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INSIDE SCIENCE
ENERGY OF THE SUN

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The gas that turns men on

Life of a neutron

Meeting in a virtual world

When the turning gets tough . . . 13 Mar 1993

Mathematics showed there is an ideal way to corner in motor racing. Only the drivers who apply this technique instinctively will become champions

Getting to the top in motor racing requires the ability to drive a car consistently close to the performance limits of its tyres, engine and chassis: the sport ruthlessly weeds out those who cannot raise their car-control skills to the highest levels. But a driver who reaches the top international level (such as Formula One or Indycar racing) finds that most competitors possess very similar abilities. So what marks out the champions?

Virtually anyone can take a car to its limits on a straight track. Most races are won and lost where the cars are moving slowest - at the corners. The skill comes in choosing a speed and path that loses the least time negotiating them. This is where champions show their mettle.

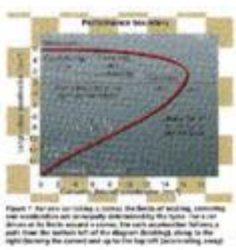
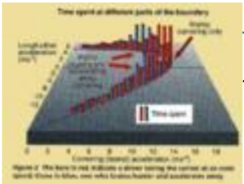


Figure 1 shows a simplified 'performance boundary curve' for one possible car and corner combination at a particular speed. Representing all possible speeds would require a family of similar curves or a three-dimensional picture. A skilled driver taking a corner slows down (applies longitudinal deceleration), corners (applies lateral acceleration) and then accelerates out and away (applies longitudinal acceleration). To control the car, the driver must ensure that the forces acting on the tyres are within the limits of their traction, and this involves a trade-off between the forces of braking and turning. As the driver corners, increasing lateral acceleration, the available longitudinal acceleration falls: high acceleration while turning too sharply causes a skid.

Top international drivers keep their cars just inside their performance boundaries almost all the time, though the boundary curve varies depending on the track conditions and the state of the car. Aerodynamic design complicates matters further. Air rushing over aerofoils on the car produces downforce that helps anchor it to the track. This allows greater cornering acceleration, but also increases wind resistance. The ratio of longitudinal to lateral acceleration alters as speed changes: at higher speeds the boundary curve becomes more flattened at the top and extends further to the right. Much of the skill that drivers acquire up to the international level lies in being able to read these changing variables, determine from moment to moment where the performance boundary lies and drive the car as close to it as possible. Acquiring this skill is a life's work, and very few drivers master it completely.

But for the elite who do, what is left to learn? Can anything help them further? Our studies with world champions indicate that one of the most important extra skills to learn is the optimum time to spend at the different parts of the performance boundary.

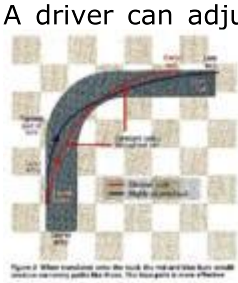


[Figure 2](#) shows a similar curve to Figure 1, with bars added to indicate the amount of time spent at each part of the curve. Taking the corner, the 'red' driver spends almost all of the time in the pure cornering region, at almost constant speed, or zero longitudinal acceleration. The 'blue' driver spends more time braking and accelerating. Both operate the car at its limit all the time.

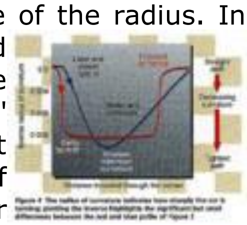
We have developed computer simulations which show that for each boundary shape there is an optimum amount of time that should be spent on each part of the curve. The simulations take account of track variables, including the lengths of the straights before and after the corner, the angle the corner turns through, its inside and outside radii, and the surface's frictional coefficient. They also have to deal with vehicle variables, which are much more complex because they are interrelated: the cornering acceleration available at each speed depends on how hard the driver is braking and the line the car is taking. Cornering will cause the car to roll, and braking while cornering may cause it to yaw - so that it no longer points in the direction it is travelling. These factors alter the downforce, and thus the degree of cornering acceleration that can be applied before a skid occurs. From data acquired in repeated runs, we have built up matrices to describe the boundaries for cars under various conditions, and have fed these into the simulation.

The optimal solution differs from corner to corner, and from car to car on the same corner. What is clear is that a world champion will usually adopt a driving pattern that matches our computer simulations, whereas less skilled drivers consistently do not. This appears to distinguish true champions from other high-ranking drivers. More surprising is that, regardless of experience, most drivers never master this skill - and remain unaware of its importance.

Tighter routes to results



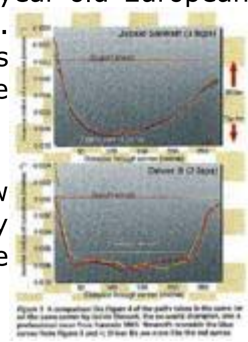
A driver can adjust the time a car spends on each part of the boundary curve by taking different paths through a corner. [Figure 3](#) shows two possibilities. The red line is a completely even, circular path. The blue line is a very skewed path, in which the driver has started to turn later. The turn quickly becomes tighter than the smooth curve, but the driver exits in a wider curve further down the following straight. (There are of course infinitely more possible paths.)



