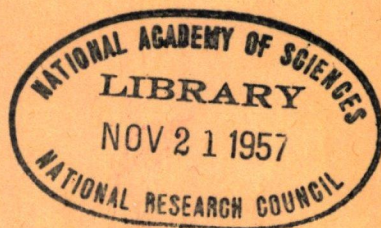


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" Bulletin 51

***Squeal of Tires
Rounding Curves***



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Bulletin 51

Squeal of Tires
Rounding Curves

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Squeal of Tires Rounding Curves

Joseph Barnett
Chief, Urban Highway Branch
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THERE HAS been general acceptance of the theory that if a vehicle in making a turn develops tire squeal it is, or is on the verge of, skidding laterally. In recent discussions with Ralph Moyer, one of the leading investigators of factors relating to skid resistance, he criticized certain standards of the American Association of State Highway Officials regarding safe speed on curves because his tests, using tire squeal as evidence, indicated excessive speed. It is not unnatural that tire squeal should be considered evidence of lateral skidding or excessive slippage, because drivers are familiar with a similar sound when jamming brakes and skidding forward.

I question that tire squeal is indicative of lateral skidding or even impending skidding when vehicles travel on curves. It does not fit in with another observation regarding tire squeal of which there is no uncertainty. When vehicles travel on the same curve at the same speed tires with low pressure squeal louder than tires with high pressure and vehicles traveling on the same curve begin tire squeal at lower speeds with low-pressure tires than with high-pressure tires. This was generally noticed when most passenger-vehicle models changed to lower-pressure tires about 1948.

The following theory is advanced for the reason for tire squeal when vehicles travel on curves. Vehicle tires rest on the pavement with a contact area generally oval in shape.^{1/} With low-pressure tires the area is larger and the oval is longer for the same weight. As the tire proceeds around a curve, as shown in Figure 1, it can do so only by the contact area of the tire twisting around its center with the front end sideslipping in one direction and the rear end sideslipping in the other direction. It is my belief that this sideslipping of the ends of the contact

^{1/} - "Determination of Variation in Unit Pressure Over the Contact Area of Tires," L. W. Teller and J. A. Buchanan, Public Roads, Vol. 18, No. 10, December 1937.

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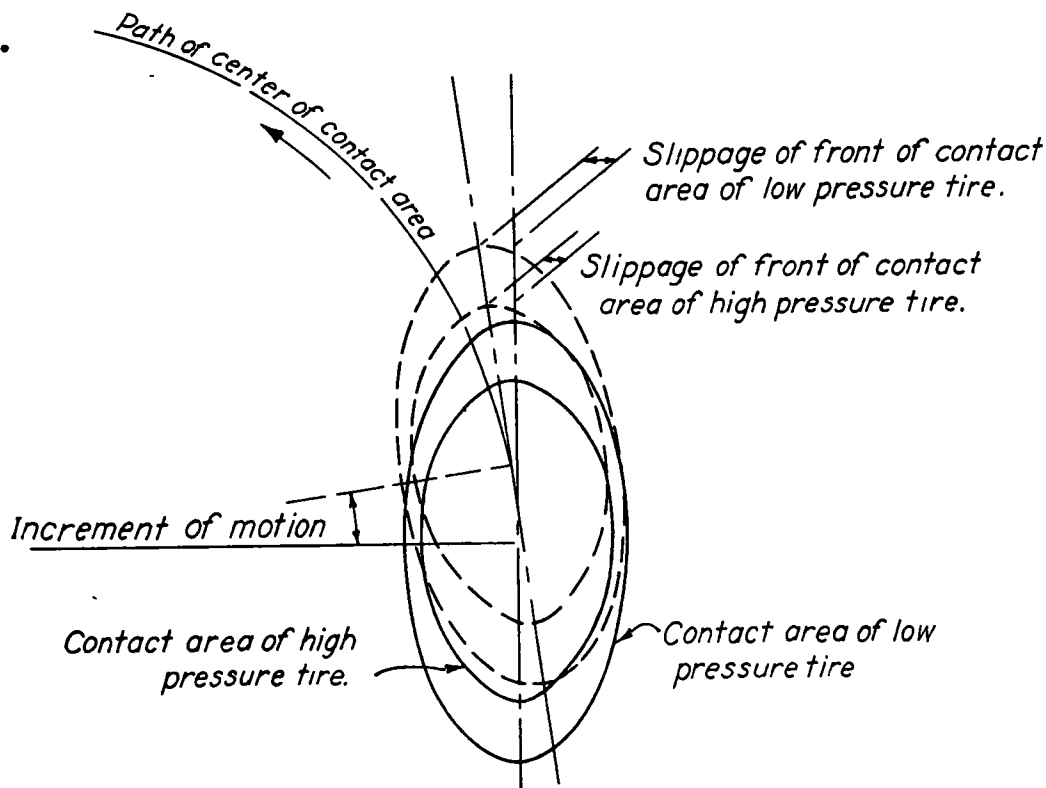


