The man behind the Chaparrals explains vehicle dynamics in language your wife can understand

WHAT MAKES CARS HANDLE?

BY JIM HALL, WITH DAVID E. DAVIS, JR.

This is a discussion of automobile handling, or dynamics, presented in language that any intelligent reader can understand. Its purpose is to help the average reader—not the automobile engineer—to comprehend the forces that control and limit the behavior of a moving automobile. We'll explain the phenomena of over/understeer, and we'll explode some myths in the process. A lot of the experts in this field are going to disagree violently with some of the facts that we're presenting, but our expert is one of the best, and it won't be the first time that's happened to Car and Driver *anyway.*

We asked Jim Hall to teach us the fundamentals of automobile dynamics because we believe that he knows as much, or more, about the subject as anybody else (see page 4). If you have any doubts, the great success and technical advances of his Chaparrals should settle them.

From this point on, it's Jim Hall's show. The material presented, and the pattern of presentation are his, and we have attempted to use his words as much as possible, reconstructed from a solid week of conversations, demonstrations, and tests, during which he taught us these fundamentals, and proved his points to our complete satisfaction.

—David E. Davis, Jr.

In *any* car driven by the rear wheels, there are fundamental dynamic advantages in rearward weight-bias. This is generally achieved by sticking the engine behind the driver, but engine placement alone doesn't really mean anything—for instance, there are quite a few front-engined cars that carry the greatest percentage of their weight on the rear wheels. Even if somebody came up with a racing powerplant that only weighed five pounds, rear-drive cars would *still* handle better with rearward weight-bias. There are also a number of secondary advantages: the engine and drive train become a compact "one-piece unit," visibility can be improved with the bulk of the engine behind the driver, and a rear-engine chassis can actually be strengthened and reinforced by the transaxle structure.

Historically speaking, racing, and road racing in particular, has led the way with innovations and developments that ultimately found their way into our regular passenger cars. This is also true in this rear weight-bias business. Any vehicle that runs on tires can benefit from these fundamental advantages, whether it's a race car or a passenger car or a Greyhound bus. And when we say

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fundamental, we're not theorizing, we're talking basic physics.

There aren't a whole lot of rear-engine, or rear weight-bias cars around yet, but we're going to see more of them in the future. Practically everybody in Europe builds one of some size or another, and there are a handful here in the States, too. The Corvair and the Corvette, the Ford GT, and most American station wagons carry a greater percentage of their weight in the rear. Since these advantages *are* fundamental, and since they do apply to the entire range of rear-drive vehicles, we're not going to limit this to a discussion of the Chapparal, or race cars generally.

Any useful vehicle must be capable of changes in body velocity and direction. According to one of Newton's laws, any mass (like an automobile) undergoing a change in velocity or direction must be acted upon by some external force. Newton also said, "For every action, there must be an equal and opposite reaction."

Vehicles generally fall into two classes: (1) those in which the reaction is accomplished by the discharge of a portion of the vehicle's own mass, as in rockets, and (2) those in which the reaction forces are applied by some external mass such as water, air, or ground, as in boats, aircraft, and automobiles.

The automobile propels and guides itself through reaction to the ground. Automobiles and similar vehicles are unique in that these forces are generated through and limited by the friction of the tires. *Nearly everything connected with the subject of automobile dynamics, or handling, is related directly to the unique qualities of tires.* A great part of this discussion will deal with that relationship, but we ought to get back to the fundamentals for now.

It's important to understand the balance of forces acting on a car in a turn. Figure 1 is a "force diagram", or "free-body diagram", which shows the forces acting on a ball that's being propelled in a circle at the end of a string. The centrifugal force generated goes in a straight line from the hand through the ball's center of gravity. The reaction force is the string, which prevents the ball from leaving the circle and flying away, out of control.

Figure 2 is practically the same, except that the ball has been replaced by a car going around a circle. Centrifugal force remains the same, represented by a force pushing out from the center of the circle in a straight line through the car's center of gravity. But the ball's string has been replaced by the car's tires, which provide a reaction force through their friction with the pavement. As long as the reaction force provided by the friction of the four tires is equal to the centrifugal force generated by the car as it goes around the circle, it will stay on its path (i.e., maintain equilibrium). But should the centrifugal force become greater than the friction force of the tires, the result will be exactly like the ball's string breaking—the car will leave the circle (i.e., lose equilibrium), out of control. Remember, *for a vehicle to remain in equilibrium, the sum of all the forces must be equal.*

