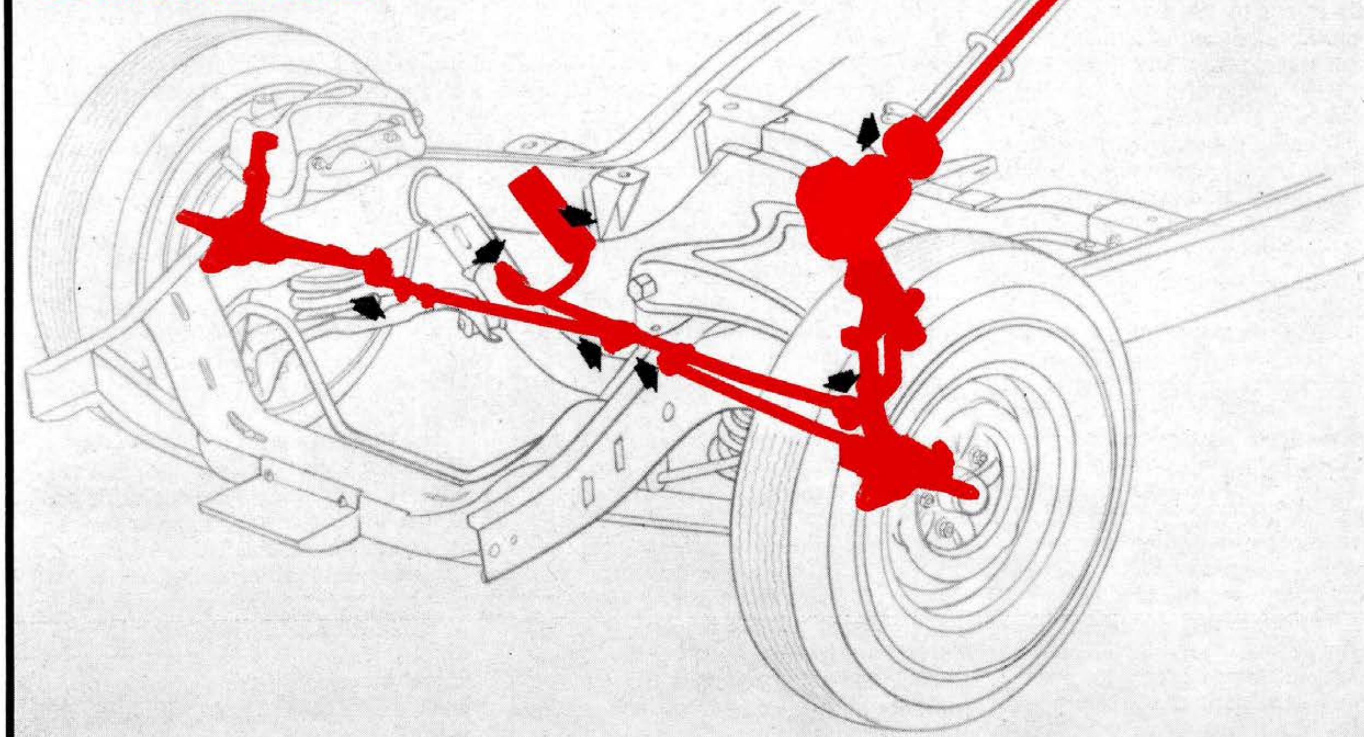
SCIENCE AND THE CHASSIS

THE STEERING SYSTEM PART IV

BY ROGER HUNTINGTON



LATE FORD steering linkage is an excellent compromise between space and geometry requirements.

THE STEERING SYSTEM doesn't have any deep influence on the way a car handles and corners (other than the feeling of sharp, precise control given by a quick steering ratio). The purpose of the steering system is nothing more than to control the direction of the car. Nothing to it—but just let the system be improperly designed, or out of adjustment, and then watch its influence on handling and cornering. The car can be downright dangerous. We take steering systems for granted; when they're right we don't notice them. And modern auto engineers usually have them right before the car design ever goes into production. Our purpose here is to show how and why they're "right."

The Ideal System

The requirements of an ideal steering system are not too hard to picture: It should have zero internal friction, so 100% of the manual force on the steering wheel will be multiplied into turning force at the road wheels (though this requirement isn't important with power steering). The steering gear should be partially reversible so that turning torques at the road wheels will give some feeling at the wheel, so the driver can sense what the car is doing. Steering without any feedback feels vague and dead. On the other hand too much feedback, or reversibility, can cause wheel-fight that fatigues the driver and actually reduces his feel and control. The old Ford Model T steering system had a very low ratio and was almost fully reversible—it could yank the wheel right out of your hand when a front wheel hit a rut.