Figure 1. Twisting of contact areas of tires on curves.

area, necessary if the area is to twist as the tire proceeds around a curve, is the cause of tire squeal and not the lateral skidding of the tire as a whole. This theory fits in with the fact that low-pressure tires begin to squeal at a lower speed in traveling around a curve than high-pressure tires traveling on the same curve in that the sideslipping of the ends of the contact oval increases rapidly in amount as the contact oval increases in length, as indicated in the figure.

It would be well if this theory could be proven or disproven by research, preferably in cooperation with the automotive and tire industries. The design of curves to accommodate various speeds is made in much the same manner as any other engineering design. The limiting factor is determined first and the value adopted for design is chosen after allowing some factor of safety. If the squealing of tires around curves is used as the criterion for determining impending skid and the squealing of tires does not represent impending skid, but instead is merely an indication of the theory advanced herein, then the design of curves is starting with a false fundamental premise. There are, of course, many other factors in the design of curves, such as probable condition of pavement surface, sway of vehicles on their springs, and the ability to steer within reasonable lateral limits; but impending skid is one impor-

tant factor, and the elimination of any false premise in measuring impending skid would be a step in the right direction.

It is of interest that when low-pressure tires were first introduced there was noticed a considerable amount of squealing of tires rounding curves, particularly at intersections of streets where sharp turning is necessary. The amount of such squealing has become perceptibly less, almost to the point of elimination, despite the use of the same low-pressure tires on all new models and an increase in the percentage of vehicles with low-pressure tires as old models are replaced by new ones. Might this be due to the fact that drivers have trained themselves to reduce speed around sharp curves to avoid the unwelcome squealing of tires? Or might it be because drivers seek to lessen the physical effort needed to steer by putting more air into tires than the amount recommended by automobile manufacturers? Might it be due to a change in the design and composition of tire treads caused by changes in the availability of natural rubber? All these questions invite research necessary to determine friction factors at impending skid and thus narrow the uncertainty regarding this fundamental design factor.

Discussion

RALPH A. MOYER, Research Engineer, University of California — Barnett raises questions on an important phase of the operation of motor vehicles on highway curves which should be of interest to engineers responsible for the design of highway curves, tire manufacturers, and all drivers. As was mentioned by Barnett in his paper, this writer for many years has been engaged in conducting skid resistance tests on various road surfaces and on highway curves and has had an opportunity to make observations regarding tire squeal. In this connection the writer has also had the opportunity to confer with research engineers of tire and car manufacturers and has observed tests conducted by these research engineers where tire squeal was one of the factors under investigation. While tire squeal was considered more or less as an incidental factor in the tests referred to above, I can report that much is known about tire squeal. In fact, as far as the highway engineer is concerned, I believe that the discussions will provide fairly complete answers to all of the questions which Barnett raised.

Observations have clearly indicated that tire squeal is not a reliable criterion for the determination of a safe design speed for highway curves, nor is it a reliable indication of the speed at which the driver will lose control of the vehicle on any given curve. As Barnett has correctly pointed out in his paper, the speed at which tire squeal starts on a given curve may vary considerably depending upon the tire pressure and the type of tire used. It should be recognized, however, that there are many other factors beside tire pressure which have a bearing on the speed at which tire squeal starts on a given curve. Furthermore, I have observed certain road and tire conditions where tire squeal will not appear at all, and under these conditions the car will skid sideways off the curve or will go into a spin without an audible warning.

In the design of rural highway curves, many designers compute the minimum safe radii of the curves for various design speeds using a safe side friction factor of 0.16 in the general curve formula:

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

where

R = radius of the curve in ft.

V = design speed in mph.

e = superelevation in ft. per ft.

f = design coefficient of friction

For the low design speeds of 20 and 25 mph. when computing minimum radii of curves at intersections, a side friction factor of 0.25 is used by some designers. In the AASHO Policy on Intersections at Grade, the design coefficient of friction is given as 0.54 for a 20 mph. design speed. My observations have indicated that tire squeal rarely develops on curves at a speed where the side friction factor is less than 0.25. Furthermore, on such a surface the speed on the curve may generally be increased until a speed is reached where the tire squeal is very pronounced and the side friction factor is in the range of 0.45 to 0.50 before the car will start to skid sideways or the driver lose steering control. In my experience a friction factor of 0.54 on a curve is not only unsafe but on surfaces of the tire-squeal type is not likely to be attainable within the usual range of design speeds.

