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Highway Design for Motor Vehicles: A Historical Review

Cornell Local Roads Program
Tech Tips

PART 6: DEVELOPMENT OF A RATIONAL SYSTEM OF GEOMETRIC DESIGN

As noted in Part 5, R.A. Moyer determined at the Iowa Engineering Experiment Station that when a side skid coefficient of 0.30 was developed by a vehicle while rounding a curve, the resulting sensation of side pitch outward was decidedly uncomfortable to the vehicle's occupants. Joseph Barnett of the Bureau of Public Roads (BPR) thought that this feeling of side pitch might be used as a basis for a rational system of geometric design, provided sufficient agreement could be found among individuals as to what was comfortable.

Road Test by Volunteers

To obtain information on how side pitch affects the occupants of a vehicle, the BPR in 1935 asked ordinary drivers to perform road tests in their own vehicles on curves of known radii and superelevation. The drivers were asked to report the minimum speed at which the occupants of the test car began to feel a side pitch outward. This feeling of side pitch, as the BPR already knew from Moyer's work, was well below the speed at which side skidding occurs, so the researches felt the corresponding speed would be a safe one to use in curve design.

Several hundred drivers in all parts of the United States responded to the appeal, making over 900 tests on many kinds of road surfaces. Side friction factors, *f*, were then worked out for each test, using the formula:

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

Where,
e=Superelevation rate in feet per foot.
f=Side friction factor.
V=Speed in miles per hour.
R=Radius in feet.

As was expected, there was a wide spread among individual observations, but the average values were very close to $f = 0.16$ on both dry and wet pavements at speeds below 60 mph, falling off to about 0.14 at 70 mph (figs. 1 and 2).[1]

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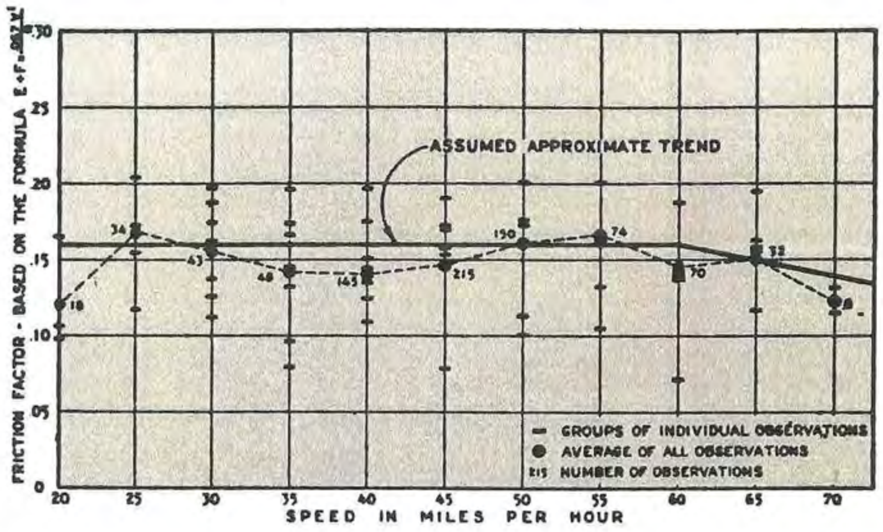

Figure 1: Average side friction factor when side pitch is noticed [1]

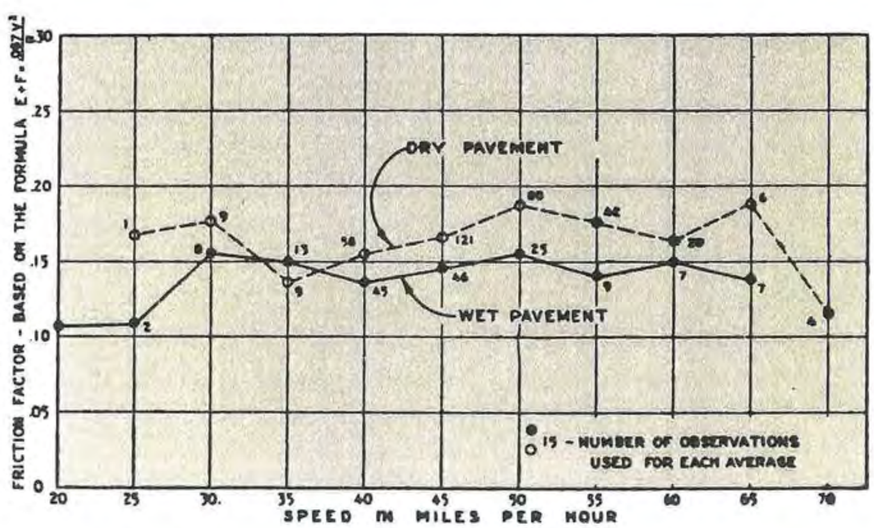

Figure 2: Average side friction factor when side pitch is noticed. Dry vs. wet pavements [1]