Correct steering geometry is important (we'll discuss this later). But just as important is how the camber, caster and toe-in change as the wheel moves up and down over road bumps. This can cause wheel-fight and vague handling, too. It's a problem of linkage geometry. The ideal system would have zero geometry change with wheel deflection (or at least any change would be precisely pre-planned on the drawing board). This is not easy to arrange with simple, inexpensive linkage. Another requirement of the ideal steering system would be minimum flexibility in the linkage. Any bending or bowing of the control rods or deflection in the bushings softens the feel at the steering wheel. Excessive flexibility can make the car wander at speed.

Finally, the overall steering ratio must be a careful compromise. Steering ratio refers to the number of degrees of steering wheel rotation required to give one degree of turning at the front wheels. This can vary anywhere from 10;1 to 30:1. "Quicker" steering (i.e., a lower ratio) gives more precise, positive control. But the inexpert driver might tend to overcontrol in emergencies—and a lower leverage ratio also increases the effort required at the steering wheel. The steering gets heavy with very low ratios, especially with nose-heavy cars, so there has to be some compromise. Note the situation on the ▶

THE STEERING SYSTEM

new Corvette Sting Ray: Chevrolet puts two holes in the steering arms so the tie rod balls can be changed to give two different overall steering ratios. The standard ratio is 19.6:1—then you can quickly change the setting to give 17.0:1 for racing. This is a good answer to the compromise.

Front End Geometry

This refers to the various angular relationships designed into the network of front wheel pivots and linkage that control the attitude of the wheels as they roll along the road. These angles are vital in the controllability and feel of the car. Here's a run-down on the major geometry factors:

Camber—We've talked about this before in relation to suspension geometry. The camber angle refers to the tilt of the wheel in a direction across the car. Positive camber is when the top of the wheel tilts away from the center of the car; negative is when the top tilts inward. A little positive camber on the front wheels has long been considered an aid to good steering control and minimum tire wear. Back in the days of the high-crowned roads, positive camber helped keep the tire tread surface perpendicular to the road surface. It also put the line of action of the vertical wheel load inward toward the strong inner bearing. Today these considerations aren't so important and our modern cars generally use very little positive front camber. What they do use is more to assure zero effective camber when the weight of the car bends the spindle upward slightly. It also helps to compensate for bearing wear. The idea is to get nearly zero wheel camber (or vertical positioning) under normal operating conditions.

Kingpin inclination—Modern cars with ball-joint front ends don't actually have kingpins; but the principle is still the same. A line drawn through the axes of the two ball joints would represent the kingpin inclination. This generally slants in toward the center of the car at the top. If you project this line to the ground line it will generally fall 1-2 in. inside the center of the tire tread. The distance between this point and the center of the tire tread is known as the scrub radius. It will be obvious that road forces against the wheel will use this scrub radius as a lever arm to try to pivot the wheel about the kingpin line. That's why they slant the kingpin line—to shorten this scrub radius. If the line were vertical, and the scrub radius 4-5 in., the driver would get terrific wheel-fight. On the other hand, if the kingpin line were inclined enough to bring the ground contact right at the center of the tire we would have what we call "true center-point" steering. We don't want this either. Steering forces are reduced, but the steering has a dead feel. The car tends to wander because the driver can't feel the front end the way he should. Detroit engineers have found that a scrub radius of 1-2 in. is about right. They get it mostly from this inclination of the kingpin line, which averages 6°.

There is one other more obscure (but important) advantage of this inclination. A little thought will show that pivoting the wheel about an inclined kingpin will require that the front of the car be lifted slightly when the wheels are turned. This effect tends to bring the wheels back to straight ahead after a turn—the same as caster does. It gives a stabilizing effect in the steering. In fact, on modern cars, kingpin inclination is a more important factor in the self-centering of the steering than caster angle.

Caster—Caster is actually kingpin inclination turned through 90°. In other words the top of the kingpin (or the axis of the ball joints) is slanted back toward the rear of the car instead of across the car. This brings the extended axis ahead of the wheel center at the ground line and this gives a self-centering action to the steering—just as a caster on a table centers itself to trail behind the force line when the table is pushed across the room. The principle is that the weight of the object is concentrated behind the swivel axis.

