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Foreword

To highway administrators, design and maintenance engineers, and others with special responsibility for highway safety, the interaction between the vehicle and the traveled surface has become a subject of prime importance. This RECORD brings together seven papers which cover a variety of aspects of the tire-pavement friction problem. An eighth paper deals with the closely related problem of road profile measurements.

One of the principal causes of pavement slipperiness is the presence of water in the tire-pavement contact area. Under this condition, tire rubber properties and tread design play important roles in reducing skidding. Carr points out that the tire-pavement friction coefficient arises from a deformation component due to large-scale surface irregularities and an abrasive component due to fine-scale surface roughness. Two properties, hysteresis and modulus, determine the relative friction of a rubber on a slippery road. Keen examines the three zones of contact between a tire and a wet surface as a means of determining an optimum tire tread design. He establishes a preference for continuous ribs and grooves as opposed to block designs.

In a concise review of the present state of knowledge of the pavement slipperiness problem, Meyer concludes that optimum design of surface courses will depend on a full understanding of the mechanisms of rubber friction, of tire-pavement contact, and of the aggregate polishing process. Suggested are several areas for potential improvement of tire-pavement friction. Harris' paper deals with one such area, road surface texture, and presents the British Road Research Laboratory's view that all roads require a harsh texture when wet and that high-speed roads require a coarse texture as well.

Tire hydroplaning can occur when the speed of the vehicle, pavement surface texture, water depth on road, tire inflation pressure, tire tread design, and vertical load are combined in such a fashion that the tire loses contact with the pavement. The paper by Horne explains how these factors affect the fluid pressure buildup in the tire-pavement footprint, and suggests two promising methods of eliminating hydroplaning by reducing this pressure.

Domandl and Meyer point out that skid-resistance measurements remain the most practical method of characterizing the frictional properties of highway pavement, but slip measurements are needed for research purposes. They describe the conversion of the Penn State road friction tester to measure tire-pavement friction under slip.

A properly applied coating of linseed oil is a commonly accepted method of reducing environmental and deicing chemical deterioration of portland cement concrete pavements. A preliminary report by Kubie, Gast and Cowan examines the effect of linseed oil on skid resistance of pavements and concludes that, when certain precautionary measures are taken, a treated concrete surface will rapidly recover its original dry skid resistance.

The paper by Darlington and Milliman concerns itself with the evaluation of accuracy, reliability, and applicability of the General Motors rapid travel profilometer for highway purposes.

Contents

Contribution of the Rubber Compound to the Wet Skid Resistance of Tires

C. I. CARR, UNIROYAL, Inc., Detroit

•OUR firm has continuing research programs directed toward understanding factors that will improve the skid resistance of tires. The work reported here represents part of the research effort being conducted to understand the effect of rubber compositions on skid resistance.

Only the major interactions which occur between road surfaces and rubber compounds and the properties of the compounds which offer a major contribution to the coefficient of friction are discussed in this paper. Emphasis is placed on the practical aspects of skid resistance which are the concern of every driver, rather than extreme conditions infrequently encountered in normal driving. The contributions of tires to skidding in these instances are usually minor compared with other aspects of the problem, whereas there are extremely important and commonly occurring situations in which the tire can make a major contribution.

Thus, we will omit reference to snow and ice, to dry skids, and to hydroplaning. Snow and ice are frequently encountered in northern areas, but two factors make them constitute a less urgent problem for our immediate concern than that of skid resistance on wet pavements above freezing. First, coefficients of friction are normally very low, drivers are aware of the dangers, and they are more likely to take appropriate precautionary efforts. Second, because of the low coefficients, mechanical devices are usually required for maximum traction, and the contribution to friction which the tire alone can make is small.

Long skids on dry surfaces also represent a situation to which the tire can make only small contributions. Available coefficients with tire materials on a paved road surface range between 0. 8 and 1. 0. Accidents involving dry skidding as a primary factor, therefore, have driver error as a major component.