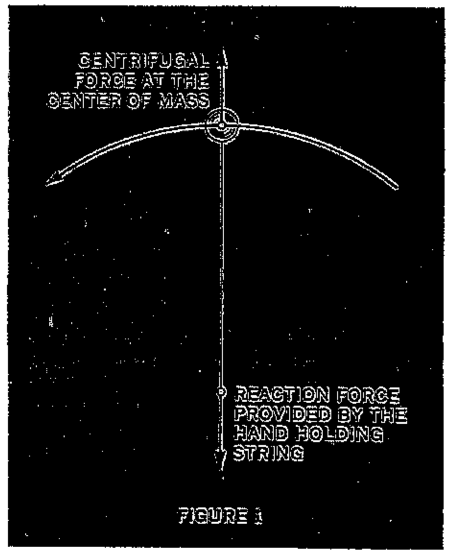

FIGURE 1

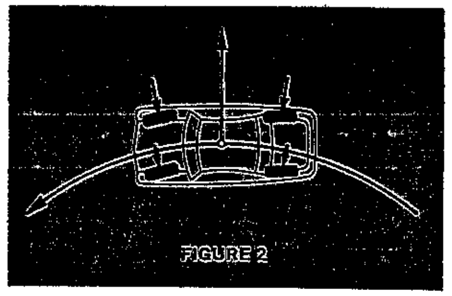

FIGURE 2

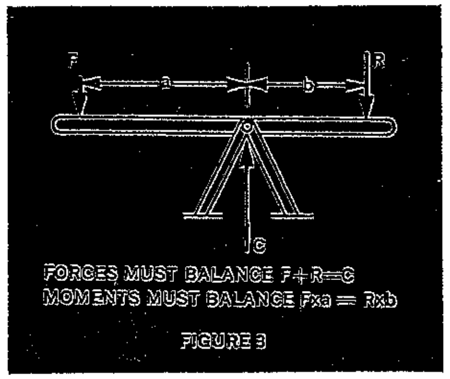

FIGURE 3

> "Any vehicle that runs on tires can benefit from rearward weight-bias."

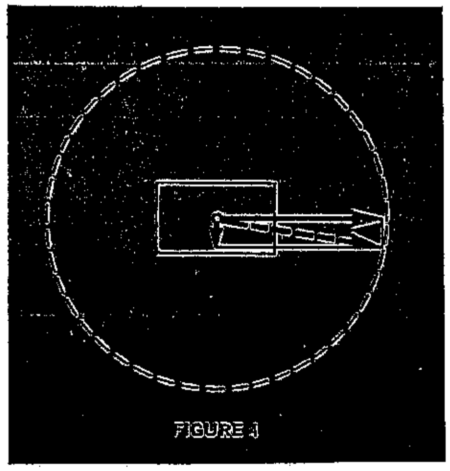

FIGURE 4

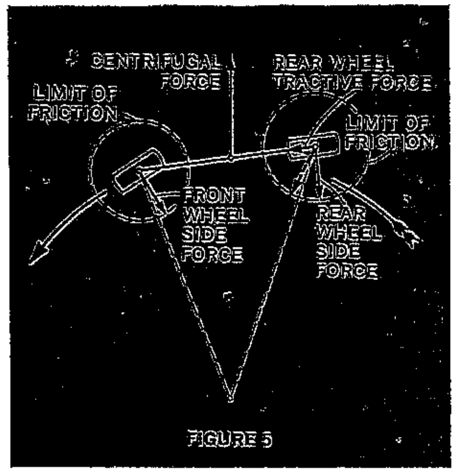

FIGURE 5

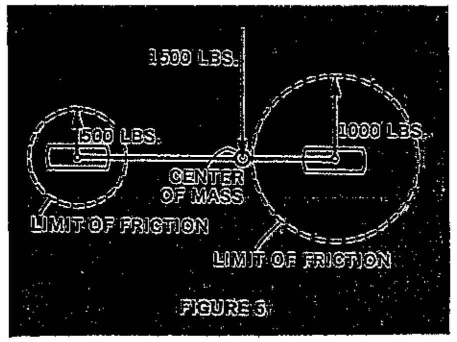

FIGURE 6

Not only does the sum of the forces have to be equal, *the sum of the moments must also be equal*—just as they equal in Figure 3, the teeter-totter. A "moment" is a force at a distance: for instance, the relationship of force "F" and distance "a" to the fulcrum. For the teeter-totter to be in a state of equilibrium, forces "F" and "R" must equal force "C", and moment "a" must equal moment "b". That simply means that the heaviest kid has to sit closer to the fulcrum in order to balance the teeter-totter. In a car, if the turning moments are not "balanced" or equal, the vehicle will turn around either axle, or its center of gravity—either increasing or decreasing the radius of the circle.

Everything we know about automobile dynamics is based on the application of the simple rules outlined above and pictured in Figures 1, 2, and 3. If that was *all* there was to it, automobile design would be as exact a science as simple mathematics, but there are some complicating factors—most important of these are the basic and unique qualities of tires that we mentioned before. In order to understand the behavior of an automobile, you must have some knowledge of (1) the *frictional* characteristics of tires, and (2) the *elastic* characteristics of tires.

Friction forces are the same in all directions. For example, the force required to slide a book sideways is exactly the same as lengthways, regardless of its proportions. Try it—take a fish-weighing scale, or any similar scale, and connect it to a book or some similar mass. No matter whether you pull sideways or lengthways, the force required to move the book will always be the same. In the same way, a sled has absolutely no directional integrity on a *hard, smooth* surface. Regardless of its runners, it can be moved sideways just as easily as lengthways.

Suppose it takes a force of 100 oz. to slide the book in Figure 4. If a force of 98 oz. is applied on the right side, the book won't move. However, if you apply another force of 20 oz. *sideways* the book will start to slide in the direction of the dashed arrow. The net result, or "resultant", of the two forces (100 oz.) was sufficient to overcome the friction force of the book, and make it slide. Remember, *if two or more forces are acting on a body, their resultant cannot be greater than the limit of friction.* The dashed arrow in Figure 4 is the resultant, the "net" or equivalent single force. The circle represents the limit of friction—no one force, or the resultant of all the applied forces, can exceed this limit, without breaking the book loose.

