Pointed the Right Way

story by john hagerman

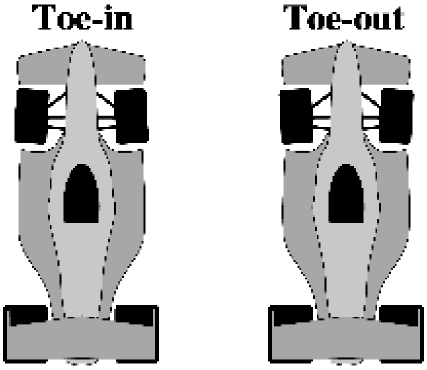
Camber, Caster and Toe: What Do They Mean?

The three major alignment parameters on a car are toe, camber, and caster. Most enthusiasts have a good understanding of what these settings are and what they involve, but many may not know why a particular setting is called for, or how it affects performance. Let's take a quick look at this basic aspect of suspension tuning.

UNDERSTANDING TOE

When a pair of wheels is set so that their leading edges are pointed slightly towards each other, the wheel pair is said to have toe-in. If the leading edges point away from each other, the pair is said to have toe-out. The amount of toe can be expressed in degrees as the angle to which the wheels are out of parallel, or more commonly, as the difference between the track widths as measured at the leading and trailing edges of the tires or wheels. Toe settings affect three major areas of performance: tire wear, straight-line stability and corner entry handling characteristics.

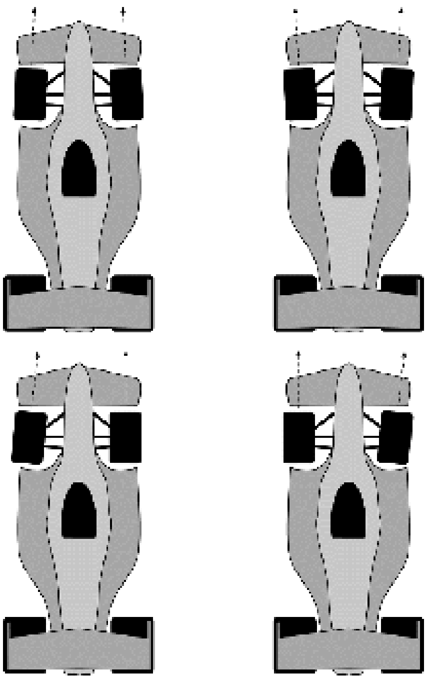
For minimum tire wear and power loss, the wheels on a given axle of a car should point directly ahead when the car is running in a straight line. Excessive toe-in or toe-out causes the tires to scrub, since they are always turned relative to the direction of travel. Too much toe-in causes accelerated wear at the outboard edges of the tires, while too much toe-out causes wear at the inboard edges.



So if minimum tire wear and power loss are achieved with zero toe, why have any toe angles at all? The answer is that toe settings have a major impact on directional stability. The illustrations at right show the mechanisms involved. With the steering wheel centered, toe-in causes the wheels to tend to roll along paths that intersect each other. Under this condition, the wheels are at odds with each other, and no turn results.

When the wheel on one side of the car encounters a disturbance, that wheel is pulled rearward about its steering axis. This action also pulls the other wheel in the same steering direction. If it's a minor disturbance, the disturbed wheel will steer only a small amount, perhaps so that it's rolling straight ahead instead of toed-in slightly. But note that with this slight steering input, the rolling paths of the wheels still don't describe a turn. The wheels have absorbed the irregularity without significantly changing the direction of the vehicle. In this way, toe-in enhances straight-line stability.

If the car is set up with toe-out, however, the front wheels are aligned so that slight disturbances cause the wheel pair to assume rolling directions that do describe a turn. Any minute steering angle beyond the perfectly centered position will cause the inner wheel to steer in a tighter turn radius than the outer wheel. Thus, the car will always be trying to enter a turn, rather than maintaining a straight line of travel. So it's clear that toe-out encourages the initiation of a turn, while toe-in discourages it.



With toe-in (left) a deflection of the suspension does not cause the wheels to initiate a turn as with toe-out (right).

The toe setting on a particular car becomes a tradeoff between the straight-line stability afforded by toe-in and the quick steering response promoted by toe-out. Nobody wants their street car to constantly wander over tar strips-the never-ending steering corrections required would drive anyone batty. But racers are willing to sacrifice a bit of stability on the straightaway for a sharper turn-in to the corners. So street cars are generally set up with toe-in, while race cars are often set up with toe-out.

