SCIENCE AND THE CHASSIS PART II

FUNDAMENTALS OF SUSPENSION

BY ROGER HUNTINGTON

LAST MONTH we discussed the construction and operating characteristics of the pneumatic automotive tire. Tires give the final contact between the car mass and the road it runs on—so must supply the grip to resist all the combinations of forces that act on a car in motion.

This month we will study the basic principles of the suspension system that flexibly connects the car body, or sprung mass, to the tire-wheel assembly. A suspension system does more than just cushion the ride. The various resistance relationships between front and rear suspensions have a vital influence on the actual vertical loads on the four tires that are exerted by all the forces acting on the body. This aspect is the next logical step in our understanding of the chassis.

The Masses

The fundamental automotive suspension layout is very simple. There is the main structure of the car—the body, frame, engine, etc.—suspended above the wheels and axles through various types of springs. The weight actually suspended on the springs is known as the "sprung mass." The weight of the wheels, tires, axles, brakes and suspension members that move up and down with the road wheels is the "unsprung mass." The two masses are connected basically by the suspension springs.

Shock absorbers serve to damp out the relative oscillations between the two spring-suspended masses. They do this by forcing oil through a restricted passage. The vertical energy of the sprung and unsprung masses is converted to heat in the oil. If you didn't have shock absorbers (more correctly called "dampers") the body would pitch and bounce up and down continually in a slow, rolling motion. The wheels would hop up and down, and the suspension stops would "bottom" against the chassis on the bigger bumps. The car would be all but undriveable.

This natural oscillation of spring-suspended masses has other significant aspects in the suspension picture. As you know, any mass suspended on a spring will oscillate up and down, when excited by an outside force, at some fixed frequency. This natural frequency depends only on the relative stiffness of the spring and the weight suspended on the spring and is not affected by the frequency of the outside exciting force. Theoretically, your car body should tend to bounce at a more or less fixed frequency on any type of road surface. This is actually the case: the natural ride frequency of modern automotive suspensions is generally between 65 and 90 cycles per minute.

Or, at least this is the case where the heavy sprung mass is oscillating on the chassis springs. But this isn't the whole story. Imagine that the sprung mass is acting as a solid suspension base and the unsprung masses (wheels, tires, brakes, etc.) are oscillating on this base. Spring stiffness would be the same but the suspended weight would be much less. So the natural frequency would be higher by an amount inversely proportional to the square root of the suspended weight. This is known as "wheel hop," and the frequency is between 150 and 220 cpm. Keep in mind that the shock absorbers must damp both oscillations. This is one of the toughest problems faced by the chassis engineer: How to control the high-frequency wheel-hop without compromising the ride by getting too little damping of the slower body oscillation.

There is a lot more to this sprung-unsprung mass relationship, but it doesn't concern us vitally right now. We'll discuss it thoroughly in the article on ride.

Handling the Roll Couple

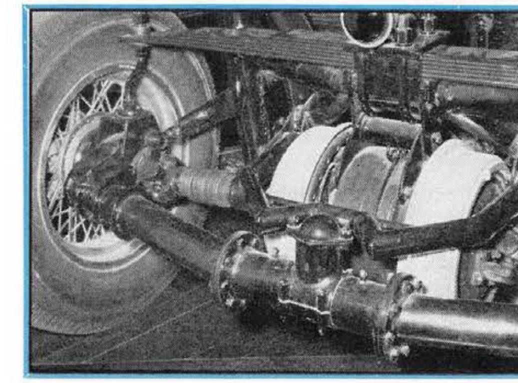
Imagine a car rounding a corner. Obviously, centrifugal force is going to pull outward on the overall mass, and its line of action can be considered to be at the center of gravity of the mass. And this, of course, will set up a lever action (or "roll couple") that acts to lift weight off the inner wheels and throw it on the outer ones. (It's the very same type of lever action that transfers weight from front to rear wheels when you accelerate—or from rear to front wheels when you throw on the brakes.) As long as the c.g. is above ground level, which it has to be, you will get this weight transfer when inertia forces act on the car.

