

The Mark Ortiz Automotive

CHASSIS NEWSLETTER

PRESENTED FREE OF CHARGE
AS A SERVICE TO THE
MOTORSPORTS COMMUNITY
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WELCOME

Mark Ortiz Automotive is a chassis consulting service primarily serving oval track and road racers. This newsletter is a free service intended to benefit racers and enthusiasts by offering useful insights into chassis engineering and answers to questions. Readers may mail questions to: 155 Wankel Dr., Kannapolis, NC 28083-8200; submit questions by phone at 704-933-8876; or submit questions by e-mail to: markortiz@vnet.net. Readers are invited to subscribe to this newsletter by e-mail. Just e-mail me and request to be added to the list.

IDEAL SPINDLE OR STEERING GEOMETRY

I have a fairly simple question for you, but I don't know how simple the answer will be. In any literature I read, we are always dealing with things like kingpin inclination (KPI) and scrub radius. Usually these cannot be eliminated in a sedan with big tires, and we are told in the books to "not have too much". But if I have more design freedom, and it is possible to get zero scrub, and zero or very close on kingpin inclination, would this be a favorable setup? I know that scrub + caster can give weight jacking, and that KPI gives a self-centering effect, but otherwise both of them seem like something I want to get rid of. So to sum up, is it a good idea to completely eliminate scrub, or KPI (or any other variables) entirely if the design allows?

To help readers who are less conversant with steering geometry, I am inserting some comments of mine from the August 2002 newsletter, which explain various steering geometry parameters and their effects:

The *steering axis* is a line about which the wheel steers, usually through the two ball joint centers of rotation in an independent suspension, or the kingpin axis in a beam axle. This line can be defined by the point where it intersects the ground and by its angular orientation. These are commonly described in terms of the X and Y coordinates of the ground intercept, with respect to a local origin at the contact patch center, and the transverse and longitudinal angles relative to ground plane horizontal.

The front view distance from ground intercept to contact patch center, or local Y, is called *scrub radius*, or *steering offset*. It would make more sense to call the top view distance from ground intercept to contact patch center the scrub radius, but most people use the term to mean the Y or transverse component of this. This quantity is generally considered positive when the contact patch center is outboard of the ground intercept.

The side view distance from ground intercept to contact patch center, or local X, is called *trail*, or sometimes *caster trail* or *mechanical trail*. It is positive when the ground intercept is forward of the contact patch center.

The front view angle of the steering axis from ground vertical is called *steering axis inclination* (SAI), or sometimes *kingpin inclination* (KPI). It is positive when the steering axis tilts inboard at the top, which is almost always the case.

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The side view angle of the steering axis from ground vertical is called *caster*. It is positive when the steering axis slopes rearward at the top.

These parameters are controlled partly by the design and adjustment of the control arms, and partly by the design of the spindle, or spindle/upright assembly, together with the hub and wheel.

The term *spindle* can mean either the stub axle, or pin, that carries the bearings, or the assembly including this pin and the upright, especially when these are one piece.

The spindle or spindle/upright determines two important parameters: *spindle inclination* and *pin lead* or *pin trail*.

Spindle inclination is the front-view inclination of the steering axis, relative to pin or wheel vertical, as opposed to ground vertical. Spindle inclination approximately equals SAI minus camber. Spindle inclination is almost exactly identical to SAI when camber is zero. It is exactly identical when both camber and caster are zero.

The steering axis and the wheel axis do not have to intersect, unless we want the right and left uprights to be identical parts, with bolt-on steering arms and caliper brackets. The steering axis can pass behind the wheel axis, as it does on a bicycle. The perpendicular distance between the two axes is called *pin lead*. This is equivalent to the dimension we call fork rake on a bicycle. If the steering axis passes in front of the wheel axis, that's *pin trail*. So pin trail is negative pin lead, and vice versa.

Effective pin length is the distance, along the wheel axis, in front view, from the steering axis to the wheel centerplane. This distance depends on the wheel and hub as well as the spindle/upright.

We now have sufficient vocabulary to describe and discuss basic steering and spindle geometry. If we can specify all the quantities above, we have enough data to construct a stick model of the basic steering geometry.

We may want to add steering arms. For purposes of spindle/upright design, we can define the position of the outer tie rod end with respect to the pin and the steering axis. We may define a height from pin axis to tie rod end center of rotation. To do this in a manner appropriate for drawing the upright, or inspecting it when removed from the car, this should be the vertical dimension in side view, assuming zero caster and camber -- in other words, we are projecting to the wheel plane, and taking the steering axis in side view as our local vertical.

