WHAT MAKES CARS HANDLE?
Part II
By Jim Hall with David E. Davis, Jr. (Car & Driver May 1965)

Part one of this article explored the fundamentals of automotive dynamics, or handling. Among other things, we established the fact that the rear-engined car, with its rearward weight bias over the tractive wheels, has a fundamental advantage over the conventional front-engine, rear-drive configuration from almost every standpoint. This is especially true in high performance cars.

Just looking around, it would seem that automobile designers have been a little slow to utilize this inherent advantage, but you can read some history and maybe see why. The early experiments with rear-engined cars were evidently pretty hairy, and if you look at the cars involved, it's understandable. Stirling Moss once said, "The poor road-worthiness of the 1934 Auto Union damned the rear-engine principlefor twenty years".

Bad experiences with cars like the Auto Unions gave support to the popular misconception that the heavy end must be forward for stability - in anything. Various examples are cited to "prove" that the weight belongs in the front-using the arrow, for instance-but it ain't so. Both the cave man's arrow, with its great flint head, and the modern version, with its light metal tip, owe their directional stability to the rearward placement of the feathers; it doesn't really make any difference where the weight is.

Compare the modern jet plane, with its wings far back on the fuselage, to a World War I pursuit plane, where the wings and the engine and all the mass were concentrated right in the front. The truth is that weight distribution, by itself, has nothing to do with good or bad, safe or unsafe vehicle behavior – whether we're talking about arrows, or airplanes, or automobiles.

These, and similar misconceptions, and the human being's innate resistance to change, may explain why so few people have been willing to accept the rear-engined car. The significance of these prejudices is pretty apparent in the reluctance of the old timers at Indianapolis to accept the "funny little cars".

What are these advantages? Well, let's examine a few. On acceleration, the initial predominance of weight on the rear-engined car's rear wheels, plus the force transfer from front to rear, gives the rear tires extra friction force. This is essential to produce large tractive forces, plus side forces for tractional control. It's also true at very high speeds where the tractive forces increase due to air resistance.

For a race car, rearward weight bias is a plus in both performance and controllability. The average driver, in any passenger car, will probably never use these advantages on dry pavement. But when the road gets slippery from rain or snow, every driver has to operate at or near the limit of friction, and these advantages can make the difference between going or not going, and maintaining control or losing it.

Another advantage occurs in braking. Due to the transfer of vertical force from rear to front, a car with equal weight distribution, or with a slight forward weight bias, must do most of the braking with the front wheels. This puts a lot of energy into the front brakes in the form of heat, and they'll get plenty hot on a series of hard stops from high speeds. At the same time, however, the rear brakes aren't working too hard, and they have relatively little heat to dissipate.

A rearward weight bias tends to offset this vertical force transfer so that the braking effort can be more equally distributed between the front and the rear wheels. This puts less heat into the front brakes and more into the rear, resulting in more uniform brake temperatures and faster dissipation of heat by the whole system.

Structural problems are simplified with the rear-engined car. Forward visibility is far better. The rear-engined car lends itself to more efficient aerodynamic shape. Noise and cockpit temperature problems are also substantially reduced.

But let's get back to handling. If there weren't any tire slip angles, the advantages of rear weight bias could be achieved with no further effort. However, since slip angles can't be completely eliminated, we have to consider tires, roll steer effects, and lateral dynamic force distribution-the three ways that we have to equate slip angles or to compensate for the differences that occur between front and rear.

First, tires-the effects of the difference between front and rear slip angles can be minimized by making those slip angles as small as possible. Such factors as large tire sections, wide rims, optimum tire pressures, carcass construction, tread, and rubber compound, all contribute to the reduction of slip angles.

Also, front and rear slip angles can be equated, or "balanced", by putting tires with greater cornering ability on the heavy end of the car. This can also be achieved by higher pressures, wider rims, et cetera.

Roll steer effects are self-steering effects, caused by the roll of the body due to centrifugal force. "Any" degree of roll-steer may be designed into the front or rear suspension, or both. Roll steer doesn't change the slip angles, but moves the wheels to compensate for them. There are two forms of roll steer effects: Toe change, that is, a change in the wheel's direction of travel, and, camber change, a change in the angle between the wheel and the road surface.

