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V9N3 April 1999 | UK £3.70 | USA $7.95 | ENGINEERING

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The Design & Tuning of Asymmetrical Racecars

PART 1: FUNDAMENTALS

In track racing, asymmetrical setups are used more commonly than is generally believed. A great many short-track and circle-track racecars are purpose-designed to exploit asymmetry of the chassis and other components. However, the techniques are widely used in other forms of racing on oval tracks and, indeed, road circuits. This is the first of a comprehensive, four-part examination of a wide range of racecar asymmetries and, by way of introduction to the subject, it deals with fundamental considerations.

By MARK ORTIZ

We generally think of a car as a symmetrical object. Its right side is a mirror image of its left side, except for a few details. When we first study vehicle dynamics, we model and imagine the car as symmetrical.

A symmetrical car is easiest to comprehend, and it's a pretty close approximation of most street vehicles.

Close enough, in fact, so that street vehicle engineers do not need to concern themselves at any great length with the peculiarities of asymmetrical vehicles. When street vehicle engineers do concern themselves with chassis asymmetries, it is usually with a view to eliminating them or, at least, minimising their effects.

One exception is the use of small amount of caster stagger (caster inequality) in road cars. This creates a light steering 'pull' that is sometimes intended to counter prevailing road camber. Alternatively, it may be used to take up play in the steering and make the car less prone to wandering.

Another exception is the use of asymmetrical locating linkages and/or unequal rate springs in live-axle rear suspensions, to counter the effects of driveshaft torque. In racecars, asymmetrical linkages can be used in a far greater variety of ways, some of which augment the influence of driveshaft torque (Part 4 of this series will investigate these effects at length). But in street vehicles, the object is to counter an undesired effect, and make our wheel loading more symmetrical, rather than less so.

In rallying and off-road racing, a similar desire for symmetry prevails. Our vehicle will encounter a huge variety of turns, right-hand and left-hand in essentially equal number. We want consistent behaviour in both directions.

One might suppose that the same would hold true in closed-course road racing. Here, however, asymmetrical setups are considerably more common than most people imagine. Exactly how common is hard to determine. The matter is surrounded by secretiveness and controversy. Some race engineers and setup specialists say they use asymmetrical setups for every track, and credit the practice with a major share of their success. Other experts insist that a road racing car should act the same in right and left turns, and that asymmetrical setups are a crutch (or a last resort), except perhaps for one or two tracks.

Logically, there are a number of reasons we may wish to enhance a road racing car's cornering in one direction, at the expense of the other. Unless the course includes an overpass, it inevitably requires us to turn 360deg more in one direction than the other, each lap. The shorter and simpler the layout, the greater the percentage of yaw motion in the dominant direction, and the degrees of yaw motion required are only a rough indication. Due to differences in design and number of turns, the car may easily spend more than three times as many seconds per lap cornering one way, as it spends cornering the other way.

Often, one or two corners are more important than the rest. A corner takes on more significance if it precedes or follows a major straightaway – it definitely matters more if it's the only good place to pass. Therefore optimising the car for right or left turns may get us quicker laps – or it may not be quicker but may still confer an advantage in traffic. In the latter situation, we might prefer a symmetrical setup for qualifying, and an asymmetrical one for the race.

Finally, there is oval track racing, where all turns go the same way – ordinarily left. The car still needs to turn right occasionally, but no one questions the need to optimise the setup for left turns. All the cars are asymmetrical, and everybody knows it. Asymmetry prevails in weight distribution, tyre size, spring rates, damper properties, steering geometry, suspension design, brakes, tyre compounds and tread patterns, aerodynamics, spring pre-loads, ride height settings, caster and camber adjustment – practically every setup or design parameter imaginable. Even inside the engine, we find oiling and breather systems, carburettor floats, and carburettor jetting all designed for left-turn operation. In the least restricted cars, the engine is both offset and tilted to the left.

Chassis asymmetries, then, are monumentally significant in certain types of racing, yet almost totally irrelevant to street vehicles. Historically, formally trained engineers have primarily worked for street vehicle manufacturers or their suppliers. It has fallen to racers themselves to understand and use asymmetrical design and setup. In doing this, racers have built up a substantial body of experience and expertise. However, the whole process has been highly informal. The knowledge has been transmitted almost at the level of oral tradition and folklore.

