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The Design & Tuning of Asymmetrical Racecars

PART 3: YAW MOMENT EFFECTS

In Part 2 of this series (V9N4), we explored dynamic load transfer. We considered how vehicle accelerations change the load distribution among a car's tyres. Load distribution matters to us because it affects the car's oversteer/ understeer balance. Most of us have a general understanding of understeer and oversteer. We don't hesitate to use the terms. Yet if we try to define them precisely, we see that there are several different approaches. We end up with subtly possible meanings, depending on the approach we take.

By MARK ORTIZ

We have been speaking of 'oversteer' and 'understeer' in terms of the balance of available lateral acceleration at the front and rear. This is 'limit' oversteer or understeer: which end sticks better; which end lets go first; whether we hit the wall nose-first, tail-first, or side-on.

A car also exhibits understeer, oversteer or neutral steer in sub-limit conditions. In order to develop any lateral force, a tyre must run at a 'slip angle'. This term comes from nautical and aeronautical vocabulary. It denotes the angle between the direction in which an object is pointing, and the direction in which it is travelling. It does not necessarily imply sliding contact between tyre and road.

At modest lateral force, the tyre's slip angle is absorbed by deformation of its carcass and tread. Actual slippage of the rubber across the pavement is confined to a small region at the rear of the footprint, and the footprint lies at an angle to the wheel. As lateral force becomes greater, this angle grows some, and the zone of actual slippage grows forward within the footprint. At the point of breakaway, the entire footprint is scuffing across the road.

We can define sub-limit understeer or oversteer in terms of slip angles. If the average of the front slip angles is greater than the corresponding average at the rear, we have understeer. If the rear tyres have the greater mean slip angle, we have oversteer.

Alternatively, we can define understeer and oversteer in terms of steering wheel angle required to maintain course. If the driver needs to hold the wheel at the same angle as would be needed at near-zero lateral force, we have neutral steer. If the required steering input is greater than this baseline, we have a car that understeers. If the required input is less, the car oversteers.

That is, an understeering car under-responds to a steering wheel input, and requires the driver to increase the input to compensate. An oversteering car over-responds to a steering wheel input, requiring an input reduction or even reversal (opposite lock or counter steering). This way of defining oversteer and understeer has a nice semantic congruence: we can see where the terms come from.

Finally, we can define oversteer and understeer by comparing front wheel slip angle with body or frame slip angle (sometimes called 'drift angle'). This is similar to comparing front and rear slip angles, but not the same, since rear wheel steering effects can create angularity between the rear wheels and the body centreline.

These distinctions are subtle, but the angles involved are small, and real confusion can result if we don't pay attention to the way we define oversteer and understeer.

For example, a car may be cornering with the rear wheels at a greater slip angle than the fronts. The car may also have deflection understeer and roll understeer properties that are greater than the slip angle disparity. The driver has to steer more than at low speed, and the car is understeering as defined by required steering wheel position.

Is the car really in a state of oversteer, or understeer, masked to create perceived understeer? As this car is pushed closer to the limit of adhesion, the tyre slip angles will generally increase more rapidly than the roll steer and deflection steer, and the tyre slip angle difference will also grow. The car will reach a point where it has both real and perceived oversteer.

In the following discussion, unless otherwise stated when we refer to oversteer or understeer, this means 'actual' behaviour – as defined by front *versus* rear slip angles or rear *versus* front lateral acceleration capability. This mode of definition creates the greatest agreement between sub-limit and limit behaviour, and is most relevant to racecar handling.

What Constitutes a Steering Input?

Data-acquisition systems generally use steering wheel angle as a measure of steering input. Commonly, the system will be programmed to generate a calculated 'speed-corrected steer' channel. Yet every driver knows that the steering wheel is not the only thing that will steer the car. The throttle will steer it. The wind will steer it. Sometimes the brakes will steer it. Bumps will steer it. Hitting a puddle with the right or left wheels will steer it.

Indeed, some vehicles steer with no steering wheel at all. Tanks, bulldozers, snow cats, and rubber-tyred skid steer loaders all steer entirely by braking wheels on tracks on one side while powering the other side. These vehicles will turn on a dime (although the dime may not look quite the same afterwards).

All steering effects have one thing in common: they generate a net 'yaw moment' – a rotational force around a vertical axis.

A net yaw moment reacts against the vehicle's yaw inertia, or polar moment of inertia in yaw. Racers call this "polar moment" for short. The yaw moment, reacting against yaw inertia, creates a yaw acceleration and a yaw velocity. This means that we change the vehicle's yaw position – what direction it points.

We can define steering, then, as the control of yaw moments. We may regard anything that creates a yaw moment as a steering input.