Weight transfer can be readily calculated on the slide rule. Assume that the c.g. is 22 in. above ground level and the tread between wheels is 60 in. Then the theoretical lateral weight transfer in a turn would be 22/60= 0.37 x the centrifugal force acting on the car mass. This figure can be considered the leverage ratio of the centrifugal force trying to tip the car over. Further, let's say you are rounding a turn of 40 ft. radius at 60 mph. In this case it is easily calculated that the centrifugal force will be 0.60 x the car weight (in other words, it is 0.6 "G"). Thus, the actual weight transfer in this case would be 0.37 x 0.60=0.22 x the car weight. If the car weighs 4000 lb., transfer would be lifting 4000 x 0.22=880 lb. off the inside wheels and dumping the weight on the outside wheels when rounding the above curve. If the car has 50-50 front-rear weight distribution, this weight transfer would be divided equally between the front and the rear pairs of wheels.

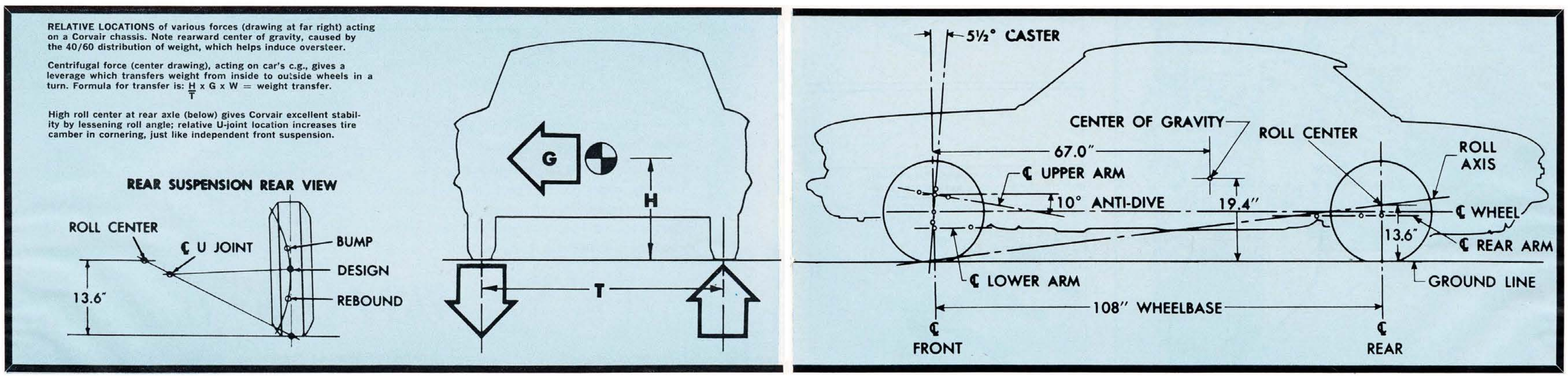
This, of course, is a simplified way of looking at lateral weight transfer. In actual practice things get much more complicated. This is because the sprung mass is suspended on springs—and thus doesn't roll about the ground contact point, but pivots around an axis connecting the front and rear roll centers. These are nothing more than the points about which the sprung mass tilts (or rolls) when acted upon by a side force—such as a cross wind or centrifugal force in a turn. Because the roll centers of the front and rear suspensions may be at widely different heights above ground level, the sprung mass as a whole will actually pivot about an axis that connects the two centers from front to rear. This is the "roll axis." It generally slants upward from front to rear (since the front roll center is usually near ground level). And it will also be obvious at this point that the roll couple acting on the sprung mass does not lever about the ground contact point, as figured earlier in the simplified explanation. It works about the roll axis. Also, the unsprung mass should not be included in this calculation, as it is not pivoting about the roll axis (it must be allowed for separately). The net effect is to shorten the lever arm and reduce the roll couple.