Much of this 'folk wisdom' is valid, but it has inevitably been haphazardly organised, and there had generally been insufficient analysis from first principles. Here and there, outright falsehoods have become enshrined as gospel.

This series of articles will attempt a more systematic and scientific investigation of chassis asymmetries and their effects. Hopefully, the reader may emerge with a better understanding, not only of what does what, but why.

We will not attempt a thorough exposition of vehicle dynamics here. But we do need to go over a few physical principles that are especially relevant to chassis asymmetries and their effects.

Tyre Load Sensitivity

A tyre's coefficient of friction is not a constant: it diminishes as tyre load, or normal force, increases. As we load a tyre more, we do get more traction from it, but at a decreasing rate. If we increase the load by

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50%, the tyre does not deliver 50% more grip: there is a gain, but a diminished one.

As we add load, moreover, the gain not only diminishes continuously, it diminishes faster: that is, as normal force increases, friction force increases, but at a decreasing rate. Coefficient of friction decreases, at an increasing rate (see **Fig 1A** and **Fig 1B**).

What this means to us as we try to corner fast is that a front or rear wheel pair delivers best cornering force when loaded equally (**Fig 1C**). Contrary to widely held belief, this is true on most types of dirt surface, as well as all types of pavement.

The foregoing statement does assume that the two tyres are identical. In oval track racing, the right tyre may be dramatically larger than the left. In that situation, the tyres will deliver best cornering force when loaded approximately in proportion to their size. Differences in tread compound, carcass construction and inflation pressure will also influence optimum load distribution somewhat.

These nuances are mainly of academic interest, however. In practice, all racecars need more load on the inside wheel, and less on the outside one, than we can get. We know this because there are various ways to increase inside wheel loading at one end of the car, at the expense of the other end. When we do any of these things, the end with increased inside percentage always delivers more cornering force, and the end with increased outside percentage delivers less.

Wedge

To deal with this issue of giving one end of the car more inside percentage at the expense of the other, we need a vocabulary. We speak of load distribution inequality in terms of 'wedge' and 'crossweight' (or 'diagonal percentage'). These terms originated in oval track racing, but they are gaining currency in road racing, and even in passenger car engineering.

The term 'wedge' comes from the days when most American sprint cars used transverse leaf spring suspension, at least at the rear. The teams found that they could adjust the car's cornering balance in left turns by inserting a wedge between the rear spring and its mounting pad on the frame. Normally, the thick end of the wedge was on the left: this increased the loading on the left rear and right front tyres. The greater the angle of the wedge, the greater the effect. To this day, a car with more left percentage at the rear than at the front is said to have positive wedge, or to be wedged, for left turns.

To my knowledge, nobody has established a universally agreed convention as to what constitutes positive wedge for a right-turn condition. For our discussion here, positive wedge means that the rear has more inside (rather than left) percentage than the front. This way, all following comments regarding wedge's effect on cornering balance will apply equally for left and right turns. Where no turn direction is stated or implied, oval track convention will apply: positive wedge means more left percentage at the rear.

In the old days, people measured wedge in inches. You measured it by placing a socket on your jack, positioning this under the rear axle centre section, and lifting until the left tyre started to come off the ground. By then, the right tyre would already be some distance off the ground. You measured that distance, and that was your wedge.