With four-wheel independent suspension, the toe must also be set at the rear of the car. Toe settings at the rear have essentially the same effect on wear, directional stability and turn-in as they do on the front. However, it is rare to set up a rear-drive race car toed out in the rear, since doing so causes excessive oversteer, particularly when power is applied. Front-wheel-drive race cars, on the other hand, are often set up with a bit of toe-out, as this induces a bit of oversteer to counteract the greater tendency of front-wheel-drive cars to understeer.

Remember also that toe will change slightly from a static situation to a dynamic one. This is is most noticeable on a front-wheel-drive car or independently-suspended rear-drive car. When driving torque is applied to the wheels, they pull themselves forward and try to create toe-in. This is another reason why many front-drivers are set up with toe-out in the front. Likewise, when pushed down the road, a non-driven wheel will tend to toe itself out. This is most noticeable in rear-drive cars.

The amount of toe-in or toe-out dialed into a given car is dependent on the compliance of the suspension and the desired handling characteristics. To improve ride quality, street cars are equipped with relatively soft rubber bushings at their suspension links, and thus the links move a fair amount when they are loaded. Race cars, in contrast, are fitted with steel spherical bearings or very hard urethane, metal or plastic bushings to provide optimum rigidity and control of suspension links. Thus, a street car requires a greater static toe-in than does a race car, so as to avoid the condition wherein bushing compliance allows the wheels to assume a toe-out condition.

It should be noted that in recent years, designers have been using bushing compliance in street cars to their advantage. To maximize transient response, it is desirable to use a little toe-in at the rear to hasten the generation of slip angles and thus cornering forces in the rear tires. By allowing a bit of compliance in the front lateral links of an A-arm type suspension, the rear axle will toe-in when the car enters a hard corner; on a straightaway where no cornering loads are present, the bushings remain undistorted and allow the toe to be set to an angle that enhances tire wear and stability characteristics. Such a design is a type of passive four-wheel steering system.

THE EFFECTS OF CASTER

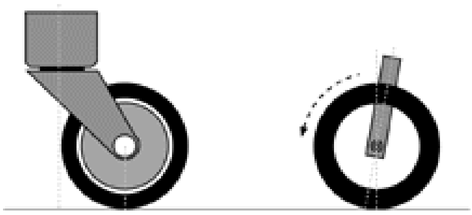
Caster is the angle to which the steering pivot axis is tilted forward or rearward from vertical, as viewed from the side. If the pivot axis is tilted backward (that is, the top pivot is positioned farther rearward than the bottom pivot), then the caster is positive; if it's tilted forward, then the caster is negative.

Positive caster tends to straighten the wheel when the vehicle is traveling forward, and thus is used to enhance straight-line stability. The mechanism that causes this tendency is clearly illustrated by the castering front wheels of a shopping cart (above). The steering axis of a shopping cart wheel is set forward of where the wheel contacts the ground. As the cart is pushed forward, the steering axis pulls the wheel along, and since the wheel drags along the ground, it falls directly in line behind the steering axis. The force that causes the wheel to follow the steering axis is proportional to the distance between the steering axis and the wheel-to-ground contact patch-the greater the distance, the greater the force. This distance is referred to as "trail."

Due to many design considerations, it is desirable to have the steering axis of a car's wheel right at the wheel hub. If the steering axis were to be set vertical with this layout, the axis would be coincident with the tire contact patch. The trail would be zero, and no castering would be generated. The wheel would be essentially free to spin about the patch (actually, the tire itself generates a bit of a castering effect due to a phenomenon known as "pneumatic trail," but this effect is much smaller than that created by mechanical castering, so we'll ignore it here). Fortunately, it is possible to create castering by tilting the steering axis in the positive direction. With such an arrangement, the steering axis intersects the ground at a point in front of the tire contact patch, and thus the same effect as seen in the shopping cart casters is achieved.

The tilted steering axis has another important effect on suspension geometry. Since the wheel rotates about a tilted axis, the wheel gains camber as it is turned. This effect is best visualized by imagining the unrealistically extreme case where the steering axis would be horizontal-as the steering wheel is turned, the road wheel would simply change camber rather than direction. This effect causes the outside wheel in a turn to gain negative camber, while the inside wheel gains positive camber. These camber changes are generally favorable for cornering, although it is possible to overdo it.

Most cars are not particularly sensitive to caster settings. Nevertheless, it is important to ensure that the caster is the same on both sides of the car to avoid the tendency to pull to one side. While greater caster angles serve to improve straight-line stability, they also cause an increase in steering effort. Three to five degrees of positive caster is the typical range of settings, with lower angles being used on heavier vehicles to keep the steering effort reasonable.



Like a shopping cart wheel (left) the trail created by the castering of the steering axis pulls the wheels in line.

WHAT IS CAMBER?