The exact location of the roll center for a given suspension layout depends on the suspension linkage geometry. Calculating it on paper is quite a complex procedure so we won't go into it here. It's enough to say that the roll center can be placed nearly anywhere by juggling the linkage geometry (within reasonable limits). The r.c. of a conventional front wishbone layout is generally around ground level, or not over 4 in. above. On a conventional solid rear axle it's at about the height of the spring perches. On a swing-axle rear, the r.c. is usually 2-4 in. above the height of the inner U-joints; on a de Dion rear it's about the height of the cross tube; and on the modern "fully-articulated" rear independent linkages, as used on the sports and Grand Prix racing cars, roll centers are generally 2-5 in. above ground level—but can readily be placed anywhere the designers want them . . . . even adjusted at the track, by varying the control arm pivots.

Obviously, roll center height is a vital factor in the operating characteristics of a given suspension system. The height of the roll axis controls the roll couple that tries to tilt the body under centrifugal force (by controlling the length of the lever arm). This, in turn, controls the actual angular roll of the sprung mass; and this works back ▶



DE DION REAR puts heavy differential (and brake drums in this case) on the rear of the frame, but wheels are carried on a solid cross-tube which controls lateral movement.



RELATIVE LOCATIONS of various forces (drawing at far right) acting on a Corvair chassis. Note rearward center of gravity, caused by the 40/60 distribution of weight, which helps induce oversteer.

Centrifugal force (center drawing), acting on car's c.g., gives a leverage which transfers weight from inside to outside wheels in a turn. Formula for transfer is: $\frac{H}{T} \times G \times W$ = weight transfer.

High roll center at rear axle (below) gives Corvair excellent stability by lessening roll angle; relative U-joint location increases tire camber in cornering, just like independent front suspension.

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to control the camber tilt of the wheels. We learned last month that camber angle has a large effect on the cornering power of a tire. Thus, cornering can be improved by preventing too much positive camber on the outside wheel in a turn—by limiting the body roll with a high roll axis. Or in some cases you can balance out the handling better by lowering the roll center at one or both ends.

Distributing the Roll

Picture once again the sprung mass, suspended above the four wheels on four springs. Now picture a side force applied to the sprung mass at its c.g. —representing centrifugal force in a turn. This forms a roll couple about the roll axis. But here's the vital question: How is that roll couple distributed and transmitted through the springs to the front and rear wheels, to set up the vertical and side loads which determine the response of the tires?

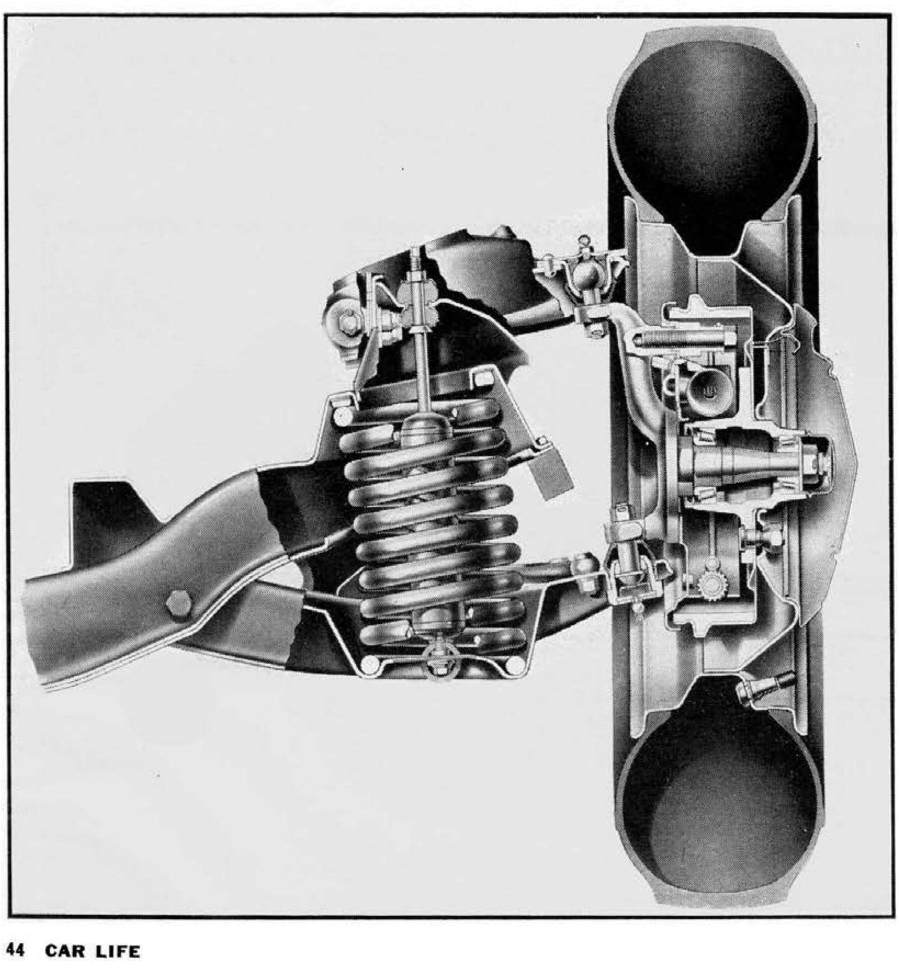
Without going into the laws of statics, which tell us why, let's state it thus: The roll couple on the sprung mass will be distributed between front and rear wheels in proportion to the relative roll stiffnesses of the front and rear suspensions. Roll stiffness refers to the resistance that a suspension system gives to any tilting of the sprung mass supported by it. It would depend on the spring stiffness, transverse span between spring centers, leverage ratio of suspension arms, stiffness of anti-roll torsion bar that might be used, etc. Roll stiffness is generally expressed in the number of ft.-lb. of roll couple necessary to tilt the sprung mass one degree. When a roll couple acts on the sprung mass it will be split between front and rear wheels according to these relative roll stiffnesses of front and rear suspensions.