But there's another effect of the caster angle that most enthusiasts don't realize: Because the wheel is carried on a spindle outside the kingpin axis, it will be obvious that the front of the car must be lifted somewhat when the wheel is steered toward the outside and would be lowered slightly when steered inward. That is, in a right turn the car would be lifted on the right side, lowered on the left. There isn't enough vertical movement here to cause any noticeable rolling of the body. But the effect on spring deflection is to unload the outside front wheel in a turn. This reduces the understeer tendency. The greater the positive caster angle, the greater this loading effect. Some sports and race car designers have been able to do quite a little with the oversteer-understeer relationship by adjusting front end caster angle. But it hasn't been a popular factor on mass-production cars. Positive caster increases the heaviness of the steering, so Detroit has always played it cool. In fact, some late cars have zero, or even negative, caster. With a pneumatic tire the effective center of the tread-road contact patch falls a little behind the geometric center anyway. So the engineers can get a slight caster effect in the steering, even with a very slight negative angle in the kingpin axis.

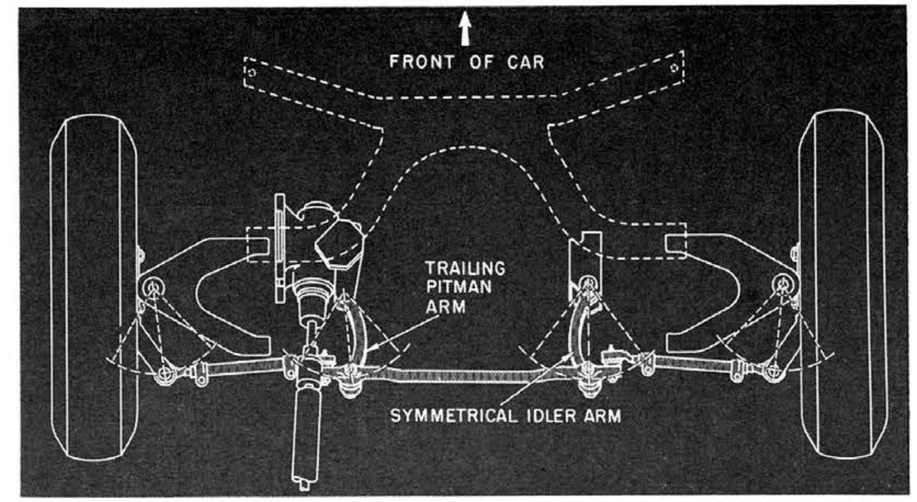
Toe-In—Pivoting the front wheels so the tires are a fraction of an inch closer together at the front than at the rear is called toe-in. The average amount for current American cars is about ⅛ in. (measured from the outside of the tread). This slight toe-in assures that the wheels will roll straight when road forces bend the spindles back slightly. It wouldn't take much toe-out to cause excessive tire wear.

Toe-out on turns—It is obvious that the inside front wheel follows a shorter radius than the outside when a car turns a corner—therefore it should be angled inward a little more to prevent excessive tire scrub. (If both wheels were steered at exactly the same angle, theoretically they would both have to slide some on the pavement.) It is very easy to allow for this by merely angling the steering arms inward slightly; then the two arms strike different arcs when the wheels are steered, and the inside wheel will turn at a steeper angle. Optimum conditions seem to be when the lines drawn through the kingpin axes and the ends of the steering arms intersect just ahead of the rear axle. This is often called the Ackerman effect. On American cars this toe-out on turns is generally measured by taking the angle of the inner wheel when the outer wheel is turned exactly 20° from straight ahead. This inner wheel angle will generally vary from 22 to 26°. But some cars use zero toe-out turns—and some have even found it expedient to use a negative Ackerman effect. In other words, the inner wheel turns at a smaller angle than the outer. This would theoretically give considerable tire scrub on slow, sharp corners in town. But apparently the effect is not serious and apparently these particular steering angles give a better feel to the handling in everyday driving.

It all goes to point up the fact that there are no hard and fast rules for suspension and steering setups. What works best with one chassis combination might not be right with something else. Experience and experiment are the paths to success.