There has been considerable recent discussion of loss of control by hydroplaning. For passenger cars this requires a special combination of circumstances, including an element of driver carelessness. It is probably more related to tire design than tire compounds and has been given less consideration in this portion of the work.

In the course of ordinary driving almost every driver will frequently encounter wet pavements. Records at the Newark Airport Weather Station are probably representative of most of the highly populated northern and eastern parts of the country, and so indicate the frequency with which drivers will be driving on wet pavements. At Newark, rain falls on an average of 122 days out of the year. On these days approximately 25 percent of the time represents actual periods of rainfall, and it is reasonable to assume that pavements are wet at least twice this long. Thus, a large proportion of drivers in this country are driving on pavements that are wet a substantial part of the time. On such pavements friction coefficients of tires can be, and frequently are, much lower than the friction coefficients available when the same pavement is dry. Our own data indicate that coefficients may be found as low as 0. 25 on suburban streets and 0. 4 on major highways at low speeds.

One of the major elements of concern for vehicles moving on wet roads is that drivers appear to be unaware of the loss in available coefficients and so drive at very nearly the same speeds that they drive on dry pavement (Fig. 1). This situation clearly

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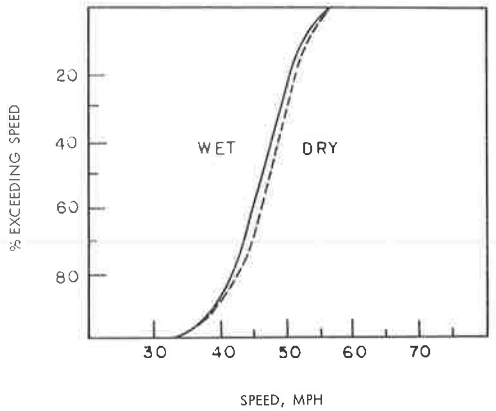

Figure 1. Speeds on a rural curve in New York State.

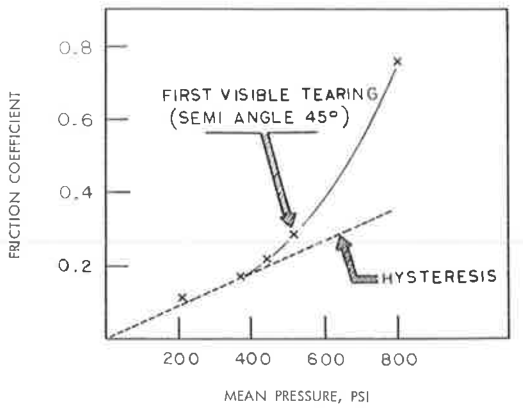

Figure 2. Lubricated friction of cones sliding on a rubber surface at very low speeds. The calculated contribution of hysteresis to friction is shown by the dashed line.

puts a heavy demand on the contribution of the tire to wet skid resistance, and therefore we have included only wet surfaces in this research.

Our studies of the properties of tire compositions and their effect on wet friction have been greatly facilitated by the development of the portable skid tester at the British Road Research Laboratory. This instrument was described by Giles, Sabey, and Cardew (2) at an ASTM symposium in 1962. In agreement with results in England (3), we find there is very good correlation between locked-wheel sliding of vehicles on actual slippery roads and laboratory tests with the portable tester on appropriately chosen surfaces. We have used this instrument extensively in our work.

ROAD SURFACES

With a background established for considering factors involved in wet friction of tires on roads, we can examine what these factors are. Since the surface of the road on which the tire moves determines the range of wet friction coefficients available, it is important to know the features in that surface contributing to friction in order to be able to study intelligently the contribution which tire compounds can make. Firm quantitative ideas about this can be traced to the important early work of Tabor (4, 5), amplified by the extensive studies at the British Road Research Laboratory (3).

It has been recognized for many years that an essential characteristic of slippery roads is that the aggregate exposed at the surface has been polished by the passage of traffic (3). Recent progress has come with the recognition that it is possible to make reasonably quantitative estimates of the state of the road surface without reference to its previous history.