We can also define oversteer and understeer in ▶

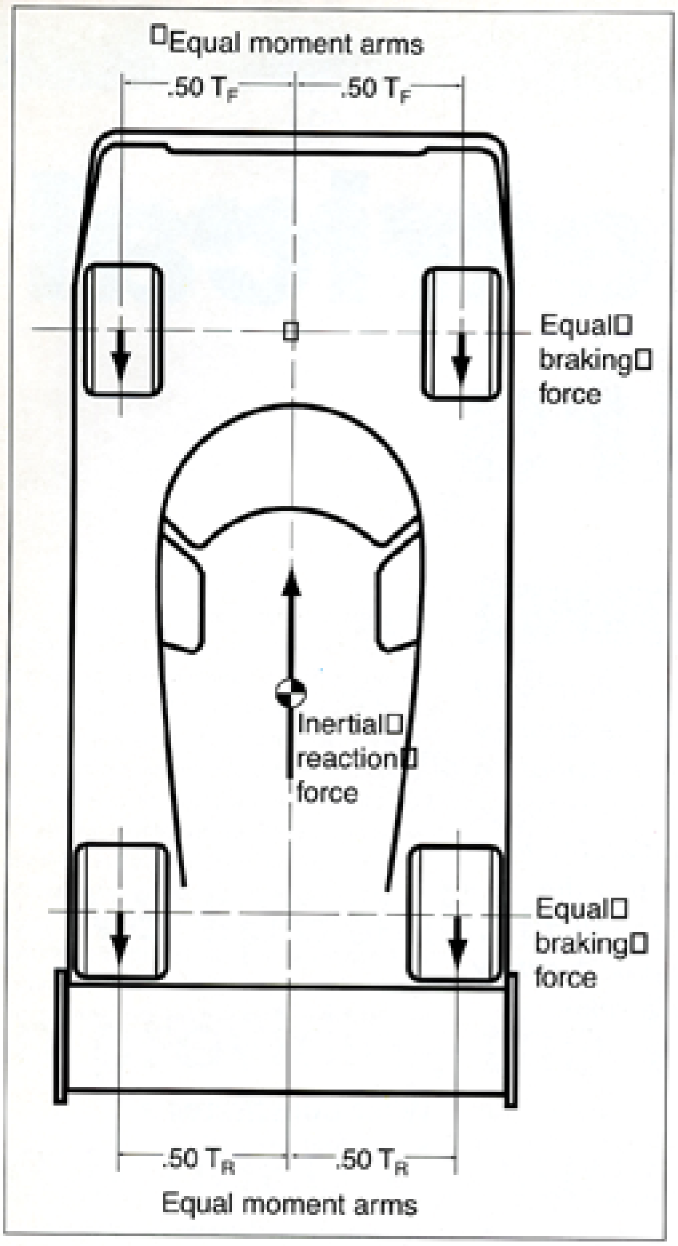


FIG 1 A simple case of yaw equilibrium – a symmetrical racecar under braking.

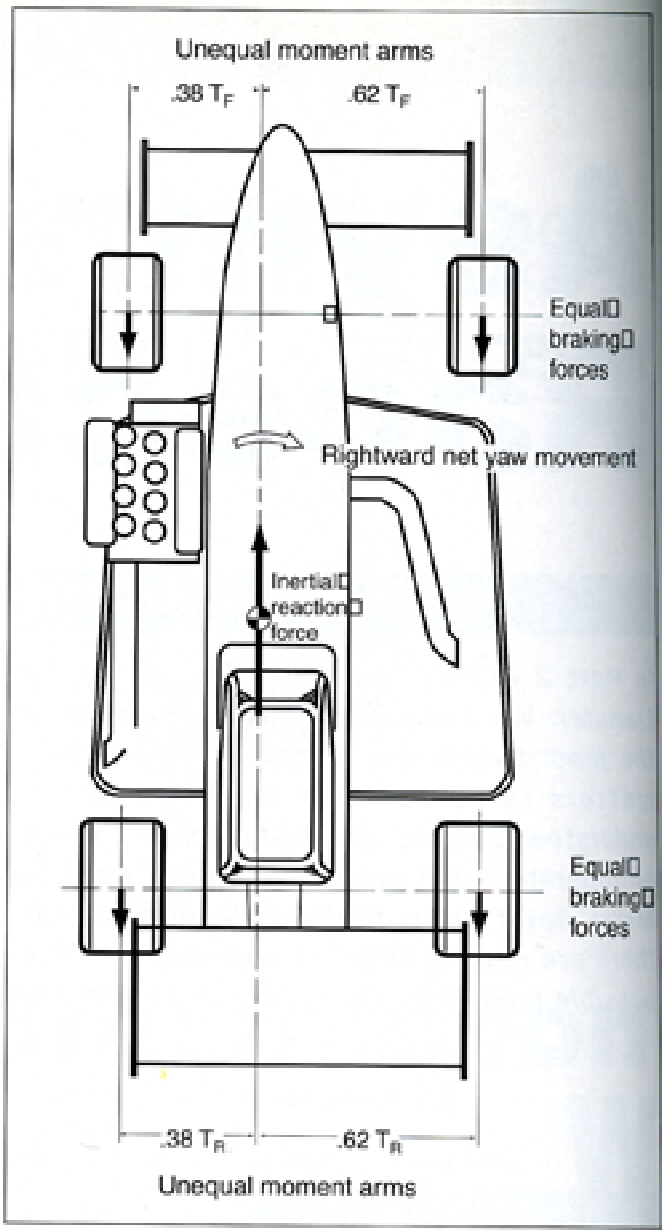


FIG 2A A left-heavy racecar with equal left and right braking forces generates rightward net yaw moment.

terms of net yaw moment. In oversteer, the car's net yaw moment rotates it into the turn, if the driver does not create a yaw moment reduction with the steering wheel.

In understeer, the car's yaw moment rotates it outward, relative to what the desired manoeuvre requires. The driver must adjust by supplying an inward yaw moment correction, using the steering wheel.

Yaw Equilibrium

When the sum of the yaw moments of the vehicle is zero, the vehicle is said to be in a state of 'yaw equilibrium'. In such a condition, the vehicle's yaw velocity is constant (not necessarily zero) and its yaw acceleration is zero.

The simplest case of yaw equilibrium is straight-line travel. Steady-state cornering (constant speed, constant radius) is the next simplest. Less obviously, a car can also have a constant yaw velocity if its speed and its turning radius are both increasing or decreasing together at the same percentile rate.

Any time the vehicle is not in yaw equilibrium, it will accelerate in yaw.

Balance and Imbalance in Yaw Moments

We closed Part 1 with illustrations of yaw moments created by a longitudinal force and a lateral force, generated by a single tyre. We noted that, in real life, we have all four tyres generating lateral and longitudinal forces simultaneously.

The interplay of these forces and moments governs the car's yaw behaviour. Understanding the factors that increase or decrease the yaw moments generated by individual wheels and wheel pairs is an important key to suspension tuning.

Let's start with a simple case: a symmetrical car in braking. **Fig 1** shows such a car in yaw equilibrium. All that is required for equilibrium is that the right and left wheel pairs generate equal rearward force. Ordinarily, we match the properties of the right and left wheels at each end of the car. However, we can also obtain yaw equilibrium if the front and rear wheels generate equally and oppositely mismatched braking force.

Now let us consider a car with 62% of its weight on the left. In this case, the left wheels must generate 62% of the rearward force for the car to have yaw equilibrium. If the right and left braking forces are equal, the car will try to turn right under braking. When the driver trail-brakes into a left turn, this rightward yaw moment will tighten the car – influence it towards understeer. **Fig 2A** illustrates.

Fig 2B shows the same car, with a 62:38 left:right brake bias at both ends.

Fig 2C shows an alternative solution: equal rearward force at the front, dramatically unequal rearward force at the rear. We will discuss below how such inequalities may be created. For now, let us simply note that a car as shown will brake in a straight line without a steering correction by the driver, and will trail-brake into a turn with a balance similar to its steady-state cornering behaviour. (Front:rear brake proportioning and other setup variables also effect this, as with symmetrical cars.)