Tire manufacturers are very conscious of tire squeal since they consider it an objectionable feature in tire design. By making certain changes in the rubber compound and in the design of the tire, it is possible to increase or decrease the speed on a given curve at which tire squeal will develop. Even with the low-

pressure tires now in general use, friction factors as high as 0.35 and 0.40 are entirely possible before tire squeal is observed. I have felt that a certain amount of tire squeal is desirable, since it gives the driver warning that he is operating at what I consider to be an excessive speed for a curve where skidding is a hazard, and in providing a warning, it also provides a safety factor which should keep the driver out of trouble on the curve. The difficulty here is that tire squeal does not provide a dependable factor of safety, since as I mentioned before, tire-squeal speeds vary widely, and in fact, tire squeal may actually not appear at all under certain conditions.

Barnett raises some questions concerning the cause of tire squeal and advances a theory to explain why tire squeal develops at a lower speed as the tire pressure is decreased. My observations indicate that tire squeal occurs when tread rubber slips or is dragged over dry glazed or polished surfaces. Tire squeal is especially noticeable when driving in a curved path on dry glazed asphalt surfaces, on polished concrete surfaces, on dense-graded pavements with heavy paint markings and over the smooth rails of street car tracks. Tire squeal does not develop on curves on open-graded coarse-textured surfaces or on wet surfaces. It does not develop on ice or packed snow, except at very low temperatures.

A glazed or polished surface texture contributes to tire squeal for several reasons: first, because it provides a lower effective friction force between the tire and the road surface than an open-graded coarse-textured surface, therefore, slip occurs more easily; and second, because the more highly polished the surface, the less the abrasion and the smaller the amount of debris continuously formed in the areas of contact of the tire with the road surface. The presence of debris, such as soft rubber particles or sand, or the presence of water serves as a lubricant and suppresses or entirely eliminates the squeal.

The photographs in Figure A show a typical glazed asphalt surface on which tire squeal was very pronounced when driving on curves on this road in the dry condition. Also shown are the friction values in braking tests on this surface for both the dry and the wet condition. A significant feature of these test results is the marked decrease in the friction values obtained at the higher speeds of 40 and 50 mph. on this surface in both the dry and the wet tests and the very low friction values obtained in the wet tests at the higher speeds of 40 and 50 mph. These test results and, other observations which I have made indicate that tire squeal may be a better indicator of surfaces which are slippery when wet than of the safe design speeds on highway curves.