In such a side view, we may construct a horizontal line from tie rod end to steering axis. This is our *side view steering arm length*.

We may project a top view from the side view, and locate the lateral position of the tie rod end. If we have a longitudinal line corresponding to the side view steering arm described above, we may construct a transverse line from it to the tie rod end, and measure that distance. This we may call *steering arm offset*. It will usually be outboard for a front-steer layout, and inboard for a rear-steer layout. I don't know what sign conventions other people use, but I generally call outboard positive for front steer and inboard positive for rear steer. Thus positive offset is the direction that gives us positive Ackermann.

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In terms of coordinates, we are establishing a local origin where the side view steering arm meets the steering axis. The side view steering arm length is our local X, and the steering arm offset is our local Y.

This doesn't mean there's anything wrong with assigning global or front-suspension coordinates to the tie rod ends when doing an overall front end layout. I'm just pointing out that at some point you will have to deal with the spindle/upright/steering arm unit as a sub-assembly, off the car, and it helps to be able to measure and discuss it that way too.

Now we have a fairly complete vocabulary to describe steering geometry, so we can discuss what effects these parameters have.

Trail causes *lateral* forces at the contact patch to produce a torque about the steering axis. This causes the steering to seek a gravitational/inertial center. The driver feels lateral cornering force through the steering. He also feels the lateral force that the tires must generate to make the car run straight on a laterally sloping, or cambered, road surface. It is worth noting that this is only one component of the self-centering forces the driver feels. Another is the tire's own *self-aligning torque*, which is present whenever the tire runs at any slip angle. This will provide some feedback of cornering force even in the total absence of trail. This effect is sometimes described as mimicking trail. The amount of tire self-aligning torque, divided by lateral force, is sometimes called *pneumatic trail*. Note that this is a calculated value which depends on tire properties, and not an actual steering geometry parameter.

One important distinction between the forces from trail and tire self-aligning torque is that tire self-aligning torque is not a linear function of lateral force. It builds at a decreasing rate as lateral force increases, and at a point a bit short of maximum lateral force it actually begins to decrease. This means that if our car has little or no trail, the steering will start to go light a bit *before* the point of tire breakaway. Some argue that this is a good thing, especially for a passenger car, because it gives the driver a signal to ease up short of the point of actual loss of control. In a race car, this type of steering feel requires that the driver be accustomed to driving just a controlled increment beyond the point where the steering wheel tells him/her that the limit of adhesion has been reached. If the driver is used to having more trail, he/she will often find this very difficult.

Trail also causes a small lateral movement of the front of the car with steer, in the direction of steer. We might call this *steer yaw*. It can rationally be argued that this improves turn-in, both by yawing the car promptly and by causing the rear wheels to develop a slip angle promptly.

Scrub radius or steering offset causes *longitudinal* forces at the contact patch to generate a torque about the steering axis. If right and left scrub radii are equal and longitudinal forces at the right and left wheels are equal, no net torque at the steering wheel results. The driver feels the *difference* between the longitudinal forces at the front wheels. The driver feels one-wheel bumps, brake pulsations, and crash impacts where one wheel hits something, in direct proportion to scrub radius.

A car with a lot of scrub radius is sensitive to wheel imbalance and tire and brake imperfections, has a lot of "wheel fight", and has greater tendency to injure the driver's hands in one-wheel crash impacts or curb or pothole impacts. A car with very little scrub radius is less subject to these problems, but the steering will tend to be numb and uncommunicative.

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A car with large scrub radius *may* steer more easily at parking speeds, depending on other parameters, provided the brakes are not applied. This is because the wheels can roll as they steer rather than purely scuffing. With the brakes applied and the car stationary, a car with a small scrub radius steers more easily.

Caster causes the front wheels to lean in the direction of steer. With a given spindle/upright geometry, more caster implies more trail.

Caster combined with trail causes *steer drop* or *steer dive*. The front of the vehicle drops as the wheels steer away from center, if caster is equal on right and left. This tends to cause an anti-centering force at the steering wheel. It is the reason why the front wheels of a dragster at rest tend to flop to one side or the other.