Like the book and the sled, *a sliding tire is incapable of steering*

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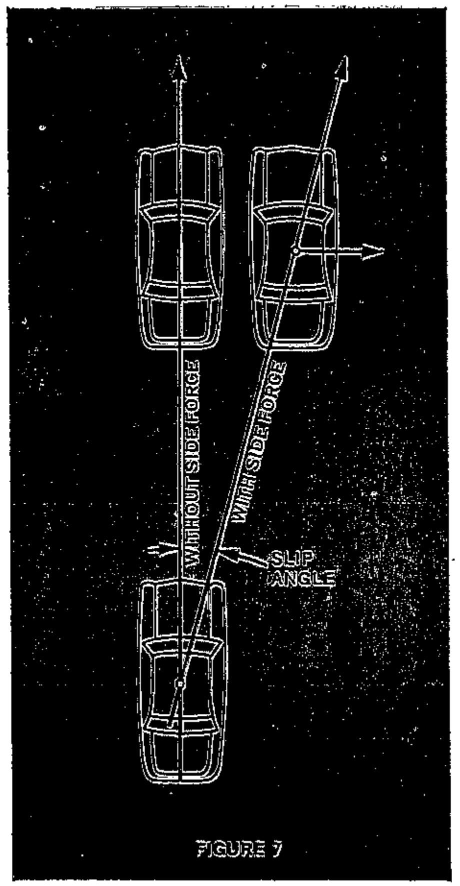


FIGURE 7

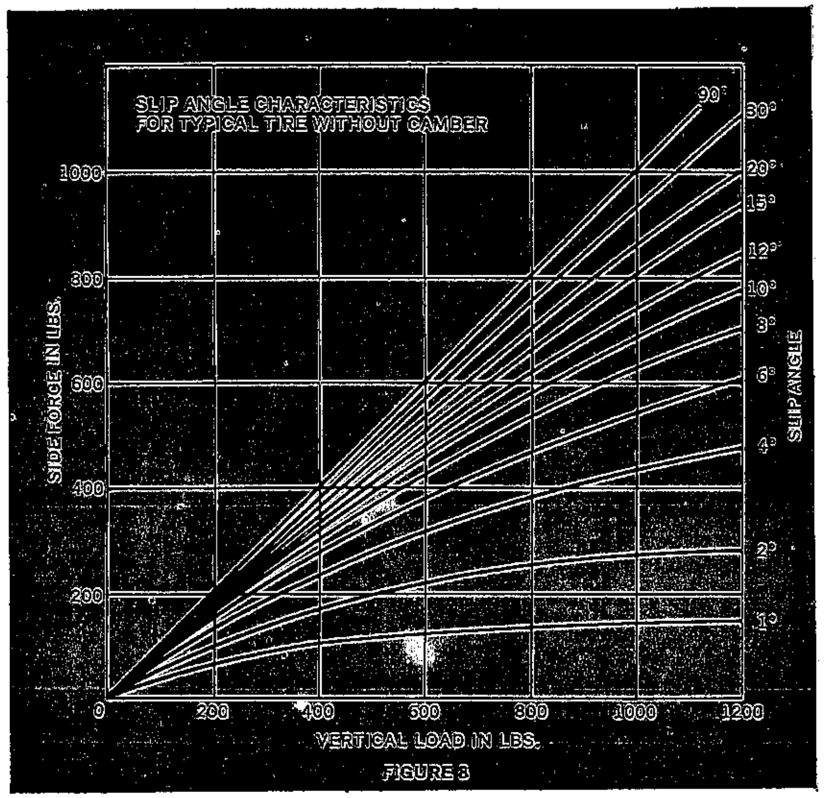
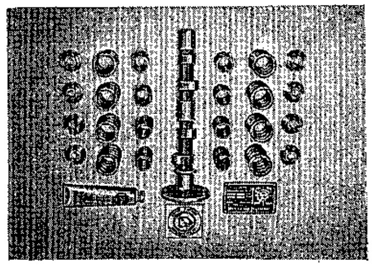


FIGURE 8



or maintaining a desired course. This means that an automobile tire must be rolling to maintain control or directional stability.

This is important, because, while rolling, the tires are required to provide the driving (traction) and braking forces as well as the sideways (cornering) force. The force diagram for a tire is the same as the one for the book. Figure 5 shows this (we have drawn a two-wheeled car for the sake of simplicity). The circle around the axis of each wheel represents the limit of friction. Recalling that the resultant of all the forces acting on a tire cannot be greater than the limit of friction, the force diagram shows that braking or traction will limit the amount of side force the tires can produce. The traction force does not necessarily limit the cornering ability of the driving wheels, but it does have a big effect on the behavior of the car while cornering.

The forces (Figure 5) that act on a car in a corner are (1) centrifugal force, (2) front and rear wheel side forces, (3) rear wheel traction force. Braking force is also a factor, but we'll get to that later.

The limit of friction we talk about is based on the "coefficient of friction". This coefficient of friction is defined as the sliding force divided by the weight. For practical purposes, this value is essentially constant for any pair of surfaces and is independent of weight. For tires on any normal paved surface, the coefficient of friction is roughly 1.0 —so that, for example, a wheel that's supporting 1000 lbs. is capable of supporting a side force of 1000 lbs. and a wheel that supports 500 lbs. will support a side force of 500 lbs. (Some race cars have coefficients as high as 1.3.)

