

Here we tackle the tough questions :

"Ackerman? Or not? Does it matter?"

Dale Thompson from Racing Car Technology looks for some answers. What's your view? Have you any test data? **Email Dale on racetech@ozebiz.com.au**

Ackerman? Anti-Ackerman? Or Parallel Steering?

Ackerman steering geometry is used to change the dynamic toe setting, by increasing front wheel toe out as the car is turned into the corner. Racers are interested because of the potential to influence the handling of the car on corner entry and mid corner.

Our interest at Racing Car Technology is to look for further developments in racing car set up for our customers. We have been setting up racing cars with our "Weight Transfer Worksheet" (WTW) for a few years now. By track testing we got confirming data, and showed that if you have a baseline set up that is close, you can make changes the driver feels, and improve the car further.

The major elements of suspension set up remain spring changes and anti-roll bar and shock absorbers adjustments. A drawback in the weight transfer model is that we consider the tyres a given. We calculate a roll angle for the car of so many degrees per G (lateral G). This gives us an idea of what roll rate (roll stiffness) is required for the sort of cornering power we think the car will achieve. But it is evident that the tyres, and particularly the tyre slip angles are of interest in optimising grip. We influence tyre slip angles with toe setting (static and dynamic toe).

Ackerman Steering Geometry

The typical steering system, in a road or race car, has tie-rod linkages and steering arms that form an approximate parallelogram, which skews to one side as the wheels turn. If the steering arms are parallel, then both wheels are steered to the same angle. If the steering arms are angled, as shown in Figure 1, this is known as Ackerman geometry. The inside wheel is steered to a greater angle than the outside wheel, allowing the inside wheel to steer a tighter radius. The steering arm angles as drawn show 100% Ackerman. Different designs may use more or less percentage pro-Ackerman, anti-Ackerman, or Ackerman may be adjustable. (In fact adjustable Ackerman is rare. This could be the car designer saying to us, "Do not mess with this.")

Full Ackerman geometry requires steering angles, inner wheel and outer wheel, as per Figure 1. The angles are a function of turn centre radius, wheel base and track.

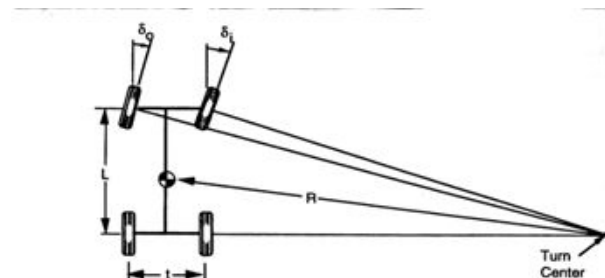
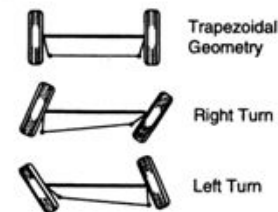


Fig. 8.2 Ackerman turning geometry.



Ackerman geometry requires that:-

$$\delta_o = \frac{L}{(R + t/2)}$$

$$\delta_i = \frac{L}{(R - t/2)}$$

Figure 1

In practise, the steering angles achieved are not perfect Ackerman geometry. This is not of concern. We are only interested in the fact that we can have some degree of increasing dynamic toe out and that it is exponentially increasing with steering angle. See Figure 7 below for some example curves. So we shall consider "Ackerman" a term to describe any progression of dynamic toe out generated by the steering geometry. If it is our choice to use Ackerman, we must use a high percentage because, for small steering angles, Ackerman is minimal.

We will also look at the static toe setting, because of it's interaction with Ackerman.

Suspension movement may also cause changes in toe (bump steer). Toe could change with roll angle of the car, but probably not in any controlled way we could use. Usually, bump steer will be set at zero as part of the workshop set up. In addition to toe changes, effective steering ratio is quite variable in most steering systems. Drivers do not appear to have problems with this. (Although steering ratio is a consideration for designers – yaw response to given steering angle).

Tyre Slip Angle - the major variable in the Ackerman story

Tyre slip angle is simply the difference between the steered angle of the wheel and the direction the tyre foot print is taking. The mechanism responsible for creating the slip angle interacts with a number of the suspension settings on the car. For instance, the rolling tyre deformation at the tyre foot print, results in a reactive force, the so called "pneumatic trail", that applies a "self aligning torque" on the steering axis. The driver can feel this through the steering, in addition to any "caster trail" that may be built in to the suspension geometry. Here though, our interest is the interaction of slip angle with dynamic toe.

