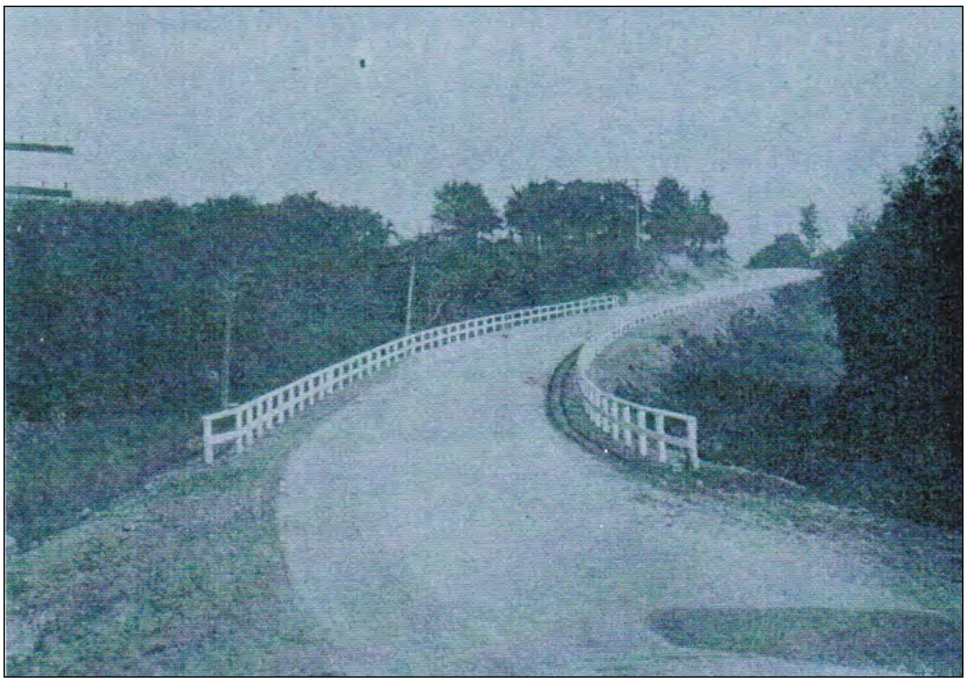
PUBLIC ROADS • Vol. 39, No. 4 • March 1976

Highway Design for Motor Vehicles: A Historical Review

Cornell Local Roads Program
Tech Tips

PART 5: THE DYNAMICS OF HIGHWAY CURVATURE

Before the appearance of bicycles and automobiles on the highway, vehicle speed on the smoothest surfaces seldom exceeded 8 mph. At this speed the width of the road and the length of the vehicle were much more important than speed for determining road curvature. A four-horse team pulling a freight wagon was about 50 feet long. This rig would go around a curve of 105 feet radius without leaving the carriageway if the pavement were at least 12 feet wide. For an 18-foot pavement the radius could be only 77 feet.



On widened curves which are improperly banked the traffic swings to the inside of the curve to take advantag of the crown, leaving an untravelled lane on the outer edge (4)

Of course, during part of the maneuver the rig would be occupying the entire roadway including the lane for opposing traffic, so roadbuilders tried to get longer radii where possible. In 1908 the Permanent International Association of Road Congresses (PIARC) recommended that the minimum radius be 50 meters

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Tech Tips are published by the Cornell Local Roads Program with support from the Federal Highway Administration, the New York State Department of Transportation, and Cornell University. The content is the responsibility of the Local Roads Program.

(165 feet), and also that transition curves be placed between each end of the curve and the adjoining tangent to reduce the abruptness of the change from straight line to curve.(1)

In the early 1900's the practice in France was to use a 50-meter minimum radius on the national roads in fairly level country, but this was shortened to 30 meters in more difficult terrain. On district roads 15 meters was the minimum radius. In Austria the minimum radius varied from 24 to 49 meters on main roads, 20 to 30 meters on district roads, and as low as 10 meters on minor roads. (1) New York on the other hand strove for a minimum radius of 200 feet wherever possible. (2) For very small changes in directions - 10° or less - some road engineers used no curve at all.(3)

Since the time of Trésaguet, and indeed back to the Roman era, engineers had cambered or crowned road pavements to shed water quickly. This crown was applied uniformly to the entire road, curves as well as straightaways. Animal-drawn traffic traveling only 2 to 3 mph had no difficulty rounding the curves, even though they were apt to be of short radius. Motorists, however, found the crowned curves irksome. They wanted to travel at 20 to 25 mph but were unable to take the curves at that speed without cutting the curve to utilize the banking afforded by the crown in the opposing lane.