From the standpoint of friction, weight distribution—that is, front or rear weight-bias in itself—has no effect on the balance of the car in a corner. On the other hand, inertia forces (acceleration, braking, and centrifugal) act on the mass of the vehicle, and are distributed according to the distribution of the vehicle's mass. In other words, the centrifugal force generated in a corner would be twice as great on the 1000 lb. wheel as that of the 500 lb. wheel (see Figure 6). But this has no effect relative to the limit of friction because the 1000 lb. wheel is capable of twice the side force of the 500 lb. wheel. Thus, all the forces are balanced, the vehicle in a state of equilibrium, and there is no turning moment. Remember the example of the teeter-totter?

This is an important point to remember. From the standpoint of friction, weight distribution alone has no effect upon the "balance" of a car in a corner—there is absolutely *no truth* to the commonly held belief that "the heavy end of the car will always break away first".

Fore and aft forces, like accelerating and braking, can change the distribution of vertical forces supported by the tires (weight transfer). (The atmosphere can also have this effect, but that starts to get us into aerodynamics, which is a whole new subject, best saved for another story.) Acceleration results in a force transfer from front to rear, while deceleration has exactly the opposite effect. The importance here is that these forces are made to change without affecting the distribution of mass. This does cause the vehicle to change its "balance" because the potential force at either end is changed without changing the center of mass. More important, this force transfer has a very significant effect on the sideways (lateral) deflection of the tires in a corner, which we'll explore in detail later on.

So much for the frictional characteristics of tires. Now we come to their *elastic* characteristic. This is the most important and the least understood of all the factors influencing the behavior of a car in a corner. Friction only affects the behavior of the automobile at or near the limit of adhesion. The typical