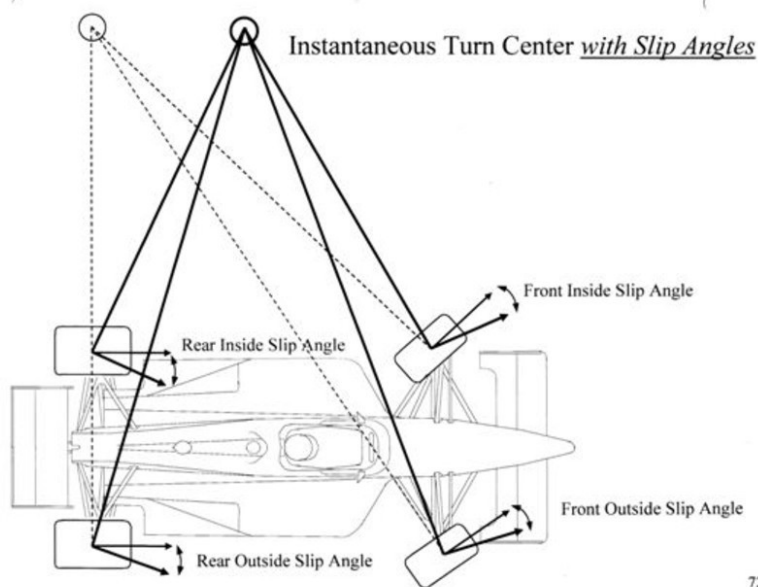


Figure 2

When the car is cornering at racing speeds, steering Ackerman geometry is modified dramatically by the tyre slip angles, as per Figure 2. With racing tyres at maximum lateral G, we might be looking at 5,6,7 or 8 or more degrees, and generally more slip angle again for dot road legal racing tyres. Low profile tyres work at lesser slip angles. Currently, the stiffest racing tyres, as used in IRL, operate at around 2 degrees slip angle. Dirt tyres (speedway, rally) might operate up to 40 degrees slip angle.

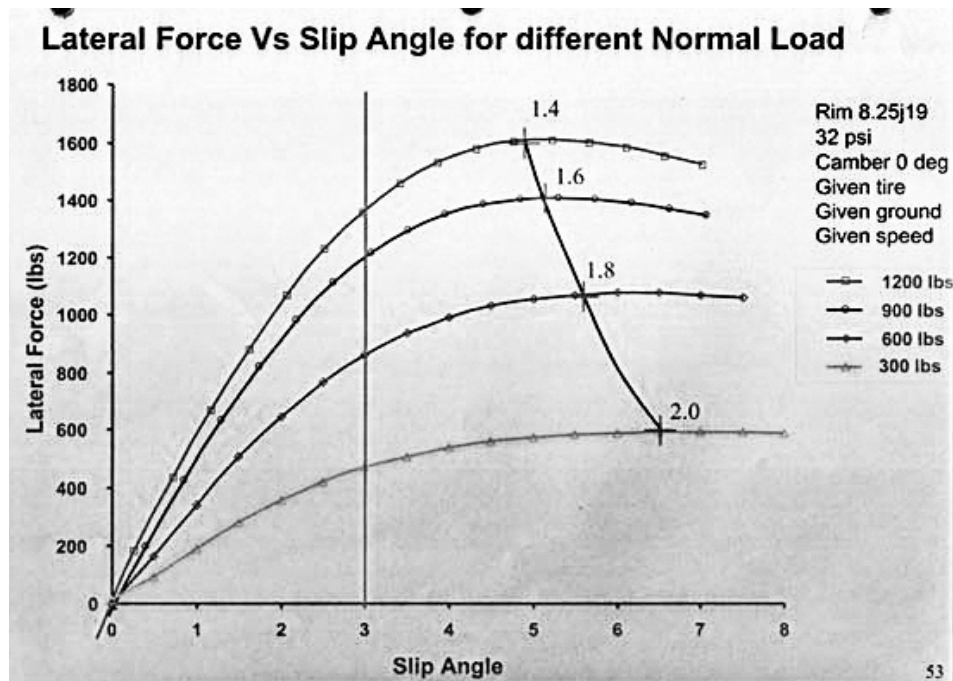


Figure 3

As the car corners, the tyre load varies side to side, and the slip angles increase and decrease in response to any change there might be in the torsional spring rate of the tyre. Vertical tyre loading varies with cornering weight transfer, and also the tyre loading and unloading in response to bumps in the road surface. Lateral tyre loading varies according to the lateral G force. The following is a representation of the sort of numbers involved:-