The third way to equate, or "balance", slip angle differences between the front and the rear is lateral dynamic force distribution. In cornering, there's a transfer of vertical force from the inside wheels to the outside wheels. Since vertical force has a direct effect on tire slip angles, the distribution of this force transfer can be used to "balance" the slip angles.

Due to centrifugal force, the mass of the vehicle rolls on its suspension. This roll can be utilized to "steer" both front and rear wheels to compensate for oversteering or understeering slip angles. This can be done very effectively since the angular displacement of the body relative to the wheels depends on the centrifugal force, as do the changes in slip angles. Therefore, the suspension geometry can be designed- to steer the wheels in the compensating direction.

There are disadvantages, however, in that a high degree of roll itself is negative. With the discussion of tire characteristics in Part 1, we've shown that slip angle changes occur with changes in vertical force. Since the body has mass, it takes some interval of time for it to roll through some increment of angle. During this period of time, the vertical forces are changing on the tires, so that the slip angles are changing, and the vehicle path is continuously changing as well. The result is a car that's sloppy and slow in response.

There's one point of view that roll has an advantage, in that the driver is less apt to get into a corner too fast due to his consciousness of the high degree of roll. I don't buy this view because he's already in trouble if he's gone in too fast, and I think he'd have a better chance to recover with the more responsive car.

In addition, it's pretty difficult to match roll steer to the non-linear tire characteristics you encounter at the very high lateral accelerations experienced in racing.

One of the considerations in suspension design is control of camber; that is, the angle of the plane of the wheel relative to the horizontal plane of the road. A wheel at such an angle exerts a side force, as you can see from the diagram in Figure16. If the road surface were removed for a moment, it's clear that a

FIGURE 16

FIGURE 17

FIGURE 18
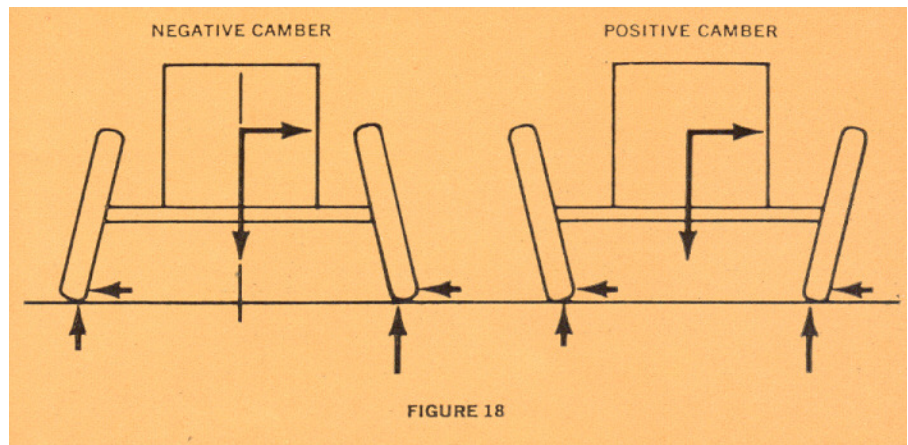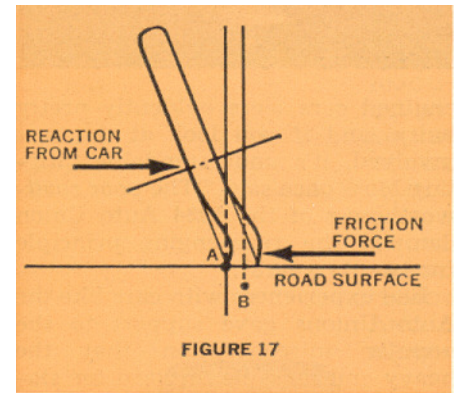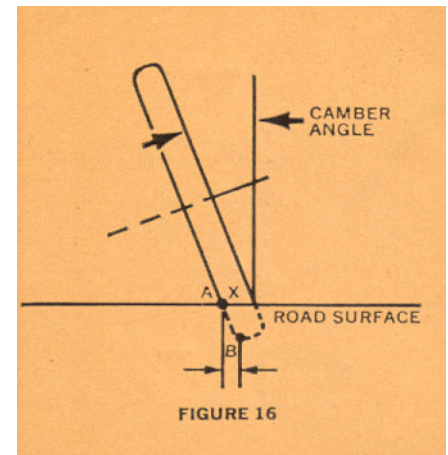
particle of rubber (X) would move sideways with rotation from point A to B. However, if the road surface is in the position shown, the same particle (X) would be restrained by friction in a line through A. The wheel and force diagram would then look like Figure 17. This friction force produces a thrust on the vehicle to the left.