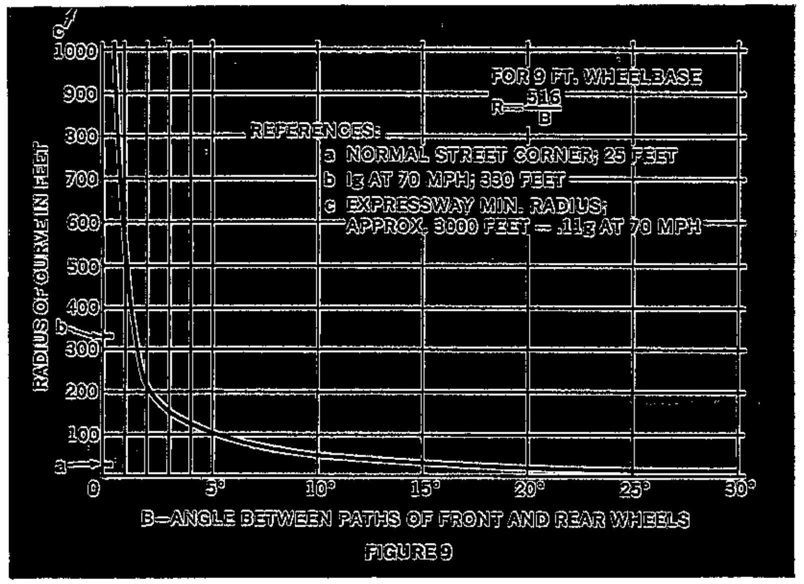


FIGURE 9

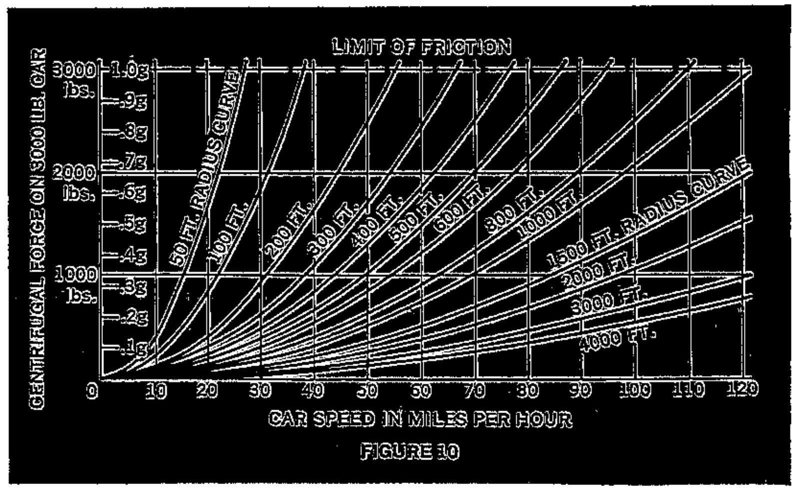


FIGURE 10

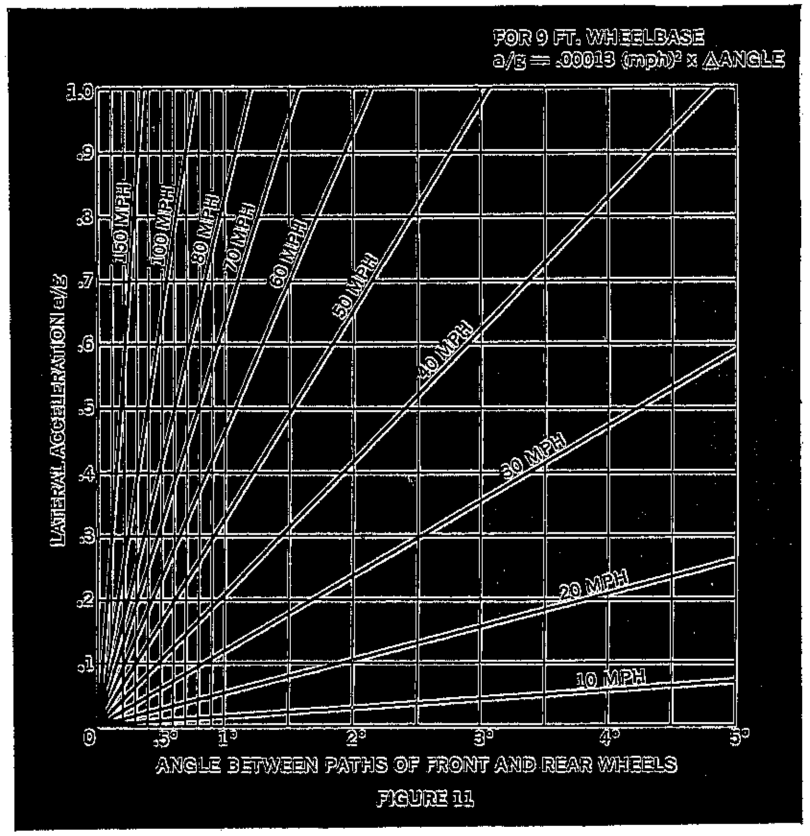


FIGURE 11

"It is not necessarily true
that 'the heaviest end of the car
will always break away first'."

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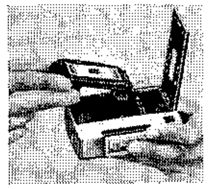

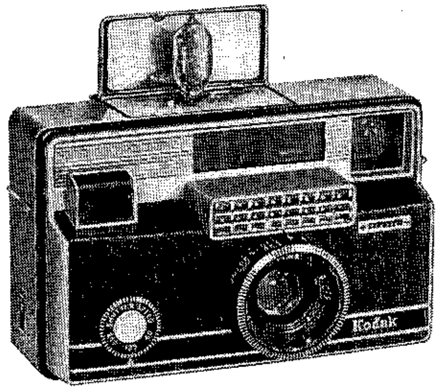

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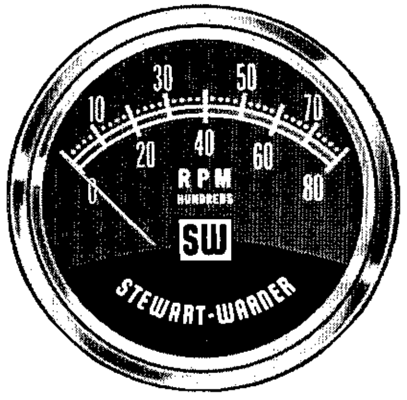

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enthusiast driver has experienced it in hard cornering or wheelspin, but the average citizen will only approach this limit in the avoidance of an accident (though he has often encountered it on ice or snow or wet pavement). Conversely, the elastic characteristic of the tires is significant throughout the driving habits of every driver—whether he's a conservative plugger or a hot dog.

A tire subjected to a side force will deflect just like any other elastic body. If it's rolled along a flat surface in this deflected condition, it will diverge from the path that would have otherwise been in line with the wheel. *The angle between the center plane of the wheel and this divergent path is called the slip angle.* (Note: this does *not* mean that the tire is sliding.) If the front and rear tires are deflected by the *same* amount (i.e., if the slip angles are equal) this path will be a straight line. If the front and rear tires are deflected by *different* amounts (i.e., if the slip angles at one end are greater than at the other) this path will be curved.

This is a crucial point, and it must be understood if you're going to get anything out of this. *Any change in the curvature of the vehicle's path results in a change in centrifugal force which changes the deflection of the tires which changes the curvature, et cetera.* This coupling between slip angles, radius, and centrifugal force is the basis for all automobile dynamic behavior.

If the change in slip angle is greater in the front than in the rear, the curve gets larger, *reducing* the centrifugal force and thus bringing the car back into a state of equilibrium. Such a car is self-compensating, in that it will seek that radius which results in a balance of forces (equilibrium) independent of the driver's reactions. Understeer is often called "safe" because of this. The truth is that the radius where equilibrium is restored may be far larger than the road permits—meaning that the car might just understeer straight off into the trees.

On the other hand, if the change in slip angle is greater in the *rear* than in the front, the car may *not* be self-compensating. The larger change in the rear slip angles steers the car into a smaller circle, *increasing* the centrifugal force which further reduces the circle, et cetera. If this rate of slip angle change is fast enough, the car could become uncontrollable, regardless of the driver's skill.

If the rate of change in slip angle is greater in the front than in the rear, the resulting condition is called understeer.

If the rate of change in slip angle is greater in the rear than in the front, the resulting condition is called oversteer.

If the rate of change is equal, it is called neutral steer.