Curves Banked to Equalize Wear

Aside from the danger involved, curve-cutting greatly increased the wear on macadam surfaces by concentrating the traffic on the inside lanes of curves. About 1912, some roadbuilders began to *supererevate*[1] or *bank* the sharper curves of new roads to encourage auto drivers to stay in their own lanes. Practice varied widely among highway organizations as to the amount of superelevation to use, or, indeed, whether to use it at all. In the United States, New York - a leader in the superelevation movement - used a straight two-way crown of one-half inch per foot, or 4 percent, on macadam roads and one-fourth inch on concrete pavements. This crown was carried around curves of radii longer than 500 feet, but sharper curves were superelevated 1 inch per foot for macadams and five-eighths inch per foot for rigid pavements. Apparently, these values were purely empirical, the transverse slope being regarded as a function of the nature of the pavement surface rather than the radius of the curve. In fact, a widely respected authority on road design from New York asserted that "Variation in superelevation for curves of different radii is a useless refinement and good practice rarely adopts superelevation for radii greater than 800 feet."(2) This empirical approach to superelevation on highways seems strange when one considers that every educated civil engineer of the period had a thorough understanding of the dynamic basis of superelevation as practiced by the railroads.

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1. The term superelevate, like others in highway engineering, comes from railroad practice. The railroads canted their tracks on curves by elevating the outside rail.

At this time, 1912 to 1915, horsedrawn vehicles were still an appreciable part - approximately one-third-of the total traffic on all main roads in the United States; and there was a real danger that if a sharp curve were superelevated sufficiently to make it adequate for a speed of 30 or even 20 mph, the cross-slope would be so steep that slow-moving, horse-drawn vehicles would slide sideways when the surface was slippery. Furthermore, there was considerable public hostility to providing any superelevation due to the opinion that it encouraged high speeds and reckless driving on curves. Not until about 1920 had animaldrawn traffic become so negligible in the United States that it could be disregarded in highway design. Until then, superelevation rates were a compromise - an excellent example of how so - called standards evolve from a consensus, sometimes without scientific support.

Curve Widening

Concurrently with superelevating sharp curves, some States also began to widen them on the inside. This was partly a concession to curve-cutting and partly because the rear wheels of a vehicle do not track exactly in the path of the front wheels on a sharp curve. There was no consistency in the amount of widening among the States that practiced this innovation. West Virginia, for example, used only 3 feet of widening for curves of 75 feet radius, while New York used 3 feet for curves of 1,500 to 2,500 feet radius and went up to 8 feet on 300-foot-radius curves. Generally, however, the amount was scaled somewhat to the radius, and extended all around the curve. The transition from the normal pavement width on tangents to the widened curve section was accomplished in several ways: Michigan and New York used a circular curve of longer radius than the centerline for the inside edge of the pavement, while Pennsylvania and Washington used spiral transition curves such as those adopted by railroads for track easements. (4) This seems to have been the first use of spiral curves on highways in the United States, although PIARC had recommended the use of spirals on roads as early as 1908.

By 1920 animal-drawn vehicles had practically disappeared from the main roads of the United States; and engineers, for the first time, could design highways for motor traffic only. Of the earlier features of road design one of the first to go was the high crown. Tighter, smoother surfaces such as cement concrete, paving brick, asphaltic *carpets*, and bituminous macadam did not require a steep crown for transverse drainage. High crowns caused vehicles to veer to the right. Even more important, crossing and recrossing a steep crown during the overtaking maneuver was not only uncomfortable for drivers but hazardous. By 1925 crowns on concrete pavements were generally about one-fourth inch per foot, or 2 percent, and today one-eighth inch per foot, or 1 percent, is usual.