FIGURE 19

The wheel may be tilted either inboard or outboard (Figure 18), and since the outside wheel has the greatest centrifugal force, it provides the maximum cornering power. Negative camber adds to the cornering power while positive camber subtracts.

Since neither negative nor positive camber can increase or decrease the ultimate side force of the tire, and since it does increase tire wear, it should be generally minimized. However, there must be deflection or compliance of the suspension and structure in any car. Therefore, some amount of static camber may be necessary so that the wheel will be as perpendicular as practical for uniform tire wear at high side forces.

Lateral dynamic "weight" transfer refers to the lateral transfer of the vertical forces at the tires, in cornering. The rate of force .transfer at the front or rear, expressed in its percentage of the total, is called roll couple distribution.


FIGURE 20

There are two basic approaches to the control of roll couple distribution-spring rates in roll and relative roll center heights.

Figure 19 shows how a cornering car without springs transfers force in proportion to the ratio of the height of its "center of mass" and the track, or tread. The higher the center of mass, the larger the force transfer. In fact, this can be expressed with this equation: $F_o - F_i = F_c x^{h/t}$. Figure 20 shows the same condition if the mass of the vehicle is sprung. With minor exceptions, the force transfer is the same but the rate has changed, as in Figure 21.

If both ends of the vehicle are similarly sprung, the selective use of front and rear spring rates can give "any" desired rate of force transfer between the front and rear wheels.

FIGURE 21

Figure 22 shows very stiff rear springs and relatively soft front springs, as would be used to support a rear engine. As centrifugal force is generated, the rate of vertical force transfer will be higher in the back than the front. With the same tires, front and rear, the slip angle change will be faster in the rear than front and the car will over steer for two reasons: First, due to the predominance of rearward weight and, second, due to this weight, higher rate (stiffer) springs are required in the rear to give the desired ride control. The dynamic distribution of "weight", that is, verticail forces at the tire, would look something like Figure 23.