This is where the confusion starts. Everybody and his brother has an opinion, and too many claims and counterclaims are made on the basis of oversteer *or* understeer. It's prac-

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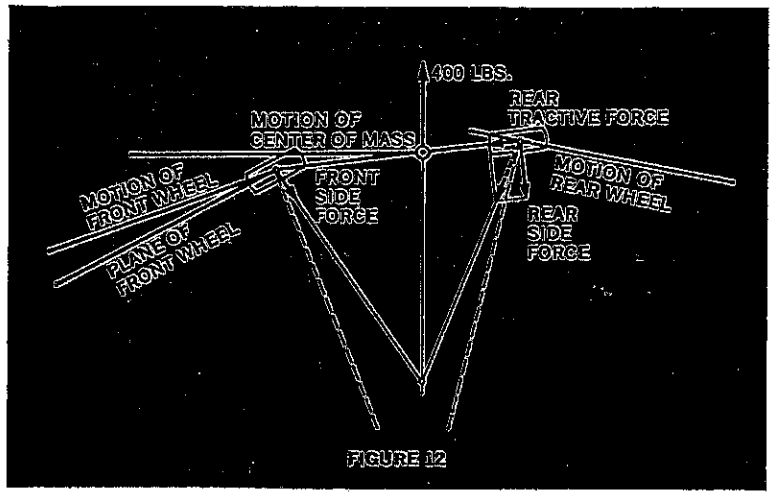


FIGURE 12

> "Within certain limits, oversteer can be both useful and desirable."

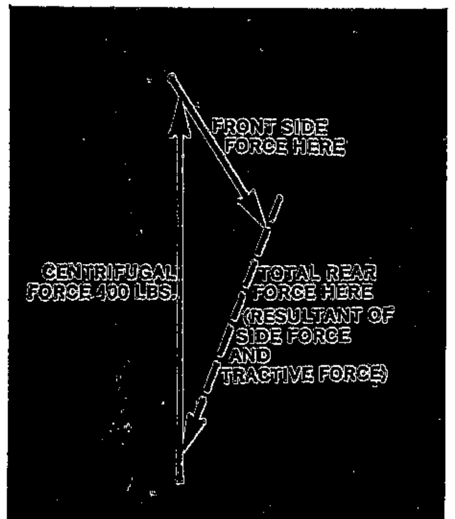


FIGURE 13

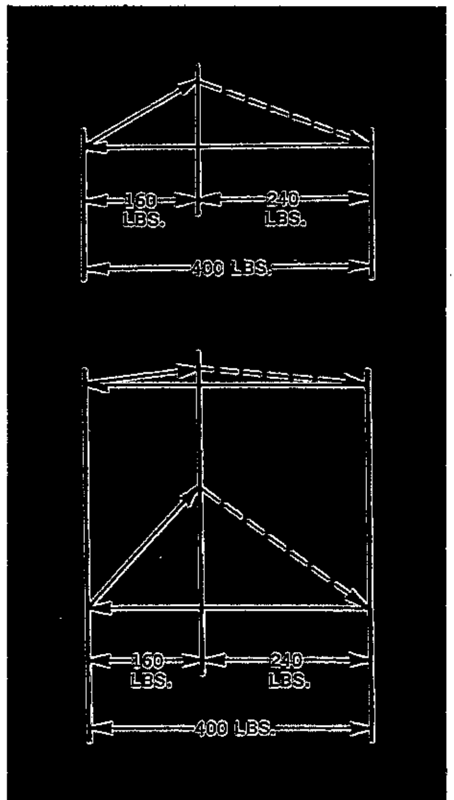
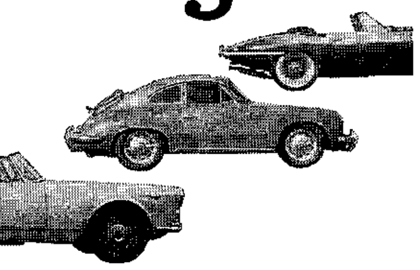


FIGURE 14

Any New Foreign Sports Car



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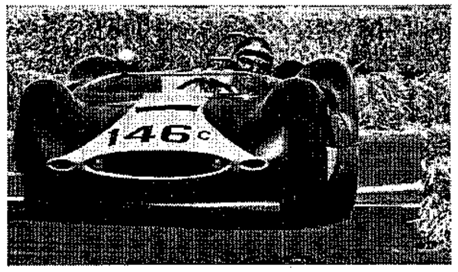

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tically impossible to argue this subject on an "either/or" basis—there's no "good" or "bad" connotation involved, they are simply transient conditions in vehicle behavior. What's important is not "which", but "how much of which". There are acceptable and useful degrees of both. The degree varies in any given car with changes in speed, traction, braking, distribution of passengers and luggage, et cetera. Neutral steer is only an imaginary boundary between over/understeer. The likelihood of actually attaining neutral steer over any broad, useful range is pretty remote since it's really just a phase, a delicate balance affected by dozens of factors.

Furthermore, there's no such thing as a *state* of over/understeer. They are, in fact, *events*. It's the self-compensating or self-energizing characteristic that's significant in a car's behavior. These are what the driver can *feel*, and what he talks about. He expects his car to do what he wants, not what it wants. This is what makes a car *easier* or *more difficult* to handle (not *easy* or *difficult*).

We've established that oversteer is a transient where the proportionately greater increase in rear slip angles results in a smaller turning radius, which increases centrifugal force, which makes the radius still smaller, et cetera. However, if each increment-increase in centrifugal force produces successively *smaller* increments of radius reduction, it's possible for the car to achieve a state of equilibrium. *Thus, contrary to a popular misconception, it's quite possible to attain "stable" oversteer.*

There will always be some speed at which the degree of oversteer, however small, will result in self-energization. Increasing self-energization will require increasing degrees of driver skill, and ultimately this requirement can exceed *any* driver's capability. However, oversteer can be both useful and desirable.

