REPORT OF PROJECT COMMITTEE ON TRACTIVE RESISTANCE AND ALLIED PROBLEM

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FURTHER SKIDDING TESTS WITH PARTICULAR REFERENCE TO CURVES[1]

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SYNOPSIS

This report presents the additional data secured and the analytical studies made since the 1933 meeting of the Highway Research Board

Further tests on ice and snow were made because study of accident statistics in Iowa and Connecticut showed that a large proportion of skidding accidents occur in the winter It was found that reasonably safe coefficients of friction (0 3 to 0 5) can be obtained on ice if the chains are designed to provide contact between chain and ice at all times and if the load is great enough to make the chains cut into the ice

High coefficients are necessary when applying brakes and when driving on curves To provide the greatest safety under all ordinary road conditions the analysis indicates that brakes should be adjusted to obtain the maximum braking power on surfaces with coefficients of from 0 6 to 0 8 using brake power rates of 1 5 to 2 0

The frictional requirements on curves were determined from theoretical analysis of the forces acting on the vehicle when driving at constant speed, when accelerating and when braking When driving at constant or accelerating speed the driving force has a component which opposes centrifugal force, but when braking the braking force supplements the centrifugal force This explains why braking on a curve is so hazardous A maximum useful coefficient of friction of 0 3 is recommended for use in the design of highway curves As the result of this study the maximum superelevation recommended where icy road conditions are encountered is 0 1 ft per ft , and the maximum curvatures recommended are for main roads 5 deg , for secondary roads 10 deg and for mountain roads 15 deg

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[1] The material in this report has been abstracted from Bulletin 120 of the Iowa Engineering Experiment Station, "Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relation to Highway Safety " The figures and tables referred to by number in this report are in the bulletin Copies of the bulletin may be secured from the Iowa Engineering Experiment Station or from the Highway Research Board

The need for transition curves for high speed driving is analyzed. Speed is the greatest problem in safe operation on curves because the coefficients of friction decrease with increased speed, stopping distances, steering angles and centrifugal force increase as the square of the speed, required transition length increases as the cube of the speed and the shift toward the center formed by the path of the car increases as the sixth power of the speed.

At the Thirteenth annual meeting of the Highway Research Board, the writer presented a report on "Skidding Characteristics of Road Surfaces." In this report a complete description of test methods and equipment was given. Coefficients of friction for new and smooth tread tires on wet and dry surfaces were reported for skidding both straight ahead and sideways, at speeds of 3 to 40 miles an hour. The results of tests on asphalt, tar, road oil, portland cement concrete, brick, gravel, cinders, asphalt plank, steel plates, and wood plank surfaces were reported. Many tests were reported showing the effects of tire pressure, wheel loads, types of tire tread, and temperature. The report provoked considerable comment and many criticisms and suggestions were made which proved to be helpful in bringing the investigation into the final form as reported in the Bulletin 120 of the Iowa Engineering Experiment Station. This report deals with those phases of the investigation which were carried out since the annual meeting last year. The work consisted largely of interpreting the data that had been collected, conducting further tests where needed, and determining the frictional requirements for various driving conditions such as when braking or driving around curves.

The relative importance of skidding, as a cause of highway accidents, was determined from a study of highway accident statistics for Iowa and Connecticut. For the year 1933, skidding was found to be a contributing factor in 24 percent of all highway accidents in Connecticut and a direct cause of 7.5 percent. In Connecticut, 48 percent of all skidding accidents occurred during the four winter months, in Iowa, 82 percent of all skidding accidents occurred in the winter months. It is reasonable to conclude, from these data, that snow and ice were the major causes of skidding accidents in those states. For this reason further tests were run on snow and ice, with and without tire chains.

Four types of tire chains (Fig. 7) were used in the tests on ice, (1) standard four-link type balloon chains with round steel links, 6-in. spacing between cross-chains, (2) standard two-link type balloon chains, 3-in spacing between cross-chains, (3) claw chains, wedge-shaped steel links, four-link type, and (4) claw chains, two-link type. The results of the tests with chains (Fig. 29) indicated that reasonably safe coefficients of friction, ranging from 0.30 to 0.50 can be obtained on ice, *if* the chains are designed to provide contact between the chain and the ice at all times and if a high concentration of load is applied at the point of

contact, causing the chains to cut deeply into the ice. For tire sizes of less than six inches, the two-link chains accomplished this purpose, but with larger tires, or with low pressure tires (Fig. 30) the load may be distributed over too many cross-chains, under which condition the chains will not cut into the ice. Hence, a wider spacing between cross-chains should be used for these tires. An increase in the coefficient with an increase in speed was observed in all the tests with tire chains. The coefficients on ice for the tires without chains ranged from 0.05 to 0.22. The lower values being observed on a wet sleety surface, where the water served as a lubricant, and the higher values on dry ice at temperatures below freezing where liquefaction of the ice was not so likely to take place.