Under forward acceleration, the direction of the tyre forces is reversed, but the principles are the same. A symmetrical car requires a left:right split proportional to lateral weight distribution, as with braking force. If our 62% left weight car receives equal

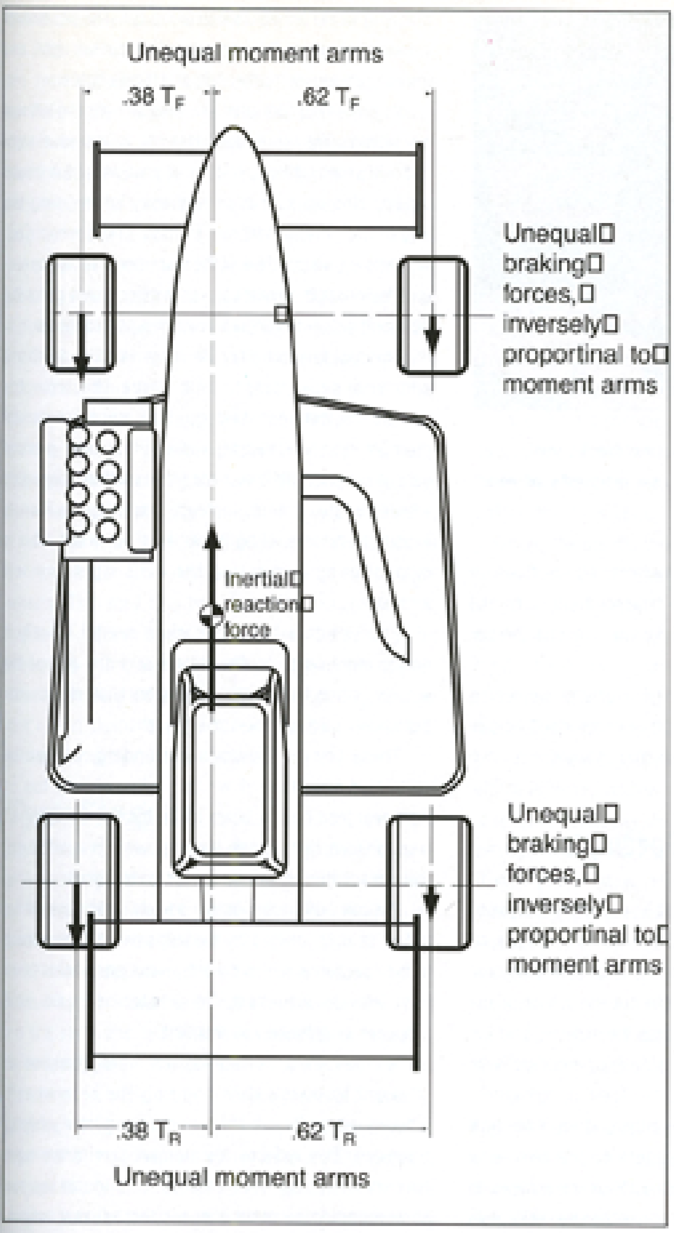


FIG 2B Yaw equilibrium under braking, using braking forces only, for a left-heavy racecar.

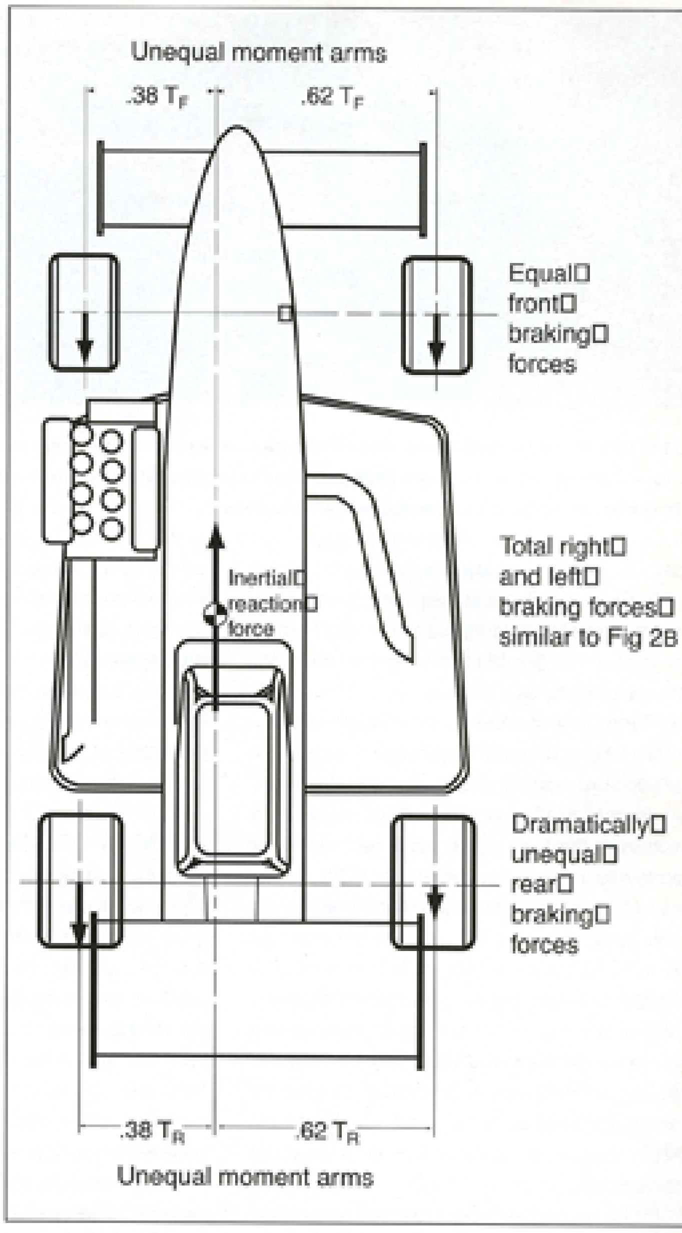


FIG 2C Yaw equilibrium as in Fig 2B, using unequal braking force at the rear only.

propulsion forces from both rear wheels, it will try to turn left under power. When powering out of the left turn, this will loosen the car – influence it towards oversteer.

In the case of lateral (or centripetal) acceleration, the principles are again the same, particularly the need for forces to be inversely proportional to their moment arms about the centre of gravity (CG). We do need to consider one further complication: a tyre can generate a forward or rearward force without generating a lateral one. But a free-rolling wheel can only generate lateral force by operating at a slip angle, which inevitably creates a rearward drag force.

In theory, a driven wheel can be provided with just enough power to counter the drag. In this condition, we can have purely lateral force. In practice, we seldom see this on all four wheels at once. We may imagine a car having all-wheel-drive, with toe, camber and power distribution perfectly matched to produce purely lateral force on all four wheels. This would be the only situation where we would not have yaw moments due to the tyre drag when cornering.