Relating Superelevation to Speed

Another product of the new motor-oriented thinking was the belief that one should be able to travel all parts of the highway - curves as well as tangents - at the legal speed limit, which was then 25 to 30 mph in most States. This belief prompted more thorough studies of the curvature-superelevation relationship, one of the earliest of which was in 1920 by Luedke and Harrison of the Bureau of Public Roads.[4] By mathematical analysis they showed that complete superelevation necessary to offset the centrifugal force generated by a vehicle traveling around a curve could be calculated by the formula:

$$e = \frac{V^2}{15R}$$

Where,

e=Superelevation in feet per foot.
V=Vehicle speed in miles per hour.
R=Curve radius in feet.

They then showed that for a speed of 25 mph a cross slope of 0.21 foot per foot or 21 percent would be needed to supply complete superelevation for a curve of 200-foot radius. This was five times the current practice, which was to bank curves of 150 to 500 feet radius at a rate of one-half inch per foot, providing a cross slope of only a little over 4 percent. And yet Luedke and Harrison knew from experience that an auto could easily negotiate a 200-foot radius curve with 4 percent superelevation at 25 mph. The difference, about 17 percent, could be accounted for only by " ...the stability of the vehicle itself," or its ability to resist side skidding. Expressed another way, the ½ -inch superelevation provided horizontal resistance to compensate for a speed of about 11 mph on a 200-foot radius, and the resistance required for higher speeds was provided by the side-friction of the vehicle's tires.

Luedke and Harrison were also concerned with the manner in which the transition from a crowned to a superelevated section was accomplished. Assuming a constant velocity in the formula $e = \frac{V^2}{15R}$, e should increase uniformly as the centrifugal force is developed, that is, as the radius decreases. If the cross slope is developed too rapidly, the driver will feel uncomfortable and will try to lengthen the transition distance by swinging toward the center of the road or even into the opposing lane in extreme cases. To remedy this, Luedke and Harrison recommended inserting a transition curve of variable radius between the tangent and the curve on which the driver could gradually adjust to the horizontal change in direction as the outer edge of the road was elevated smoothly to the required superelevation. Such *spiral curves* were commonly used on railroads to lessen the shock of the change from linear to curvilinear motion, but no highways in the United States at this time had spiraled centerlines.

Although they did not use centerline spirals, those States that used superelevation at all had their own transition methods, and generally they accomplished the transition in a distance of about 100 feet. New York, however, made the length of transition a function of the curve radius, varying from 35 feet for curves of 2,500 feet radius to 85 feet for curves of 300 feet radius.

The First Spiraled Centerline

The earliest fully spiraled road centerline was the high-speed test loop of the General Motors Proving Ground in Michigan, constructed in 1926, where spiral easements were applied to three 1,000-foot-radius curves. After 12 years of operation the director of the Proving Ground stated that it would have been a great mistake to have omitted the spirals.[(5)]

The first public highway to have a fully spiraled centerline was the Mount Vernon Memorial Highway in Virginia, designed by the Bureau of Public Roads in 1929. The BPR engineers first laid out the location on a large-scale map with a flexible spline, a new technique borrowed from New York's Westchester County Parkways. They then resolved this line, which was actually a *free form*, into circular and spiral curves so that it could be staked on the ground by current surveying methods. The resulting alignment consisted almost wholly of relatively flat curves none of which had a radius shorter than 1,200 feet. Curves of less than 2,000 feet radius were spiraled at each end. One spiral curve was 1,512 feet from end to end-possibly the longest ever to be incorporated in a highway. Of course, a spiral of this length went far beyond the requirements of transitioning and into a still-unexplored realm-that of esthetics and visual impact. This mighty spiral also refuted the arguments of those who claimed that spiral curves were dangerous because their constantly changing curvature kept the driver off-balance. Actually, after its completion in 1932, one could drive the 15-mile length of the Mount Vernon Memorial Highway in complete safety at 55 mph, and almost without hand steering.