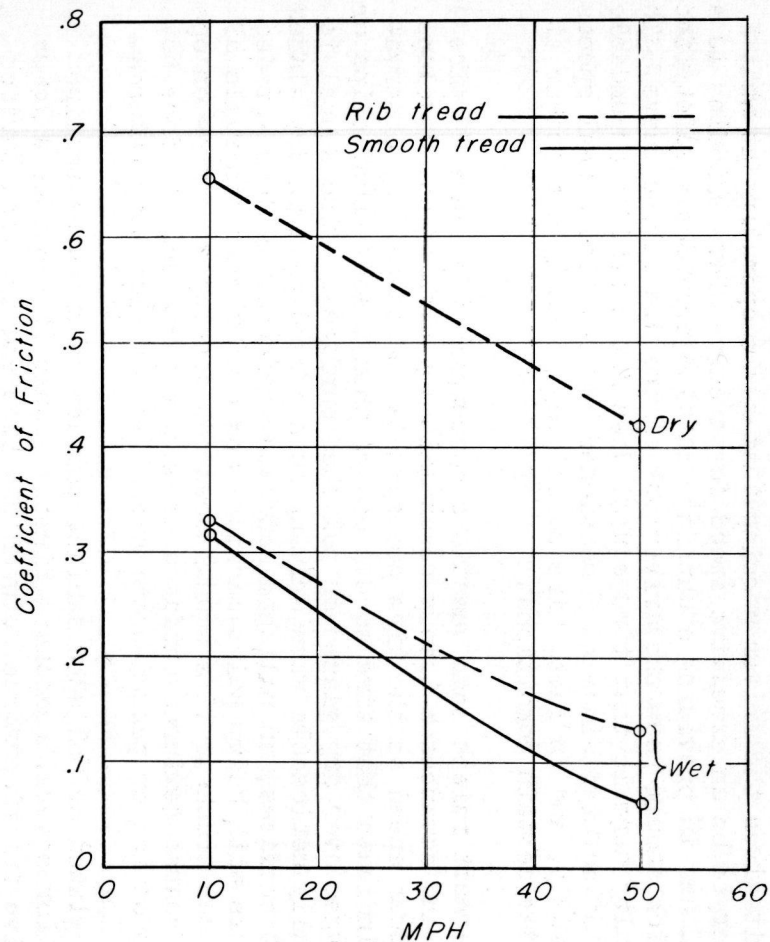
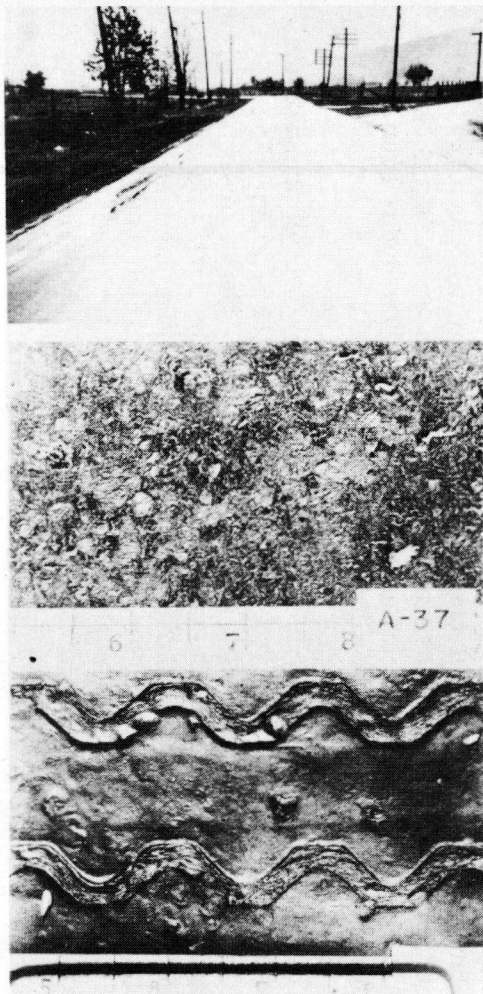


Figure A. Friction values on a surface contributing to excessive tire squeal. A typical dense-graded, bleeding, asphaltic surface.

The photographs in Figure B show a typical open-graded coarse-textured asphaltic surface of the nonsquealing type. Also shown are the friction values obtained in braking tests on this surface for both the dry and the wet condition. The friction values on this type of surface are higher than on the glazed surfaces; also there is a much smaller drop in the friction values on this type surface with an increase in speed than on the glazed surfaces. Accordingly, the skidding hazard on surfaces of this type is not as great as on the glazed surfaces.

Attention should be directed to the interpretation of the friction values given in Figures A and B. These friction values were obtained in braking tests using the truck-trailer towing methods where the maximum braking forces which can be developed on the given surface at the given speed are measured with a dynamometer and are then converted into coefficients of friction. Measuring the friction forces in this way does not present the serious skidding hazard encountered in measuring the maximum side friction forces on highway curves by actual driving tests. For the low friction values measured in tests on ice, the maximum braking friction values have been found to be about the same as the maximum side friction values measured in circle tests. On surfaces with maximum friction values exceeding 0.07 to 0.10 measured on ice, the maximum friction values obtained in braking tests will be 40 to 80 percent higher than the maximum side friction values obtained in circle tests. Thus, where the maximum friction values in braking tests on dry pavements will normally be in the range of 0.60 to 0.80, the maximum side friction values in circle or curve tests will normally be in the range of 0.40 to 0.50.

Tire squeal is very pronounced in the braking tests on dry surfaces, since in these tests the wheels are locked and all the elements of the tire tread in contact with the road surface are slipping or sliding over the surface. In the curve tests the slipping is more gradual as the speed on the curve is increased. The initial tire squeal on curves is not as loud as in the locked-wheel braking tests.

In Figure C a schematic diagram is shown to indicate how the side friction forces are developed by a pneumatic tire to resist skidding sideways on a curve for the condition when tractive forces are present. Road tests have shown that as a vehicle is driven forward on a given curve at increasing speeds, the tires develop slip angles which increase with speed and which provide the frictional resistance required to hold the vehicle on the curve. The frictional resistance required to hold the vehicle on the given curve as the speed is increased is normally obtained by increasing