These two cornering paths can be defined by their radii of curvature at each point, and this can be plotted to highlight the differences between the two paths. Tiny differences in paths are better highlighted by plotting the inverse of the radius. In [Figure 4](#), the red line shows this profile for the circular path, and the blue line that for the skewed path. A driver following the circular path spends almost all the time at the 'cornering only' region of the performance boundary, keeping the speed almost constant throughout the corner. The tighter minimum radius of curvature of the skewed path forces the driver to enter the corner more slowly, but the gentler exit path allows a higher exit speed. Because the 'blue' driver changes speed more while passing through the corner, these differences are reflected in the time bars being spread more evenly round the boundary curve; the 'red' driver's time bars are more clustered.

In reality, most drivers take very similar paths through a corner. The differences are so small - typically around 10 centimetres - that they usually go unnoticed by even the keenest observer. To measure the differences we have developed a radio tracking system which can determine the position of the vehicle to an accuracy of 1 centimetre every hundredth of a second around an entire race track. It works by measuring the phase of radio reflections at receivers located around the track. Unscrambling the multiple reflections including those from obstacles around the track is a difficult task that requires a sophisticated computer program and parallel-processing transputers. Ford is now using this system for car development.

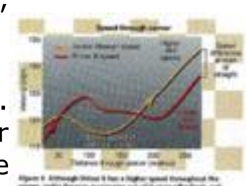
Using our location system we compared the paths taken by two drivers round one corner of a Ford test track. One was Jackie Stewart, a three-time Formula One world champion now aged 52. 'Driver B' was a highly competitive 24-year-old European driver now in Formula 3000 racing, the level below Formula One. Figure 5a shows the curvature profiles measured on three passes through the corner by Stewart. Figure 5b shows two passes of the same corner by driver B in the same car.



There are two obvious differences. First, Driver B's profiles show lots of wobbles and inconsistencies, while Stewart's are extremely smooth and consistent. More important is the overall shape of the plots.

The corner has an inner radius of 150 metres and an angle of turn of 85 degree. The inside edge is therefore at least 223 metres long, though the drivers follow a wider and therefore longer path. Driver B's curvature profile is much flatter than Stewart's: the radius of his path 50 metres into the corner remains almost unchanged until after 230 metres. The bottom of his profile is almost square. Stewart's profile is much more rounded, closing up to a tighter entry curve about 100 metres into the corner and then straightening out to almost twice the minimum radius after 230 metres. Driver B's path is like the red line in Figure 4, while Stewart's resembles the blue line.

Stewart actually spends more time in the corner than Driver B because he has to take the sharper curve more slowly. However, he can exit faster because of his wider finishing radius, and this higher speed advantage stays with him all the way down the following straight, more than making up for time lost in the corner. Taking the corner and the straights on either side as a single problem, Stewart found the fastest solution (see Figure 6).



Choosing how much to skew the corner is a very complex problem. Skewing too much (that is, turning too late) means that the corner must be taken so slowly that the time lost there cannot be recouped fully in the following straight; it may even result in a lower exit speed. Skewing too little (turning early), like Driver B, can also lose speed in the straight.

We have developed a measurement that we call the 'k number' , which describes how skewed a curve the driver has taken through the corner. A path which is completely circular throughout has a k of 0. Higher values of k describe increasingly skewed paths. Specifically, k refers to how quickly the path flattens out. Our computer simulations try different values of k, then look at the paths that result for various car boundary performances and work out the time taken for the corner. The simulations show that there is no single optimum value of k for all cars or corners: a car taking different corners will require different solutions. Even for the same corner, different cars will require different values of k. This is shown in [Figure 7](), which plots k against the time taken by two cars, a BMW M series set up by Schnitzer (the World Group A Saloon car champion works team) and a Ford Laser Tx3i (a 1.8-litre fuel-injected model derived from the Ford Escort) to complete a single corner and the two straights on either side. The minimum time for the BMW occurred at k=13.8. For the Laser Tx3i it was closer to k=4, which means for best results in this corner the Laser should be driven in a much rounder curve than the Schnitzer.

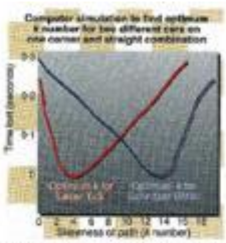
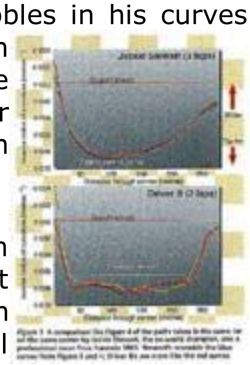


Figure 7 Even on the same corner, different cars have different "best" lines. The Ford Laser Tx3i, based on the Ford Escort, must be driven on a gentler curve than the racing BMW

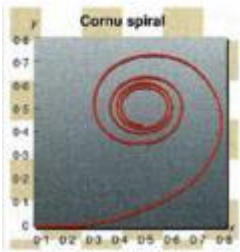
In general, the shorter the corner and the longer the straights either side, the more the path should be skewed. Similarly, the greater the ratio of the car's potential forward acceleration to cornering acceleration - a measure defined by the car's speed and performance characteristics, not the corner - the more the path should be skewed.