Let's take an example. Consider Chevrolet's rear-engine Corvair. This has a front roll stiffness of 182 ft.-lb. per degree, and a rear stiffness of 293 ft.-lb./degree. The amount of roll couple absorbed by the front suspension would thus be: $182 \div (182 + 293) = 38\%$ of the total roll couple. The rear end would take the other 62%. Notice that this front-rear roll stiffness is almost in proportion to the front-rear weight distribution. This is usually the case in passenger car design. Front-engine cars generally have front roll stiffnesses about 50% greater than the rear stiffness. This distributes the roll couple 60-40 front and rear. If the front were twice as stiff as the rear the distribution would be 67-33.

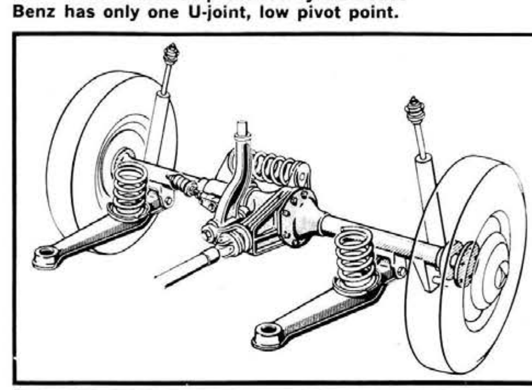
More on Wheel Loads

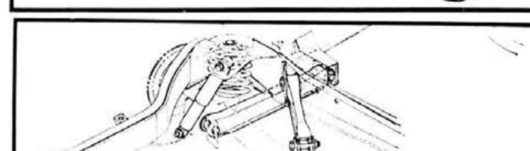
But this roll couple distribution isn't the whole story on weight transfer in a turn. We still have to consider the unsprung masses. These will be acted upon by centrifugal force also and their c.g. is generally considered to be at the height of the wheel center. This effect will give additional weight transfer. Furthermore, any time a roll center is above ground level there will be a component of the centrifugal force on the sprung mass that acts laterally at the roll center to transfer additional weight from inside to outside wheels. This transfer is proportional to the sprung weight on that suspension, roll center height and tread width. Add all these roll couples together to find the total weight transfer—and the resulting actual wheel loads.

TYPICAL FRONT suspension layout with long and short A-frames, coil spring and tubular shock absorber inside the coil. Ball joints are used on most modern passenger cars.