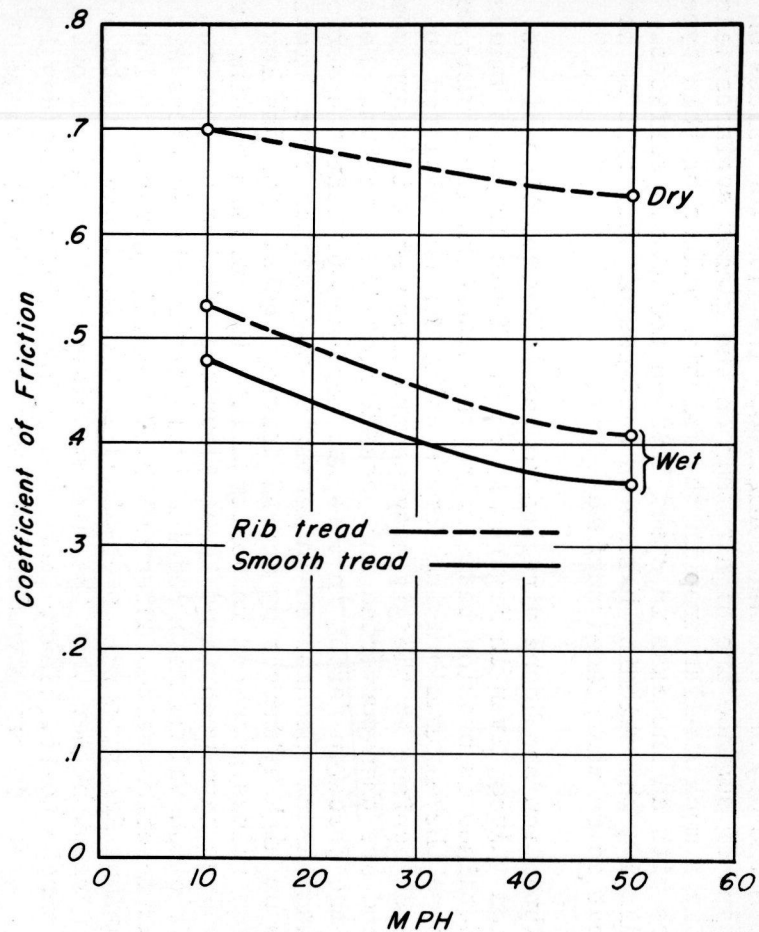
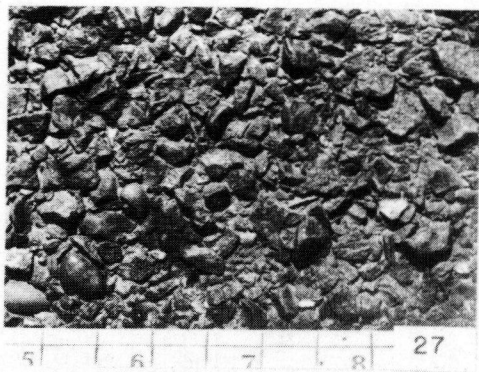


Figure B. Friction values on a "non-squealing" type surface.

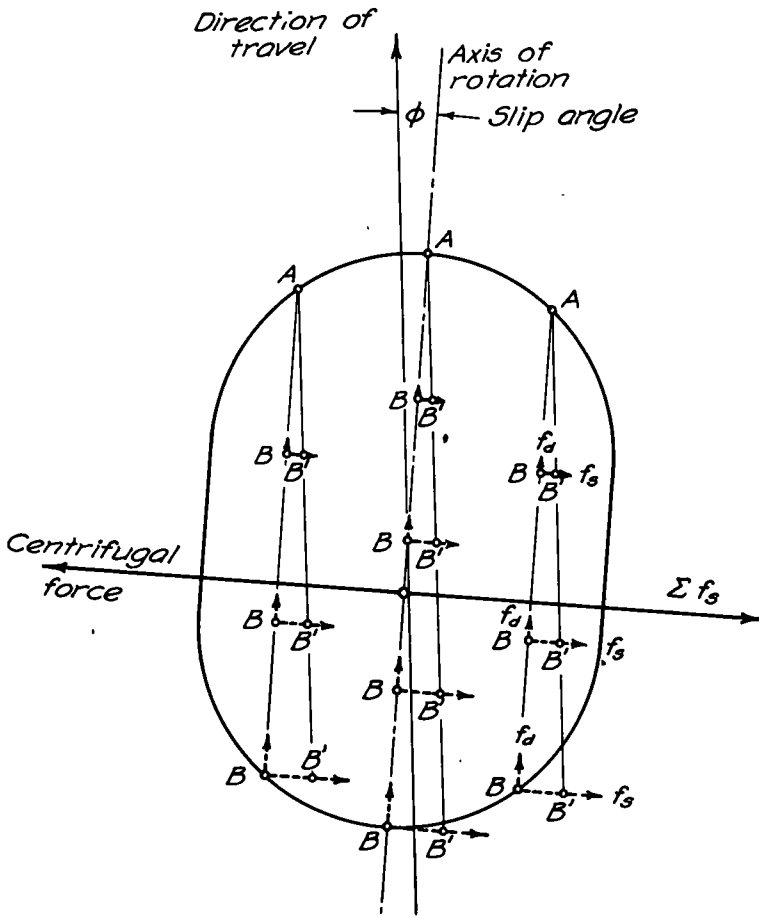


Figure C. Schematic diagram indicating how lateral friction forces (f_s) are developed by a pneumatic tire to resist skidding sideways on a curve when traction forces are also acting on tire.