Figure 3 is an example graph of Lateral Force vs Slip Angle from Claude Rouelle's race car engineering seminar. If we are going to get a handle on how toe angles work, tyre data like this helps. As cornering force builds on the tyre, the slip angle is increasing quickly. The slope of this part of the curve, the "tyre stiffness", is a measure of the responsiveness of the tyre to steering inputs. When maximum cornering force is reached the curve flattens out. If the driver is easy on the tyres he will drive in this area of the curve. If the driver stresses the tyres more, he uses higher slip angles, with similar cornering force (lateral force, grip), but with the possibility of overheating the tyres. The graph also shows the affect of changing load on the tyre. The 300lb blue curve might represent the inside tyre. It has a high co-efficient of friction, 2. Thus maximum lateral force is 2 times vertical load. The 900lb curve might represent the more heavily loaded outside tyre. The co-efficient of friction is less at 1.6 and therefore the maximum lateral force is only 1.6 times vertical load.

Tyre Load and Slip Angle vs Lateral Force

Plotting the two variables on the X axis, against lateral force on the Y axis is perhaps the best representation of tyre performance. The data, known as "carpet plots", are generated by the tyre companies at their test facilities. It can show us what happens at small slip angles and lateral force, and how the picture changes as we approach the limit, maxing out the slip angle and applying big weight transfers.

First thing of interest is that as the front outside tyre is loaded up in a corner it will adopt a higher slip

angle than the more lightly loaded inside tyre. The loaded tyre will toe out more than the lightly loaded inside tyre. We expect that the more heavily loaded tyre will control the trajectory of the car in the corner, so all the toe out generated will be seen at the inside tyre. Ackerman geometry will also produce toe out. Add to this the static toe out you generally run on a racing car. How much toe out can the car take before it starts dragging the inside wheel? Will the inside tyre be giving away grip? It is apparent, that gain or loss in grip will be at the inside tyre, assuming that outside tyre grip is at a maximum, and that the car is balanced.

There are a number of observations we can make at this point:

- Say the car is cornering at maximum lateral G and the difference between the outside and inside slip angles is one degree. This equates to an increase in toe out of 6mm. This is a significant change in toe that we might expect to influence handling.
- As the tyre traverses the corner, any change in tyre loading due to driver input or road surface will result in toe changes (due to the slip angle changes). These changes are additional to any Ackerman and bump steer resulting from the steering and suspension geometry. The interdependence of slip angle with all the variables is hard to visualise. But fortunately, it seems we do have a large window where the inside tyre grip will be OK. The tyre in Fig 3 shows pretty constant grip level when lightly loaded between 4 and 8 degrees, indicating the inside tyre particularly, can handle a lot of slip angle variation, and still offer near maximum grip. This means that mid corner, even though the toe angles might be pretty wild, we can have near maximum inside grip. Looking at the toe and slip angles, it appears as if we might be dragging the inside tyre, but not so while we maintain near maximum grip.
- At corner entry, we expect there will be greater need for precision in the dynamic toe setting. Initially, there is no Ackerman, so we are only looking at the static toe setting, plus the developing slip angles.

What the Guru's Say

Costin & Phipps, "Racing & Sports Car Chassis Design", 1961. For performance and racing cars, they recommended a small amount of anti-Ackerman, and did not discuss any circumstance where Ackerman might be used. "Owing to weight transfer, the outside wheel always runs at a higher loading than the inside wheel, and therefore higher slip angles, which necessitate greater lock".

Carroll Smith, "Tune to Win", 1978. Referring to anti-Ackerman, he writes it "cannot be right". He suggested that racing car steering angles are generally too small for Ackerman to build, and that in the mid corner, the inside tyre is not sufficiently loaded for it to have much affect anyway (meaning for Ackerman effect - in general consideration of inside tyre grip is a major focus for set up). For corner entry he preferred to use small amount of static toe out and/or, interestingly, small amount of bumpsteer toe out in bump. Because of the difficulty of predicting dynamic ride height side to side, it may be preferable to run the static toe out required with zero bump steer. Those teams with wheel position sensors and data logging could tell for sure. "Engineer in Your Pocket", 1998. No mention of Ackerman. This is significant. Twenty years after "Tune to Win" Carroll Smith must have considered Ackerman adjustment still only a small part of set up.