Design Speeds Proposed for Highways

After the 1935 road tests, Barnett proposed that superelevation on curves be designed to counteract only the centrifugal force for three quarters of the *assumed design* speed, relying on side friction to supply the remaining horizontal resistance, up to a maximum side friction factor of 0.16 at 60 mph. He defined assumed design speed as "the maximum reasonably uniform speed which would be adopted by the faster driving group of vehicle operators, once clear of urban areas" and urged that all features of geometric design - curve radii, superelevation, curve widening, transition curves, and even gradients - be made consistent with the chosen design speed.[(1)]

To understand the novelty of Barnett's proposals, one should realize that up to this time the design policy of most roadbuilding organizations was to locate roads on long tangents as much as possible and to join these tangents by the flattest curves commensurate with the topography and the available funds. There was little consistency in curve design except to avoid very sharp curves, especially at a hill crest or the foot of a steep grade. Most designers superelevated the curves to counteract all centrifugal force for a speed equal to the legal speed limit, which might be 35 to 45 mph,[1] but not exceeding a cross slope of 10 percent. If 10 percent was less than the theoretical superelevation for the legal speed, the driver was expected to slow down and round the curve at a lesser speed for his own safety.

In 1937 the Bureau of Public Roads published a curve manual setting forth Barnett's *balanced design concept*. The manual recommended that superelevation be designed for threefourths of the design speed, with side friction limited to 0.16, and that transition spirals be applied to all curves of 3,800 feet radius or less using the American Railway Engineering Association's 10-chord spiral as the preferred transition curve. This manual, of which Barnett was the principal author, had a strong influence on subsequent geometric design practice in the United States and abroad.[(2)]

The design speed or *balanced design* concept became a permanent feature of geometric design policy in the United States with its adoption by the American Association of State Highway Officials (AASHO) in 1938. AASHO defined design speed as " the maximum approximately uniform speed which probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones," and then went on to state:

> A principal factor affecting the choice of a design speed is the character of the te rrain. In general, rolling terrain will justify a higher design speed than mountainous country since the cost of constructing almost every highway detail will be less. An important highway carrying a large volume of traffic may justify a higher design speed than a less important highway in similar topography due to the fact that the increased expenditure for right of way and construction will be offset by the savings in vehicle operation, highway maintenance, and other operating costs.
>
> A low design speed should not be assumed for a secondary road, however, if the topography is such that vehicle operators probably will travel at high speeds ...Drivers do not adjust their speed to the importance of the road but to the physical limitations of curvature, grade, sight distance, smoothness of pavement...[(3)]

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1. In its 1930 Standards the American Association of State Highway Officials recommended that superelevation be ca lculated to offset the centrifugal force generated at a vehicle speed of 35 mph.

Percentile Speed Studies

The main problem posed by the design speed concept was how to decide what the design speed should be for a particular set of conditions. Just what was the " maximum approximately uniform speed adopted by the faster group of drivers? " This would be impossible to determine for roads not yet built, but the BPR engineers thought they could find a solution to this problem by analyzing the speeds adopted by drivers on roads already under traffic.

Fortunately, the Bureau had available for analysis a large number of speed observations that had been made in 1934, 1935, and 1937 with its speed-measuring device - the *speedmeter*. This mass of data included speed measurements on over 260,000 vehicles at 40 different locations. When plotted accumulatively, the speeds measured at any location invariably assumed the familiar S-shaped curve characteristic of a random distribution. This was true regardless of the number of lanes or the traffic volume, and over a rather wide range of speeds (fig. 3).[4]

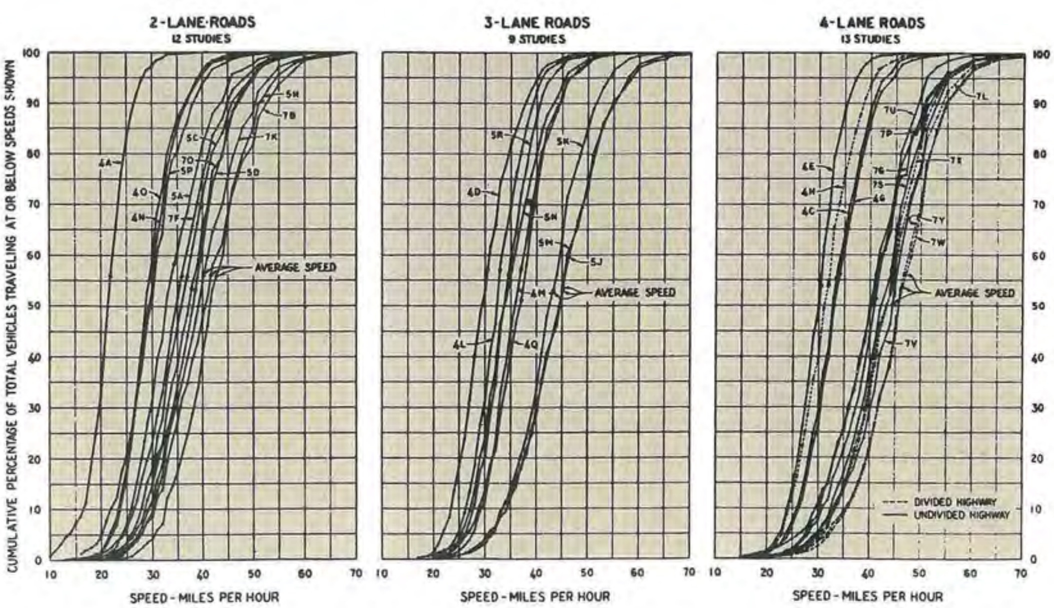

Figure 3: Speed distribution curves for 34 roads of two, three, or four Janes [4]