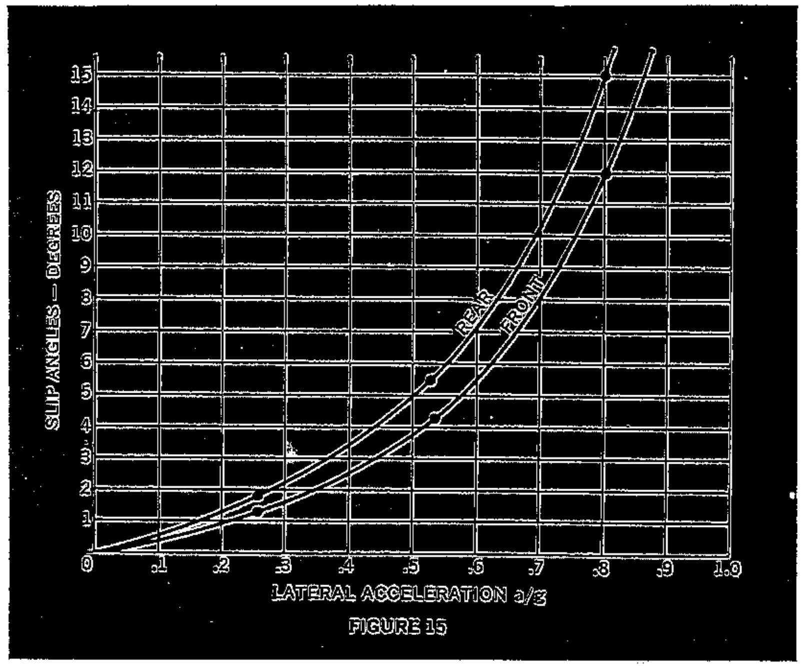


FIGURE 15

> "From the standpoint of friction, weight distribution has no effect on the 'balance' of a car in a corner."

Well, now that we've defined slip angles, and their basic relationship to over/understeer, we'd better examine them in detail. It's safe to say that if it wasn't for slip angles—if we could have cars that literally cornered "on rails"—there'd be no such thing as over/understeer. *Slip angles, and not weight distribution or engine location, are the determining factor in the way a car negotiates a corner.*

Slip angles can cause a car to be "steered" or deviated from its path by factors other than a change in the angle of the steering wheels. There are several such factors, and they're listed here for reference.

1. A change in centrifugal force.
2. Changes in atmospheric forces (wind gusts).
3. Changes in the plane of the road surface.
4. Changes in the plane of the wheels, due either to suspension deflection or to "toe" and "camber" changes in the suspension geometry.
5. Changes in vertical force or pitch, due to acceleration or deceleration.
6. Changes in vertical force due to lateral weight transfer.

The graph in Figure 8 shows the relationship of vertical force (i.e., weight) and side force to slip angles. It should be noted that although a tire's ability to produce a side force increases with increasing vertical loads, the resultant slip angle also increases, getting progressively closer to the tire's limit of adhesion (line 90 on the graph, representing 90° of slip angle).

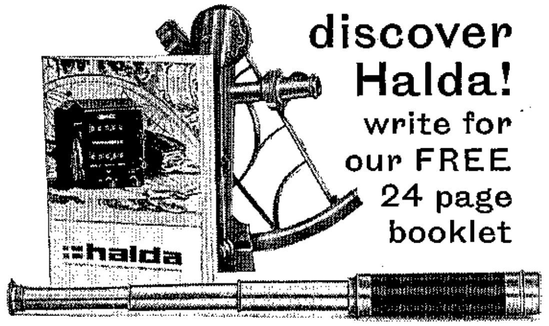
Let's consider a typical passenger car, being gradually deflected from its course into an ever-diminishing turning radius. The increasing deflection of the tires and the resulting slip angles will determine the precise path of the car as the turn tightens. If there is a difference between the paths of the front and rear wheels, the car will generate a curve which will produce a change in centrifugal force, which will cause further tire deflection and a changing curvature in the car's path. This curve is shown in Figure 9, and shows the angle between the paths of the front and rear wheels of a car with a 9-ft. wheelbase. This angle—the difference in the paths of the front and rear ends of the car—often results in the tail-out cornering attitude of racing cars, and is sometimes erroneously referred to as a "four-wheel drift", or a "power-slide". All it is, really, is the natural attitude of a cornering vehicle at a given speed—there's no "drifting" or "sliding" going on at all.

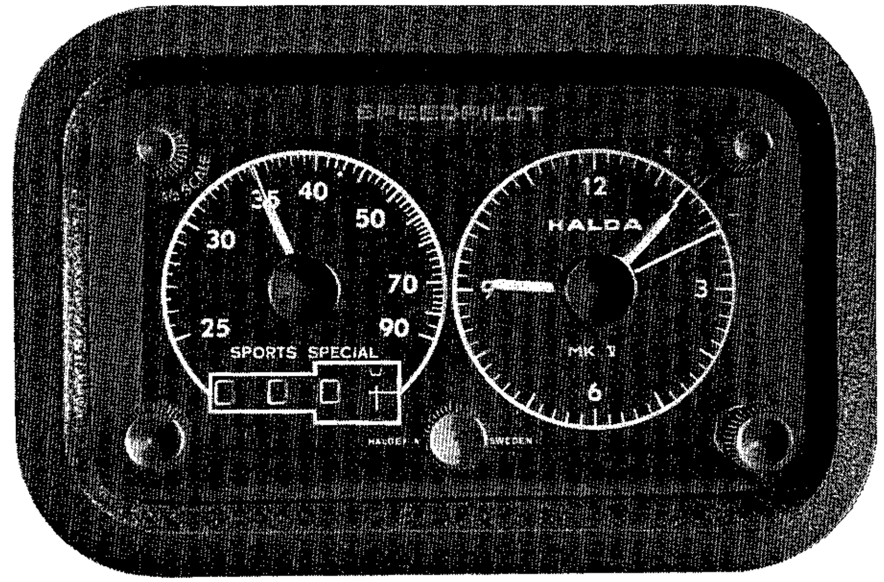
The curve in Figure 10 illustrates the effect of velocity and radius on centrifugal force. Figures 9 and 10 can be combined to show the relationship between the difference in path angles, centrifugal force, and car speed. Study the two for a moment, and you'll see just how critical tire characteristics are in cornering.