The results of tests on dry and moist packed snow (Fig. 31) clearly indicate that the coefficients on snow, free from ice range from 0.30 to 0.55 and are therefore notably higher than on ice. The tests on snow revealed skidding characteristics similar to those of untreated gravel or cinders except that the coefficients for snow were about 0.2 to 0.3 lower. The coefficients on snow increased with an increase in speed, a characteristic, also, observed on gravel. Although this characteristic is on the side of safety, it cannot be said that safety is increased with an increase in the rate of speed, because, as will be shown later, the frictional requirements for stopping and driving on curves increase as the square of the speed and since the coefficients of these surfaces are moderately low to start with, the margin of safety on these surfaces decreases with an increase in speed.

In Bulletin 120, a detailed description of all the surfaces tested is given, covering the history of the surface, the materials and methods of construction, the surface texture and the estimated traffic on the surface.

A careful study was made of the surface characteristics of typical surfaces for the purpose of explaining the coefficients of friction observed on these surfaces. In the previous report, the observation was made that an important factor in pavements having high coefficients when wet, was the presence of gritty particles which gave the surface a sandpaper-like texture and, conversely, that the glazing or polishing effect of traffic on certain surfaces was responsible for low coefficients when wet. Photographs of the magnified surfaces, (Fig. 22 to 25), inclusive, revealed another important characteristic especially of the asphaltic surfaces. In the photographs of surfaces on which high coefficients were measured in the wet condition, it was observed that many particles of aggregate on the surface were *not* coated with asphalt on the side exposed to traffic. The photographs of certain other asphalt surfaces indicated that an excess of asphalt had a tendency to flush to the surface and create a glazed condition of the surface which was reflected in the low coefficients on these surfaces when wet. The photographs of the magnified concrete and brick surfaces indicated the polishing effect of traffic on

these surfaces and provided a possible explanation for the slight decrease in coefficients observed on these surfaces as compared to the coefficients on surfaces with a "sandpaper" finish

High coefficients of friction between tires and road surfaces are necessary for two important driving operations; when applying the brakes, and when driving on a curve While it is possible to cause a car to skid on any surface during either of these operations, it is desirable to construct surfaces which will meet the frictional requirements in the ordinary emergency stopping and turning operations

Safe stopping distances and the coefficients of friction which should be available when braking, may be determined from an analysis of the forces acting on the vehicle when braking, and a consideration of the effect of various stopping rates on the passengers in the vehicle Retarding forces which act on a vehicle when the brakes are applied with the car in gear are engine resistance, air and rolling resistance, and braking resistance, also grade resistance if the vehicle is on a descending grade. The relative importance of these forces is discussed in the bulletin. The most important force, however, during an emergency stop is the braking force and it is this force that determines very largely what the frictional requirements of the road surface should be If it is desired to stop a vehicle in the shortest possible distance, it is necessary to bring both front and rear wheels into the impending skidding condition That this is a practical impossibility can be demonstrated by a mathematical analysis of the mechanics of braking

The maximum braking force on each wheel, front and rear, may reasonably be assumed to be fixed The ratio of the braking power at the front wheels to that at the rear wheels is known as the braking power ratio The application of brakes is accompanied by a weight transfer from the rear to the front wheels, which varies with the braking force (Fig 52). The results of the mathematical analysis shown graphically in Fig 53, indicate that for a given brake power ratio, it is possible to bring all four wheels to the point of impending skidding for only one value of the coefficient of friction In view of the variations possible in the road surface and in the braking power of cars, it is therefore practically impossible to bring all four wheels to the point of impending skidding Variations in brake power ratio and surface conditions are quite likely to cause a locked wheel condition in the front or rear While neither of these conditions is conducive to safety, locking of the front wheels is generally less likely to cause a dangerous side skid than locking the rear wheels To provide the greatest safety under all ordinary road conditions, this analysis indicates that brakes should be adjusted to obtain the maximum braking power available on surfaces with high coefficients (0 6 to 0 8) using brake power ratios of 1 5 to 2 0

The rate of stopping, corresponding to an average coefficient of 0 5, is 16 1 feet per second per second or one-half the acceleration of gravity

From the point of view of the safety and comfort of the passengers, this represents the reasonable maximum rate of stopping

After due consideration of all the factors which control braking, the results indicated that surfaces which are to be considered reasonably safe from skidding, should provide a straight skid coefficient of friction of 0 4 at 40 miles per hour under *all* conditions

Safe speeds for various traffic conditions depend largely on the safe stopping distance for these conditions The most important factor in stopping is the available effective coefficient of friction In an emergency stop, at least half a second is required for the driver to "size up" the situation and take appropriate action In this half second reaction time, the car will travel a given distance before the driver can apply the brakes. In Fig 55, stopping distances, including the reaction time distance, are given for various coefficients of friction On the basis of this study, minimum clear sight distances of 1,000 feet, 600 feet, and 350 feet are recommended for main trunk, secondary and mountain roads respectively.