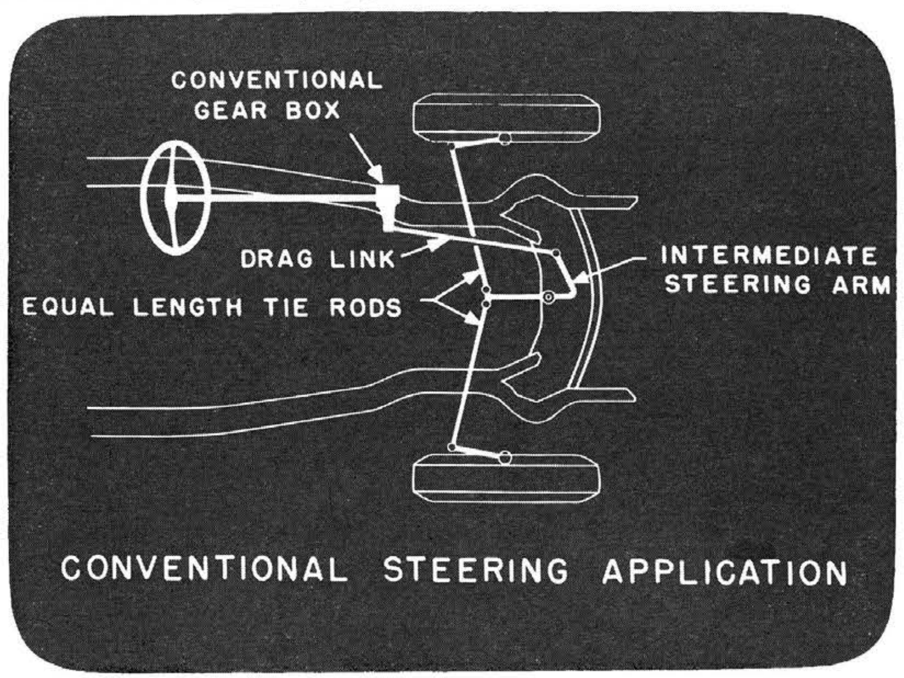
Steering Linkages

The purpose of the steering linkage is nothing more than to transfer the rotary output motion at the steering gearbox into rotation of the front wheel spindles about the kingpin axis (or ball joint axis). There are many possible basic layouts. The essential ingredients in the linkage system would include the Pitman arm, which splines to the steering gear output shaft and transfers this rotary motion to an immediate linear motion. Then we gener- ▶

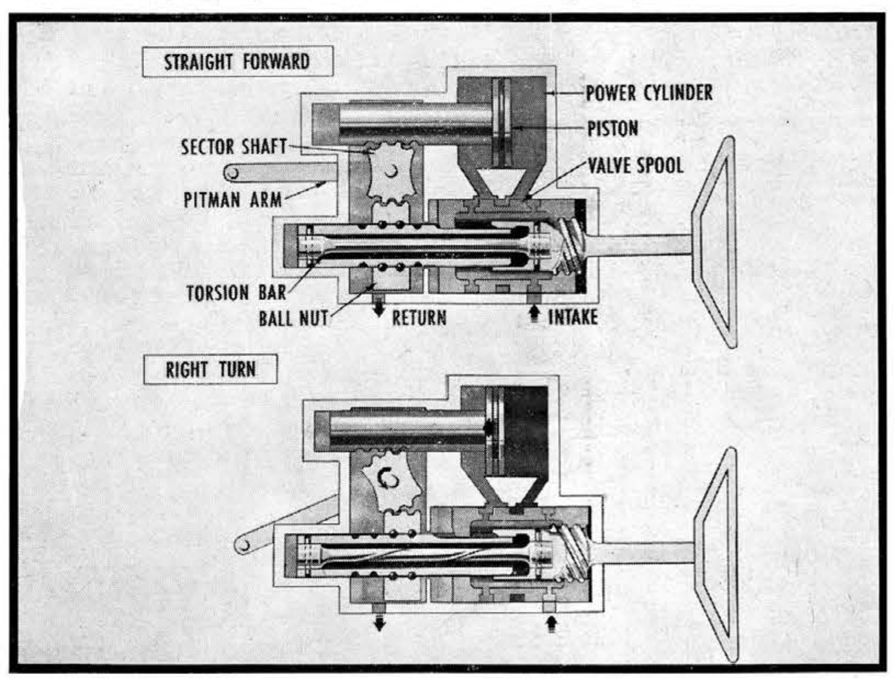


DODGE LINKAGE has final tie rods to the wheels nearly same length as lower suspension arms.