Caster combined with scrub radius causes the car to drop as the wheel steers forward (toes in), and lift as the wheel steers rearward (toes out). When this occurs on the right and left wheels as one steers forward and the other steers rearward, the result is *steer roll*. The car leans away from the direction of steer. The wheel loads also change. The car de-wedges: the inside front and outside rear gain load; the outside front and inside rear lose load. This effect can help the car turn in slow corners, especially with a spool or limited-slip differential. In excess, it can create low-speed oversteer and over-sensitivity to steering angle. In general, cars running on lower-speed tracks need more steer roll, and cars on fast ovals should have very little.

The camber change associated with caster is favorable, particularly for road racing cars, which usually cannot get favorable camber on both front wheels any other way. We can have too much of this good thing, but that's extremely uncommon.

Steering axis inclination (SAI) causes both front wheels to gain positive camber as they steer away from center.

SAI combined with scrub radius causes *steer lift*. The front of the vehicle rises as the wheels steer away from center. This induces a self-centering force in the steering which seeks vehicle center rather than inertial/gravitational center. This is particularly useful in passenger cars because it reduces the car's tendency to follow road camber, and therefore reduces the need for the driver to pay close attention in casual driving on roads with varying slope. The centering force also tends to suppress steering shimmy.

In race cars, the camber change associated with SAI is unfavorable on the outside wheel. The self-centering force increases steering effort, which is a factor for any vehicle without power steering. It also creates what could be considered a false message to the driver about the lateral forces present at the contact patches. There is therefore a rational case for using more caster and less SAI in a race car.

With the packaging constraints we usually face, more SAI generally implies less scrub radius. The main limitation will often be how far outboard we can place the lower ball joint without having it too close to the brake disc. If the wheel has generous negative offset, we may instead be limited by the wheel rim hitting the control arms in some combinations of suspension motion and steer. Either way, we often cannot place the entire steering axis as far outboard as we would theoretically like to. Using SAI allows us to at least get the ground intercept further outboard in such cases. With MacPherson strut front ends, large amounts of SAI are necessary if we are to obtain any camber recovery in roll.

Consequently, in many cars we see SAI used for reasons not directly related to SAI's own dynamic effects.

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A full discussion of **Ackermann effect** (increase of toe-out with steer) is beyond our scope here, but we can at least say that in low speed turns with the wheels steered into the turn, the car generally needs toe-out on the front wheels. For high-speed sweepers or ovals, the front wheels generally need toe-in instead. The key determining factor is whether the *turn center* -- the instantaneous center of curvature of the car's path -- is ahead of or behind the front axle line. Other determining factors include the tendency of the loaded wheel to want a larger slip angle than the unloaded one, and what yaw moments we wish to create with the tire drag forces.

The attitude of the front wheels at any given instant depends on both the static toe setting and the change in wheel-to-wheel toe with steer. This means that optimum Ackermann depends on static toe setting.

It should be clear, then, that there is no such thing as perfect Ackermann properties. But we can at least say some definite things about what geometric parameters will do to Ackermann. In particular, increasing steering arm offset increases Ackermann effect.

Ackermann for oval track cars is often asymmetrical. The side view steering arm length is less on the left wheel than on the right. This produces more Ackermann when steering left than when steering right.

We should mention that if we are willing to tolerate a bit of additional complexity, there are ways around some of the tradeoffs in steering geometry. For example, it is possible to create a self-centering force by springing the steering system. This can mimic the self-centering that we get from SAI, without the adverse effects on camber. We can also damp the steering to reduce kick and shimmy.

We can get small SAI and small scrub radius at the same time by using compound control arms (two single links replacing the usual wishbone or A-frame) and dual ball joints. This gives us an instantaneous virtual ball joint outboard of the linkage itself. We can adopt this arrangement at the upper end of the upright, or the lower end, or both.

When using dual ball joints, it is important not to splay the two links too widely. Otherwise it may be possible for the linkage to snap over center if it has to take an impact near full lock. As a rule of thumb, it is probably advisable to have the front link around 25 degrees forward from transverse and the rear link around 25 degrees back.

Ackermann also gets interesting when using dual ball joints. As we steer, the steering axis moves rearward with respect to the ball joints and tie rods on the outside wheel and forward with respect to the ball joints and tie rod on the inside wheel. This means we lose Ackermann as we steer if the steering linkage is behind the wheel axis (rear steer layout), or we gain Ackermann as we steer if we have a front steer layout. Conversely, it is difficult to get the outer tie rod ends far enough outboard to have positive Ackermann at small steer angles with front steer. With rear steer, it is easy to get the tie rod ends inboard far enough to have initial positive Ackermann, but it is hard to avoid having too much initial positive Ackermann. It becomes very important to evaluate the steering geometry through the full range of steering motion. In many cases, we find that outer tie rod end packaging limits our steering axis location, rather than ball joint and control arm packaging.