We have measured numerous drivers in a range of cars over four years in Britain, the US, Germany, Japan and New Zealand, and found that only champions uniquely seem to possess the ability to approach the correct k number, although even they are not perfect. Lesser drivers seem to fall into certain stereotyped patterns, and they fail to adjust their driving appropriately for different conditions - even though they still drive the car at the boundary limit. This explains why some drivers can be expert in one type of car yet struggle in a different class. The true champion, on the other hand, can quickly approach the optimum k for any car. For example, on our test track Stewart consistently drove a slightly different line with a Ford Mustang than with a Ford Thunderbird; these differences are predicted in our computer model.

Looking at data collected from accelerometers on the cars driven by Stewart and Driver B, it is Driver B who turns out to have had slightly higher cornering accelerations throughout the entire curve. As a younger driver, with slightly faster reflexes, he can drive the car slightly closer to the limit than the retired Stewart. However, Stewart is still quicker because he selects better k values. Driver B called on tremendous car-control skills to take the car closer to its performance limits. The trouble is, they were the wrong parts of the limits, and he pushed the car so hard that he had difficulty controlling it. This is what caused the wobbles in his curves [(Figure 5b)](). Information derived from our computer simulation could make up for the sensitivity to car and track that all but the best drivers lack. By debriefing drivers after practice circuits, or giving them instructions by radio, it should be possible to train them to choose a better k under different conditions.



So what do our findings imply for Nigel Mansell, transferring from Formula One to Indycar racing? Among other differences, most Indy tracks have steeper banking - up to 9 '12' - than is usual in Formula One. Cornering on a slope means that part of the lateral acceleration acts in the direction that the driver perceives as



downwards (Figure 8), and this can fool people used to level tracks into underestimating the ratio of lateral to longitudinal acceleration acting on the tyres. As a result, they may try to corner too late and too sharply. Mansell will have to learn how to interpret these differently perceived forces to find the optimum k: at 200 mph on a quarter-mile corner (as at the Indianapolis 500 racetrack), the banking creates a 2 per cent difference in the perceived ratio of lateral to longitudinal acceleration - small, but significant at those speeds.

Other drivers who have switched from Formula One to Indycar racing confirm that this is a real problem. Initially they consistently overestimate the required k - that is, they turn too late. It takes time to learn to turn in earlier, to take the more even line that a banked track requires. The problem is further compounded by the different aerodynamics of Indycar and Formula One designs. Even drivers supposed to be at the peak of their abilities find the change confusing. One who made the switch needed a year to adjust.

Unfortunately, finding the optimum solution is nowhere near as simple as just looking at the acceleration ratios as we have done here. There are many other variables, such as tyre slip (in which the tyres slide, minutely, during cornering without the car skidding out of control). Also, complex interactions between the throttle and a car's steering have an important effect which differs from car to car. However, we believe that the next revolution in motor racing could well come from using sophisticated mathematical analysis and real-time feedback techniques to give drivers a competitive advantage. Military pilots already rely on real-time computer analysis and feedback from head-up displays to assist them in combat. Applying many of those techniques, together with the type of mathematical treatment outlined above, will certainly make as big a contribution as standard telemetry analysis of the car itself has already made.

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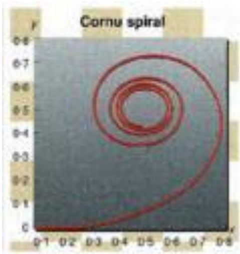
Nigel Mansell does this in his head - can you?

Deciding how late to turn into a corner is a matter of getting the right value for k. We start with the cornu spiral (a curve whose curvature K at any point is proportional to the distance from the zero point). This spiral can be generated from the Fresnel integral, usually used for analysing intensities of diffraction patterns, which generates two variables x and y from the value of a third, u. Each value of u gives a different value of x and y when the pair of integrals generating them are solved (see equations).

$$y = \int_0^u \cos\left(\frac{\pi u^2}{2}\right)$$

$$x = \int_0^u \sin\left(\frac{\pi v^2}{2}\right)$$



We then look at the path taken by the driver, analyse the small section around its tightest radius of curvature, and scale it to the cornu spiral. Then we slide the driver's curve along the spiral, looking for the point where the two curves match most closely. This happens at a particular value of the Fresnel integral's top value u. The k value is then the inverse of u.

Of course, we do this on a computer after exhaustive measurements on the track. The drivers have to find the best k using just their senses and instinct. Perhaps it's not surprising that so few of them truly master the ability to find the right line.

KERRY SPACKMAN and SZE TAN
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