When they analyzed these curves, the BPR engineers found that although average speeds varied widely from road to road - from as low as 22 mph on some up to 47 mph on others the average always fell in the 50 to 60 percentile of the drivers, clustering around the 55 percentile. With this relatively constant relation, the engineers could analyze and compare speed distribution patterns for many roads even though their average speeds might be quite different. From the speed distribution curve (fig. 3) for a particular road they read the speed traveled by, say, the 90 percentile[2] of drivers. They then divided this speed by the average speed of all drivers on that road to obtain a ratio *K*. When the *K* values for the 90 percentile of all two-lane roads studied were plotted, as in figure 4, they fell into a straight-line curve with remarkably little scatter. In figure 4, for example, *K* for the 90 percentile of all two-lane roads was 1.240, showing that the fastest 10 percent of the drivers were traveling about 1¼ times the average speed regardless of what that average speed might be.

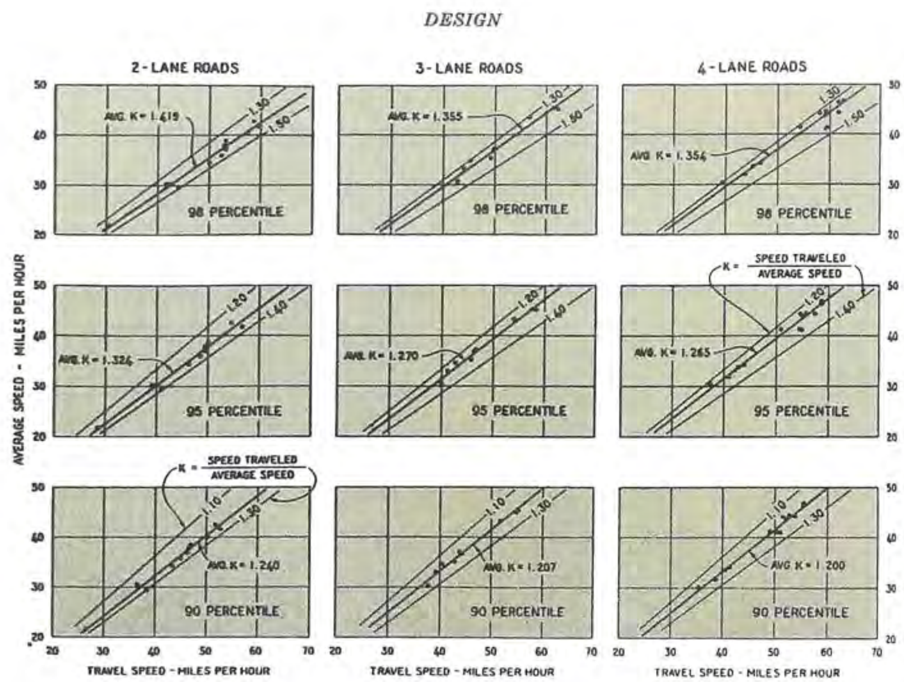

Figure 4: Ratio of the speeds of the 90-, 95-, and 98-percentile drivers to the average speed of all drivers (4)

The researchers worked up similar curves for all percentiles and when they plotted the resulting K values accumulatively, a curve such as that shown in figure 5 resulted. In this curve, the value of *K* is 1.0 at the average speed, which is found to be that of 55 percent of the drivers; in other words, the average speed of travel is a 55 percentile speed. The 100 percentile speed is found to be 1.92 times the average and the 10 percentile is only about three-fourths of the average. Figure 5 shows that over half of the 236,734 drivers observed were traveling at or below the average speed and only 10 percent were traveling as fast as 1.2 times the average. The analysts' problem then became one of selecting a cut-off point in this upper range. In the end, they recommended that the

2. The 90 percentile speed would be the speed exceeded by the fastest 10 percent of the drivers. It might be 28 mph for one road and 51 mph on another, depending on the design of the road and the traffic.

speed rating of any existing highway be considered as the speed of the 95 percentile - or possibly even the 98 percentile - of the drivers using that highway. By analogy, the design speed of a future highway should be the speed that only 5 or possibly 2 percent of the drivers will exceed after the road is built.(4)

In defense of these percentile speed values the BPR analysts showed that if the curves on a highway were designed for maximum superelevation of 10 percent and 0.16 side friction at the 95 percentile speed, only 5 percent of the vehicles would require more than the designed side friction. Of these, only a minuscule proportion (0.2 percent) would require more than 0.30 side friction, considered by Moyer and others to be the maximum for safe operation on wet pavements.