The Beginnings of Access Control

The earliest access-controlled motor highway in the United States was the Long Island Motor Parkway, built originally on private right-of-way as a race course for the Vanderbilt Cup. Opened to traffic in 1908, this 40-mile road was paved with concrete and was one of the first roads in the world to have superelevated curves. When not used for racing, the parkway was opened to pleasure vehicles as a toll road. The European counterpart of the Long Island Motor Parkway was the *Avusbahn*, begun in 1913 but not completed until 1919. This German ancestor of the *autobahnen* ran in an absolutely straight line from Charlottenburg to Berlin with no direct access to the traffic lanes and no grade crossings.

In 1923 an Italian corporation began construction of a high-speed toll road from Milan to Lake Como for the exclusive use of motor vehicles. It was laid out as a series of long tangents joined by superelevated curves of 500 meters minimum radius, and there were no crossings at grade with other roads or railroads. The Milan-Lake Como *autostrada* was followed by six others - all built to the same high standards. Although financially unsuccessful as toll roads, these Italian *autostrade* were the first motor roads of any considerable length to be built with full access control - that vital principle of modern freeways.

In the early 1920's most drivers ran in the middle of the road, stradding the crown. They gave way to the right only for passing

We have seen that in the early days of the automobile, roads were narrow and crowns were steep. Consequently, most drivers ran in the middle, straddling the crown, and few considered this unusual. When two vehicles approached each other, both had to move to one side in order to pass. *Safe sight distance* was the distance required for a driver traveling at the ordinary touring speed of 20 to 30 mph to turn out and pass an approaching car without applying his brakes.[(2)] Inquiry among auto clubs as to what drivers felt this distance should be showed rather general agreement on distances of 200 to 300 feet.

According to road tests made in Erie County, N.Y., about 1912, a car traveling 20 mph could be brought to a safe stop in 40 feet, while one traveling 40 mph could be stopped in 140 feet with the emergency brake. For safe design the New York State Department of Highways at this time required 250 to 300 feet of sight distance on curves and a minimum curve radius of 200 feet.[(2)]

By the early 1920's, highway accidents had become a source of grave concern in the United States and abroad. Most of the serious accidents were attributed to recklessness and excessive speed, but skidding was also blamed for a very significant share. This last was a subject that seemed amenable to solution by engineering research and design.

The Beginnings of Skid Research

As early as 1922 the Iowa State Experiment Station, under T. R. Agg, had made some experiments to determine the tractive resistance of automobiles on various types of road surfaces.[6] The primary purpose of these studies was to develop data on road economics in support of good roads programs. However, almost as an afterthought, the experiments also included studies of the sliding friction of rubber tires on various road surfaces. A test car with brakes only on the rear wheels was towed at a speed of 3 to 5 mph and the brakes were applied gradually until the rear wheels started to slide. The pull exerted on the tow line was measured with a Burr dynamometer and a Kohlbusch dynamometer. The researchers then calculated the coefficient of friction from the simple relation: The coefficient of friction equals the force required to cause the wheels to slide divided by the weight on the wheels.

The coefficients for uniform straight sliding as measured in these tests ranged from 0.179 on hard-packed snow to 0.517 on wet concrete and 0.715 on dry concrete. Coefficients about 10 percent higher were observed while the wheels were still turning, just before sliding began.

To measure side-skidding coefficients, the test vehicle was secured parallel to a very heavy truck with the tow line and dynamometer between them. They then drove off at the same speed in slightly diverging paths. The dynamometer was read when the wheels of the lighter test vehicle began to slide sideways. For safety reasons it was impossible to conduct this test at speeds faster than 3 mph. Coefficients thus measured ranged from 0.269 on natural sandy soil to 0.431 on dry wood block pavement, with dry concrete about 0.401.