The frictional requirements on curves were determined from a theoretical analysis of the forces acting on the vehicle when driving at constant speed, when accelerating, and when braking on curves This analysis was supported by the measurements of steering angles, paths of wheels, slip angles and the coefficients of friction obtained in the tests with five different types of cars on 5-, 10-, and 28-Deg curves

When driving on a curve, friction between the tires and road surface is necessary for two distinct purposes, to resist either the driving or retarding force in the line of travel and to oppose centrifugal force which acts normal to the path of travel The true frictional resistance may reasonably be assumed to be the resultant of these two forces

The frictional force to counteract centrifugal force varies with speed, degree of curvature, and superelevation On a curve not superelevated, all of the centrifugal force is resisted by a frictional force which prevents the car from skidding sideways On a superelevated curve, a gravity force is introduced which, at the speed for which the curve is superelevated, is equal and opposite to the centrifugal force At this speed the frictional force to counteract centrifugal force is zero However, if the speed of the car is increased, a frictional force is required at both the front and rear wheels to supplement the gravity force This frictional force is developed at the front wheels by turning the wheels at an angle, (the steering angle) greater than the theoretical steering angle required to hold the wheels on the curve at the speed for which the curve is superelevated. This excess in the steering angle is known as the slip angle At the rear wheels the frictional force necessary to counteract centrifugal force is developed in the same way That is, the car assumes such a position, or "attitude," on the curve that a slip angle is developed at the rear wheels.

In Figure 56 diagrams of the external forces acting on a car are given for three conditions of driving—constant speed, acceleration, and braking This analysis indicates that when driving at constant speed or when accelerating, the driving force has a component which opposes centrifugal force, whereas, when braking, the braking force has a component which supplements centrifugal force This explains why braking on a curve is so hazardous and is, no doubt, the cause of many accidents

In the side skid tests with the trailer unit (Fig 2) the true frictional resistance against skidding sideways could be measured directly, and accurately, for any desired slip angle for speeds up to 40 miles an hour In the tests on curves, measurements of the steering angles and the paths of the front and rear wheels were taken at various uniform speeds ranging from 10 to 70 miles an hour on curves where the latter speed was permissible The slip angles at the front and rear wheels were computed from these measurements The coefficients of friction at the front and rear wheels were determined from the direct measurements for variations in the angles of inclination (slip angles) of the test trailer (Fig 37) Theoretical coefficients were then computed for the speeds at which the cars were operated on the given curves A comparison of coefficients at the front and rear wheels, obtained from the steering angle and slip angle measurements, with the theoretical coefficients furnished a basis for establishing useful coefficients of friction necessary to counteract centrifugal force In making these computations, corrections were made for the effect of superelevation at the given speeds on the given curve

The excess side slip for the rear wheels as compared with the front wheels (Fig 58) may be large enough at the higher speeds on a given curve to cause the rear wheels to track outside the front wheels At speeds lower than that for which the curve is superelevated, a negative slip is necessary to counteract the unbalanced gravity force When driving on a curve, therefore, the wheels are continually slipping sideways except at the particular speed for which the curve is superelevated

In Figure 59 variations in the steering angles are given for cars with standard front axle and cars with individual front wheel suspension, at various speeds on 5-, 10-, and 28-deg curves on dry portland cement concrete The increase in steering angle with an increase in speed is clearly shown in this diagram Large variations in steering angle were observed in the tests with the cars with front wheel suspension In Figure 61 the coefficients of friction utilized at the front and rear wheels in these tests are given for the same cars The coefficients required at the rear wheels of several cars were two to three times greater than the coefficients required at the front wheels The coefficients of friction required on the rear wheels of the Studebaker equipped with low pressure tires and for the front wheel suspension cars were from 25 to 100 percent higher than the theoretical coefficients computed at the higher speeds, especially on the 28-deg curve The side sway, or body roll, observed

especially on the cars with front wheel suspension, raised the frictional values at high speeds on the 28-deg curve to practically double the value required for cars free from roll action These results indicate that a fairly large frictional force is required to counteract the effect of body roll and that the useful coefficients to counteract the effect of centrifugal force in the design of curves should be reduced to about one-half of the maximum side skid coefficient which the surface can provide in the wet condition