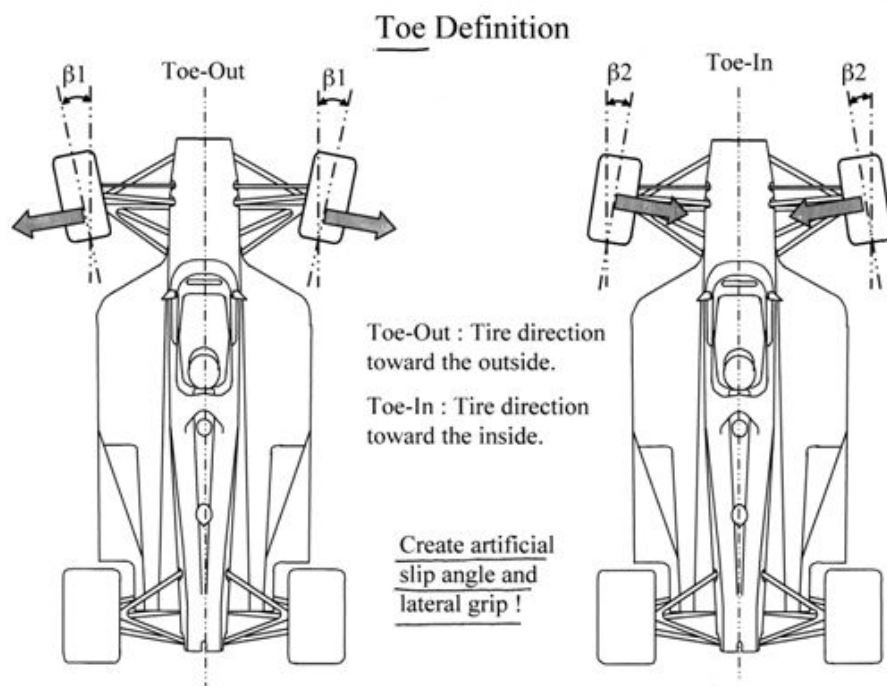
Don Alexander, "Performance Handling", 1991. He writes that anti-Ackerman was used in earlier years. But that by the 90's, "Ackerman steering has returned, often exceeding 100 percent geometry", eg for vehicles with high aero down force. However, he has got his explanation of the slip angle effect the wrong way round, and does not expand further. Finally, he says Ackerman is a design element, not a tuning tool the racer will use.

Paul Valkenburg, "Race Car Engineering & Mechanics", 1992. Taking into account the slip angles, "at first glance it might seem" ... "Ackerman steering may be a disadvantage. On the other hand, scientifically obtained tyre data tends to indicate that the lighter the tyre load, the higher the the slip angle required for peak cornering power. This would indicate that Ackerman is in fact usefull in racing cars. "

....."although there probably isn't enough steering motion to have a significant effect. Only your skid pad or test track will tell for sure."

Allan Staniforth, "Competition Car Suspension", 1999. Writing about inside tyre grip he says "My own view, not applying to Ackerman alone, is that any single thing that helps the contact patch do a better job and enjoy a happier existence has to be worth any trouble to achieve." He does not say when, or under what conditions, he would use Ackerman. Later he did an article in one of the technical mags (or was it Simon McBeath?) where he got very keen on Ackerman, and did some testing on a hill climb car. Unfortunately, I can't find the magazine.

Eric Zapletal, "Race Car Engineering" magazine, August 2001. This is part 3 of a series on "Ackerman Explained". He offers a number of "kinematic steer angle curves", representing steering systems with a lot of Ackerman, for various slip angles. At the end of the article he does give some further clues as to how Ackerman may be used. He points out how the car will turn by braking one side of the vehicle - tanks, bulldozers and other "skid-steer" vehicles are examples where it is the only steering mechanism. He points out that modern Vehicle Stability Systems (VCS) use the ABS braking system to brake an individual wheel to counter the yaw motion of the vehicle and control oversteer and understeer. "One of the easiest ways to take advantage of this yawing power (in racing cars) is to use dynamic-toe changes. Dynamic toe out of the front wheels generates just the right sort of differential- longitudinal forces that help yaw the vehicle into the corner." I think he is saying if the inside front tyre drag is a bit more than the outside, this will help turn the car into the corner.



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Figure 4

Claude Rouelle, Optimum G race car engineering seminars (www.optimumG.com). Claude points out that static toe out or toe in setting creates an "artificial" slip angle at each front tyre, and therefore lateral grip. See Figure 4. Toe out can help inside tyre grip. In particular, toe out helps compensate for negative camber on the inside wheel. Negative camber can be optimised for the outside wheel, but will always work against you on the inside wheel.

The tyre curves re-enforce this idea. At zero slip angle we always have zero lateral grip. For any slip angle we generate in the tyre we can read off lateral force on the diagram.