In 1927 the Iowa researchers expanded the tractive resistance and braking tests. For the braking tests the test vehicle was a stripped-down touring car chassis equipped with four-wheel brakes and balloon tires and weighted to give a gross load of exactly 500 pounds per wheel. The vehicle was towed at a speed of 4 to 5 mph while the pulling force was measured with the Kohlbusch dynamometer. For side skidding measurements, two towing vehicles were used-one to pull the test vehicle forward and the other to pull it sideways in a skid. The coefficients for both straight and side skidding thus measured were substantially higher than those measured in the 1923 research.[7]

British, French, and American Skid Testers

Meantime, the British Ministry of Transport was developing a skid tester to measure the resistance to skidding of highway surfaces. This was a test wheel equipped with a standard pneumatic tire which was towed by a motorcycle from an outrigger. The wheel was attached to the outrigger through a vertical pintle so that it was free to swivel from side to side like a dolly, through an arc of about 20°. For running a test the wheel was set at an angle of 18° to the direction of travel, so that in effect, it was dragged over the road surface. The frictional force thus generated tended to push the wheel into a position parallel to the direction of travel and the force required to do this was measured by an oil-pressure dynamometer. Vehicle speed and dynamometer pressures were automatically recorded on a chart driven by clockwork carried in a sidecar mounted on the outrigger. Tests were usually run during rain when the coefficient of friction was lowest.(8)

Three skid testers based on the same principle as the British apparatus were developed in France about the same time. In 1932 Moyer at the Iowa Engineering Experiment Station, and Stinson and Roberts at the Ohio Engineering Experiment Station simultaneously developed trailer-type skid testers. The horizontal force required to pull these test trailers after the brakes were applied was measured by a dynamometer and automatically recorded along with the speed on clockwork-driven charts. Both trailers could be adjusted to measure either straight-line skidding or side skidding. The Iowa skid tester was pulled by a truck carrying a water tank and sprinkler with which the pavement could be flushed just ahead of the test wheels. The Ohio researchers made all their tests during appreciable rainfall, after the dust had been washed from the road surface.(9, 10)

The Three Types of Skidding

All these investigations showed that there were basically three types of skidding. The first was a locked-wheel slide, which occurred when the brakes were applied suddenly as in a panic stop. The coefficient of friction, that is, the ratio of the force causing the tires to skid to the load on the tires, for this *straight skid* condition was referred to as the *kinetic coefficient of friction*. Applying the brakes gradually to the point where the wheels were turning but skidding was imminent produced the *skid impending condition* at which the *static coefficient of friction* was measured. The third type of skidding occurred if the tires were skidded sideways as when rounding a curve with inadequate superelevation.

For paved road surfaces such as asphalt and concrete the *skid impending* condition gave the highest coefficient of friction, especially at high speeds; but, as Moyer pointed out, this coefficient had little practical application since few automobile braking systems were perfectly adjusted and even fewer drivers had the skill to bring their vehicles to a fast stop without locking at least one wheel. Most skid resistance measurements were therefore made for the skidding straight ahead or side skid conditions.

All observers found tremendous differences in skid resistance between different types of surfaces, between dry surfaces and the same surfaces when wet, between the same surfaces tested at low speed and at high speed, and between various tread patterns and inflation pressures of tires. In the Iowa tests new tires skidding straight ahead on wet asphaltic concrete surfaces generated coefficients of friction of 0.80 at 10 mph and 0.55 at 40 mph. For the same wet surfaces and tires the side skid coefficients were 1.0 at 10 mph dropping to 0.85 at 40 mph. For wet portland cement concrete and new tires the straight skid coefficients were 0.65 at 10 mph dropping to 0.40 at 40 mph while the side skid values were 0.80 at 10 mph and 0.60 at 40 mph. If there was mud on the concrete, the straight skid and side skid coefficients at all speeds might drop to 0.20 or

0.25; and if the surfaces were icy, they might be as little as 0.15 or even 0.05. The Iowa researchers concluded that to be reasonably free from the danger of skidding when wet, road surfaces should have a side skid coefficient of 0.50 or higher at 30 mph and a straight skid coefficient of at least 0.40 at 40 mph.(9)

Stopping the Vehicle - Driver Reaction Time

But Moyer did not stop there. He went on to show that if a driver requires one-half second to size up the situation and react by pressing the brake pedal, then it will take 250 feet to bring his vehicle to a stop from a speed of 56 mph on a road surface with a coefficient of friction of 0.50. For a speed of 81 mph this stopping distance would increase to 500 feet. Such a stop would impose a decelerative force of 16.1 feet per second per second-one-half the acceleration of gravity - on the occupants of the car, which Moyer thought would be a reasonable maximum for safety and comfort. To allow for more slippery surfaces, slower reaction times, and less effective braking systems, Moyer recommended that a minimum clear sight or stopping sight distance of 1,000 feet be adopted for main highways.