Since the "heavy" outside wheel provides the predominant cornering force, this car with typical tire characteristics, would oversteer. High rear tire pressure would reduce oversteer. Roll understeer would also reduce the effect of oversteer .
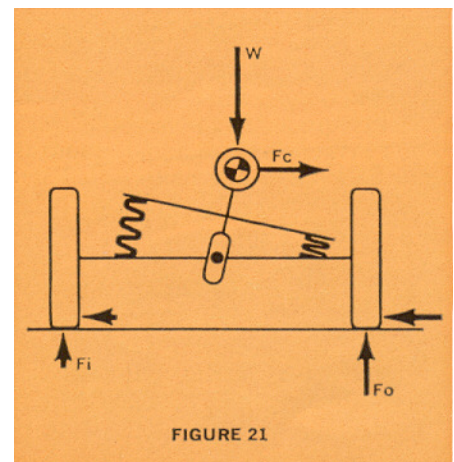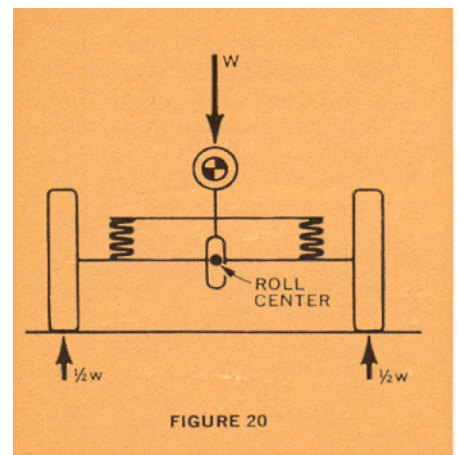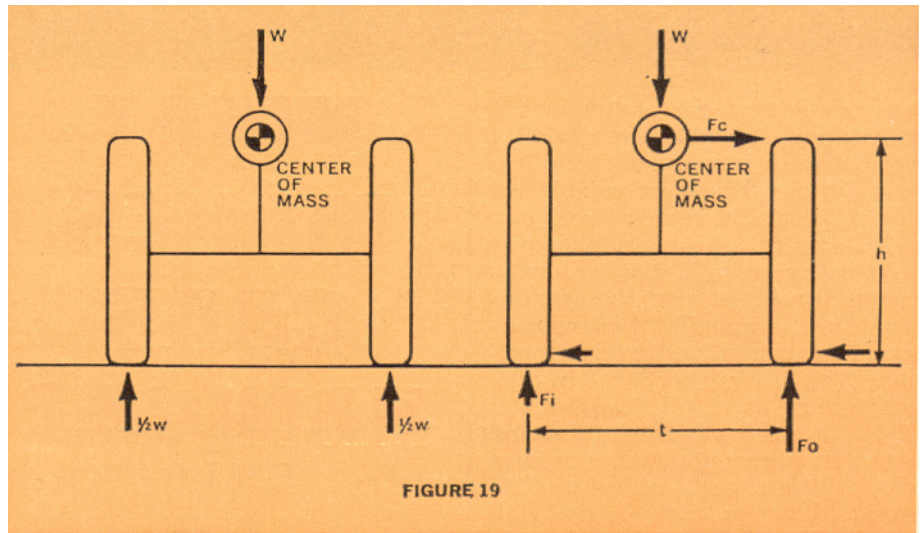
A more direct solution, however, would be to alter the springs to increase the relative stiffness in the front to achieve the desired relative rate of force transfer. They could be increased so that the rate of transfer would be the same, more, or less. However, this wouldn't be tolerable from the standpoint of ride.

A better solution is to maintain the required vertical rate for ride but increase the roll rate. This can be done by adding a torsion bar between the mass and the front wheels so that it twists in roll but does not twist when both wheels hit a bump together (Figure 24). This is called a stabilizer bar.

The stabilizer bar doesn't affect the ride when both front wheels move up and down over bumps and undulations together, but it does affect the ride if only one wheel hits something like a bump or a pot hole. For this reason, there's a limit to the roll stiffness that's tolerable with a stabilizer bar. Furthermore, an excessively heavy stabilizer bar will result in "road wander"-the car will tend to follow the lateral undulations of the road surface.

Now let's talk about roll centers. Roll centers are points, determined by suspension geometry, about which the car tends to rotate when subjected to a side force. You can understand how roll center heights affect the dynamic force transfer by looking at the forces acting on an axle. For simplicity, we will consider a schematic vehicle having solid front and rear axles as shown in Figure 27, although the discussion applies to independent suspensions as well.

An imaginary line connecting the roll centers is called the "roll axis". In Figure27, it's shown as a shaft connected to the axles by bearings at the roll centers so that it's free to rotate. The mass of the car is represented by a ball attached to the roll axis at the location of the center of mass (center of gravity) which is above the roll axis.