For a race car running static toe out, I think the cornering mechanism might be something like this. At initial turn in, the inside wheel is toed out and already carrying a small slip angle. Full static weight plus any weight from trail braking plus aero load if any is still on the tyre, so it responds instantly to point the car into the corner. The outside tyre is also toed out, but in wrong the direction to turn the car. So the car must roll out the initial slip angle, and then start from zero to build slip angle in the correct direction. As the car starts to transfer weight in the corner, the outside wheel gains effectiveness turning the car in. The inside wheel starts to reduce lateral force and the outside wheel builds lateral force as the load on the tyre increases, and the relative advantage of the camber gain increases outside tyre grip even further.

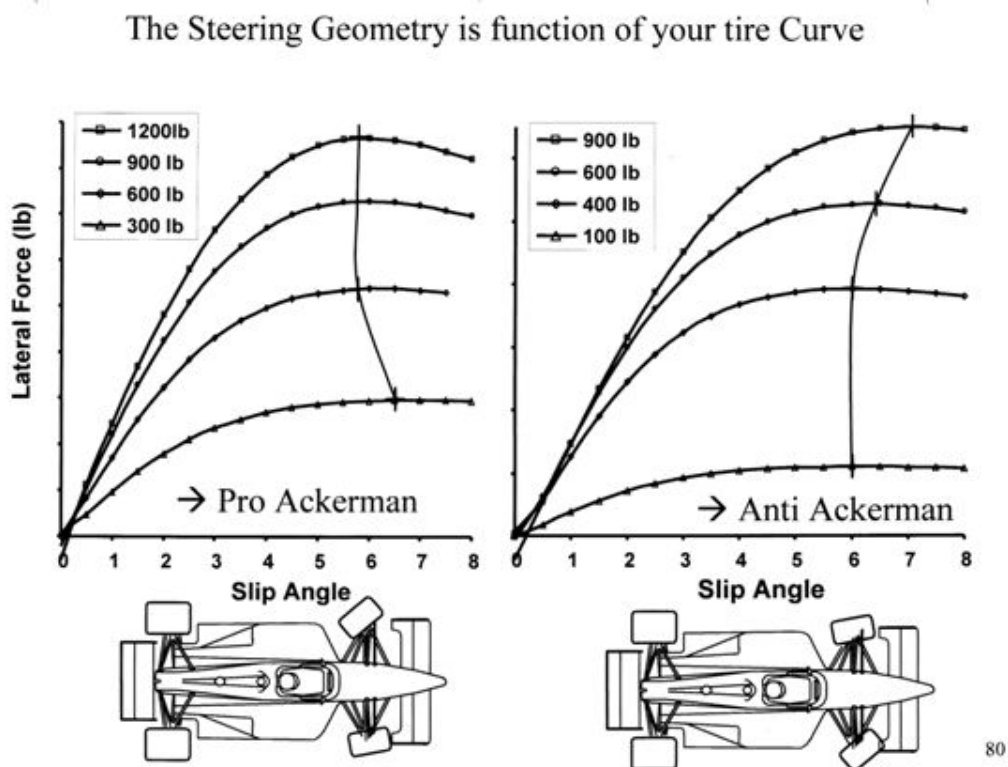


Figure 5

Claude says the steering geometry preferred will be a function of the tyre curve. In Figure 5, if the tyre curve shows max force at increasing slip angle for the lightly loaded inside wheel, this infers pro-ackerman. Or if the tyre curve shows max force at reducing slip angle, we would expect anti-ackerman to be best. Again the curve is fairly flat at the top, so does the slip angle matter all that much? However, in amateur racing we do not have any tyre data, so we cannot use any of this, but take the ideas on board for insight only.

To determine whether the race car will be better with dynamic toe in or toe out, pro or anti-ackerman, we need to test. Claude suggests a test, as per Figure 6a and 6b, where we analyse whether static toe in or toe out is best, in slow corners vs fast corners. I guess we should use a parallel steering set up, or close to, to do the test. Given that a slip angle variation side to side of one degree equates to a toe setting of 6mm, I think we could choose somewhere around that for our toe in and toe out test settings. It's a question of how sensitive the car is to toe change. It could be you need a toe setting of 10mm (in or out)

to get a result from the test. A team who has done a lot of testing may already be aware how much will be significant. A rule of thumb is more toe (in or out) required for tyre operating on large slip angles (soft side wall), and less toe for low profile tyre operating on smaller slip angles (stiff side wall).