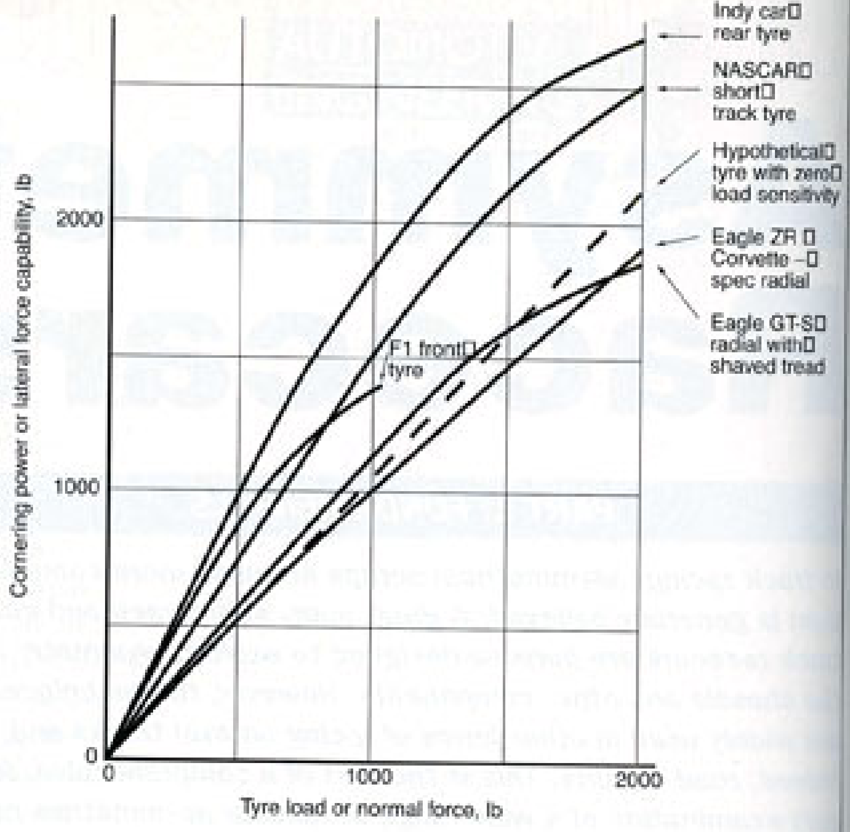

Fig 1A: Tyre lateral force as a function of tyre load, based on Goodyear data cited in Milliken & Milliken, *Race Car Vehicle Dynamics*, SAE, 1995, pp76-80.

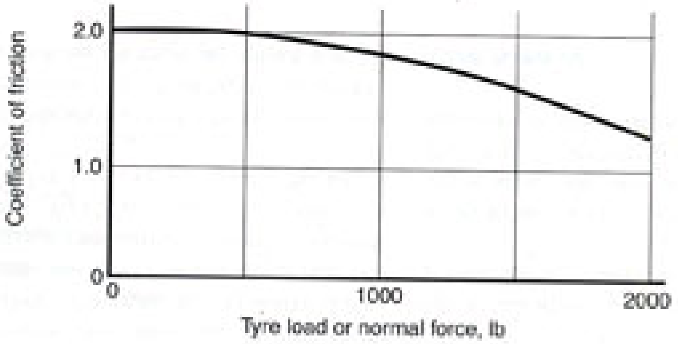

Fig 1B: Tyre coefficient of friction as a function of tyre load for Indy car tyre in Fig 1A.

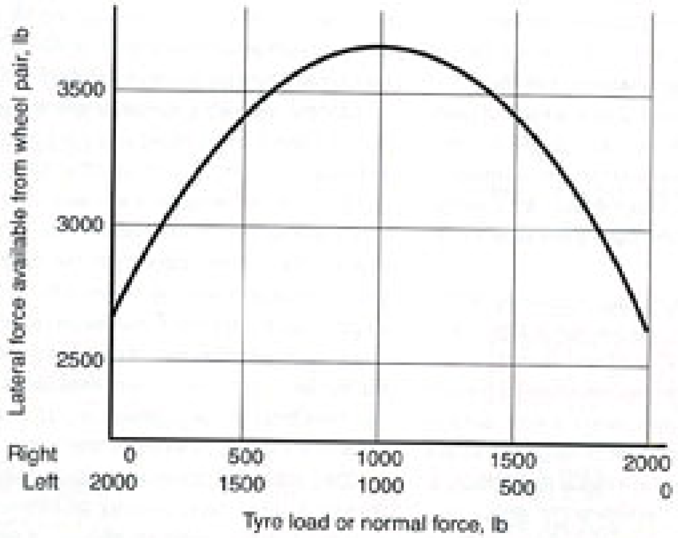

Fig 1C: Wheel pair lateral force as a function of load distribution, for a pair of Indy car tyres as above, at 2000lb combined load.

Of course, there was no way accurately to translate that measurement from one car or setup to another. Spring rates, overall left percentage, frame stiffness, tyres, driveline offset and other variables all affected the measurement.