With rear-drive, a car in steady-state cornering experiences drag forces on the front wheels. For speed to be constant, the rear wheel pair must exert an equal and opposite net propulsion force. With an open differential and identical rear tyres, the rear tyres will receive equal drive force. Their net propulsion force is this drive force *minus* their own drag forces, which may or may not be equal.

For simplicity, we are ignoring aerodynamic drag, which adds a further propulsion demand and can also create significant yaw moments.

A 'Straightforward' Enigma

Not only does each tyre have a slip angle, but the body, the frame, the tub, the wing or wings, indeed any part of the car has a slip angle – sometimes also called an 'attitude angle'.

To define the slip angle of any component of the racecar, we must decide what would constitute a slip angle of zero. In a cornering situation, we can say that the car's path has an instantaneous centre of curvature. We can construct, or imagine, a line from the car's origin to this centre of curvature. We can then define a perpendicular to this radial line, at the car's origin. This will be its instantaneous direction of travel.

Simple enough. But, where is the car's origin, exactly? The CG? The midpoint of the four tyre footprints? The middle of the rear axle? All these points are differently positioned along the car's length. Therefore, a 'radial' line from each of them to the centre of curvature lies at a slightly different angle.

For a wheel or a wing, do we define zero slip by a radial line from the component's origin, or the car's? These questions are somewhat complex with a symmetrical car. With an asymmetrical car, they can become bewildering.

As elsewhere in physics and mathematics, there are no right or wrong zero points, datums, origins, or inertial frames – just more and less convenient ones, and the opportunity to confuse ourselves if we are careless about defining our choice.

In straightline travel, things can be simper, if the car and the setup are symmetrical. If the car or the setup is asymmetrical, defining 'straight forward' can be anything but straightforward!

The car's direction of travel when running straight may not may not correspond to any feature on the ▶

This Dirt Modified runs under WISSOTA rules, which allow generous engine set-back, yet impose an indentical tyre size limit front and rear. These cars cannot use large amounts of rear tyre stagger without becoming prohibitively 'loose'.

vehicle. The four wheels may all point different directions, so that no two have a common axis. To create a precise mathematical model of such a vehicle, to proceed from tyre data to behaviour prediction, is a daunting proposition.

Fortunately, most of us only need a repeatable datum for wheel alignment, and the ability to predict the effects of one design or setup choice relative to another.

We may do wheel alignment with beams of light or taut strings (I still use strings). Either way, we establish parallel reference lines on either side of the car, and measure our wheel's toe position from these. On cars with readily removable bodywork, we can attach our stringing bars or optical devices to the chassis. This provides a convenient, repeatable measurement datum.

However, this method presents problems on cars with bodies welded or riveted to the frame. If the front or rear overhang receives some crash damage, our anchor points are apt to be moved or destroyed. We need a way to locate our datum frame from the wheels, the hubs, or a frame rail.

In US oval track racing, the most popular technique is to lay a taut string against the two points on the sidewall of the right rear tyre, and take all measurements from that. This method has a number of disadvantages. First of all, two points randomly selected on a tyre sidewall are not a very reliable reference. Even if we select these points carefully (rotating the wheel and checking runout), two points roughly a foot and a half (450mm) apart offer a short measurement base for a line running the length of the car. Finally, the right rear wheel, like the other three, has a toe angle relative to the car, which may not be zero even if we "squared the axle to the frame" when we installed it. If the right rear is toed in, our string may want to pass through the right front wheel, rather than alongside it.

A better way to string an asymmetrical oval track racecar with fixed bodywork is to use two parallel strings on stringing bars, with the bars supported on stands ahead of and behind the car. One string (commonly the right one) is positioned by measurement from the frame on the front and rear hubs. If we use the hubs, our datum line moves if we adjust lateral axle position or camber.

The frame is the best reference, but it may be at a different height then the strings, and the body may be in the way. We can get around these problems by making blocks that seat against marked locations on the frame, pass under the lower edge of the body, and rise again outside the body so that we can lay our string against them.

Again, there is no "right way". However, we need a consistent, repeatable method, and we need to pay close attention to what effects setup changes may have upon our measurements.

Effects of Toe Settings

It may be tricky to define a slip angle with mathematical precision, but it is generally simple to know whether a given adjustment increases or decreases it. If we toe-in the front or rear pair, that increases the slip angle on the outside wheel of the pair when cornering, and reduces the slip angle on the inside one. This increases outside drag and decreases inside drag. That tightens the car. Toe-out, conversely, has the opposite effect on drag distribution, and loosens the car. Rear wheel toe-out engenders yaw instability, especially under power. Rear toe-in, used in moderation, aids driveability and improves subjective 'feel'. This is just as important with a beam axle as with independent rear suspension.

As in our earlier examples using straightline braking, the effect of a tyre's cornering drag depends not only on the magnitude of the force, but also on its moment arm about the CG. For a left-turn situation, moving any wheel with net drag rightward tightens the car. Moving any dragging wheel leftward loosens the car. The position of a driving wheel has the opposite effect: further right, and the car gets looser; further left, and it gets tighter.

Asymmetrical cars often use unequal right and left rear toe settings. We can express rear toe as individual right and left wheel settings, relative to a frame or tub based datum. This works out conveniently when using the alignment methodology I have recommended. Alternatively, we can think of the rear wheels as having toe-in or toe-out attitude relative to each other, plus a collective rightward or leftward angularity with respect to the car.

This perspective may be more familiar to those who run beam axles, and check the axle for straightness before installation, then string the car off the right rear tyre. People who use this latter method cannot measure right rear toe – the method takes this wheel's angle as zero. Instead, rear axle position is expressed in terms of right rear 'lead' (or 'trail'). This is measured by comparing the car's right and left wheelbase.