Moyer probably got his figure for driver reaction time from earlier research in which Moss and Allen in 1925 investigated the personal equation in driving.(11) These investigators mounted two revolvers under the running board of a car pointing down to the road. They then tested 57 drivers of different ages, sexes, and intelligence. The observer, who rode in the front seat beside the driver, fired one pistol as the signal for the driver to apply the brake. The first indication of pressure on the brake pedal fired the other gun automatically. Shells loaded with red lead were used so both shots left red spots on the pavement. Since the vehicle speed was known, the reaction time could be calculated by measuring the distance between the two spots; thus if the speed was 44 feet per second and the distance between spots was 22 feet, the reaction time was 0.5 second.

Moss and Allen found that reaction times varied from 0.31 second to 1.02 seconds, with an average of 0.54 second. Reaction time varied little with the age and sex of drivers or with vehicle speed, but tended to be shorter for persons of high intelligence and for practiced drivers. They thought it likely that in a randomly selected group of drivers many could be found with reaction times as high as 1.5 or even 2 seconds.

How Side Friction is Developed

Moyer went even further than recommending safe stopping distances. Using three standard automobiles as test vehicles, he ran a series of tests on actual highway curves to determine how the balancing frictional force which counteracts the centrifugal force is developed. When a vehicle is steered around a curve at very low speed, the front wheels are turned at an angle to the axis of the vehicle. This *theoretical steering angle* depends on the radius of the curve and the wheelbase of the vehicle (fig. 1). If the speed of the vehicle is increased, some centrifugal force will be developed which must be resisted by side friction between the tires and the road. To develop this side force the driver must turn his front wheels a little more than the theoretical steering angle, thus in effect dragging or scuffing the tires a little. The additional angle causing this slippage is the slip angle, On a level curve this *slip angle* will vary with the speed, the coefficient of friction between the tires and the road, and the design of the vehicle's front wheel suspension. It may vary from only a few minutes for very flat curves or low speeds to several degrees for high speeds and sharp curves.

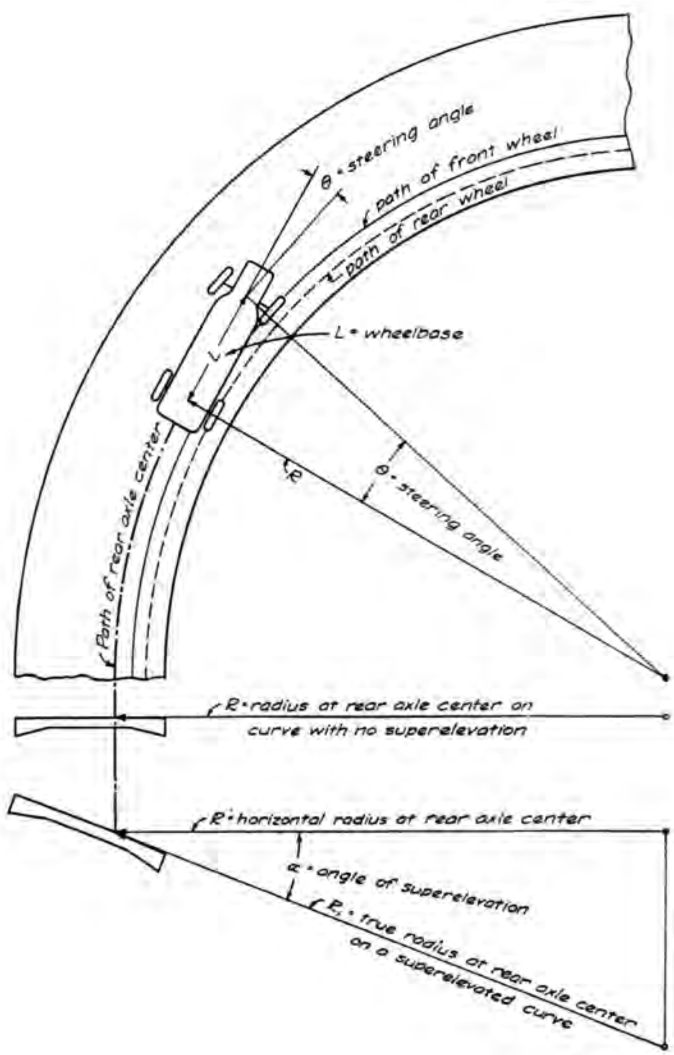

Figure 1: Vehicle rounding curve at very low speed [9]

