Paper 5530.

" A Laboratory Investigation of Skidding on Roads." †

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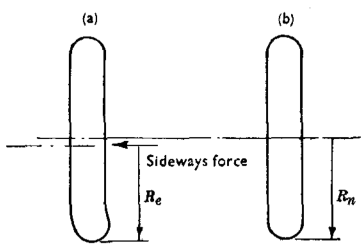
Mr. David J. Brown observed that the Author had stated that occasionally the number of revolutions of the skidding wheel per revolution of the turntable were greater when the wheel was running at an angle than when the wheel was running at zero angle of skid. Mr. Brown wished to propound the theory that when the wheel was skidding sideways the tire could be distorted sideways so that the point of contact would be at a point on the outer wall of the tire (*Figs. 23*). That point of contact being at a smaller radius than the normal one, the effective circumference would be less and thus the revolutions of the wheel would increase.

Figs. 23.



(a) Tire skidding at an angle R_e = effective radius
(b) Tire skidding at zero angle R_n = normal radius

Professor F. G. Royal-Dawson observed that he agreed that the rate of gain of centripetal acceleration, expressed as C feet per second per second in a second, could be represented in terms of the rate of lateral application : but he noted that the tests had been confined to a single wheel at various skid angles. On roads, instead of a single wheel, a group of four wheels—two guiding and two trailing—had to be considered. In that case the centrifugal force was applied, not to a single wheel, but to the vehicle's centre of gravity, which was usually near the back axle, so that the rear wheels, travelling tangentially, received the bulk of the lateral pressure. Thus, in effect, the tendency to skid applied to the rear wheels only, whilst the guiding wheels held their ground. Experiments on those lines might be made up to a certain point on a model-apparatus ; but for design purposes full-scale road conditions should be observed for the satisfactory determination of C values, for the following reasons :—

There was wide differentiation in practice between light and heavy vehicles, and between low and high speeds. For instance (*a*) a light car

† J. Instn Civ. Engrs, vol. 27 (1946–47), p. 179 (Dec. 1946).

travelling at 20 miles per hour might swerve with an initial C-value as high as 8 without skidding or overturning. An example of that had been described by Professor Royal-Dawson in 1942.[1] On another occasion, under somewhat similar conditions, but with a sharper swerve, the car overturned without skidding. Both cases occurred on a dry surface without super-elevation. (*b*) Heavy vehicles, with their longer wheel-bases and higher steering-gear ratios, were unable to make such sudden movements, and were unlikely to reach a value of C higher than 4, even at low speeds. In either category the tendency to overturn rather than skid depended upon the height of the centre of gravity. In ordinary practice a car with a low centre of gravity was more likely to skid than overturn, whereas a two-decker omnibus had a greater tendency to overturn. (*c*) At high speeds, say 60 miles per hour, a different set of conditions came into play. Slight unevenness on the road surface caused vertical oscillations, which were intensified as the speed increased, inducing fluctuations of normal pressure, or load, especially on the guiding wheels. During the uplift the vehicle tended to move forward tangentially, thus flattening the alignment, and to correct that the steering angle had to be increased as the wheel bumped down again. That jerked the action of centrifugal force on the rear wheels, causing a series of lateral impulses, or pushes, instead of steady pressure. Therefore prudence suggested that at high " design " speeds C should be kept as low as possible, as the possibility of occasionally exceeding such speeds could not be excluded. In 1936 Mr. L. R. Robertson and the Author had pointed out [2] that as between C values of 1, 2, and 3 there was a greater margin for acceleration between 1 and 2, than between 2 and 3. Moyer [3] had also pointed out that at a speed of 80 miles per hour it became difficult to steer within a 10-foot lane on a 3-degree (1910-foot) curve.

The action of skidding was well demonstrated when a racing motorist deliberately skidded round a sharp corner on a cinder track to gain time, as illustrated on p. 162 of Professor Royal-Dawson's book on " Road Curves," where it would be observed that the front wheels kept to the course. Obviously public highways could not be designed on those lines.

With regard to coefficients of adhesion for " design " purposes, it was common practice to limit the centrifugal ratio to 0·25 and the super-elevation to 0·10, leaving the difference 0·15 as the maximum available for lateral friction as a safe limit (except for very low speeds).