the steering angle and the resulting slip angle, as shown in Figure C. The slip angle causes the tire to be distorted in such a way that as the wheel rolls forward the points of contact A will take the position of points B' within the area of contact, with the amount of distortion B B' increasing as the tire rolls along the area of contact and as the slip angle is increased. Tire slippage develops at the points in the tire contact area where the distortion of the tire and the tread is so great as to cause the tire to lose its grip on the road surface and to slip sideways. Any tire feature which promotes slippage within the area of contact, such as the use of low inflation pressures, will cause tire squeal on dense-graded polished or glazed surfaces.

Tire squeal may be affected by many factors, of which the following are the most important: tire-inflation pressure, road temperature, rim width, softness of tread compound, curvature of tread, load carried by tire, type and condition of road surface, and many design features of tire and vehicle. For the low-pressure tires developed since the end of World War II, tire squeal on curves will generally start when the side friction values are of the order of 0.25 to 0.30, whereas for the higher pressure pre-war tires, tire squeal developed with side friction values of 0.30 to 0.40.

Tire squeal may quite commonly be observed when vehicles make sharp turns at street corners in cities where high friction values are developed at relatively low speeds. Developing high side friction values at low speeds on city streets is permissible from a safety point of view, since our tire friction test results, as given in Figure A, indicate that the friction values at 20 mph. may be 60 percent higher than at 50 mph. It is partly for this reason that I favor the use of a relatively high friction factor of 0.25 at 20 mph. and a low friction factor of 0.12 at 70 mph. when computing the minimum radii of curves.

A small percentage of drivers will always drive on curves at speeds higher than the design speed. Under certain tire and pavement conditions, the tires on the vehicles driven at these higher speeds will squeal. If drivers would recognize tire squeal as a warning of speed too fast for conditions and as an indication of a slippery pavement condition, then tire squeal on curves would serve a useful purpose. Due to the variable nature of tire squeal, it is unlikely that many drivers will recognize it as a warning signal. Hence, the most useful purpose of tire squeal may be to the highway engineer who may use it as a possible indication of a slippery-when-wet type of road surface.

R. D. EVANS, Manager Tire Design Research, Goodyear Tire and Rubber Company — The invitation to discuss Barnett's paper of tire squeal before a Highway Research Board group and to give the views of the tire engineer, relative to the squeal problem, was welcome. For, to quote Moyer, "tire people are very conscious of squeal and consider it objectionable." And the reason for this is very clear: regardless of the many factors which may contribute to squeal, the typical motorist does not like it any more than he likes other kinds of automotive noises. So he complains of it. And since the tires are obviously involved, his attention focuses on them, and

his complaint about squeal is likely to be confined to them. Also, some motorists are inclined to consider the tires unsafe when squeal occurs. Seldom do they admit that their driving may be too snappy. Nor does it seem to be realized that some feature or condition of the car, or the texture of the roadway, may contribute to the situation. Ordinarily it is the tire alone at which the finger of dissatisfaction is pointed.

So, for years squeal has been a problem for tire engineers; consequently, a considerable amount of test evidence has been accumulated.

There will be general agreement with Barnett's analysis of the mechanism of squeal. However, it is not necessary that the whole tire be actually slipping sidewise in order to cause squeal but only that some elements of the tread be slipping as the tire squirms through and out of road contact.

I agree with the opinions that squeal cannot be used as a reliable index or guide of safe speed on curves, because there are so many variable factors which may contribute to squeal without in similar degree influencing or governing the safe speed. Moyer mentions one clear illustration of this. Certain types of smooth bituminous road surfaces may cause squeal with a particular car at, say, 30 mph. on a certain curve. Let us assume that under these conditions the lateral acceleration is $0.3g$, which would be a safe speed and well below the side skid point. When this same surface is wet, there may be no squeal, and with the same $0.3g$ side force may be dangerously close to the skidding or slipping point.

Next will be presented a portrayal of some of the factors which govern the incidence of squeal, and also the test methods by which the effect of these factors may be evaluated.