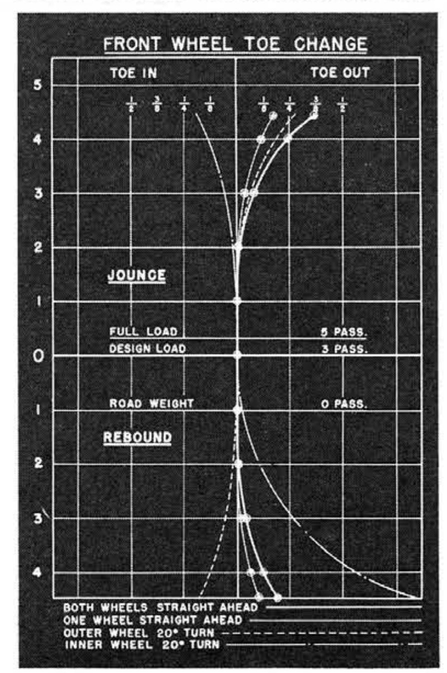
TYPICAL LINKAGE layout with equal-length tie rods.



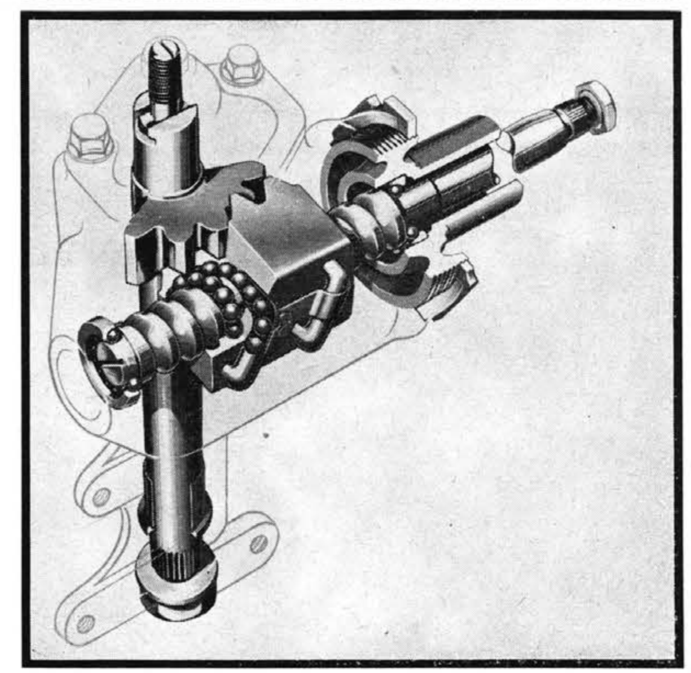
FORD POWER steering unit works torsion bar which twists to give "feel."



FRONT WHEEL toe change at different loads.



RECIRCULATING BALL gear: the nut rides on a circuit of ball bearings.



ally have a drag link that transfers this motion either forward or sideways to some sort of idler arm or bellcrank. The idler arm (or arms) gives lateral motion to operate the tie rods going to the wheels. These connect to ball sockets on the ends of steering arms that are forged integral with the wheel spindle, or sometimes bolted on. Of course there are dozens of possible variations on this basic theme.

The big problem when designing a steering linkage is to get minimum possible steering geometry errors, while still having an economical setup that misses all the components on the chassis. This is getting tougher and tougher all the time. The ideal linkage is not hard to picture: It would have the final tie rods to the wheels just about the same length, and on roughly the same plane, as the lower suspension control arms. Then both links would strike the same arc as the wheel moved up and down over bumps and there would be no self-steering. When the tie rod is a lot longer than the lower control arm, the wheel moves inward on the control arm on jounce; but the tie rod strikes a longer arc, so its end doesn't move in as far—and the wheel is automatically steered inward a little as the wheel moves up. This effect can be serious on very rough roads.

Or the smart chassis engineer can sometimes put this effect to work for him. Chevrolet did on the new Corvette. In order to put the front roll center 3.25 in. above ground level the engineers had to lower the inner pivots of the upper control arms—and this caused considerable camber change toward the negative when the wheels went up over bumps (on the jounce stroke). This camber tilt, in a turn, causes a gyroscopic reaction (called precession) that tries to steer the wheel inward.