The following Table showed C-values for speeds which might be considered reasonably safe from skidding or overturning, when exceeding the " design " speed at $C = 1$. Thus, if the curve were designed for 50 miles per hour at $C = 1$, it would automatically take 63 miles per hour at $C = 2$.

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[1] " Psychology of Steering in Relation to Road Curve Design." Proc. Instn Mun. Cy. Engrs, vol. 68 (1941–42), p. 332 *et. seq.* (see p. 338).

[2] L. R. Robertson and D. F. Orchard. " Modern Road Transition Curves." *Ibid.*, vol. 62 (1935–36), p. 1003.

[3] See Author's bibliography (Ref. 13).

But that should be regarded as the limiting safe speed for that curve. If such a speed were likely to be exceeded, the curve should be designed for 60 miles per hour at $C = 1$, automatically providing for 70 miles per hour (approximately) at $C = 1{\cdot}5$ (more accurately $C = 1{\cdot}6$ for 70·2 miles per hour). As a rough rule, a curve designed for any speed at $C = 1$ would permit of an increase of 10 miles per hour with safety.

TABLE OF SAFE SPEEDS FOR VARIOUS c-VALUES.

C-value.	V ratios.	V : miles per hour within safe limits.						
1	1	10	20	30	40	50	60	70
1·5	1·145	11·4	22·9	34·3	45·8	57·2	68·7	80·1
2	1·26	12·6	25·2	37·8	50·4	63		
2·5	1·36	13·6	27·2	40·8				
3	1·44	14·4	28·8					
.....	....	....						
8	2·0	20 (light cars only)						

Professor Royal-Dawson hoped that the Author would continue his investigations in the light of the foregoing observations.

Mr. C. G. Giles and **Mr. J. S. Wilson** observed that at various times they had been associated with full-scale and model studies of road slipperiness carried out as part of the programme of the Road Research Laboratory.

The very comprehensive series of measurements of sideway force and braking force coefficient described by the Author had been made with a rubber tire running on a circular plate-glass table under both lubricated and dry conditions. In consequence the coefficients measured in all tests under lubricated conditions were extremely low, and it was unfortunate that the study was not extended to include other, and rougher, surfaces, such as ground glass, which give a higher range of coefficient with liquids as lubricants. If two " road " surfaces of differing roughness had been employed the relation between the Author's results and those of full-scale work might have been easier to deduce. The arbitary surface used was so smooth that the governing factor might well have been the comparatively rough surface of the tires. In those circumstances it was perhaps not surprising that the Author's apparatus, measuring sideway force coefficients of from 0·02 to 0·05, should give curves (*Fig. 4*) which did not agree closely with those obtained with the skidding motor-cycle on actual road surfaces with coefficients ranging from 0·1 to 0·9. On the full scale no evidence of instability or discontinuity in the values of sideway force coefficient had been detected ; instead the coefficient rose from zero to a definite value as the angle of skid increased and thereafter remained constant. It was surprising to find, in *Fig. 3,* that a skidding angle of 6 degrees gave higher coefficients over a wide range of speeds than both greater and smaller angles of skid. Was any significance ascribed to that particular angle ?

With regard to dry skidding, measurements had been made at the Road Research Laboratory of the radial reaction (sideway force) between a tire, constrained to roll in a circular path, and a road surface. When the radius of the path was of the same order as the radius of the tire quite large sideway forces were exerted, even when the wheel had its plane tangential to the path of rolling. The force was brought about by distortion of the portion of the tire within the contact-area and, in the case of circular road machines, where it would lead to " scrubbing " of the road surface, it was eliminated by arranging for " cone rolling " of the tire. By analogy with those results obtained with full-sized tires, it seemed probable that on the laboratory apparatus described in the Paper sideway force coefficients ranging from 0·1 to 0·2 would arise on the dry surface at zero angle of skid owing to that effect. Had that been observed by the Author ?

Measurements of sideway force and braking force on road surfaces suggested that the smoother the surface the more important became the rubber hardness and tire texture in determining the coefficient of friction. In the Author's work on lubricated surfaces coefficients of friction were very low. He had given no indication as to whether the actual values measured were affected, as seemed likely, by changes in the tire surface due to wear, or in the rubber hardness due either to temperature-changes or the use of tires made from a different " mix."

On the full-scale, markedly lower coefficients occurred in warm weather, and some of that reduction has been related to a reduction in tread rubber hardness as the temperature of the tire increased.