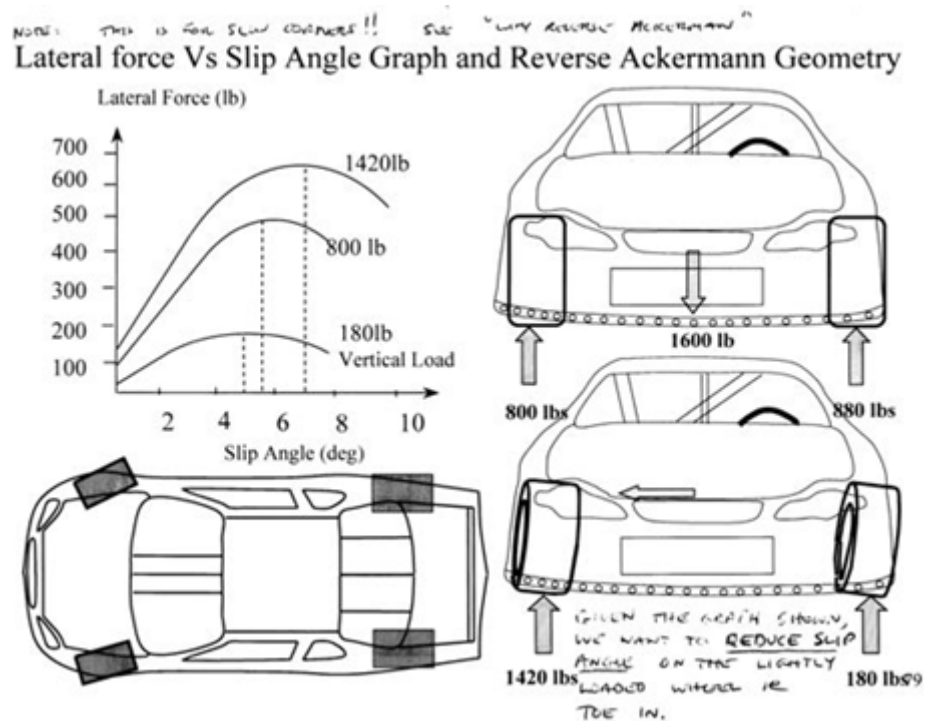


Figure 6a

Why reverse Ackermann ?

Front Toe in Test

SEE BACK TO THE REPRESENTATION OF THE NASCAR

	Slow Corner	Fast Corner
Static Toe In	+++	-
Static Toe Out	-	+++

Driver's comments :

Toe-out is better in fast corner.
Toe-in is better in slow corner.



IF YOU MAKE GAINS WITH THIS, YOU ARE IMPROVING INSIDE THE CURVE.
(AND VICE VERSA, YOU LOOSE MORE ON THE INSIDE THAN THE OUTSIDE.)

Solution is static Toe-out with Reverse Ackermann Geometry because :

- fast corner \leftrightarrow small steering angle \leftrightarrow toe-out setting practically unchanged
- slow corner \leftrightarrow high steering angle \leftrightarrow fast variation from toe-out to toe-in

Figure 6b

You need to be able to do the tests back to back. So you must be able to change and measure the toe setting at the circuit. You are looking for fairly small differences in handling performance here, so data logging is invaluable. We use a Race Technology DL1 logger that we can easily attach to the car with velcro strips and power it from it's own battery. The resulting speed and lateral G traces are extremely accurate and will easily show any differences from lap to lap.

Claude's example solution in Figure 6b is static toe out with anti-Ackerman geometry, as follows:-

Fast corner: small steering angle, therefore toe out setting virtually unchanged.

Slow corner: high steering angle, therefore fast variation from toe out to toe in.

Track Testing for Ackerman and Toe Effects

So it may be possible to test what initial toe setting you should use, and whether Ackerman, or anti-Ackerman is faster. To have any chance of the test being successful, the baseline set up and balance of the car must be very good. If the driver has to fight the car, you don't know what the steering angles will be.

The difficulty with the test is to be able to sort out the initial toe effects from the Ackerman effects. It would be great to be able to start on a 200 ft skid pad (as used in the US) and look at the steady state mid corner situation first. There should be a range of slip angles that will produce maximum inside grip, and therefore maximum lateral g on the skid pad, all else being equal. If we can't use a skid pad, then we will need to use

At each stage of the tests we must know what steering angles we are achieving in the corner and what toe in or out applies.

I wonder what toe and Ackerman they run in categories with fixed suspension rules such as Porsche Cup cars and Aussie racing cars? With few possibilities to adjust the set up, toe and Ackerman would be of greater interest in improving the car.