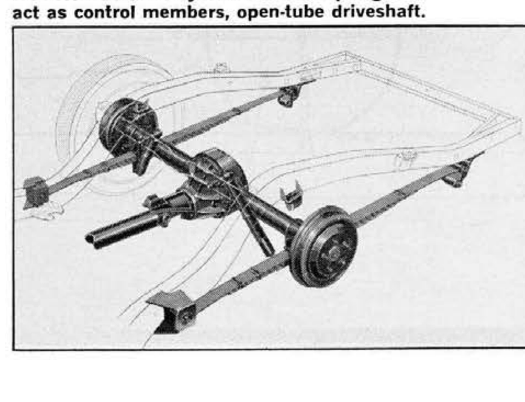


SWING AXLE rear as practiced by Mercedes-Benz has only one U-joint, low pivot point.





COIL SPRING rear is common with GM products.
HOTCHKISS drive system has leaf springs to act as control members, open-tube driveshaft.



Consider the case of the Corvair again and calculate some actual wheel loads for a sharp 40-ft.-radius turn at 60 mph (0.6 G lateral acceleration). Here we have a total sprung weight of about 2170 lb. with driver only, with 60% over the rear wheels. The c.g. of the sprung mass is about 12 in. above the roll axis, so the total roll couple is 1300 ft.-lb. (2170 x 0.60 x 1). According to the relative front-rear roll stiffnesses, this will be distributed 500 ft.-lb. on the front and 800 on the rear. To this we must add another 880 ft.-lb. on the rear only to allow for the 1300 lb. of sprung weight on the rear acting sideways at a height of 13.6 in. (height of the rear roll center). The front roll center is at ground level, so there's no effect there. Finally we have about 130 lb. of unsprung weight in front and 200 lb. in the rear, both pulling laterally at 0.6 G at the wheel center height of 12 in. This adds 80 ft.-lb. to the front roll couple and 120 to the rear. Totals: Front, 580 ft.-lb.; rear, 1800 ft.-lb.

To get the actual lateral weight transfer we divide these couples by the tread width in feet—which is 4.5 (54 in.) on the Corvair. Thus, front transfer is 580/4.5=130 lb., and rear is 400 lb. Now, each front wheel normally would be carrying 500 lb. (with 40-60 weight distribution) when the car is running in a straight line, with 750 lb. on each rear. Thus, in the 0.6 G turn, we would get 565 lb. on the outside front, 435 lb. on the inside front; the load on the outside rear would be 950 lb., with 550 lb. on the inside rear.

It is important to understand not only how the wheel loads build up in a turn but their actual magnitude in a specific situation.

Wheel Load vs. Slip Angle

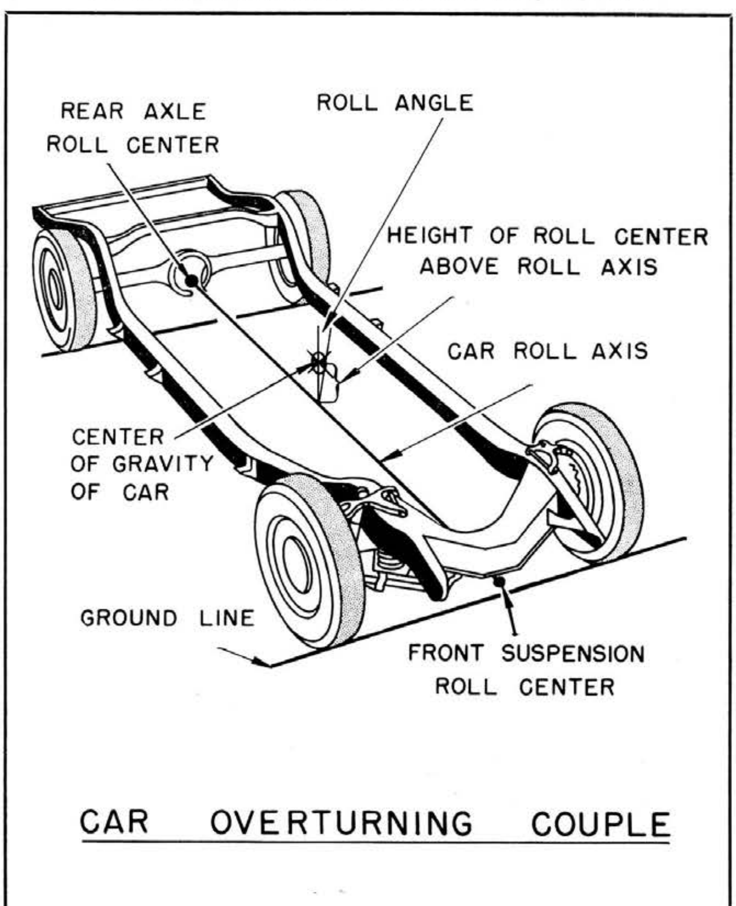
We learned last month that the side thrust developed by a tire, running at a given slip angle, increases with the vertical load on the tire—up to a point, after which the curve peaks out and falls off. By using these curves of tire side thrust performance we can figure the actual slip angles in a given turn, by figuring the required total side thrust to balance centrifugal force and reading slip angle opposite the load level. This is more or less a cut-and-try procedure, because the slip angles of both tires at each end of the car must be virtually equal (neglecting the small effect of built-in steer geometry), but their total side thrust must just equal the centrifugal pull on that end of the car.