The contribution of the road surface to the wet friction coefficient may be conveniently considered to consist of two parts: a deformation component and an abrasive component (6). The deformation component is contributed by the relatively large-scale irregularities in the road surface, with root-mean-square elevation of 0.01 in. or larger. The abrasive component is contributed by a finer scale roughness with acute angular projections at the surface.

These two components of a surface appear to be sharply distinguishable experimentally by evaluating the friction of rubber materials of low and high hysteresis. The deformation component contributes more to friction in a high-hysteresis rubber and very slightly to friction in a low-hysteresis rubber.

Figure 2 shows that this difference can be demonstrated very simply in the laboratory. According to these data there is a critical apex angle at which a cone will tear a rubber surface as it slides over it, even with a lubricant. Tabor (5) pointed out in 1958

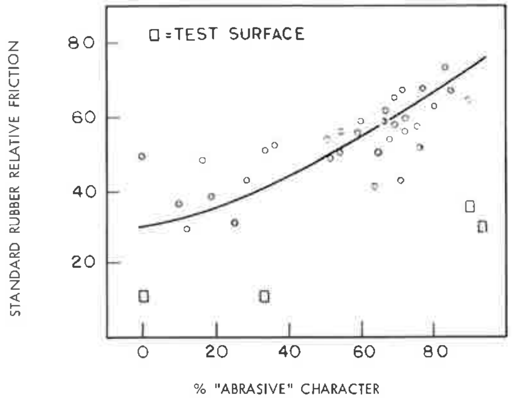

Figure 3. Character of roads in two suburban New Jersey communities. Friction less than 50 represents a slippery surface.

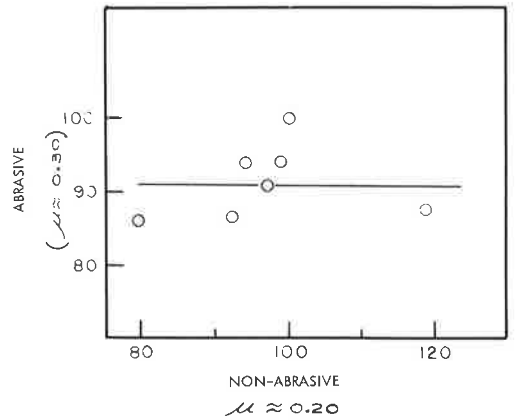

Figure 4. Relative friction on low-coefficient surfaces.

that the experiments of Sabey (7) at much higher sliding speeds, characteristic of those which might be encountered by tires, fall into a very similar pattern.

This laboratory demonstration lends confidence to an empirical procedure which has been developed in our laboratories for analyzing actual road surfaces. By measuring the lubricated friction of two rubber samples with a wide difference in hysteresis (8), we can separate the components of a road surface in a reasonably quantitative way. The friction of the high-hysteresis rubber is determined by both components, whereas that of the low-hysteresis rubber is primarily determined by the abrasive component; therefore, that portion of the road surface friction contributed by the deformation component is a function of the difference between the coefficients of friction of the low- and high-hysteresis rubbers.

Figure 3 shows this relation for a number of roads (6) in northern New Jersey which have been roughly rated as slippery or nonslippery by local highway patrol officers. In the same figure are plotted data for typical test surfaces used in the laboratory in studying rubber friction.

The ordinate represents "skid resistance" (2) of a standard rubber sample, which is approximately proportional to the coefficient of friction. A value of 50 represents a road marginal for skid resistance. The abscissa represents the percent abrasive character of the surface. Test surfaces shown in the figure as having 0 and 90 percent abrasive character are, respectively, wavy glass and a terrazzo surface occasionally used for testing tires for skid resistance.

It follows from these data that an important aspect of tire friction on wet slippery roads is the behavior of rubber tread materials on superficially rough but nonabrasive surfaces, where hysteresis plays a dominant role. On such surfaces physical properties of the tire tread which can be measured in a laboratory determine absolutely the relative friction differences between tire materials. These properties are derived primarily from the polymer used in the tire, and secondarily from the other ingredients which go to make up the final vulcanizate.