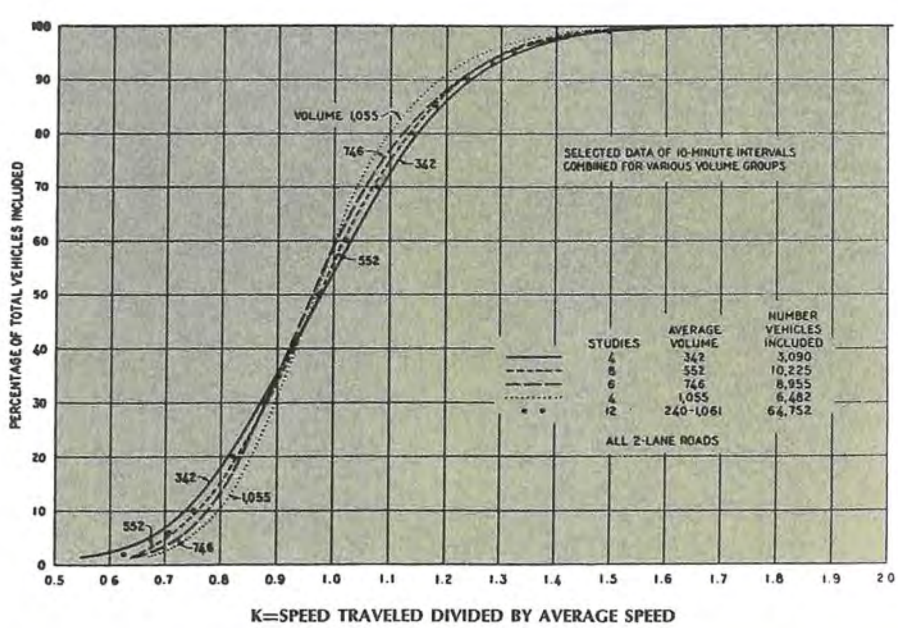

Figure 5: Ratio of the speeds of the fastest drivers to the average speed of all drivers for various percentiles of total traffic (4)

Further Driver Reaction Research

We have seen that in 1934 Moyer calculated the distances required to bring a vehicle to a stop on a level road from various speeds, assuming a perception-reaction time of one-half second. For these calculations Moyer used the well-known kinetic energy formula:

$$L = \frac{V^2}{30f} + 0.73V$$

Where,
L = Total stopping distance in feet.
V = Speed in miles per hour.
f = Average effective coefficient of friction for straight skidding.

The second part of this expression, 0.73 V, is the distance the vehicle will travel during the driver's perception reaction time, assumed to be one-half second. This figure in turn was probably derived from the 1925 research of Moss and Allen with alerted drivers, which in effect measured only the subjects' motor-reaction time, that is, the time for the driver to hear the stimulus (pistol shot) and for his nervous system to react and apply foot pressure to the brakes.

In 1934 the Massachusetts Institute of Technology carried Moss' and Allen's research a step farther. Test drivers in ordinary stock cars were instructed to follow a pilot car and to apply their brakes the instant they noticed the pilot car to be slowing down. In one series of tests the pilot car was equipped with a stoplight which lighted the moment the brakes of the lead vehicle were applied. Reaction times measured when the stoplight was used ranged from 0.2 second up to a second or more, with an average of 0.64 second. Five percent of the test drivers required more than 1 second and 20 percent occasionally registered as much as 1 second.[5]

When the tests were rerun without the stoplight, the test drivers required considerably longer times to perceive that the leading vehicle was slowing down. Drivers who reacted in 0.2 to 0.3 second to the stoplight required as much as 1.5 seconds to react without it. The researchers concluded that, making allowance for inattention - which had been eliminated from these tests - and for variations in personal capabilities, a perception-reaction time that would include most drivers should be between 2 and 3 seconds.

This range was adopted by AASHO in its first standard for stopping sight distance, approved February 1940, which allowed 3 seconds for a speed of 30 mph to 2 seconds for 70 mph. (Presumably drivers would be more alert at the higher speeds.) The AASHO standard also assumed a variable coefficient of friction ranging from 0.50 at 30 mph to 0.40 at 70 mph. These assumptions resulted in minimum sight distances of 200 feet at 30 mph up to 600 feet at 70 mph. The rate of deceleration with a friction factor of 0.50 was 16.1 feet per second per second, or one-half g, which according to the National Bureau of Standards, was the maximum for comfort.[6]

AASHO Special Committee Begins Intensive Study of Design Problems

By 1936 the fruits of research were becoming so abundantly available that the Bureau of Public Roads and the State highway departments began to feel the need for a special small working committee "to bring the available information on highway design up to date, develop new data based on research and experience and present them in usable form."[7] R. E. Toms, Chief of the Design Division of the BPR, proposed that the Bureau assign a small force of experts to devote full time to the work of the committee and that the American Association of State Highway Officials appoint a special committee consisting of senior

State administrative design engineers to guide and review the work of the BPR task force. This proposal was approved by AASHO in February 1937 and a Special Committee on Administrative Design Policies was organized with Thomas H. MacDonald, Chief of the Bureau of Public Roads, as chairman, and Joseph Barnett of the BPR as secretary. Toms and 12 outstanding design engineers from the States made up the rest of the Committee. Later, this Committee became the Operating Committee on Planning and Design Policies.(7)