On p. 83 the Author had referred to the " seasonal variation " of sideway force coefficients for which curves were given in " Road Research Technical Paper No. 1." Those curves had been re-examined and Mr. Giles and Mr. Wilson considered that it would be more correct to regard the curves showing values of coefficients at 30 miles per hour as the significant curves, since the values of the coefficient at higher speeds had the greater effect in determining the " stopping-distance." Those curves showed that maximum values of the coefficient generally occurred in December and January, and minimum values in June and July.

On p. 184 the form of a curve on page 114 of the Road Research Laboratory's Annual Report 1935–36 had been attributed to an imperfect supply of lubricant. That point had been specially investigated in experiments where the lubricant was drained away from the test-surface, while the wheel rotated at speed, until only a drop remained at the area on contact of the wheel and surface. The friction remained constant until the lubrication failed suddenly and the wheel " seized " on the surface, the friction mounting instantaneously to many times its lubricated value. No zone of transition corresponding to partial lubrication was detected.

It was clear from the Paper that much work still remained to be done on the subject of skidding on roads, particularly with regard to the effects of road texture. In view of the difficulty of scaling the road texture, to which the Author had drawn attention, it seemed probable that future work could best be done on the full scale. Improved techniques for measuring sideway force and braking force coefficient on actual road surfaces were being developed at the Road Research Laboratory and should enable many of the difficulties encountered in previous full-scale work to be overcome.

The contributions to the knowledge of skidding phenomena made by the Author and by Dr. Saal had been very valuable and it was regrettable that circumstances had not permitted the Author to pursue further certain interesting lines of research which became apparent during the work.

The Author, in reply, observed that Mr. Brown's theory in explanation of the fact that the number of revolutions of the skidding wheel per revolution of the turntable were occasionally greater, when the wheel was running at an angle, than when the wheel was running at zero angle of skid, could not be accepted as a complete answer to the phenomenon. The reduction in the radius of the wheel due to tire distortion when skidding at an angle was undoubtedly a contributory factor, but the actual phenomena were far more complex and were influenced by a constant state of slip between the running surface and the tire rubber falling within the area in contact. That state of slip existed whether the wheel was skidding at an angle, was being braked, or was running freely, and whether it was traversing a straight path along a fixed surface or was constrained to run along a circular path on a revolving turntable. Various aspects of that problem which were controlled largely by the ratio of hardness of the material forming the wheel and that of the running surface had been studied at length by Stanton [1] and Hele-Shaw,[2] but in all cases their postulates related to solid wheels. The case of a pneumatic tire was a little different, but the broad principles were similar. Some doubt existed whether, in determining the revolutions of the wheel per revolution of the turntable from theoretical reasoning, the indented or the unindented diameter of the tire should be taken, as the latter was presumably that which determined the actual circumference of the wheel (but which took no account of the compression longitudinally of the rubber due to indentation) ; but the former was that which gave a result agreeing more nearly (usually less than 1 per cent. in excess) with the result determined experimentally by running the wheel freely on the turntable. A further factor to be considered was that the wheel-diameter decreased when the wheel was running—a fact which it was difficult to explain, as it would be expected to increase owing to the centrifugal force acting on the tire. Measurements carried out during the tests indicated that the change in wheel-diameter due to tire distortion could not normally be expected to increase the number of revolutions of the wheel by a greater amount than the fact that the wheel was skidding at an angle could be expected to reduce the number of revolutions of the wheel per revolution of the turntable. It should, however, be borne in mind

[1] Sir Thomas Stanton, " Friction."

[2] Professor H. S. Hele-Shaw, " Cantor Lectures on Friction," J. Roy. Society Arts, Vol. 34, 1885–1886.

that the effective angle of skid was reduced by tire distortion by an amount which so far had not been determined.

Professor Royal-Dawson had raised a rather different subject, in stressing the desirability of studying the maximum permissible C values with a four-wheeled vehicle, than that under review with the model skid-machine. Two different sets of phenomena governed the choice of the maximum permissible value of C :

(1) The state between the tire and the road surface.
(2) The vehicle characteristics combined with the physical reactions of its occupants.