Nowadays, most of us have wheel scales. We measure the load on each wheel, add the left rear and right front, and call this our diagonal weight or 'crossweight'. Expressed as a percentage of total car weight, this quantity is our diagonal percentage. If you ask a racer how much wedge his/her car has, you normally get the answer in terms of 'diagonal percentage'. Compared with the old method, this number is more useful.

However, there is actually a subtle distinction between wedge and diagonal percentage. If a car is unwedged, or has zero wedge, it means that the left percentage is the same at both ends, and the rear percentage is the same on both sides. Intuitively, we might suppose such a setup would have 50% crossweight – and for symmetrical cars that is, in fact, the case. It is also true for any car with 50% rear weight. But if the car has unequal weight distribution both side-to-side and end-to-end, zero wedge and 50% diagonal are not the same!

This may sound wrong, but a few examples will illustrate. As an extreme case, consider a Super Modified. The typical left percentage for these cars is around 62%, the typical rear percentage around 57%. When such a car is set up with zero wedge as defined above, the left rear percentage is 62%x57% (35.34%). The right front percentage is 38%x43% (16.34%). Our diagonal percentage is 35.34%x16.34% (51.68%). This setting is not necessarily the one we want, nor is 50% diagonal. But the difference between the two is definitely enough for the driver to feel.

As a more moderate case, take a NASCAR Winston Cup car. Here we might typically see 53% left, 48% rear. For zero wedge, our left rear percentage would be 53% x 48%, or 25.44%. The right front would be 47% x 52%, which is 24.44%. The diagonal percentage then works out to 49.88%. On a 3400lb car, the difference between that and 50% is only 2lb per wheel. No driver can detect that. In real-world conditions, we can't even measure it repeatably. There is still a difference between zero wedge and 50% diagonal, but its magnitude is insignificant when the car is this close to symmetrical.

For a Sprint car on dirt, with 55% left and 60% rear weight, an unwedged car has 51% diagonal. When the same car has a more left-heavy pavement setup, zero wedge is more than 51% diagonal. The more asymmetrical and tail-heavy the car, the more significant the difference between 50% diagonal and zero wedge.

In oval track racing, we don't necessarily want an unwedged car. We use whatever diagonal percentage we need, to give us the car behaviour we want in left turns, and we don't worry about how the car acts turning right, but when we road-race with an asymmetrical car, the question or what constitutes an unwedged condition is no longer purely academic. We may accept giving up cornering speed in one direction to gain some in the other direction, but we still need similar balance both ways. To get this, a good rule is at least to begin testing with zero wedge.

Dynamic Wedge

We have been discussing wedge as measured during setup, with the car stationary. This is static wedge. Of course, as soon as the car starts moving, its wheel loads start changing. That means that its wedge is constantly varying. We use the term 'dynamic wedge' to denote the car's wedge at any given instant, while in motion.

Understanding and controlling dynamic wedge is central to successful chassis tuning. Springs, dampers, rollcentre locations, anti-dive, anti-lift, anti squat, asymmetrical live-axle effects, anti-roll bars and other suspension interconnections all influence vehicle behaviour primarily by their effects on dynamic wedge.

Dynamic wedge changes as the wheels go over bumps. Depending on the nature of the irregularities, the suspension will move in some combination of roll, pitch, heave and warp. The softer the suspension, the less our wheel loads change. This is true for the system as a whole, and for individual wheels. We ordinarily try to make the car insensitive to bumps. Therefore, we usually seek to minimise wedge changes due to road surface inputs, rather than cultivate them to control car behaviour.

Aerodynamic downforce and banked turns do not produce wedge changes in a symmetrical car. However, if we use stiffer springs on diagonally opposite wheels, those wheels absorb a disproportionate share of the load increase as the car is pressed down harder onto the track. A wedge change results. This can be useful on an oval track, or on a road course where we have one particular fast sweeper or banked corner that requires unique tailoring.

More often, though, racers cause themselves problems with this effect. They arrive at a diagonally stiff setup through imitation, or uninformed trial and error. The most common pattern is that an oval track racer will encounter large compression travel on the right front when entering banked left turns, decide that this must be bad, and stiffen the right front spring. A stiffer left rear typically follows, to restore front/rear and left/right stiffness balance.