Camber is the angle of the wheel relative to vertical, as viewed from the front or the rear of the car. If the wheel leans in towards the chassis, it has negative camber; if it leans away from the car, it has positive camber (see next page). The cornering force that a tire can develop is highly dependent on its angle relative to the road surface, and so wheel camber has a major effect on the road holding of a car. It's interesting to note that a tire develops its maximum cornering force at a small negative camber angle, typically around neg. 1/2 degree. This fact is due to the contribution of camber thrust, which is an additional lateral force generated by elastic deformation as the tread rubber pulls through the tire/road interface (the contact patch).

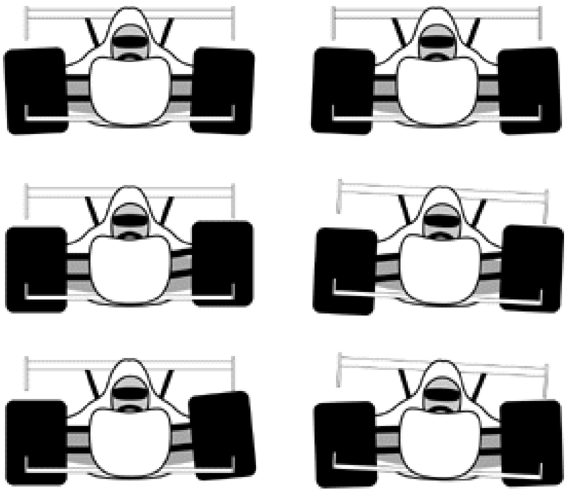
To optimize a tire's performance in a corner, it's the job of the suspension designer to assume that the tire is always operating at a slightly negative camber angle. This can be a very difficult task, since, as the chassis rolls in a corner, the suspension must deflect vertically some distance. Since the wheel is connected to the chassis by several links which must rotate to allow for the wheel deflection, the wheel can be subject to large camber changes as the suspension moves up and down. For this reason, the more the wheel must deflect from its static position, the more difficult it is to maintain an ideal camber angle. Thus, the relatively large wheel travel and soft roll stiffness needed to provide a smooth ride in passenger cars presents a difficult design challenge, while the small wheel travel and high roll stiffness inherent in racing cars reduces the engineer's headaches.

It's important to draw the distinction between camber relative to the road, and camber relative to the chassis. To maintain the ideal camber relative to the road, the suspension must be designed so that wheel camber relative to the chassis becomes increasingly negative as the suspension deflects upward. The illustration on the bottom of page 46 shows why this is so. If the suspension were designed so as to maintain no camber change relative to the chassis, then body roll would induce positive camber of the wheel relative to the road. Thus, to negate the effect of body roll, the suspension must be designed so that it pulls in the top of the wheel (i.e., gains negative camber) as it is deflected upwards.

While maintaining the ideal camber angle throughout the suspension travel assures that the tire is operating at peak efficiency, designers often configure the front suspensions of passenger cars so that the wheels gain positive camber as they are deflected upward. The purpose of such a design is to reduce the cornering power of the front end relative to the rear end, so that the car will understeer in steadily greater amounts up to the limit of adhesion. Understeer is inherently a much safer and more stable condition than oversteer, and thus is preferable for cars intended for the public.

Since most independent suspensions are designed so that the camber varies as the wheel moves up and down relative to the chassis, the camber angle that we set when we align the car is not typically what is seen when the car is in a corner. Nevertheless, it's really the only reference we have to make camber adjustments. For competition, it's necessary to set the camber under the static condition, test the car, then alter the static setting in the direction that is indicated by the test results.

The best way to determine the proper camber for competition is to measure the temperature profile across the tire tread immediately after completing some hot laps. In general, it's desirable to have the inboard edge of the tire slightly hotter than the outboard edge. However, it's far more important to ensure that the tire is up to its proper operating temperature than it is to have an "ideal" temperature profile. Thus, it may be advantageous to run extra negative camber to work the tires up to temperature.



(TOP RIGHT) Positive camber: The bottoms of the wheels are closer together than the tops. (TOP LEFT) Negative camber: The tops of the wheels are closer together than the bottoms. (CENTER) When a suspension does not gain camber during deflection, this causes a severe positive camber condition when the car leans during cornering. This can cause funky handling. (BOTTOM) Fight the funk: A suspension that gains camber during deflection will compensate for body roll. Tuning dynamic camber angles is one of the black arts of suspension tuning.

TESTING IS IMPORTANT

Car manufacturers will always have recommended toe, caster, and camber settings. They arrived at these numbers through exhaustive testing. Yet the goals of the manufacturer were probably different from yours, the competitor. And what works best at one race track may be off the mark at another. So the "proper" alignment settings are best determined by you-it all boils down to testing and experimentation.

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