When centrifugal force, due to cornering, acts at the center of mass (as in Figure 28), it tends to rotate the mass about the roll axis. This compresses the springs at the outside, increasing their load, and relaxes the springs at the inside causing their load to decrease. In addition, there are side forces
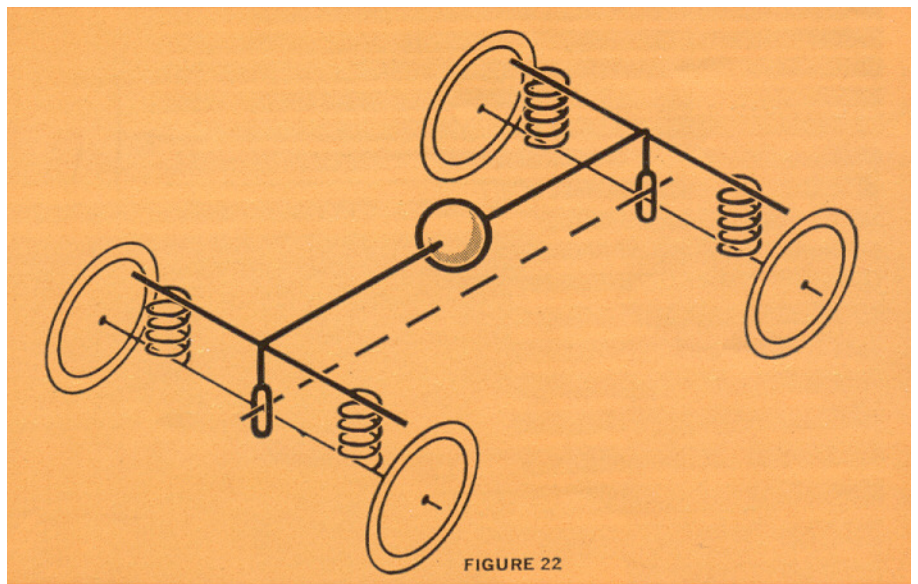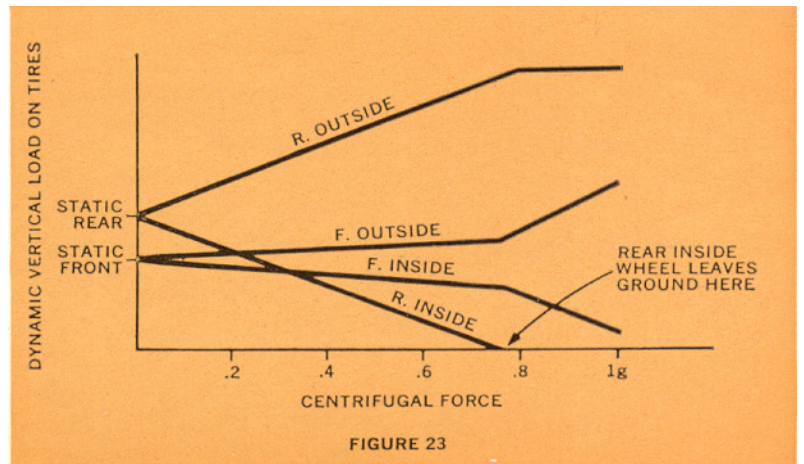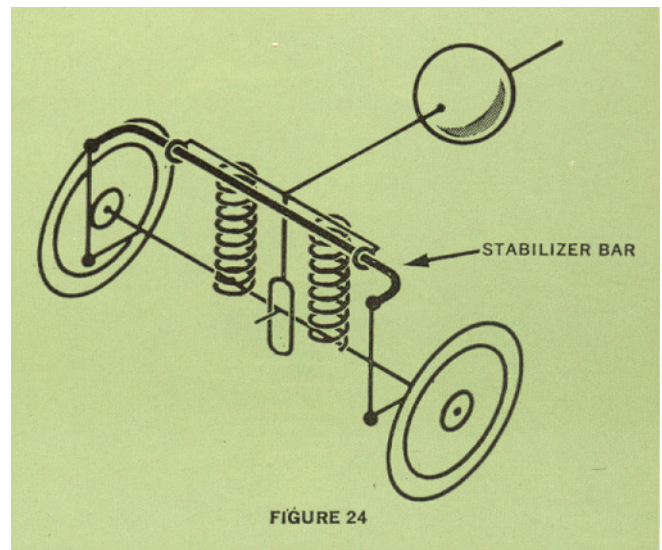

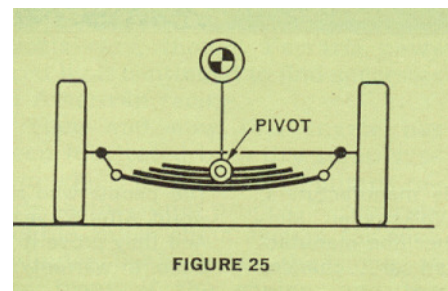FIGURE 22

FIGURE 23

STABILIZER BAR

FIGURE 24

PIVOT

FIGURE 25

at each of the roll centers whose resultant forces balance the centrifugal force. The relative magnitude of forces at the front and rear roll centers depends upon location of the center of mass (static weight distribution) .