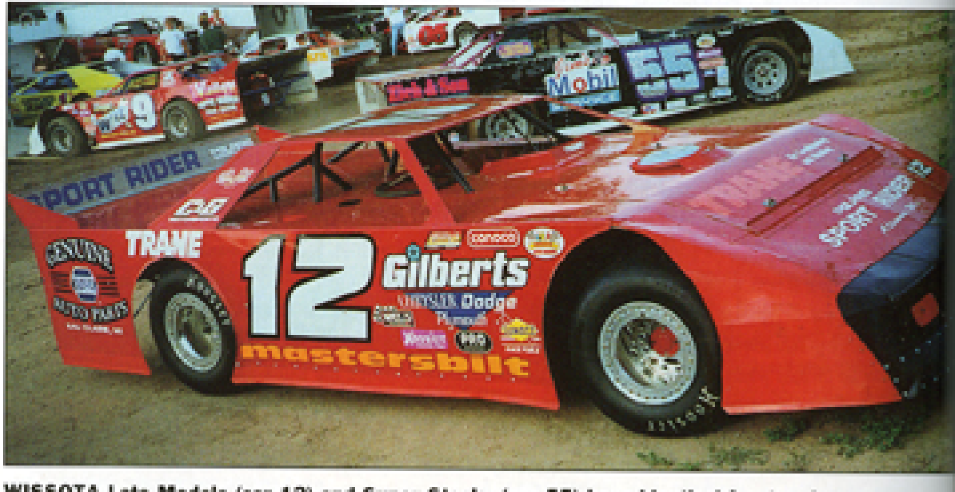
I do not care for this method myself. Surely it makes more sense to directly measure the aim of the wheels, since this is the parameter that effects car behaviour, not their fore-and-aft location.

These complexities notwithstanding, we can be certain of one effect if we add leftward rear toe or right rear lead (with a beam axle): the car will turn left less, or turn right more, under power. In a left turn, that means the car will be tighter under power.

We can explain this in two equally valid ways. If we define 'straight forward' by the frame or tub, then a force in the direction in which the left-aimed rear wheels point has a leftward component. This acts behind the CG, so it produces a rightward yaw moment.

Alternatively, if we take the rear wheel direction as 'straight forward', then pointing the rear wheels leftward moves the CG (and the dragging front wheels) rightward. This reduces the moment arm of the right rear wheel's longitudinal forces, and increases the corresponding moment arm for the left rear wheel. Assuming that both rear wheels drive, we would again expect a rightward net yaw moment change.

Under braking or a trailing throttle, things are murkier. One's first inclination might be to suppose that the effect simply reverses. Well, at the rear wheels it does but, at the front, it does not. The net effect depends on brake balance, driving style, and how we



WISSOTA Late Models (car 12) and Super Stocks (car 55) have identical front and rear tyre size limits. Late Models are allowed much wider tyres than Modifieds, but less engine set-back.

define oversteer and understeer.

With the rear wheels aimed left, on a straightaway, the rear wheels will track further left, and the fronts further right, relative to the CG path, than they otherwise would. If we change no settings except rear toe, the steering wheel will be turned further left, all the way around the track, even with no change in tyre slip angles relative to tyre or CG path. If we define oversteer or understeer in terms of steering wheel or steering shaft position, we will have a 'tighter' car, even if nothing is different where the rubber meets the road.

Even in tail-heavy cars, the front wheels usually contribute more than 50% of the braking force. That means that we get more yaw moment effect from moving the front wheels right, relative to the CG path, than we do from moving the rears left. Consequently, the car will be tighter on entry if the driver is on the brakes.

On the other hand, if the driver just lifts a little on entry, the car is being slowed mainly by the rear wheels. This may also be so under braking, if the car has a lot of rear brake. In that case, the car may be looser on entry, at least in terms of tyre slip angles. The driver or data-acquisition specialist may or may not report this – depending on how they define and measure oversteer and understeer.

Tyre Stagger

Up to now, we have been discussing the effects of unequal longitudinal forces on the right and left sides of the car. Now we will consider the ways in which we can create these inequalities.

The biggest hammer in this part of our toolbox is 'tyre stagger' – the use of the unequal-diameter tyres on the right and left wheels of the front or rear pair. Tyre stagger is customarily measured as the difference in circumference between the two tyres, in inches or millimetres. The circumference is traditionally measured by running a tapemeasure around the tyre, or by taking the diameter with a big caliper such as the stagger master, and multiplying by π. Tyre calipers are often graduated to do the multiplication for us.

These methods are acceptable because they are simple and repeatable. But what we really need to know to predict vehicle behaviour is the rolling radius of the two tyres – the distance from the wheel centre to the ground, under load, at speed. Also, it is the ratio of the right and left rolling radii that counts, rather than their absolute difference.

Rolling radius is half of the static diameter, *minus* compression due to load, *plus* centrifugal growth. With a nice, level setup surface, we can measure static rolling radius fairly accurately. Dynamic rolling radius can be measured on a free-rolling wheel by measuring wheel RPM. This also works on driving wheels with an 'open' differential, although there is some error due to slip.

If we can measure wheel RPM, we can readily calculate the ratio of right to left wheel speed – a very good indicator of effective stagger, provided the wheels are free to rotate at different speeds.

Even those of us who race without wheel speed sensors need to understand the relationship of static and unloaded tyre diameter, tyre pressure, and rolling radius. Increasing inflation pressure increases static, unloaded diameter. This effect is most prominent with bias-ply tyres. With radials, our caliper or tape will show less change. However, a radial tyre can actually show a greater change in loaded rolling radius with inflation pressure than a bias-ply.

One often hears it said that stiffness and wedge can be adjusted with tyre inflation when running radials, but that you cannot adjust stagger. Not so! The same change in tyre vertical compliance that produces the change we see in the wheel scale reading also affects the tyre rolling radius. In fact, if the change in the scale reading is greater with a radial, so is the change in rolling radius! Measuring the stagger by traditional means may be more difficult, but its influence on car behaviour is no less.

Not only do changes in a tyre's rolling radius affect its loading, but the reverse also happens. Any increase in vertical load reduces a tyre's rolling radius. The softer the sidewalls, and the lower the inflation pressure, the greater this effect becomes.

Among other things, this means that we affect tyre stagger when we alter static or dynamic wedge. It means that an oval track car loses tyre stagger as the right wheels load and the lefts unload in the turns. Ordinarily, we do not attempt to measure or control these effects, but they are present regardless.

Centrifugal growth also affects rolling radius. This effect is most visible in drag slicks. The rear of a dragster lifts visibly during a burnout, and the tyres exhibit dramatic radial growth.

In other cars, the effect is less obvious. Increasing tyre pressure reduces centrifugal growth. Again, this is not something we normally try to measure or control, but we may note that, when we a increase a tyre's inflation, we decrease its sensitivity to both speed and load. If we let pressure out of a tyre, its rolling radius diminishes, but will grow more with speed. Or, if the car makes ample downforce, a softer tyre will compress more with speed, due to downforce increase.

The influence of tyre stagger on net yaw moment and vehicle behaviour depends on whether the two wheels in question are forced to rotate at the same speed, or are braked or driven with equal torque but variable speeds, or are rolling freely. It also depends on whether the tyres are 'hooked up' or are spinning or skidding.