A diagonally stiff car isn't necessarily slow. In fact, it can go fast when all factors are optimal. However, its balance will be sensitive to speed (and therefore to tyre and track condition) and to banking angle. Such cars will qualify well if they get to run while conditions suit them, but will require 'chasing' as conditions vary during the race. Depending on track design, they may also be especially reluctant to deviate from their best line to cope with traffic.

We are generalising here, of course. Tuning a real car calls for detailed data on as many factors as possible, and an understanding of how they interrelate. We will cover asymmetrical springing and damping in detail in Part 2.

There is one more way that wedge varies as the car travels: it varies in response to the vehicle's horizontal accelerations – longitudinal and lateral. These changes are the main ones we deliberately manipulate to control car behaviour. We do this through our selection of springs, dampers, and related components, and also through suspension geometry.

Velocity & Acceleration

Colloquially, 'velocity' is another word for 'speed', and 'acceleration' is how we increase speed. In physics and engineering, the words have somewhat different meanings. A little clarification may be helpful to some readers.

Velocity denotes an object's rate *and direction* of motion. An object can change its velocity without changing speed, if its direction of motion changes. A

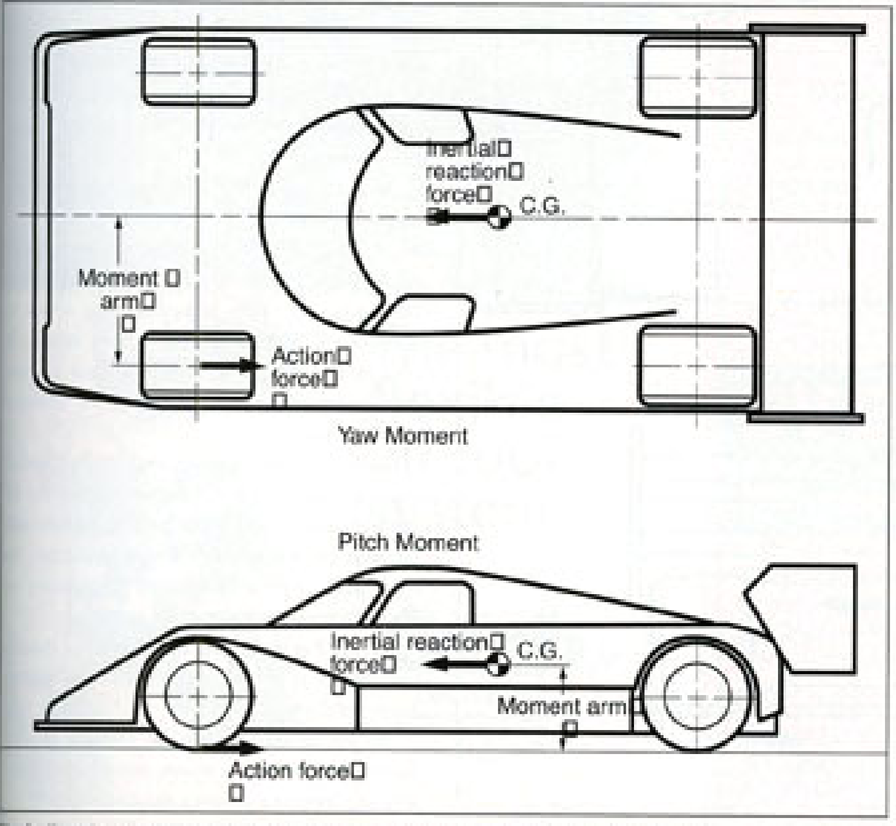

Fig 2: Tyre longitudinal force produces couple and moment in pitch and yaw.

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car's body, or sprung mass, has velocities in three linear directions, and three angular ones. If we know the speed and direction of motion in all six of these modes, we have a more complete description of the body's velocity, at a particular instant.

Acceleration is any change in any velocity. Acceleration in the colloquial sense is actually longitudinal acceleration, forward. Longitudinal acceleration rearward is what we create with the brakes. As with velocity, acceleration has both magnitude and direction, and it may exist in one of two directions, in any or all of the six modes.