Consider the forces acting on a single axle, as shown in the diagram in Figure 29. We have unequal spring forces which load the outside wheel more than the inside. We also have a side force at the roll center which is resisted by tire side forces located

FIGURE 26

at the ground. If the roll center is above the ground, we have a transfer of vertical load from the inside wheel to the outside wheel, as described earlier. .The magnitude of this force transfer depends upon the ratio of roll center height to tread width (hr/t), and also on the magnitude of the force.

Thus, there are two ways that an axle can experience dynamic force transfer. First, due to roll of the vehicle and the resulting change of spring loads, and, second, due to a side force acting at the roll center.

The relative significance of these two phenomena depends upon the height of the center of mass relative to the roll axis. Study Figure 30: if one or both of the roll centers are raised so that the roll axis passes through the center of mass, centrifugal force - acting at the center of mass - will produce no rotation about the roll axis. Since the springs aren't affected by this, the dynamic force transfer will be due entirely to side forces at the roll centers. This effect will be relatively large because the roll centers have been raised.

On the other hand, if both roll centers are lowered to the ground so that the roll axis is on the ground (as in Figure 31), centrifugal force acting on the center of mass will produce a strong tendency to rotate it about the roll axis. This will cause

FIGURE 27

FIGURE 28

correspondingly large changes in spring forces with resulting force transfer. However, the side forces at the roll centers, being at the ground, will produce no force transfer. Note that as one effect increases, the other decreases. Actually, their total must be the same in every case.

The roll couple distribution is influenced by the manner in which force transfer is transmitted to the wheels. That portion which is transmitted by the springs is distributed according to the relative stiffness of the front and rear suspensions in roll, which is influenced largely by ride requirements. This was covered in detai1 earlier. The portion which is transmitted by side forces acting at the roll centers is distributed according 'to the mass distribution (static weight distribution), and the heights of the roll centers.
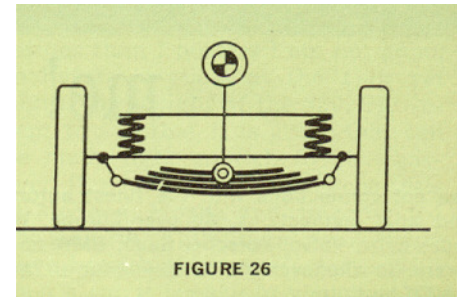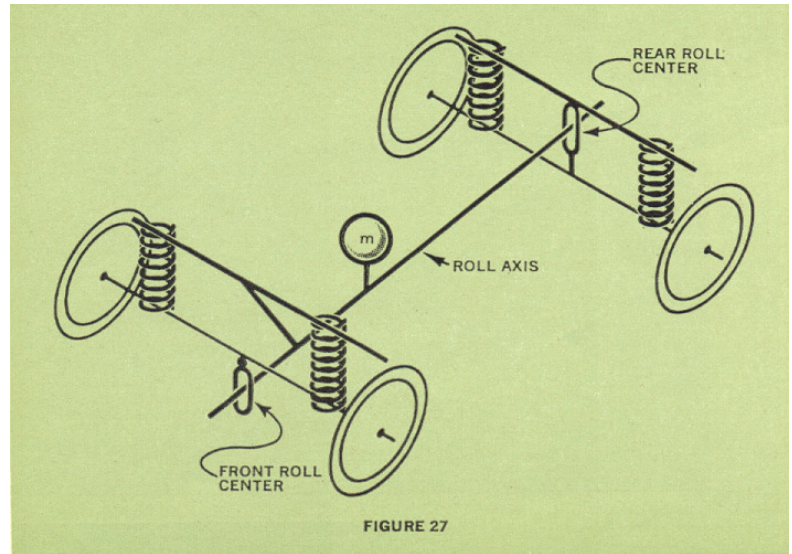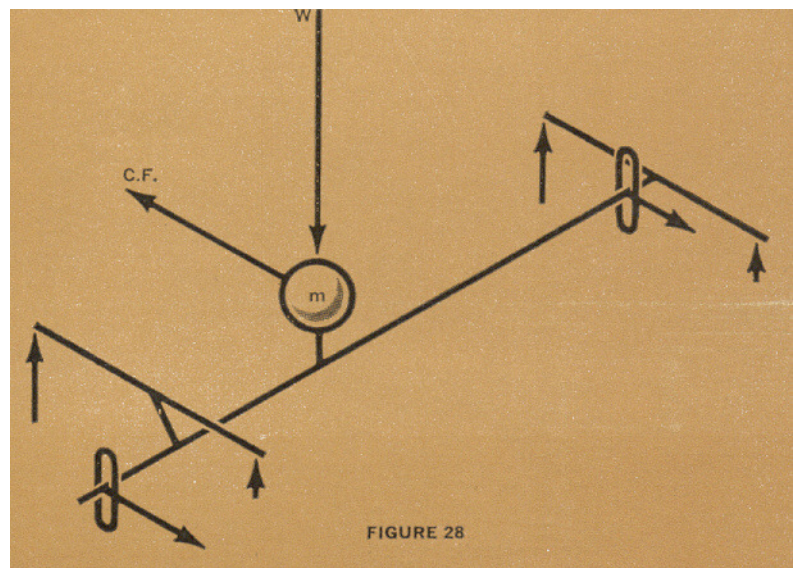
In summary, due to the influence of "mass" distribution and the inevitable dynamic force transfer on tire deflection, the engineer utilizes some degree of all the design variables significant to vehicle behavior under the influences of side forces.

