back) is usually considered excessive. Increments of toe-out are often made in 1/32 inches (how many increments then is 5/16 inches?).



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Spring Constants and Hooke's Law

When a driver turns the car, the moving tire creates wheel thrust; this is the force making the car turn into the curve. How well a car accelerates around a curve is determined by:

1. Steer angle (the angle between direction at the car's center of gravity and the direction of the wheels)
2. How well tires stick to the track (coefficient of friction)
3. Wheel load (weight of the car on the tire).

How well tires stick to the track, defined as the coefficient of friction, is determined by the tire material, the track surface, temperature, humidity and other atmospheric conditions.

You can change the load (weight) on wheels by changing the tire angles, physically moving weights around the car and by changing the springs on which the car sits. Picture how the car rolls when it turns. The car tips along a diagonal between the right front to left rear or between the left front to right rear (see the image above). If turning to the left around an oval track, you might make the right front spring 'stiffer' than the left front. A stiffer spring means it has a higher spring constant as described in Hooke's Law. The right rear spring should be softer (lower spring constant) than the left rear but stiffer than the left front.

Springs rates are given in terms of pounds of compression per inch (lb/in). A stiff spring is on the order of 400 lb/in or more, while a soft one may be as low as 95 lbs/in. Professional teams have several dozen spring sets for each car.

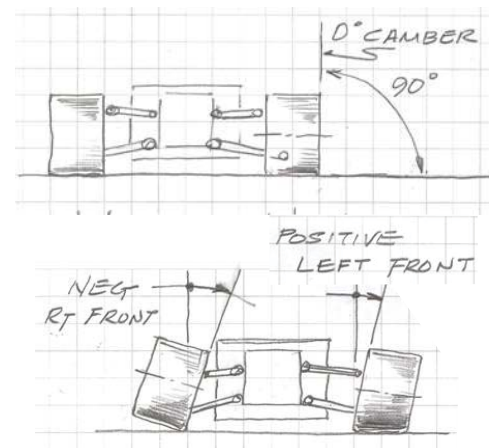
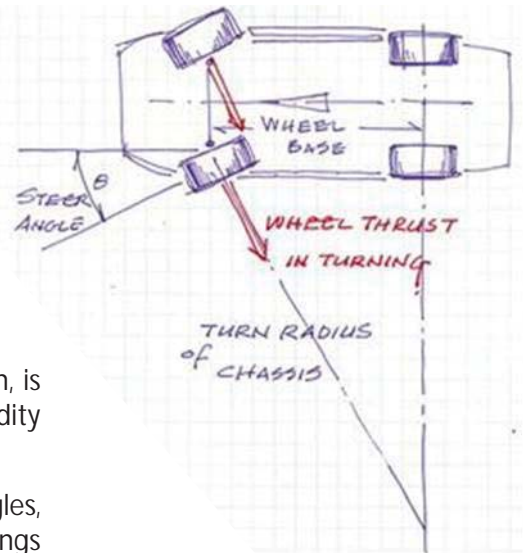
The tires are inflated just like basketballs or soccer balls. The spring rate of tires is a function of the tire pressure. Because tire pressures changes with temperature, the amount that each tire bounces will change dramatically over just the first few laps.

For all four wheels, the loads are a product nine springs:

1. The car chassis itself is a large, stiff spring (a torsional spring)
2. The chassis sits on four steel springs which each ride on a rubber spring; these are the shock absorbers.
3. The tires are springs.

Chassis Geometry: Caster & Camber

If you look at a race car from the front, the tires lean to the left (look from the back and they lean to the right). The incline between that lean and the ground is called camber. Race teams make the wheels lean to the left on a left turning oval track to improve cornering. As the car rolls to the right in a left turn, the wheels are actually straight so that they are in full contact with the track. Camber angles of 8° are considered very aggressive, while 4° is usually not enough. The left front wheel usually has a higher camber angle than the right front.



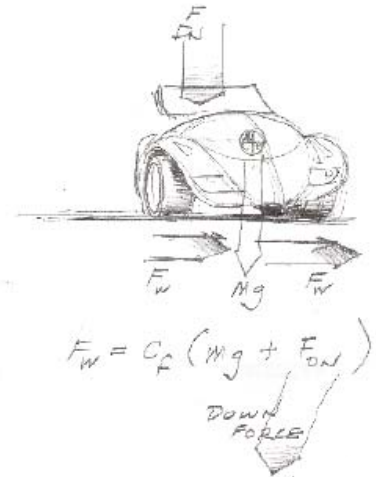
Aerodynamics

Officially, aerodynamics is a branch of fluid dynamics concerned with the study of forces generated on a body in flow (air). For professionals, solving aerodynamic problems usually means calculating various properties of flow such as velocity, pressure, density and temperature as a function of space (location) and time.

For FastTrack RC teams, these calculations are done in a 'black box' by COSMOS FloWorks, SolidWorks' Virtual Wind Tunnel (computational fluid dynamics, CFD, application). FastTrack RC teams use the COSMOS to see how well different designs work aerodynamically.

Aerodynamics is critical to the performance of race cars and can be used to control the handling of a full-scale car at high-speeds. Teams analyze and design their cars to minimize aerodynamic drag, a backwards force on the car that slows it down and optimize down-force. Down-force is like an additional load on the wheels that can improve traction. As with everything in racing, there is a trade-off to consider here. Aerodynamic components like bumpers and wings create down force which can increase cornering speeds (good), but they also increase drag and limit top speed (not so good).

Aerodynamic is only used to tune high speed characteristics. They have little or no effect on low-speed handling. Improved aerodynamics increases the overall grip of the car but can't make up for a poor mechanical set up. In other words, aerodynamic 'grip' is a way to fine-tune set-up but isn't the first thing to consider.



Engines: Improving Old Designs

Pi Research is an English company was once owned by Ford Motor Company that makes very sophisticated data acquisition systems for race cars. This technology allows teams to monitor as many as 200 channels of information and record the data up to 100 times per second. This system tracks several engine parameters, like cylinder temperature, steering, throttle, wheel speeds, wheel loads, tri-axial g loading, and engine speed.

Engines in NASCAR race cars are essentially a big block Chevy V8 engine with a solid push rod and naturally aspirated single carburetor. This engine type is pretty archaic and hasn't been commercially produced in any US vehicle since the 1970's; however, talented racing engineers wring more and more power out them. The original 1950's engines produced max 300 horsepower (hp) but they now produce more than 750 hp.

The design and manufacture of engine parts has become far more precise over the years. The dimensional tolerances have gone from several thousandths in the 1950's to less than a ten-thousandth today. This evolution allows engines to operate at much higher speeds. In the 1950's an engine would have disintegrated at 6500 revolutions per minute (RPM) but now they typically run over 9500 RPM.

Leading teams make their own engines. For example, pistons and connecting rods are each precision machined from carefully annealed single die cast billets of exotic aluminum/magnesium alloys, with each part x-rayed to detect internal microscopic flaws.

In a typical road car, as much as 15% of the power at highway speeds is consumed by the oil splashing around in the engine. Through artful design, CFD work, and sophisticated machining of the connecting rods, some race engines reduce this wasted energy to less than 5%.