The Bureau of Public Roads furnished a small technical staff under the Secretary, and the Committee started work on what were then deemed the most urgent design problems. The Committee's mode of operation was to outline a general program of work, after which the BPR task force gathered together and evaluated all the known information on each subject. If there were gaps in the existing knowledge, the BPR engineers pointed them out for further study. Eventually, the staff prepared a tentative discussion, with conclusions and recommendations for each subject. This was then criticized, evaluated, and supplemented by the Committee members until a policy acceptable to them was hammered out. The resulting policy was submitted through the Committee on Standards to the AASHO Executive Committee for letter ballot by the several States; with a two-thirds favorable vote it became an *approved policy*, and also, in effect, the national design policy of the United States on that particular subject.(8)

The first fruit of the Committee's work was a "Policy on Highway Classification," approved by AASHO in September 1938. Subsequently, the Committee brought out policies on geometric highway types (1940), sight distances on highways (1940), marking and signing of no-passing zones (1940), intersections at grade (1940) and on rotary intersections (1941), and grade separations (1944). In 1941 it compiled design standards for primary highways, and in 1945 for secondary and feeder roads and for the National System of Interstate and Defense Highways.

General Motors Corporation Deceleration Tests

In 1940 General Motors Corporation (GMC) made a series of deceleration tests at its test tracks in Michigan. For these tests the vehicle operators were eight Proving Ground executives who were experienced drivers but not professional test drivers. The test vehicles were 15 stock cars weighing from 3,000 to 5,000 pounds. The tests were run on level, dry, concrete straightaways. The drivers were required to bring their vehicles to speeds of 50, 60, and 70 mph and then stop them as quickly as possible and still keep the car within a 12-foot traffic lane. This last requirement precluded a locked-wheel slide since under this condition the vehicle is not under good control and cannot always be kept in a 12-foot lane. Since the operator chose his own time to apply his brakes, perception-reaction time was eliminated from the tests, which then measured only braking distance.(9)

The results of these tests appear in figure 6 which shows average stopping distances of 120, 200, and 280 feet for speeds of 50, 60, and 70 mph. The rates of deceleration were very close to 20 feet per second per second for all speeds - considerably greater than the comfortable maximum of the Bureau of Standards.

In another series of tests passengers were carried in the test cars, the drivers were asked to make stops at various deceleration rates, and the reactions of the drivers and passengers were recorded. These tests demonstrated that stops at a rate of 13.9 feet per second per second were severe and uncomfortable to passengers, causing packages to slide off the seats. Such stops were classified as *emergency stops* by the drivers. Stops made at 11 .05 feet per second per second were undesirable but not alarming to passengers, and those made at 8.55 feet per second per second were comfortable to all and also preferred by the drivers.