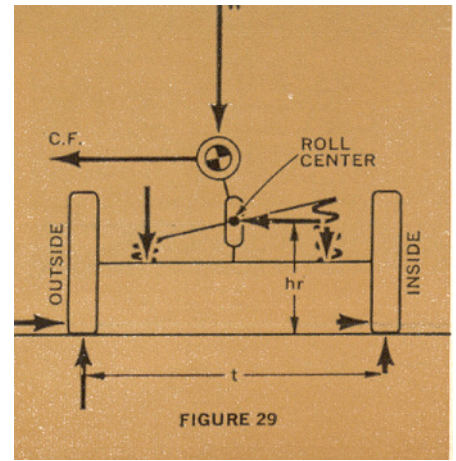1. Vehicle Proportions a. ratio of height of center of mass to tread.
2. Tire Design
a. structure, b. pressure, c. rim widths, d. tread, e. compound.
3. Suspension Design ,
a. Roll steer 1. toe change, 2. camber change.
b. Roll couple distribution, i.e. ratio of front and rear spring rates (a) Vertical spring rate, (b) roll spring rate.

FIGURE 29

I think that does it. These are known elementary physical relationships, used by the automobile designer to achieve the desired handling characteristics for a given automobile. No new natural laws have been discovered, but a lot's been learned about their specific application since those hairy adventures with rear-engined high performance cars back in 1934. The best evidence is the whole rear-engine revolution in race car design, and the fact that we've seen more and more successful rear-engined passenger cars on the street in the last ten years. There is little question that more will follow.

In part I, we set out to discuss the fundamentals of automotive behavior, and that's what we've done.

FIGURE 30

I'm not real keen on getting into any specific details of the arrangements on the Chaparral, and that why we've kept it basic. We're no deliberately holding back any information. However, the way we've applied these fundamental principles to the Chaparrals is going to be our secret. There are quite a few people building race cars who have their own notions about all this, and I'm not about to write a set of specifications for their equipment. The racing business is plenty tough enough the way it is. C/D

FIGURE 31