Common racing tyre slip angles of 6, 7 and 8 degrees are large numbers, and therefore there is potential for slip angle variation from side to side, which could toe the wheels out a lot. This implies anti-ackerman could help reduce the unwanted toe out. This is the traditional solution and the one that is most readily acceptable.

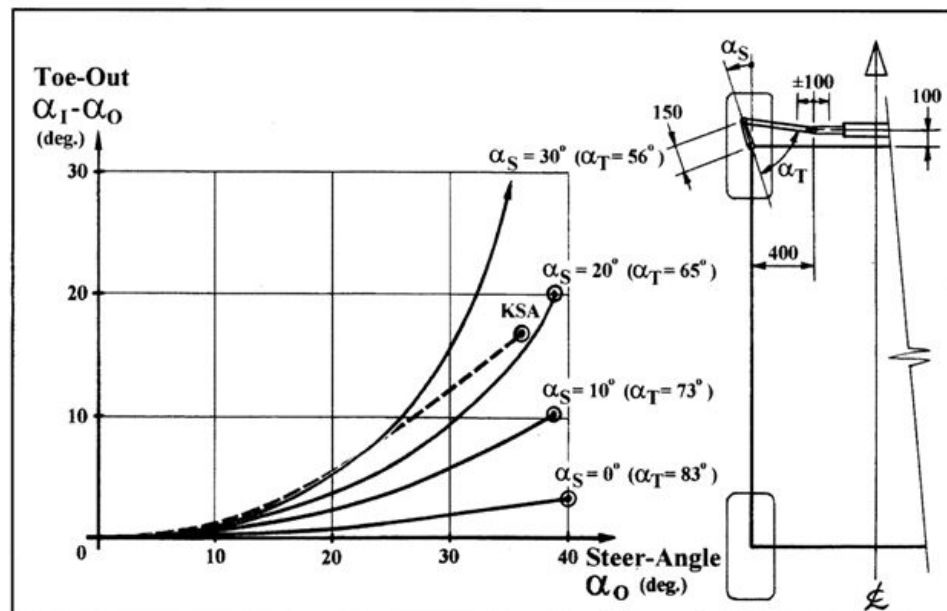


Figure 7

But pro-Ackerman is used in some categories. eg specialised hill climb racing cars, F3 racing cars. Could be 100% or more Ackerman. If you are going to use it, high percentage Ackerman is required because Ackerman is slow to build eg 100% Ackerman, 4 degrees of steer angle at the steering axis gives approx 1 degree (or 6mm) toe out overall. Four degrees at the wheels could be 180 degrees at the steering wheel in a tight corner. A big factor in what dynamic toe curve is achieved is the included angle between the steering arm and the track rod (Figure 7). As this angle becomes more acute, dynamic toe out increases. To achieve this, you move the steering rack rearward in the car. This applies for steering rack forward of the axle C/L, and rearward of the axle C/L.

Given that the traditional solution, anti-Ackerman, doesn't always fit, it seems there must be another benefit that has only been recognised more recently, or that has only become effective with modern race cars. Or are the tyre curves very much different?

How Does Pro-Ackerman Work?

Eric Zapetal's explanation does fit. That he is probably correct is well supported by his extensive writing on steering and suspension geometry in Race Car Engineering magazine. He has done the maths to amplify and support his ideas. With Ackerman steering, if we can toe out the inside wheel sufficiently, there is greater drag on the inside wheel than the outside wheel, thus creating an oversteer torque around the vehicle centre of gravity. This will help turn in, or in his words "yaw the vehicle into the corner".

With zero front toe settings, the front tyre rolling drag creates a small understeer torque. Zapetal quantifies the rolling drag as being only 1% of the vertical load. However, in the corner, the drag component of the force acting on the tyre is very much greater. Drivers of low powered racing cars are familiar with how much speed you lose if the car has understeer in fast corners. Figure 8 shows the front tyre drag components of the lateral tyre force. The drag gets greater with increasing slip angle.

Carroll Smith in "Tune to Win" page 130, calculates the front tyre drag for a Formula Ford. It is significant even for a well balanced car. Because the heavily loaded outside tyre is developing most of this drag, the net effect is an understeer torque. In a fast corner, it is hard to imagine that you could turn that around to an oversteer torque by increasing drag on the inside tyre by increasing the slip angle. Even if you could, Figure 8 shows this important concept of the oversteer and understeer torques acting on the centre of gravity. Mark Ortiz, in my view the best writer in vehicle dynamics, often uses this concept to describe how a car will gain understeer or oversteer. Even if we can't calculate hard numbers, we can hopefully predict the direction the set up will take, as we attempted with this Carroll Smith Formula Ford example, the total drag would make you slow.