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I might also mention that we can get small SAI and small scrub radius together by using an actual kingpin, as on a beam axle, and bushings rather than ball joints at the top and bottom of the upright. The kingpin can then be placed much further into the wheel and brake than would otherwise be possible. This was actually the most popular way to build independent front ends up until the mid to late 1950's.

Okay, returning to the current question, is it desirable to completely eliminate SAI/KPI, and/or scrub radius/steering offset? As the comments above indicate, these questions relate heavily to steering feel and the answers are therefore to some extent a matter of personal preference.

The nature of the track influences the decisions too. There is a stronger case for minimal SAI and scrub radius on a high-speed oval than on a street circuit. There may also be a stronger case for minimal SAI and scrub radius for off-road racing than for pavement competition.

The high-speed oval requires steadiness and freedom from vibration at high speeds. We don't want the car's properties or wheel loads changing much with steering wheel movement. We want stability and predictability more than responsiveness or communicativeness. The driver will tend to drive more in "open-loop" mode, steadily holding a smooth line, by eye, through the wide turns rather than responding reflexively to constantly changing information received through the steering wheel. He/she will still need to feel whether the front wheels have grip, and may still want the steering to seek center, but the need to sense the road wheels' exact position is much diminished.

On a street circuit or tight road course, the driver will tend to operate more "closed-loop", relying on input from the steering wheel to tell him/her where the wheels are on the road. The driver senses this by seeing the bumps in the road at a distance as they approach, and then feeling through the steering what the wheels actually run over. This is true even in a car where the driver can see every bit of the front wheels, because at speed the driver has to be looking ahead at where he/she wants to go, and not down at the wheels. Speed on a tight course depends heavily on using all the road, and that depends on being able to position the car precisely.

Road courses also tend to be bumpier and contain more varied surfaces than high-speed ovals. Consequently, the driver relies on the steering for information about the ever-changing grip level. This really is more a matter of trail than scrub radius, but in braking in conditions where there is more grip on one side of the car than the other, scrub radius may make it easier to detect lockup on the slicker side. On the downside, when the steering pulls toward the side with more traction, the driver needs to resist the pull, and maybe even steer against it a little, to keep the car pointed straight. For this reason, Volkswagen used to advertise the negative scrub radius on their cars as an aid to stability in braking.

If the car has really stiff suspension, as with current high-downforce cars, the driver will have little problem sensing which wheel hits a bump, even if he/she can't feel it through the steering wheel. On

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the other hand, a car with soft suspension has greater need for communicative steering, because it doesn't transmit so much information by other paths.

If we are running off-road, precise vehicle placement may be somewhat less critical, although there are situations where it is important. The wheels will be hitting big bumps all the time, and it becomes important to avoid beating up the driver. If the vehicle has a beam axle in front, steering oscillations and kick from lateral movement at the contact patches on one-wheel bumps are particularly troublesome. Consequently, there is a case for a small scrub radius for off-road use.

There are a lot of vehicles out there that successfully use zero scrub radius with zero SAI. Most of them have only one front wheel, but they work fine. The faster ones do often use steering dampers. I am referring of course to motorcycles. It should be equally possible to have similar geometry on two front wheels, all packaging considerations permitting.

Is that the best solution? As previously noted, it depends on what you want, or what the driver wants, in terms of steering feel. If you want light steering and minimal feedback of bumps, wheel vibration, and brake pulsation, try zero scrub radius and zero SAI. If you want a "natural" feel of which wheel is hitting a bump, you probably want some positive scrub radius. If you are trying to unload the inside rear wheel in tight turns, you want a lot of scrub radius.

It is possible to have a large scrub radius with little or no SAI. This combination is prone to oscillation, particularly at low speeds, and particularly with large caster settings. However, in a race car, it may make sense to either live with that, or damp and/or spring the steering to control it, rules permitting.

It is also possible to have large SAI with small scrub radius, or even negative scrub radius. Indeed, ample SAI is generally the easiest way to get a small scrub radius. There is a case for this sort of geometry in street cars, especially with front wheel drive and strut suspension, or with a beam axle front end. It is not a good idea for a situation where we are designing for racing, with rear wheel drive and generous design freedom.