In his tests of side skidding with the Iowa trailer, Moyer showed that the coefficient of side friction increases uniformly from zero at zero slip angle up to a maximum at 8° slip angle which depends on the tire and the road surface. Further increase in the slip angle beyond 8° produces practically no increase in friction.

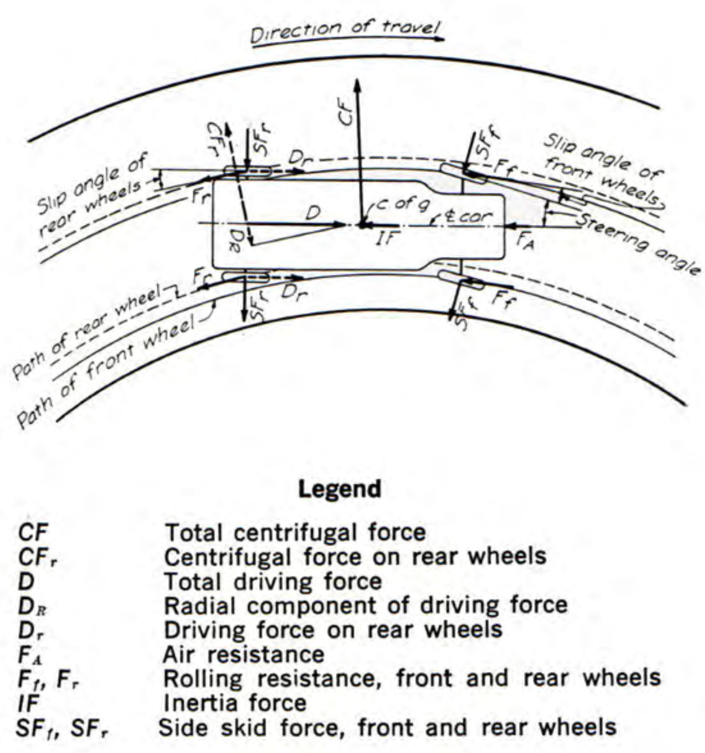

Figure 2: Vehicle rounding curve at constant speed [9]

The development of friction at the rear wheels is somewhat different because they cannot be steered. At very low speeds the rear wheels normally track inside the front wheels, the offset depending on the curve radius (fig. 1), As centrifugal force is developed by higher speeds, the rear end of the vehicle swings outward until its axis is no longer tangent to the circular path and the rear wheels are slightly angled to the direction of movement thus developing side friction (fig. 2). Now suppose the pavement is tilted or superelevated by raising the outer edge. This introduces a centripetal force due to gravity which opposes the certrifugal force; and if the curve is fully superelevated, all of the centrifugal force will be neutralized by the superelevation and there will be no need to develop side friction. When this condition is achieved, the slip angles can be zero.

Practical Limits to Superelevation

There are, however, practical limits to superelevating curves on public highways, for if the tilt is steep and the surface is slippery or icy, slow-moving vehicles may not generate enough centrifugal force to overcome the gravity force, and may slide down the tilted road surface toward the center of the curve. Because of this, most countries hold the maximum cross slope below 10 percent. Thus, even on superelevated curves, some side friction must be developed between the tires and the road surface. Although coefficients for side skidding on wet pavements of 0.50 or even 0.60 were easily developed on most pavement surfaces by the Iowa skid trailer, Moyer thought that such values could not be consistently relied on under average driving conditions, and he recommended using a value of no more than 0.30 for the useful coefficient of friction to counteract centrifugal force.(12)