As Barnett has quite rightly pointed out, squeal may occur under conditions of cornering at values of slip angle well below those at which actual side-slip ensues. How far below depends on certain factors or features in the tire itself; but it also depends very greatly on the surface texture of the road, on the effective temperature of the contacting surfaces of road and tire, and also in large degree on the conditions of load, of camber, and of slip angle to which the tires are subjected by the car and its suspension.

One of the interesting attributes of squeal, at least of the moderate speed or city variety, is that it is critical, i.e., it develops all at once when the critical speed and the critical side-

force are reached. Correspondingly, small differences in the factors contributing to squeal have critical effect. This threshold or critical behavior is not likely to be recognized by our average motorists when he complains of squeal; but extensive testing has made it very clear that exceedingly small changes in any of the factors contributing to squeal may make the difference between squeal and no squeal.

In tire-testing laboratories, much work has been done in studying the cornering and self-aligning properties of tires under various conditions of load, camber, inflation pressure, and so forth; in such tests the tire is ordinarily loaded against the smooth surface of a large steel flywheel. On this type of surface, squeal may appear at values of slip angle ranging from 2 to 3 deg. To be more specific: under a radial load of 1,000 lb., a typical present-day extra-low-pressure tire will develop 240 to 260 lb. of cornering force at 2 deg. of slip angle, and 350 to 370 lb. at 3 deg. slip angle. The value of slip angle at which squeal makes its appearance depends on the inflation pressure and on the distribution of unit pressure throughout the contact area. This means that the incidence of squeal depends to some extent on the features of the tread design; and one such feature which is of particular effectiveness is the contour shape, or flatness, of the tread.

Clearly, this is not the place to go into any discussion of the details of tire technology or design. But may I digress long enough to say that one of the things about present-day tires, as compared with those of even five or six years ago, is the substantially flatter tread contour, which improved materials permit us to utilize. Flatter treads are better in several ways, the most important of which is to give longer and smoother treadwear; but they also are beneficial from the squeal standpoint.

On the laboratory test wheels, the values of cornering force quoted above may be expressed as lateral force coefficients ranging from 0.25 to 0.37; these are far below the straight-slide coefficient of friction of tires on this same steel surface when dry, but they are well above the maximum straight-slide friction when the surfaces are drenched with water.

Explorations into the various aspects of the squeal problem are by no means confined to the laboratory; in fact, most of the testing is done with cars on special test circles. The one used by Goodyear is approximately 160 ft. in diameter, and is surfaced with very smooth sheet asphalt containing only very fine aggregate. On this circle, squeal may appear at a car speed as low as 15 mph., and ranging up to 25 mph. or even higher, depending on a number of

factors. These correspond to side-force or cornering force values of about 0.2 to about 0.5g.

It may be pointed out here that, while excellent squeal test work can be carried out on such a circle, giving really precision results, since all factors can be satisfactorily controlled, it does not follow that these test circle results will apply to the case of squeal on road curves of larger radius on which the speed of travel may be 60 or 70 mph. Therefore, the following test results are offered only as pertaining to low speed squeal, such as is common in city intersections or traffic circles.

As for equipment, it is found desirable for the speed to be indicated by a precision fifth wheel so mounted as to trail at the center of the car. Right and left turns are alternated so as to eliminate unsymmetrical wear or scrub. The driver, who quickly learns to follow the circular path with precision, slowly increases speed until squeal just appears, at which moment the observer notes the fifth-wheel speed indicator. The speed is then increased somewhat, then slowly reduced, and its value again observed as the squeal just fades out. The equipment also includes an accelerometer so mounted as to indicate the actual F_c value at the critical squeal speed. The indications of the accelerometer may or may not need correction for the angle of roll of the car, depending on the objectives of the particular test.

Inflation Pressure

This is, of course, a basically important factor. For various types of passenger tire, the effect is substantially the same: a change of pressure of 4 psi. changes the critical speed on this circle by approximately 1.3 mph., or phrased otherwise, by a lateral force factor of 0.05g. Typical results would be thus:

<u>Inflation</u>	<u>Critical Speed</u>	<u>Critical F_c *</u>
24	16.0 mph	0.27g
28	17.3	0.32

*Uncorrected for roll.

Temperature

The effect of temperature, particularly the true surface temperature of a black-top road on a bright sunny day, is indeed a substantial one.