Tyre stagger has its greatest effect with a locked rear end, or 'spool'. Both wheels in the pair must turn the same RPM at all times. This implies that, for the majority of situations, only one rear wheel drives, and the other drags. This imparts a yaw moment to the car, towards the dragging wheel.

If the car has to turn both ways, we usually run zero stagger. Both rear wheels drive when the car is running straight. When cornering, a locked rear end will force the inner wheel to drive, and the outer one to drag. This creates an outward yaw moment, tightening the car.

The severity of this effect with a locked rear will normally oblige us to use some form of differential for a road-racing (or figure-8) car. To limit wheelspin on the inside wheel, we will still use some type of limited-slip differential or 'locker'. Most of these are torque-sensitive. When we are on the power, the car acts as though it has a spool. The severity of the effect depends on the strength and abruptness of the locking mechanism.

For left-turn racing, we can use a smaller tyre on the left. If the tyre rolling radii are proportional to their distance from the centres of curvature of their paths, we get least drag when cornering, and both rear wheels drive. We may call this a condition of neutral stagger, or a 'stagger-neutral' setup. A car with more stagger than this is 'over-staggered', or has surplus stagger, or has a stagger-excessive setup. A car with less stagger can be termed 'under-staggered', or 'stagger-deficient'.

An over-staggered or under-staggered racecar is not necessarily set-up wrong – this is just a way of describing what side of the theoretical requirement we are on.

It is even possible to run 'negative' or 'reverse' stagger: a bigger tyre on the left. This is fairly extreme, ▶

Typical Late Model tyre stagger. The car shown here has 5in of stagger, as measured by tyre circumference. The left and right tyre circumferences are respectively 85in and 90in, a ratio of approximately 0.94:1. However, the rolling radii are more like 0.90:1 because the left tyre carries a lower inflation pressure. A Sprint car on the same track would use more than twice as much rear stagger, on a shorter axle.

but people do it. Obviously, a car can only be stagger-neutral for one turn radius. Even if the track has a constant turn radius, the fast line will not. Therefore every car is over-staggered or under-staggered some of the time.

As long as the tyres are 'hooked up', an over-staggered car drives with the outside tyre and drags the inside one. For any given stagger, the resulting yaw couple diminishes as we turn more sharply left. The yaw couple is normally greatest on the straightaways, and smallest at mid-turn. It is least at mid-turn, if we run low on the racetrack. The car will therefore be tighter running low than running high. This applies to all locked-axle cars, over-staggered and under-staggered alike.

It should be obvious that an under-staggered car will be tighter overall than an over-staggered one, other things being equal. It may be less obvious that stagger affects the car's response as we reach, and exceed, the limit of adhesion of the rear wheels.

Stagger's ability to generate a yaw couple depends on the tyres being 'hooked up'. If we break the tyres loose, stagger largely ceases to matter. Stagger effects aside, rear wheelspin produces oversteer. If we have a stagger effect that is loosening the car, and we spin the wheels, the disappearance of the stagger effect with wheelspin tames the onset of power oversteer.

Conversely, if the car is under-staggered, and its stagger effect is tightening it, what happens when we spin the wheels? The disappearance of the stagger effect intensifies the influence of wheelspin. Consequently, a stagger-deficient car is more throttle-sensitive than one with surplus stagger, at least when cornering.

Furthermore, it does not matter if we are using the traction of the rear tyres mainly for cornering, rather than propulsion. Stagger effect still goes away when we pass the limit of adhesion. Therefore, surplus stagger makes rear breakaway less abrupt, even in steady-state cornering or trail-braking. This partly explains why US Sprint cars usually run so much stagger – it actually makes them less twitchy at the limit. Also, as is widely recognised, it makes them turn in very smartly.

This good behaviour comes at a price, however. Any stagger at all becomes an excess when the car has to go straight. Surplus stagger adds drag in the turns, too. Even if the driver is not using full power, this costs us speed, because overcoming drag uses traction that could otherwise be used to make centripetal force.

Even if we deem the drag penalty acceptable, surplus stagger is only a viable setup option if the rules allow us to run large rear tyres and/or wings. Otherwise, the car will be prohibitively loose.

In most US Late Model and Modified Dirt classes, the rules impose an identical tyre size limit front and rear. Engine setback rules, minimum weight requirements, and the need for propulsion traction combine to produce rear weights between 55% and 60% of total. Such a tail-heavy car, without large rear tyres, must be set up so that it virtually corners on three wheels (the left front being very light, or airborne), even with very little rear stagger. With rear stagger like a Sprint car's, such a car would be undriveably loose.

I have had clients running Modifieds very successfully with zero rear stagger. I have had other racers tell me that their cars like reverse stagger.

One challenge in making such a setup work is to "free the car up" on entry. (As with mating components, 'free' is a condition between loose and tight – in other words, neutral handling.) Many racers are trying torque-sensitive limited-slip differentials in Late Models and Modifieds, especially worm-gear style differentials such as the 'Quick Trac' and 'Gold Trac'. These can work very well when they are right. However, they suffer a lot of wear, due to the violent abuse that they get in a powerful Dirt car. Gear pre-load is highly wear-sensitive, and the locking torque varies accordingly. Monitoring and adjusting the differential becomes a vital part of maintenance and setup, and it is hard to predict how much the unit's behaviour will change in a day's racing.

Other ways of loosening corner entry focus on making the chassis de-wedge under braking. We looked at some of these in Part 2, including left-stiff springing and asymmetrical suspension geometry.

In addition, there is another application of tyre stagger that can help us: front stagger.

The front wheels are free to seek their own RPM. When the brakes are not applied, tyre stagger has little influence. Reducing tyre pressure on one corner of the car increases drag on that wheel, which will produce a small yaw moment. A smaller rolling radius will reduce ride height and static wheel load if we do not reset the suspension.

If the right and left brakes are identical, both front wheels receive equal braking *torque*. A braked wheel generates a rearward force equal to brake torque *divided by* rolling radius. So front tyre stagger influences right:left brake bias. The more positive stagger we run, the more the car will turn left under braking (or the less it will turn right).

Again, the foregoing applies as long as the tyres are 'hooked up'. If we lock the wheels, their rearward force depends mainly on their loading. For corner entry, we are generally dealing with unlocked wheels – if we lock them, we can't steer. Still, we need to bear in mind how the car's brake-induced yaw moments will vary at the point of wheel lockup.

We may also have a fairly wide range of situations where one wheel locks. Tyre stagger influences this. As a rule, reducing rolling radius and increasing rearward force on one wheel makes it lock earlier. Countering this to some extent, a softer tyre has more longitudinal traction, at least down to a pressure well below the optimum for lateral grip.