When a car is travelling in a constant-radius curve at constant speed, it is constantly changing its direction of travel. That means it is experiencing an acceleration. In the inertial frame of the car (imagining ourselves in the car), this is a lateral (sideways) acceleration. In the inertial frame of the earth (imagining we're trackside), it is a centripetal (towards the centre of curvature) acceleration.

The car described above also has an angular velocity: the direction it points is changing, at a fixed rate. We call this a yaw velocity. Since this velocity is constant, our yaw acceleration is zero. But as the car entered that turn, we had to accelerate it in yaw to reach its present yaw velocity. When it exits the turn, it will require a yaw acceleration in the opposite direction, to return its yaw velocity to zero.

Action & Reaction

To accelerate an object, we must subject it to a force. The object resists this 'action' force with an inertial 'reaction' force. Action and reaction are always equal, and always occur at the same instant, in opposite directions.

A car resists a linear acceleration with its total mass. It resists angular accelerations with its 'moment of inertia'.

The moment of inertia is different for each of the three angular modes. It depends on how far the car's various masses are from each other, perpendicular to each mode's axis of rotation.

To accelerate the car forward, we apply a forward force. The car reacts with an equal rearward inertia force. The reverse happens for rearward acceleration.

In cornering , the tyres exert a force which is lateral and inward to the turn in the car's inertial frame, or centripetal in the earth's inertial frame. The car reacts with an inertia force which is lateral and outward in the car's inertial frame, or centrifugal (away from centre of curvature) in the earth's inertial frame.

Centrifugal force, then, is the inertial reaction to centripetal acceleration.

We create and control yaw acceleration through the lateral force balance between our front and rear wheel pairs. Very importantly, we also create and control yaw acceleration through the longitudinal force balance between our right and left wheel pairs. In other words, retardation (braking) and propulsion (drive) forces can steer the car. This effect assumes especially great significance in asymmetrical cars. In Part 3 of this series, we will examine the matter in greater depth.

Couples & Moments

A linear force has a 'line of action' that depends on where the force is applied to the object, and the direction in which it acts.

When a tyre generates a forward, rearward, or lateral force, that force acts at the tyre's contact patch (or 'footprint') in a horizontal direction. The car's inertial reaction force acts at the car's centre of mass, or centre of gravity (CG), also in a horizontal direction.

We thus have action and reaction forces which are equal in magnitude, and opposite in direction – with lines of action that are offset from each other. A pair of equal, opposite forces with offset lines of action is known as a 'couple'. A couple creates a rotational force, termed a 'torque' or a 'moment'.

Like any force, this moment has a direction and a magnitude. Its direction is rotational, about an axis perpendicular to the two opposing linear forces. Its magnitude is the product of the magnitude of the opposing forces and the distance separating their lines of action. This distance is called a 'moment arm'.

Fig 2 shows a single tyre applying a rearward force to a car, as it would if we applied its brake. In the side view, we see how the rearward force at the footprint and the forward inertial reaction force at the CG form a couple, creating a forward pitch moment.

In the top view, we see the same two forces. Their lines of action have a lateral offset as well as a vertical one. Consequently, our couple produces a leftward yaw moment, in addition to the forward pitch moment. These moments differ in magnitude as well as direction, since the moment arms differ.

Fig 3 shows the same tyre generating a lateral force, as it would in cornering. In the front view, we see a couple very much like the one in the Fig 2 side view. In this case, we have a leftward roll moment instead of forward pitch.

As in the first example, our forces have a horizontal offset – longitudinal this time – shown in the top view. Therefore, we again have a yaw moment, this time rightward.

Note how similar the two examples are. The direction of the force is 90deg different, but the way the action and reaction form couples and generate moments is essentially the same. Note also that both a longitudinal tyre force and a lateral one can create a yaw moment.

In a real car, all four tyres can apply lateral and longitudinal forces at the same time. These will add to, and subtract from, each other in fairly complex combinations. The resultant forces and moments may react against inertia (meaning they create an acceleration), and change the vehicle's velocity. Or they may react against structure, such as tyres and suspension systems, and change the loading of these structures.