Consider the Corvair once again: In a 0.6 G turn the total centrifugal force is 0.6 x 2500=1500 lb. And this will be distributed 40-60 front and rear (600 lb. on front suspension, 900 lb. on rear). The vertical loads on the two front tires are 435 and 565 lb. On a graph of side thrust for the Corvair 6.50-13 tire (mounted on the wide 5.5-in. rim) we find that a slip angle of approximately 4.5° will give side thrusts of about 270 and 330 lb., respectively, with 435 and 565 lb. vertical load. On the rear we have vertical loads of 550 and 950 lb. and must build up a total of 900 lb. side thrust. The graph shows that slip angle of around 5.5° would do this. The side thrusts would be 400 and 500 lb.

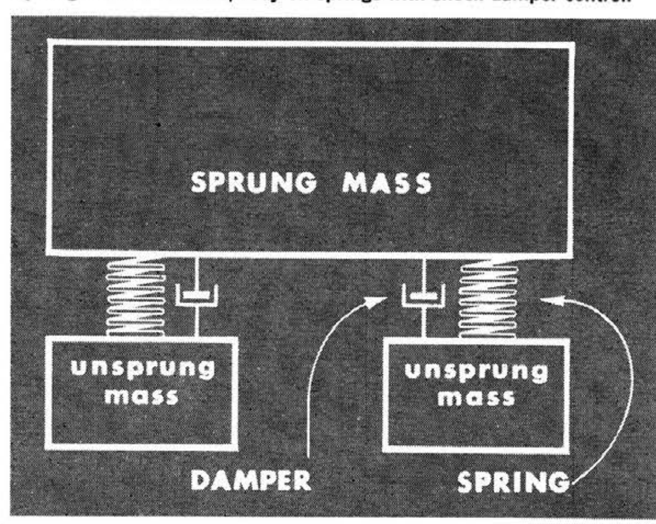
Keep in mind that the total side thrust must always just balance the total centrifugal force (or cross-wind thrust) acting on the car. The centrifugal force will be split between front and rear suspensions in the same proportion as the static front-rear weight distribution. But the side thrust on the body from a cross wind would be applied at the "center of pressure" of the body—which may actually be ahead of the front bumper! These wind forces are much smaller than inertia forces, so are rarely of any great importance in design.

Next month: Cornering and stability. ■

ROLL COUPLE of a typical car: Centrifugal force pulling on c.g. forms lever effect about roll axis which tries to tilt the sprung mass.



PHYSICAL VIEW of suspension: unsprung wheels, tires, etc., support sprung mass of chassis/body on springs with shock damper control.



VERTICAL OSCILLATIONS of sprung and unsprung masses are damped by oil being forced through restricted passages in shock absorbers.