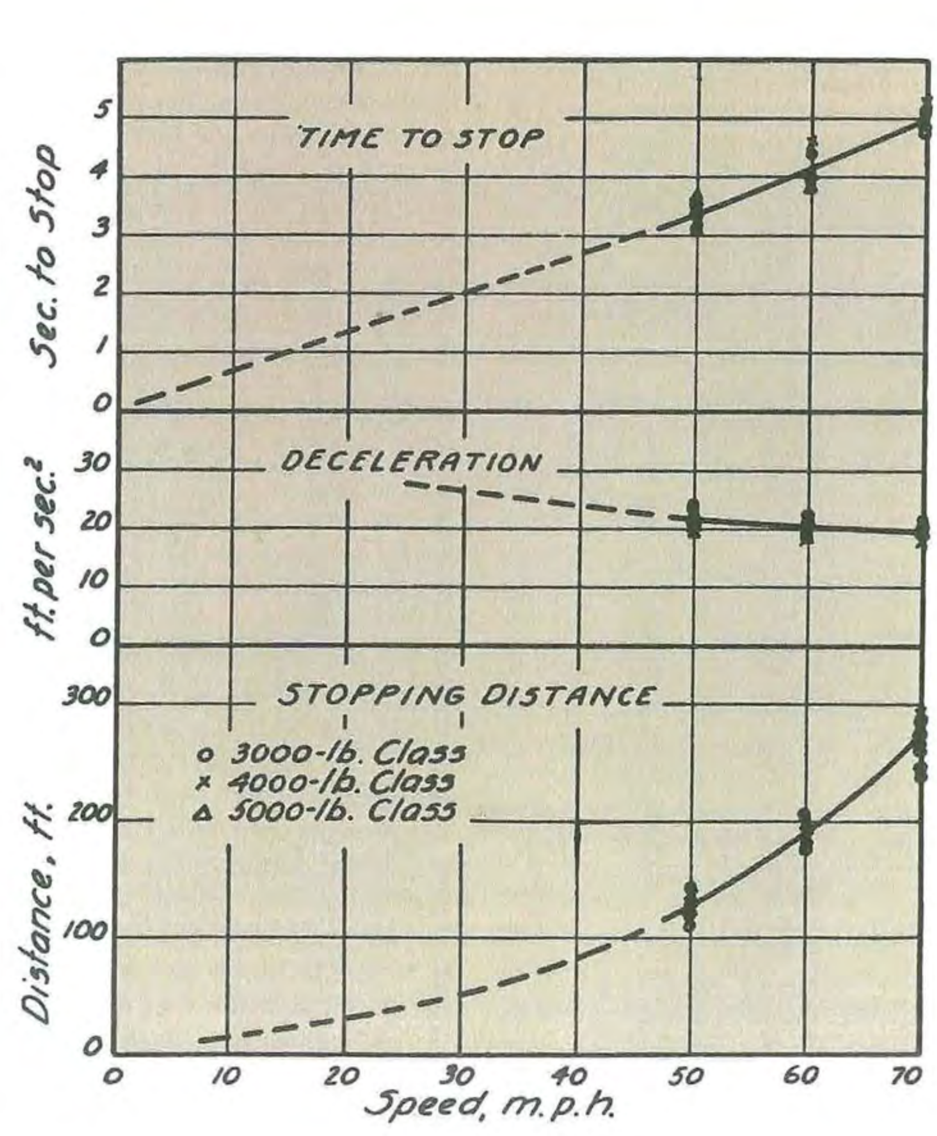

Figure 6: Maximum deceleration tests. Level grade (9)

From these tests the GMC researchers concluded that their vehicles were capable of much greater decelerating performance than was comfortable for the human occupants, and that highway sight distances should be based on human performance factors assuming a deceleration rate of 8.5 to 9.0 feet per second per second. Such a rate, with a perception-reaction time of 3 seconds would result in a minimum sight distance of 927 feet for a speed of 70 mph.

German Autobahnen Designed for High Speeds

We must now back up a few years to an important event which occurred in Germany. On September 23, 1933, Chancellor Hitler turned the first spadeful of soil for an express highway from Frankfurt/ Main to Mannheim- the first unit of an elaborate system of modern motor roads (*Reichsautobahnen*) that was to link all of the important cities of Germany. The new expressways were to be divided highways with full access control. In flat country the curves were to be designed for a speed of 180 kilometers per hour (112 mph) with 6 percent maximum superelevation. Curvature design was governed by safe stopping sight distance as calculated in the formula:[3]

$$L = 0.00394 \frac{V^2}{f \pm \tan a} + 0.278V$$

Where,

L =Sight distance in meters.
V = Velocity in kilometers per hour.
f = Friction coefficient between tires and pavement, assumed to be 0.4.
a = Gradient expressed in degrees.[(10)]

According to this formula, the safe stopping distance for 180 km/h and 0.4 friction factor was 370 meters on the level, 347 meters for a 3 percent up-grade, and 395 meters for a 3 percent down-grade. In rolling and mountainous country, to save construction expense, the Germans arbitrarily reduced the minimum sight distance to 200 meters which in effect reduced the permissible speed to about 140 km/h (87 mph).

In the German sight-distance formula the expression, $0.278V$, represents the distance traveled by the vehicle during the driver's perception-reaction time, assumed to be 1 second. For measuring sight distance to a potential obstacle on the road, the eye of the driver was assumed to be 1.19 meters above the road and the obstacle was assumed to be either another vehicle or an object projecting 20 cm from the road surface upwards. For the worst condition, that is, a curve in cut concave to the hill, a horizontal curve radius of about 2,000 meters was needed to provide safe stopping distance in flat country. In rolling country, a radius of 1,000 meters was needed. The absolute minimum radius for mountainous country was 400 meters.

At this time the German *Autobahn* curve design was the most advanced in the world. The concept of tying horizontal and vertical curvature and sight distances to speed,

3. This is the familiar kinetic energy formula used by Moyer and others, expressed in metric units

which the *Autobahn* engineers pioneered, was one of the great advances in the history of geometric design. Later research has shown that their assumed reaction times were rather low and friction factors somewhat high, but this was more than compensated for by an unrealistically high design speed. Consequently, although 40 years have passed, the alignment of these roads is still adequate for today's traffic.

The United States did not have a modern highway comparable to the German *Autobahnen* until 1939, when the 160-mile Pennsylvania Turnpike was completed. In planning the alignment for this toll road the designers applied the lessons of more than 15 years of high-speed operation on the European expressways as well as the fruits of a decade of research on driver behavior in the United States. The varied terrain traversed by the Turnpike permitted long tangents in the eastern part of the route but required some curves of 955 feet radius crossing the Allegheny Mountains. The designers went to great pains to obtain *consistency* in curve design. They joined extremely long tangents by extremely long, flat curves. Where sharper curves were necessary because of topography, they led up to them with a series of flatter curves. They spiraled all curves of 3,300-feet radius or less; provided sight distance for a speed of 70 mph for curves up to 1,910-feet radius; and provided sight distance for a speed of 60 mph for the sharper curves, only eight of which were of radii less than 1,433 feet. They designed superelevation for a side-friction factor of f=0.1 0 with a maximum cross-slope of 10 percent, attained at a radius 1,146 feet.