For example, if a car is traveling at a speed of 70 mph on a curve resulting in a lateral acceleration of .15g, the difference in paths would be only ¼ degree. If some disturbance such as an uncalculated movement of the steering wheel were to cause an increase in rear slip angle of ¾ degree, the lateral accelerations would increase to .62; far beyond normal operating limits and approaching the limit of controllability for *any* passenger car.

Take another look at Figure 8, the curve of tire slip angle characteristics, and consider again our simplified two-wheeled car—a heavy one, 1500 lbs., with 60% of the weight rearward for 900/600 lbs. distribution (Figure 12). If this vehicle is traveling in a circle at a velocity that results in a centrifugal force equal to 400 lbs. or .267% of the 1500 lb. total weight (this, incidentally, is described as a lateral acceleration of .267g), the resulting force at the front wheels would be .267 x 600=160 lbs. and .267 x 900=240 lbs. at the rear. The resolution of these forces is illustrated graphically by connecting the heads and tails of the force vectors, as in Figures 13 and 14. It is clear that the *side forces* on the tire must be somewhat larger than the balancing forces. In fact, the *balancing force* (160 lbs.) on the front wheels is the component of the front side force parallel to the centrifugal force.

How much larger the side force must be is dependent on the angle. It is, in fact, a function of the cosine of the angle. This angle is significant when operating at large slip angles and/or on small circles, and insignificant at small slip angles and large circles. The small circle need not be considered here. Let's assume that the balance or cornering force is equal to the side force. Referring to the slip angle curve again, the front tires, with 600 lbs. vertical force and 160 lbs. side force, would be operating at a 1.4° slip angle, and the rear (900 lbs. vertical





and 240 lbs. side) would be about 1.8°. In other words, in going from a straight line to this .267 lateral g curve, there would have been a 1.4° change in front and 1.8° in the rear. (Some degree of oversteer because the larger rear end deflection steers the car in a smaller circle, et cetera.) Assume that the driver is able to correct by reducing his steer angle. Now, suppose the speed is increased on this same radius until the centrifugal force is increased by another 400 lbs. (to 800/1500 lbs., or .533g). This will require a reaction force of .533 x 600=320 lbs. at the front and .533 x 900=480 lbs. at the rear. Referring again to the curve, this would result in a front slip angle of 4° and a rear slip angle of 5.5, an increase of 2.6° front and 3.7° rear. With another 400 lbs., or 1200 lbs. total which would be .8g—a requirement of 480 lbs. front and 720 lbs. rear—the front slip angle would be 12° and the rear 15°—a change of 8° front and 9.5° rear. By this process you can see that the degree of oversteer increases with the increasing speed (Figure 15). If the weight distribution is reversed, the vehicle will understeer. If the distribution is equal, it will be neutral.

If the distribution is 60% rear, the vehicle can be made to understeer by changing the relative stiffness of the front and rear tires. This could be done by using different tires, or by using the same tires with lower pressure in front, or wider rims in the rear.

From most every standpoint, except cost and cooling, the rear engine car and its rearward weight distribution is desirable. This is especially true in the handling characteristics of a high performance car. A front engine, rear drive configuration with a predominance of weight forward is an inferior race car due, among other things, to inferior acceleration and cornering capability. It has limited tractive ability, the inside rear wheel gets lighter in the corner and slips under traction, and loses its side force. This can be corrected by use of a locking differential. However, the resultant unequal tractive forces constitute a turning moment of such magnitude that it is much more difficult to cope with. The heavier the rear end, the less important this problem. In fact, all world championship race cars are rear-engine rear drives with about 60% of their weight on the rear wheels. The same is true of the world's best sports cars, and it will soon apply to American Championship, or Indy, cars as well. This is a recent trend because only recently have engineers had enough understanding to balance a predominantly heavy rear end. It's inevitable that we will learn how to cope with even more rearward weight bias and the resulting cars will be even better.

It's often assumed that all race cars are roughly alike, that an expert driver makes the difference in the corners. This is far from true. In short, *it is extremely important to realize that a rear engine car is not inherently oversteering, that it is, in fact, capable of superior handling.* Unfortunately, many people intuitively, and by hearsay, believe that the rearward concentration of mass is a controlling factor in cornering behavior. This is true only because of the slip angle characteristics of tires. If there were no slip angles, there would be no problem. As long as there is a means of controlling the slip angle through tire and vehicle design, the "problem" can be and has been solved.

(End of Part One—Jim Hall will conclude the story next month.)