One warm, but cloudy, summer forenoon, Goodyear was conducting squeal tests; and for a particular condition of tire inflation and axle load, the critical speed was 17.5 mph. The temperature of the road surface, measured by thermocouples just barely covered below the surface, was 95 F. Shortly thereafter the sun came out and shown brightly the rest of the day. Repeating the squeal test with the same tire and car setup, when the road temperature was 110 F., the critical speed was only 16.4 mph. This is almost as much difference as was found, at a constant road surface temperature, for a pressure differential of 4 psi.

Rim Width

The rims recommended and quite generally used with present-day E-I-P tires are substantially wider than those used ten, or even five, years ago.

With the same 7.60-15 tires mounted, first, on the recommended $5\frac{1}{2}$ K rims and then on $4\frac{1}{2}$ K rims, the critical squeal speeds were, respectively, 19.0 and 17.8 mph. The corresponding F_c values were 0.33 and 0.29 g.

The wider rim not only flattens the tread contour a bit but also confers more cornering power on the tire. This means that less slip angle is required to develop the lateral force required to maintain the designated circular path.

Load

Modern cars are featured by front-axle loads substantially greater than the rear. With a particular car which has been used extensively in our tests, the front-axle load with driver and a rear-seat observer was 2,150 lb. By special sand-bag loading around the front end on the front bumper, it was possible to increase this axle load to 2,560 lb. For these two cases of loading, and with the same tires at the same inflation pressures, the respective squeal speeds were 16.5 and 15.5 mph., the F_c values, 0.36 and 0.29g.

In the values of miles per hour and of F_c quoted in the preceding paragraphs, it is to be noted that they do not always correspond in the theoretical relationship that F_c should be proportional to mph^2 . This is explained by the fact that other factors, such as the particular suspension geometry, location of the center of gravity, the action of the sway bar, and so forth, have their several and combined effects, particularly in affecting the roll of the car so that the indications of the accelerometer are not necessarily proportional to the side forces between tires and roads.

Tread Compounds

There has been some opinion among drivers that certain attributes of the tread compound, particularly its hardness, or modulus, affect the squeal performance. There may well be good reason for a considerable divergence of opinion on this point, because treads of different hardness may show somewhat different relative behavior on one type of "squealy" road surface as compared with a different surface. Undoubtedly temperature is a factor here also. Two statements may suffice in this connection: (1) Within the range of hardness established by other considerations, such as rate of wear, tendency to crack, and so forth, the effect on squeal is quite unimportant as compared with such factors as discussed in previous paragraphs, and (2) the particular type of polymer involved, whether natural rubber or any of those synthetic rubbers which have proved acceptable for tread compounds, appears to have negligible effect on squeal behavior.

I may well conclude this brief presentation by giving enthusiastic assent to one of Moyer's major points: if a tire squeals on a particular area of dry road surface, it can be taken as an excellent warning that the friction will be low when that area is wet. I might even go so far as to devise a safety slogan: "If it squeals when it's dry, take it slow and easy when it's wet."

JOSEPH BARNETT, Closure — The discussion by Moyer and the one by Evans are much appreciated. They lead to the conclusion that in tests of vehicles rounding curves, made for the purpose of determining maximum safe speed by the application of a margin of safety, squeal of tires should not be used as a criterion.

A criterion for a maximum or minimum condition, which is to be used in determining safe design limits by applying a margin or factor of safety, should, above all, be based on consistent performance. Moyer, on the one hand, showed that pavement-surface characteristics have a marked effect on squeal and the side friction when squeal occurs varies widely. On some surface types, such as smooth surfaces, squeal may occur when side friction is low. On some surface types, such as coarse, open-grained surfaces, squeal rounding curves may not occur at all: the vehicle side slipping before squeal develops. Evans, on the other hand, showed that the design of the tread, the radius of the tire surface cross-wise, and the tread pattern affect squeal rounding curves and that, with certain designs, the squeal can be eliminated altogether. He

also pointed out that squeal is affected by the temperature of the pavement, the higher the temperature the greater likelihood of squeal. Surely the combination of three factors each having an appreciable effect on squeal of tires rounding curves eliminates tests using squeal as a criterion for determining highest possible side friction factors on which to base safe values. Reliance will have to be placed on determination of limiting side friction factors by measurement when actually side skidding until a less hazardous test giving consistent results is developed.

Evans' statement that composition of the material in the tread has no effect on tire squeal is of interest. There is some evidence that composition of tread affects maximum friction, and it is surprising that it does not affect tire squeal.

The Highway Research Board is organized under the auspices of the Division of Engineering and Industrial Research of the National Research Council to provide a clearinghouse for highway research activities and information. The National Research Council is the operating agency of the National Academy of Sciences, a private organization of eminent American scientists chartered in 1863 (under a special act of Congress) to "investigate, examine, experiment, and report on any subject of science or art."