Speed Trials on Pennsylvania Turnpike

Upon completion of the Turnpike, its owners arranged with the General Motors Proving Ground to test the superelevation and curvature theories used in the design by actual speed trials. These tests were made in 1940 with new elaborately instrumented stock cars driven by highly experienced test drivers. One of the objectives of the speed trials was to determine at what speed the driver felt impending loss of steering control when rounding a curve. At this point the vehicle instrumentation would record the *unbalanced side friction*, that is, the centrifugal force not countered by the built-in superelevation of the road (also known among automotive engineers as the *centrifugal ratio* or *cornering ratio*). Another objective was to determine the efficacy of spirals for keeping drivers in their proper lanes when entering curves at high speeds.

The greatest speed attained in these tests was 106.75 mph on a curve of radius 1,910 feet, running downhill on a 3 percent grade at the vehicle's top speed. This velocity was far above the speed of 70 mph for which this curve was designed, yet the driver at no time felt that loss of control was impending, even when the centrifugal ratio went as high as 0.31 .

On the other hand, the drivers had to use their utmost skill to retain control when entering spiraled 955-foot radius curves at 80 mph when centrifugal ratios of 0.32 to 0.41 were developed. These curves had been designed for 60 mph with 10 percent maximum superelevation and had spiral transitions 360 feet long. These speeds were, of course, far higher than any that would be encountered in ordinary highway operation, and were possible only because of the skill and experience of the professional test drivers.

Braking test from high speed at Andrews Air Force Base, Maryland (12)

After these tests the researchers recommended that for speeds above 70 mph no more than f = 0.10 of the unbalanced side friction should be used in designing superelevations. The drivers and the engineer observers agreed that the spiral easement curves were highly effective for keeping drivers in their proper lanes at high and moderate speeds, and in fact their use " . .. is imperative if inherent safety is to be provided." (11)

BPR Stopping Distance Tests

By 1953, average speeds on U.S. highways had increased to about 52 mph with 12 percent of drivers exceeding 60 mph and others occasionally traveling as fast as 80 mph. The performance of new vehicles, compared to that of pre-war vehicles, had improved considerably and several millions of the older types had been retired. The Bureau of Public Roads thought the time was ripe to reevaluate highway stopping distances, and ordered a series of tests to be made.(12)

The test track for these experiments was an unused concrete taxiway at an air base near Washington, D.C., the surface of which had a clean, broomed finish of good anti-skid properties. All testing was on dry pavement. The test vehicles were 53 stock cars ranging in age from new to 10 years, operated by amateur drivers. The tests were designed to measure the braking distance - the distance traveled from the moment the operator applied brake pressure until the vehicle came to a stop - separately from the perception-reaction distance, at speeds up to 90 mph. The results of these tests are shown in figure 7.

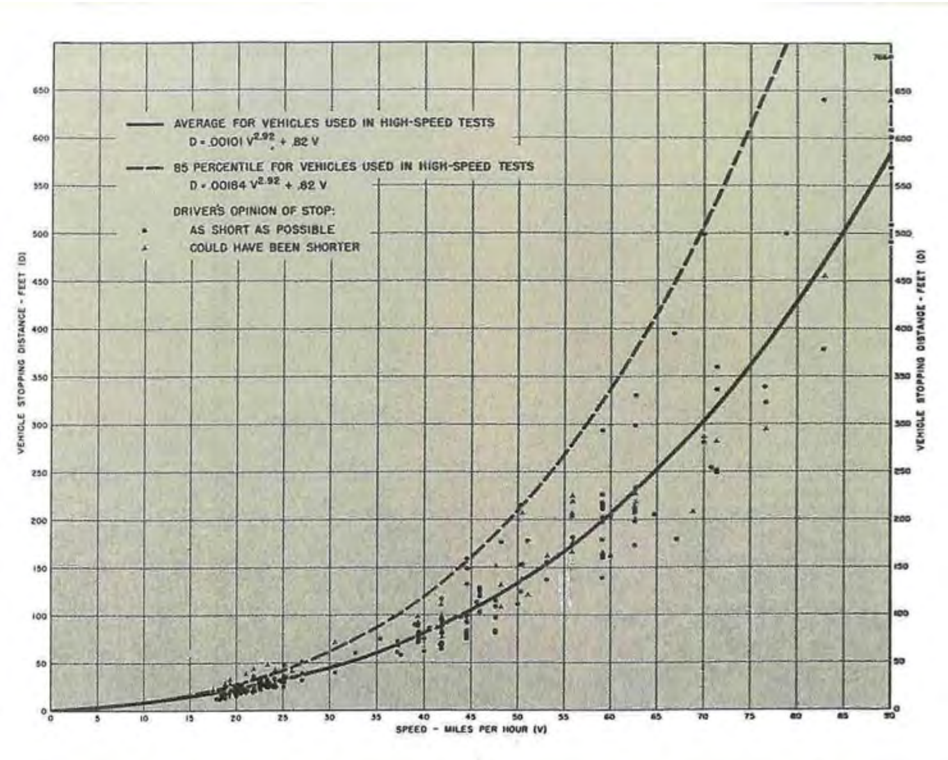

Figure 7: Braking distances during high-speed tests [12]

According to theory, the braking distance required to stop a vehicle varies with the vehicle's kinetic energy at the time the brakes are applied, which, in turn, varies as the square of the speed. However, the BPR engineers found that for high speeds the stopping distance varied as some greater power than the square. For example, the average stop from 30 mph was made in 40 feet. If the braking distance varied as the square of the speed, a stop from 90 mph should have taken 360 feet; but the actual distances logged in the tests averaged 580 feet, and the shortest crash stop from that speed was 490 feet. The researchers accounted for part of the discrepancy by the fact that brake pressure is not instantly exerted on the brake drums - it takes a fraction of a second to depress the pedal, to compress the brake fluid, and expand the brake shoes. Also, in braking from speeds of 70 mph and greater, the brakes seemed to *fade*, or lose effectiveness from heat buildup shortly after application, even though the brake pedal was jammed down as far as it would go.