So the Chevrolet engineers merely arranged the steering tie rod angles and lengths to give a small amount of toe-out on jounce to compensate for this! Specifically, at the 3-in. jounce travel point they get 2.5° of negative camber increase and 0.25 in. increase in toe-out (as compared with the settings at the static load point). This is bread-and-butter engineering at its best.

Steering Gears

The basic purpose of the steering gearbox is to act as a reduction gear for manual torque on the steering wheel rim—reducing the angular rotation by a ratio of 1:20 or so, and multiplying the torque by the same ratio. The worm gear is especially well suited to this job for a simple reason: By selecting a helix angle less than 45° we can keep the reverse efficiency of the gear (wheel driving the worm) well below the forward efficiency, when the worm on the main steering shaft drives the wheel or sector connected to the Pitman arm. This, in turn, controls the amount of steering feedback and wheel-fight. With a high-friction gear, you can make it completely irreversible (zero reverse efficiency) with a helix angle of 10-12°. But most of the older cars used helix angles of 12-22°; forward efficiencies ranged between 50 and 60%, with reverse efficiencies generally between 20 and 30%. This gave a good compromise between road feel (given by the feedback) and acceptable wheel-fight. These were all the "high-friction" gears like the Ross cam-and-lever type, worm-and-sector type, etc.

In late years the picture has been changing. Steering feedback is no longer very critical with hydraulic power steering, since the power mechanism acts as an effective shock damper. Chassis engineers have been striving for minimum friction, to give smoother operation.

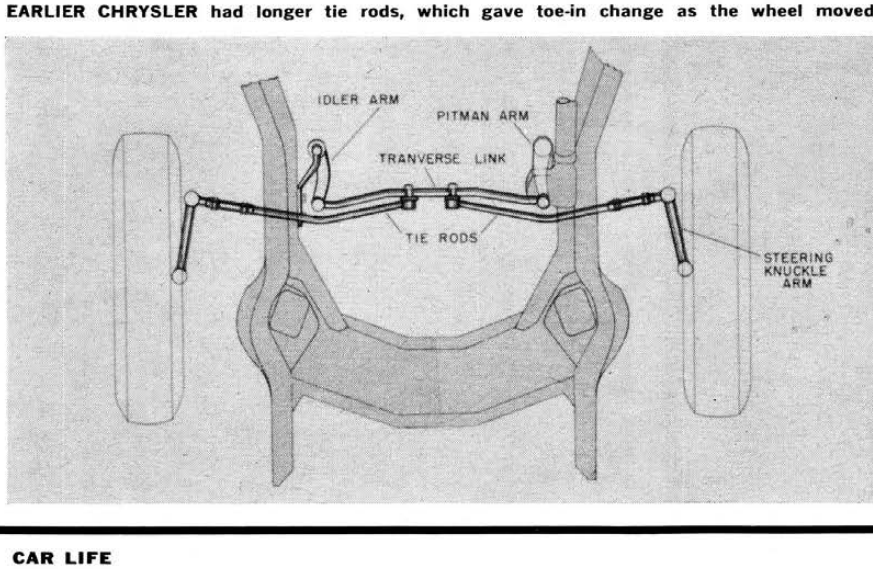
This has resulted in a general adoption of the recirculating ball steering gear on most late American cars. This has the conventional worm; but the nut rides on the worm through a circuit of ball bearings, so there is practically no friction. (Then the nut moves a sector through a conventional arrangement of meshing teeth.) The forward efficiency is over 90%, with about 80% in the reverse direction. This has proved an excellent compromise for steering feel with or without power steering. (And, of course, the amount of feel with power steering can be readily adjusted with various types of torque-sensitive valves.)

One other type of steering gear that should be mentioned here is the well-known rack-and-pinion gear, so popular on small foreign sports and utility cars. The chief virtues of this gear are light weight, low cost, simplicity and small size. It is simply a lateral toothed rack that is moved back and forth by a gear wheel turned directly by the steering wheel. The tie rods to the wheels are driven right off the ends of the rack. Nothing to it. And the rack-and-pinion gear is almost fully reversible. Forward and reverse efficiencies both generally run between 80 and 85%.

This delivers a lot of feedback through the steering, but car enthusiasts seem to like it—say it gives a feeling of being part of the car. It's obvious that feedback has never been the gremlin that early auto engineers thought.

Next month: Engineering the ride. ■

EARLIER CHRYSLER had longer tie rods, which gave toe-in change as the wheel moved.



LOW-FRICTION steering from Dodge.