To confirm this arbitrary figure based on judgment, Moyer observed blindfolded passengers in vehicles traveling on curves. When driven at speeds such that a coefficient of 0.10 was required to counteract centrifugal force, the passengers could not sense clearly whether they were on a curve or a tangent. At faster speeds such that the coefficient was increased to 0.20, the passengers could clearly sense that they were on a curve; and when the coefficient was increased to 0.30 by further speed increase, they felt distinctly uncomfortable. At this speed the passengers and drivers felt a decided side pitch and some of the cars developed tire squeal on dry pavements. The skill of the drivers was taxed to hold the front wheels on the curve. Moyer therefore concluded that " ... the maximum permissible speed on curves should not exceed that for which a useful coefficient of 0.3 to counteract centrifugal force is required." To be sure of developing this coefficient over a wide range of speeds, curvature, and driving practice, he stated that road surfaces should be constructed to provide a side skid coefficient of at least 0.60 at 30 mph, as measured by the Iowa test trailer.(9)

Dynamic Basis for Transition Curves

We have seen that as early as 1920, Luedke and Harrison had recommended inserting a transition curve of variable radius between the tangent and the circular curve to enable the driver to gradually adjust to the horizontal change in direction and the superelevated road surface. In 1932, F. G. Royal-Dawson enlarged on this idea by proposing a dynamic basis for the design of transition curves. (13) As was well-known, a vehicle traveling on a curve at constant speed accelerates toward the center of the curve at the rate of $\frac{v^2}{R}$, where v is the velocity in feet per second and R the radius in feet. On the other hand, when traveling on a tangent at uniform speed, there is no acceleration at all. The problem therefore is to achieve the change in acceleration at a uniform rate that is comfortable and safe for the driver and passengers.

The acceleration, $\frac{v^2}{R}$ on a 1,000-foot radius curve at a speed of 50 mph is 5 ⅓ feet per second per second. If the rate of change is held to 1 foot per second per second, it would take 5 ⅓ seconds to make the transition, which at a speed of 50 mph (73.3 feet per second) would require a transition curve 470 feet long. Common experience told Royal-Dawson that this was much more than was actually needed by the average driver at this speed, so he suggested using a greater rate of change for normal design, say 2 or even 3 feet per second per second.

In 1934 Moyer observed that a rate of change of acceleration of 2 feet per second per second was adequate and comfortable for the drivers of test cars on curves where side skid coefficients of 0.2 or more were necessary to keep the car turning in its proper lane.(9) With this rate of change Royal-Dawson's expression for transition length became:

$$L = \frac{1.58V^3}{R}$$

Where,
L=length of transition curve in feet.
V=Speed in miles per hour.
R=Radius of curve in feet.

This equation, Moyer observed, was practically the same as that for the American Railway Engineering Association's spiral easement curve (originally proposed by A. N. Talbot).(9)

He went on to demonstrate the value of spiral transitions to the automobile driver traveling at high speeds by an example: According to the above formula the length required to transition from a tangent to a curve of 1,000 feet radius would be 43 feet for 30 mph, 340 feet for 60 mph, and 825 feet for 80 mph. For these spiral curves the shift of the central portion of the curve toward the center, or the easement, would be 0.1 feet for 30 mph, 4.8 feet for 60 mph, and 28.4 feet for 80 mph. (This shift, known to road engineers as the offset, p, increases as the sixth power of the speed.)

At 30 mph it would be relatively easy for the driver to form his own spiral by shifting 0.1 foot on an unspiraled curve. However, at 60 mph, shifting his path 4.8 feet would be quite another matter, for the driver would have to start his maneuver outside his own lane to stay on the road. The shift of 28.4 feet for the 80 mph transition would be quite impossible on a two-lane road, even assuming the driver was willing to drive a 1,000-foot-radius curve that fast.

Not everyone agreed with Moyer on his recommended rate of 2 feet per second per second of change in acceleration on spirals. The Oregon Highway Commission, for example, was using 3 feet per second per second for figuring spiral lengths on main trunk highways about the time Moyer was making his tests.(14, 15)

The studies of driver reaction and skidding we have just examined provided the necessary groundwork for the logical development of the *balanced design* concept that has dominated all subsequent geometric design practice. We will examine this development in Part 6.

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