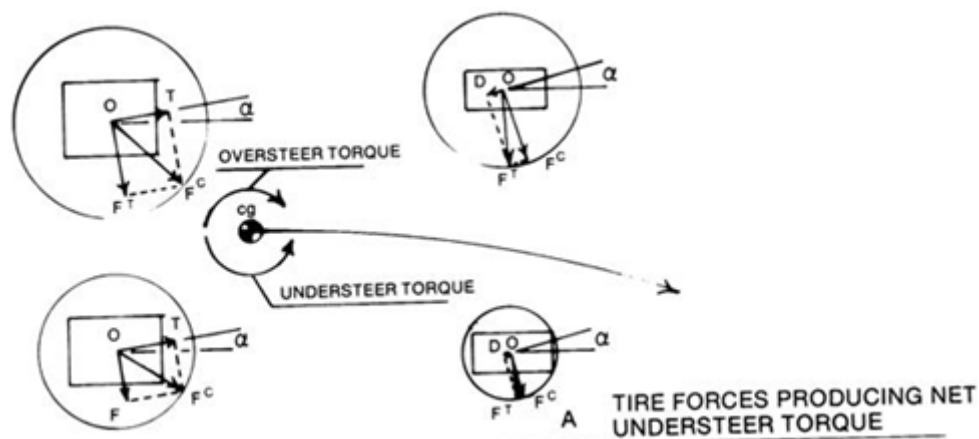


Figure 8

When Would You Use Ackerman (or Anti-Ackerman)?

- When you set the negative camber, based on the tyre temperature readings for instance, you are maximising outside tyre grip, at the expense of inside tyre grip. Toe out helps to compensate for negative camber on the inside tyre. This indicates pro-Ackerman might be useful for cars carrying a lot of negative camber.
- In using Ackerman steering we hope to be able to influence the slip angle on the inside tyre to our advantage. There will be a range of slip angles where the inside tyre will be producing near maximum grip (Figure 3). So we have a degree of flexibility in how much Ackerman we use.
- To rotate the car on corner entry we are talking about creating increasing drag at the inside tyre. As the cornering force builds the inside tyre must at some point reach its optimum lateral grip. We then use Ackerman to toe the tyre out further - say increase the slip angle a couple of degrees. The tyre grip doesn't change that much but the longitudinal component of tyre grip, the tyre drag, does increase in line with the increased slip angle. For this to work we would need to know that we have sufficient steering angle to generate the Ackerman needed.
- If in the process above, we started to lose outside tyre grip, and the driver wound on some more lock, we would have increased drag at the outside tyre. We would then lose the effect. The oversteer torque we were looking for would be overcome by the larger understeer torque.
- The above indicates that pro-Ackerman would probably not work with low powered cars in fast corners. It might also be a problem generally with heavy cars with spool or locker diffs that might want to push a bit, such as V8 Supercars.
- With pro-Ackerman, the higher slip angle on the inside tyre will put more heat into the tyre. This will help bring the tyre up to temperature, but could overheat the tyre on a longer run.
- If our race car is faster with toe in, we will use anti-Ackerman. This implies a tyre curve where the lightly loaded inside tyre has maximum grip at a lesser slip angle (Figure 6a)
- Sprint cars and similar speedway, dirt short circuits, can make a lot of use of varying degrees of pro-Ackerman. With dirt tyres we expect very large slip angles. Nascars and similar will use anti-Ackerman (Figure 6a).
- With low profile tyres the slip angles will be a lot less. The tyre drag will be less. The slip angle on the inside tyre will have a smaller drag component (Figure 8). So it may be more difficult to use pro-Ackerman to create the oversteer torque. The toe out from the slip angles will be less. The slip angle variation from outside to inside tyre will be a smaller number, requiring different Ackerman to achieve what we want.
- We will probably use initial toe out to help turn in. The idea is to get the inside tyre working as discussed earlier. Other settings you would use to help initial turn in are stiffer front shocks, and higher front roll centre height. By delaying the roll we help to keep the weight on the inside, to again keep the inside tyre working.
- We make the assumption that the outside wheel will always have the ideal trajectory, with all the toe out being seen at the inside wheel. This may not always be the case. For instance, if the car has a lot of caster and/or caster trail this might have the effect of splitting some of the toe to the outside wheel. If the outside wheel does take on some of the toe out, this will decrease slip angle and the outside wheel will lose grip.