If the rear tyres are free to rotate at different speeds, similar effects prevail at the rear. If both wheels get the same torque, the small one makes more force. As with front stagger, the car pulls towards the smaller tyre under braking. Under power, the yaw moment reverses, and the car wants to turn toward the larger tyre.

So tyre stagger effect under braking acts in the same direction whether the differential is open or locked but, under power, it acts in opposite directions! Of course, we seldom encounter intentional tyre stagger and an open differential together. However, we sometimes have unintentional stagger due to tyre variation or pressure loss. We may also have loss of lockup with a limited-slip differential, either on purpose during corner entry, or by accident under power due to wear.

Asymmetrical Brakes

In addition to obtaining unequal braking force through tyre stagger, we can arrange for the right and left brakes to make unequal torque. Common ways of doing this include limiting valves, shutoff valves, and unequal piston diameters in the calipers. In Sprint cars, the right front brake is often omitted entirely.

In most oval track classes, one brake per wheel is the norm. In Dirt Late Models and Modifieds, four working brakes are generally required by the rules. Some sanctioning bodies allow driver-operated shutoff valves to the right front; others prohibit this. Shutoff valves do not provide a range of right:left proportioning. You have a right front brake, or you don't. Running the valve 'cracked' merely makes the right front apply and release sluggishly.

A somewhat more sophisticated approach is to use an adjustable limiting valve. Limiting valves are common in road car brake systems, where they are used to control rear wheel lockup. Adjustable ones for racecars are available with stepless adjustment by the turn of a knob. Wilwood offers one of these. Another design, available from Tilton, uses a lever and cam arrangement to provide a stepped adjustment. This has advantages in repeatability and ease of use for the driver in the heat of combat. In oval track cars, front:rear proportioning is usually controlled by a dual master cylinder system with a balance bar, and a limiting valve is added for the right front.

A limiting valve, as its name implies, shuts off a line when pressure rises to a set value. Below this pressure, it has no effect. With identical front brakes, we get identical brake torque until the valve acts. Then we get a sharply increasing left:right bias as we push the brake pedal harder.

To get a constant left:right torque ratio over a range of 'apply' pressures, we need to make the brakes themselves dissimilar. Perhaps we could use the dual master cylinders and balance bar to control left:right bias, and control front:rear bias with brake design and limiting valves. Perhaps we could use four separate master cylinders, and operate them through three balance bars in series – parallel. Fascinating concepts, but untried, as far as I know.

Assuming we actuate the brakes conventionally, we can control torque proportioning with piston area and disc (rotor) diameter. Larger piston area at the caliper increases brake torque. Many popular racing calipers are available in two or more bore sizes. Popular brake discs are often available in at least two diameters. As with the tyre rolling radius, it is the radius at which the pad acts that counts. The caliper position must be compatible with the disc. If the disc has a bit more available surface than the width of the pad, we may have a little freedom on caliper location. Small differences can produce noticeable effects (note that this can also occur unintentionally).

In lower-cost classes, many sanctioning bodies require passenger car spindles, calipers and discs, with no remachining allowed. Some competitors reduce right front brake torque by breaking or

This Sprint car displays large front:rear disparity in tyre sizes. Together with ample rear aerodynamic downforce, this allows the car to run ferocious rear stagger (below), without becoming excessively 'loose'.

grinding off part of the pad material. The most effective place to remove the material is at the top or outside edge of the pad. This is often against the regulations, and can lead to forces that try to cock the piston or the caliper.

Single-piston sliding calipers generate less torque if they are seized on their pins. This often happens accidentally due to wear and rust. There are ways to make it happen "accidentally on purpose".

A safer approach, and one that will pass any inspection, is to use dissimilar pad materials. These days, the better pad suppliers make pads which vary not only in coefficient of friction, but also in CF variation with pressure and temperature. These properties afford us some additional control over both left:right and front:rear bias.

On a locked rear axle, both brakes act on both wheels. Yaw moment effects depend on tyre stagger. Sprint cars often use one rear brake for both rear wheels, mounted next to the axle centre section. Combined with a single front brake on the left, and lots of rear tyre stagger, this setup produces rearward force on both left tyres, and forward force at the right rear, in any braking short of lockup. This lets the driver turn the car with the brakes, and slow it by sliding it. In fact, it becomes difficult to drive the car any other way.

Rear brake left:right proportioning does affect the magnitude of the loads on the calipers, even with a locked rear. If the calipers mount on 'floaters' or 'birdcages', their loads react separately. If the floater or birdcage locating links are arranged to jack the car up or down (to produce pro-lift or anti-lift), then both front:rear and left:right torque proportioning will affect wheel loads in braking. As with other jacking effects, we can predict the effect on cornering balance by the effect on dynamic wedge: a force that increases wedge tightens the car; a force that de-wedges the car loosens it.

Early in the 1998 Formula 1 season, McLaren International attracted considerable attention with its 'tractor brake' system. Details of this device remain secret, but we know that it applied one rear brake or the other by a single left-foot pedal. The tractor brake was withdrawn voluntarily, under pressure, and probably won't be seen again in Formula 1. But driver-controlled individual brakes remain an intriguing possibility, particularly for short-track racing, where the driver does not have to shift gears, and can potentially operate two brake pedals.

In Off Road vehicles, driver-operated individual rear brakes have been widely used for many years. Their legality here appears certain for the foreseeable future. Elsewhere, the rule makers will have the last word. The usual pattern is that somebody has to try an idea before it is allowed or prohibited.

Asymmetrical Steering

Our primary means of creating controlled yaw moments is to turn the steering wheel. Within the steering system itself, any definable design parameter from the steering gear out to the tyre can be made different on the right and left.

Of the various possible asymmetries, the ones most commonly seen are caster stagger and unequal-length steering arms. Unequal scrub radii are also common, usually due to the use of unequal offset wheels and unequal camber settings, rather than different spindle or upright designs. (Camber affects scrub radius if we measure from the footprint load centroid instead of the wheel centre plane).

Caster stagger – unequal right and left caster settings – does not directly create a yaw moment upon the car, but it creates a pull in the steering. This torque at the steering wheel is actually normal force at the spindle (gravity, aerodynamic downforce, banking downforce), acting through the inclined motion path of the wheel. If the driver releases the wheel and lets it follow the pull, the car actually drops slightly. When the driver resists the pull, he or she is partially supporting the weight of the car!