In the tests on curves on wet and dry surfaces, approximately the same coefficients were utilized for both surface conditions for speeds at which the coefficients required to counteract centrifugal force were less than 60 percent of the maximum coefficients which could be developed on the surface The coefficients of friction on the rear wheels were greater, and on the front wheels less when making a right turn than when making a left turn

On the basis of this study a maximum useful coefficient of friction of 0 3 to counteract centrifugal force is recommended for use in the design of highway curves

Standards of superelevation are recommended for main trunk highways, secondary highways, and mountain roads (Fig 64) The maximum superelevation recommended where icy road conditions are encountered is 0 10 foot per foot The maximum degree of curve recommended for main trunk highways is 5 (1146-foot radius), for secondary highways, 10 (573-foot radius), and for mountain roads 15 (384-foot radius)

From the experience in the driving tests on curves at high speeds, the importance of introducing transition curves at the approaches to the simple circular curves commonly used in highway design today, was fully realized When driving from a tangent on to a circular curve, the steering wheel must be turned to the position required by the radius of the curve In normal driving this change is made gradually and in doing so, the driver makes a natural transition curve of uniformly varying radius providing the steering wheel is turned at a uniform rate If the driver were to attempt to make the change instantaneously, the full effect of centrifugal force would be applied to the car at that instant, causing an uncomfortable swaying of the car However, if the change from the tangent to the circular curve is made gradually, the centrifugal force is applied gradually and no great discomfort will result nor will the danger of skidding be as great as when the turn is made suddenly. In running the tests on the unspiraled curves at high speeds, it was found that if the driver attempted to turn the steering wheel sharply, the car would tend to weave on the curve, since in getting onto the curve, there was a tendency to turn the steering wheel too fast and too far, causing the driver to cut dangerously inside the curve, then in getting the car back in the proper path, the driver would cause it to swing outside the curve, and with unusually large forces (50 to 75 pounds) to contend

with at the rim of the steering wheel, this weaving action continued as long as the car was on the curve. By developing a natural transition curve when approaching the circular curve at the same high rates of speed, no such difficulty in holding to a definite path in the central portion of the circular curve was experienced This experience demonstrated the value of spiraled curves for high speed driving

An important feature in the design of transition curves is the determination of the length necessary to make the transition with reasonable comfort and safety When driving on a circular curve, at a constant speed, a uniform rate of acceleration of the vehicle towards the center of the curve is developed which varies as the square of the speed and inversely as the radius of the curve To meet a given standard of comfort and safety, the transition from the tangent to the circular curve should provide a uniform rate of change of acceleration, and it is on this basis that the formula for the length of spirals was developed.

An important factor in the determination of the length of the spiral is the vehicle speed, since the length of spiral varies as the cube of the speed Recommended lengths of spirals for main trunk highways, secondary highways, and mountain roads are given in Table 10, based on the formula for the natural transition spiral On main highways, lengths ranging from 140 to 700 feet are recommended where the design is to be based on maximum permissible speeds of 80 miles per hour Increasing the length of spiral does not introduce any disadvantages to slow moving traffic and, therefore, it is recommended that the design be based on the maximum permissible speeds

The need for transition curves for high speed driving may best be shown by the following illustration When driving on a 1,000-foot radius curve at speeds of 30, 60, and 80 miles per hour, the lengths of spiral for safety should be 40, 340, and 825 feet, respectively, and the shift in the circular curve towards the center should be 0 1, 4 8, and 28 4 feet, respectively Although it would be a relatively easy matter for a vehicle to form its own spiral and to shift 0 1 foot on an unspiraled curve at 30 miles per hour, it would be necessary to cut over into the inside lane to develop the 340-foot spiral and to obtain the 4 8-foot shift at 60 miles per hour, and it would, of course, be impossible to develop the 825-foot spiral with a shift of 28 4 feet at 80 miles per hour on a paved road which is only 20 feet wide

In fact, the marked increase in speed of vehicles presents the most alarming problem which threatens their safe operation on highway curves for the following reasons: (1) the coefficients of friction of road surfaces decrease with an increase in speed, (2) stopping distances, steering angles, and centrifugal force increase as the square of the speed, (3) the required length of transition curves increases as the cube of speed, and (4) the "shift" towards the center of the curve formed by the path of the car increases as the sixth power of speed.