It was the former which it was desired to study in the present case, and by adopting a single wheel it was possible to separate the variables relating to that from those belonging to the second factors. If tests were carried out under actual road conditions it might be very difficult to separate the phenomena peculiar to the different states. From the present model-research it did not appear that up to a certain value of C, well above that recommended by Professor Royal-Dawson, there was any increased likelihood to skid as the rate of application of sideways force was raised, in so far as the state between the tire and the running surface was concerned. Full-size tests conducted by the Author and described in another Paper [1] indicated that higher values of C than those recommended by Professor Royal-Dawson were habitually attained in practice but that, whilst the high values of C advocated by Warren [2] and Leeming [3] were reached momentarily, they were not maintained over the full length of a transition curve. There did appear to be a strong case, however, for a higher design value of C, even at high speed, than the hitherto normally accepted value of 1 foot per second^2 per second. There was, however, a likelihood that high and heavy vehicles, such as buses, might—as Professor Royal-Dawson had pointed out—operate at lower values of C than private cars ; but as those were not likely to be travelling at such high speeds, that fact would not normally affect design unless they were segregated into separate carriageways. There was, however, a need for more research on that point.

As Mr. Giles and Mr. Wilson had suggested, useful information could be obtained with rougher surfaces on the model-apparatus, and the difference in the curves of coefficient against angle of skid or percentage slip of the wheel (for braking) obtained with the model-apparatus, from those obtained with the full-scale machine, might then cease. That difference, however, occurred only after the failure-point and, as explained in the Paper, it was not thought to be fundamental, but rather a question of

[1] D. F. Orchard, "Clover Leaf Loops," J. Instn Civ. Engrs, vol. 23 (1944–45), p. 210 (Feb. 1945).

[2] H. A. Warren, "Experimental Transition Curves," J. Instn Mun. Cy. Engrs, vol. lxv. (1939), No. 21 (Mar. 1939).

[3] J. J. Leeming, " Road Curvature and Superelevation," J. Instn Mun. Cy. Engrs, vol. lxxl (1944), No. 5 (Dec. 1944).

relative speeds. If the full-scale machine which operated on a comparatively rough surface could be run exceedingly fast, or if the model-apparatus operating on a smooth glass surface could have been run very much slower, similar curves might have been obtained. The results of different workers in different countries did not show complete unanimity, even with full-scale apparatus, with regard to the behaviour of the curve beyond the failure-point, and a failure-point or region of instability had been noted by some observers.[1, 2]

It was not thought that, within limits, the roughness of the tire was a governing factor when skidding on a polished glass surface, as the tire, when pressed against the glass, assumed a similar state of polish over the contact-area to the glass. The fact that an angle of skid of 6 degrees gave higher coefficients over a wide range of speeds than both greater and smaller angles of skid, as shown in *Fig. 3*, followed from the shape of the curves of coefficient against angle of skid, and that fact could be confirmed by reference to *Fig. 4*. It was evident that, in the present experiments, the value of 6 degrees for the angle of skid was the point at which the frictional force ceased to be capable of distorting the tire further ; therefore its value could be expected to vary according to the experimental conditions, notably the tire stiffness and the coefficient of friction developed.

The scrubbing action mentioned by Mr. Giles and Mr. Wilson, which took place when a wheel was constrained to run along a circular path the radius of which was of the same order as the radius of the tire, was observed with the model-apparatus, and that phenomenon became appreciable at about the same ratio, of the radii of the wheel and its path, as appeared to have occurred in their tests. Unlike the full-size tests, that effect caused the coefficient to be zero until a certain angle of skid or radius on the turntable had been reached, even on a dry surface. That was illustrated in the curves of *Fig. 6*. It should be realized, however, that in that case the contact-area was considerably smaller than that which must have been used by them. In the series of experiments described by the Author, time did not permit tests to be carried out to determine the effect of such variables as rubber hardness and the state of the tire surface, but those variables were kept constant. The postulate was offered that the temperature was not strictly a variable affecting the coefficient of friction and that it merely exerted an indirect effect by altering other variables such as the viscosity of the lubricant and the rubber hardness.

One advantage of model laboratory apparatus was that the variables could be separated more readily, and, so long as its limitations were kept in mind, much knowledge, mainly of a theoretical nature, might be gained more quickly, which could be of immense value in interpreting the results of and in developing full-size apparatus.

[1] Karl W. Stinson and Charles P. Roberts, " Coefficient of Friction between Tires and Road Surfaces," Proc. 13th Annual Meeting, Highway Research Board, Washington, December 1933.

[2] R. N. J. Saal, " The Non-Skid Properties of Road Carpets," International Road Congress, Holland, 1938.