There are two reasons for using caster stagger. The main one is to reduce steering effort. With more caster on the right, the steering pulls left, lightening effort in a left turn. Of course, it takes more effort to drive straight on a left-banked straightaway but, if ▶

Sprint cars racing on dirt typically do not use right front brakes. The team monitors the front tyre sizes (note the circumference dimension chalked on the tyre wall), but front stagger does not affect left:right front brake bias as it would with two front brakes.

the steering forces reverse, we use a different set of muscles.

In Stock Cars and Sprint Cars, power steering is now almost universal. Since we can control assist level through modulator torsion bar selection, steering effort is not the issue it once was. However, power steering systems can fail, and they stop working if the engine quits. Even with power-assist, the steering geometry can be felt by the driver. Mid-engined oval track cars, including ChampCars and Indycars, still use unassisted steering.

The other reason sometimes cited for using caster stagger is to maintain a load on the steering system, which takes up any play. Of course, we try to minimise slop in the steering, but we usually have to live with at least a little.

One problem with using caster stagger to take up steering lash is that we still encounter the lash any time the steering force reverses. With moderate caster stagger, this will occur during corner entry and exit. With extreme caster stagger, we may avoid this, but then we lose the driver fatigue advantage. We just wear the driver out on the straights instead of the turns.

A good reason not to use caster stagger is that it interferes with the driver's ability to sense grip level and actual tyre forces through the steering. Caster stagger does not obliterate steering 'feel', but it does superimpose a false message. This may or may not be a problem for the driver, depending on whether he or she is accustomed to caster stagger. In general, oval track drivers expect caster stagger, whereas road racers don't like it.

Since both caster and caster stagger are primarily driver 'feel' issues, my usual practice is to go by driver preference.

For left-turn racing, especially with Stock Cars, it is common to make the left steering arm shorter than the right. This gives the car more Ackermann Effect (toe-out when the front wheels steer) when we steer left than when we steer right. This loosens the car when we steer left, and tightens it when we steer right. Most of the time, this is what we want on an oval.

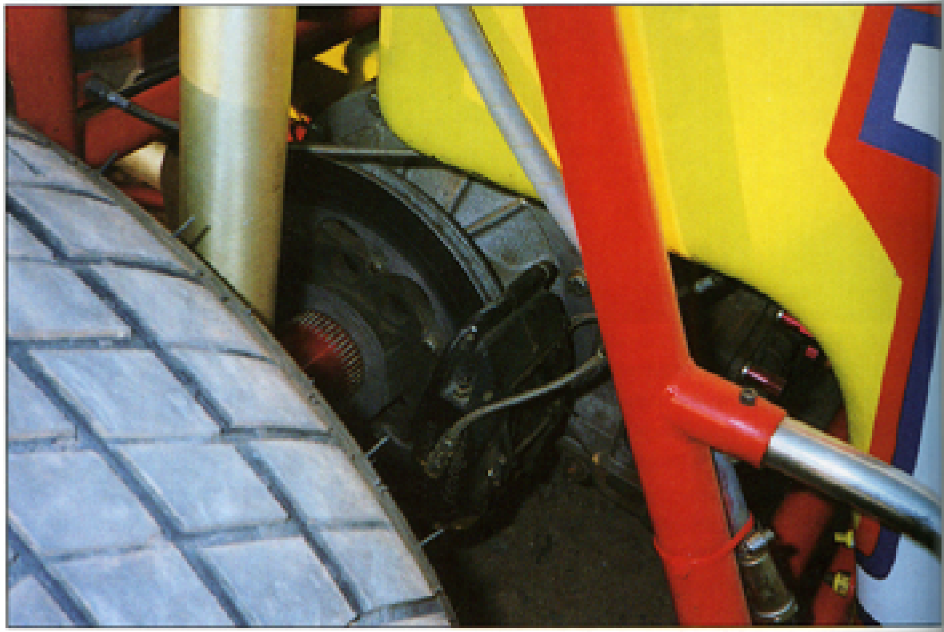
In NASCAR Winston Cup and Busch cars, the rules require us to use approved forgings for the spindles and steering arms. Wheel offset is also fixed by the rules. The only variable left to the builder is how to machine the approved forgings. Within these constraints, the only way to get positive Ackermann in both right and left turns is to build a rear-steer car – with its steering linkage behind the axle line.

Rear-steer cars therefore have some merit for road racing, and some teams prefer them. However, engine builders hate them, because the steering linkage compromises oil pan design. Also, a rear-steer design has poorer deflection steer properties than a front-steer one. A rear-steer layout gives deflection oversteer, whereas front-steer provides deflection understeer. Therefore, a front-steer car feels steadier on a Superspeedway. Together with the horsepower gain from a roomier oil pan, this factor has made front-steer cars the norm on ovals, and universal on big ovals. In these applications, unequal-length steering arms offer a way to avoid anti-Ackermann, if only for left turns.

There is also a strong case for unequal-length steering arms in a Dirt short track car, if the rules permit. More Ackermann when steering left helps us to turn-in. Less Ackermann, perhaps even some net toe-in, is desirable in an opposite-lock slide. If the car is sliding a lot, the outside front wheel will lead the inside one. In this condition, the front wheels create the least drag with a bit of toe-in!

With a beam axle front end, the entire axle may be adjusted to provide right lead or trail. This has little effect on car behaviour, since the wheels steer on the axle. Front-right lead or trail can affect rear axle alignment, if we keep the left and right wheelbases unchanged – another reason to measure rear toe relative to the car rather than go by wheelbase.

Beam axle suspensions do offer unique opportunities for asymmetry in other design parameters, some of which affect car behaviour a great deal. We will explore asymmetrical beam axle systems in detail in Part 4.



A single rear brake installation on a Sprint car. The open-tube axle allows the brake to be mounted inboard. Spool drive (no differential) permits one brake to stop both wheels. However, tyre stagger causes the right rear tyre to continue driving the car in most braking situations. The car is therefore slowed entirely by the left-side wheels. This combination produces a powerful leftward yaw moment.

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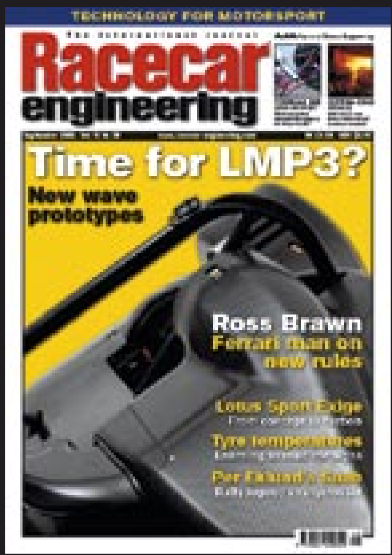

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