The BPR engineers also observed rather wide differences in the stopping distances from high speeds logged for different runs by the same vehicle and operator. At 80 mph these differences might be as much as 164 feet, even though all the conditions of the test appeared to be identical.

Because of the rather wide differences in the braking performance of different vehicles and also of the same vehicles at different times, the researchers recommended that values of stopping distance used for design of roads be based on the 85 percentile of drivers, rather than the average. Figure 8 shows the average and 85 percentile values recorded during the test project.

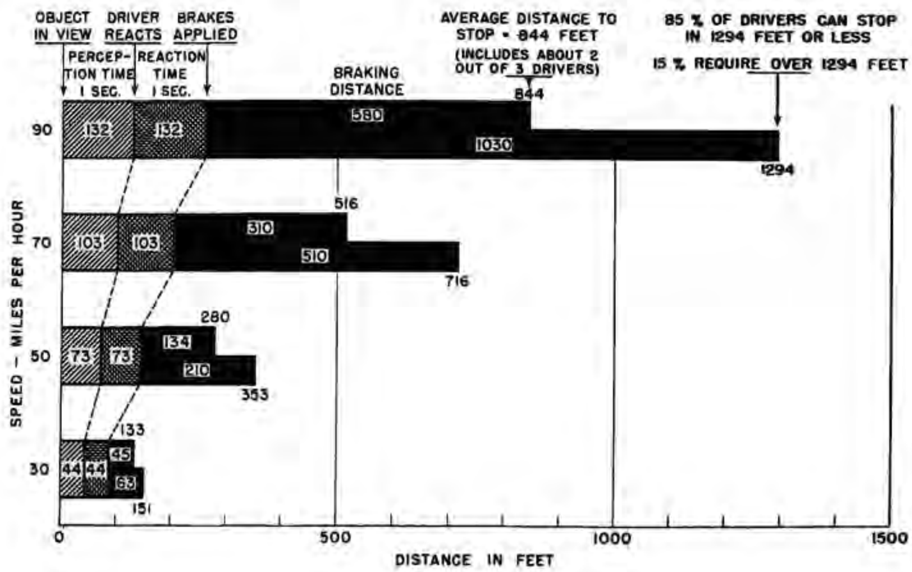

Figure 8: Driver stopping distance on dry concrete [12]

The research just described, along with a number of extensive studies of skid resistance on various roadway surfaces, suggested to AASHO's Committee on Planning and Design Policies the need for some revision of its Policy on Sight Distance, originally issued in 1940. The problem facing the Committee was not lack of information but rather extracting a workable practical policy from research results covering a rather wide range of values. With measured perception-reaction times varying all the way from 1 second or less up to 3 seconds, what was the proper value to use for safe sight distance? With pavement coefficients of friction ranging from 0.3 to 0.8 depending on speed, surface type, and wetness, what values would provide reasonable safety without prohibitive construction cost? After weighing the trade-offs the Committee finally decided as follows:

- To continue to use the kinetic energy formula:

$$L = \frac{V^2}{30f}$$

for computing braking distance;

- To adopt 2.5 seconds as the perception-reaction time at all speeds;

- To use the friction coefficient for wet concrete surfaces for figuring all stopping distances. This was quite generally accepted to range from 0.36 at 30 mph to 0.29 at 70 mph.
- To assume that during wet weather, traffic would be traveling slower than the design speed when the brakes were applied.

With these assumptions, stopping distances on a level road varied from 200 feet at 30 mph up to 600 feet for 70 mph.

AASHO Publishes Policy on Geometric Design

The Policy on Sight Distance was not the only one needing revision by 1954. The rapid evolution of highway engineering had made all of the original eight policies obsolete in some respects. Rather than attempt to revise the policies, the Committee decided to incorporate them in an entirely new publication eliminating duplications and obsolete information and adding much new material. The resulting publication, “A Policy on Geometric Design of Rural Highways,” was issued by AASHO in 1954.[13] Known as the *Blue Book* from the color of its cover, this manual went through seven printings and has had an immense influence on highway design in the United States and abroad.

The Blue Book firmly established the principle of balanced dynamic design - the design speed concept - in highway engineering. We have seen how this concept evolved for horizontal alignment, where the dynamic forces to be overcome are momentum and centrifugal force. In Part 7 we will examine the other side of the coin, the vertical alignment of the highway, where the main antagonist is gravitational force.

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