Roll and pitch moments mainly react against structure: our tyres and suspension let the car roll and pitch, but not very far. In resisting roll and pitch, the tyres and suspension absorb load changes. We often speak of these as 'dynamic load transfer' or, more informally, 'weight transfer'.

In Part 2 of this series, we will examine dynamic load transfer at length, using the principles we have discussed above.

We will consider how we may apportion dynamic load transfer among the wheels, and some ways that this apportioning governs the behaviour of the racecar. ■

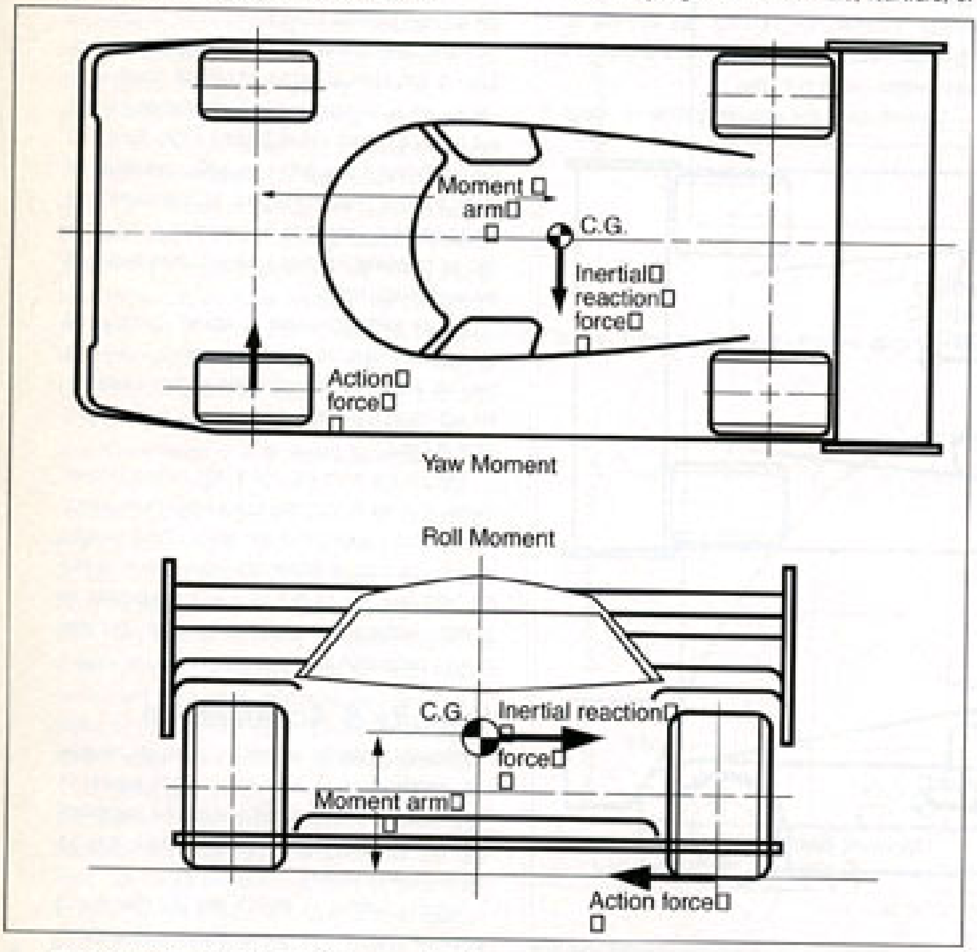

Fig 3: Tyre lateral force produces couple and moment in roll and yaw.

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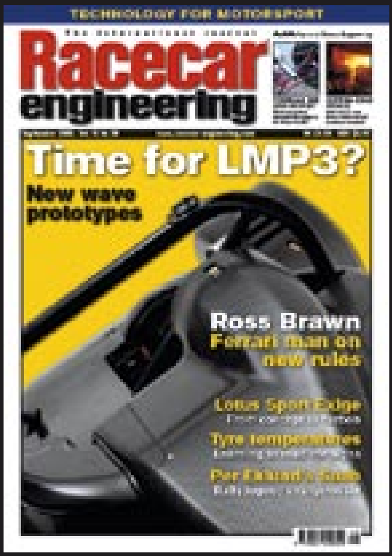

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