The choice of hard surface for testing rubber is important, as may be obvious from the preceding discussion, but this has not always been taken into account. Thus, Bassi (9) used porphyry and terrazzo tiles because he found asphalt to be abraded by the rubber specimens. Briggs, Hutchinson, and Klingender (10) and Aarbach, Hallman, and Brunot (11) used ground glass without discussing in detail reasons for the choice. Our experience indicates that there could be poor correlation between significant variables and wet skidding resistance of tires caused by the surface chosen for testing. For example, there are a number of statements in the literature that hardness is positively correlated with skid resistance (2, 10, 12). On actual slippery roads the correlation is

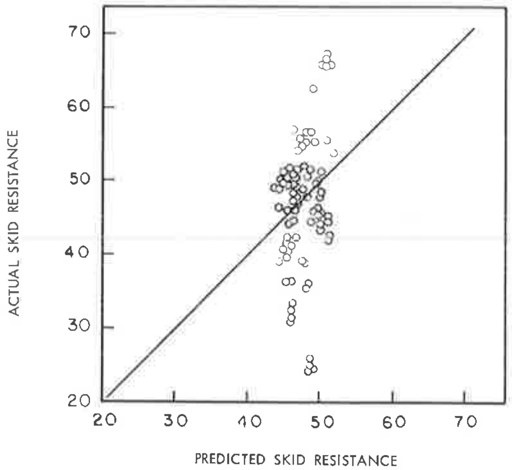

Figure 5. Hardness alone as a predictor of wet skid resistance.

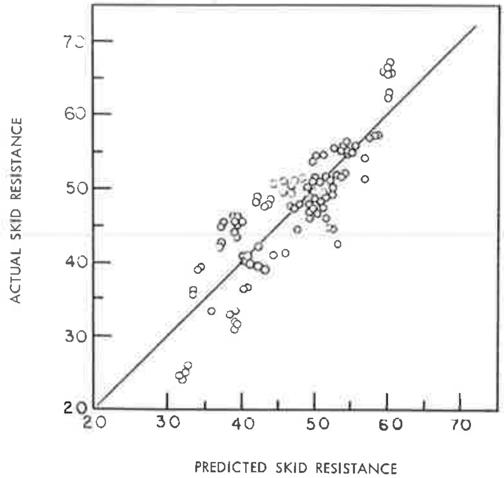

Figure 6. Resilience alone as a predictor of wet skid resistance.

negative, and we find a positive correlation only on abrasive surfaces. Roads which are highly abrasive are rarely slippery. Generally speaking, any test surface which depends on abrasiveness for friction will give results which are relatively poor for evaluating practical tire tread materials. This is especially true for low-friction test surfaces.

A typical example is shown in Figure 4. The relative friction of a number of tire tread materials on a low-coefficient abrasive surface is compared with that on a low-coefficient nonabrasive surface, both tested with the laboratory tester (13). The latter correlates with tire performance on an actual road; the former does not. The non-abrasive surface offers a means of discriminating between compounds which relates to actual road surfaces.

RUBBER COMPOUND

Skid resistance is a property of the tire tread composition, and no general statement about specific components can be made without considering the composition as a whole. Rubber, oil, and black are the most important constituents, and their ratios determine properties. Fine details of the nature of the carbon black filler, of the hydrocarbon extender, of the method of vulcanization, or of many other variables in compounding have small effects on wet friction. They can usually be neglected in considering skid resistance of tires.

Two properties, hysteresis (as measured by rebound resilience) and modulus (Shore A hardness), determine the relative friction of a rubber composition on a typical slippery road within the experimental error. A linear combination of these properties will predict with a very high degree of accuracy the relative friction of two tire materials on a surface (4).

Figures 5, 6, and 7 illustrate this for a surface typical of actual slippery roads.

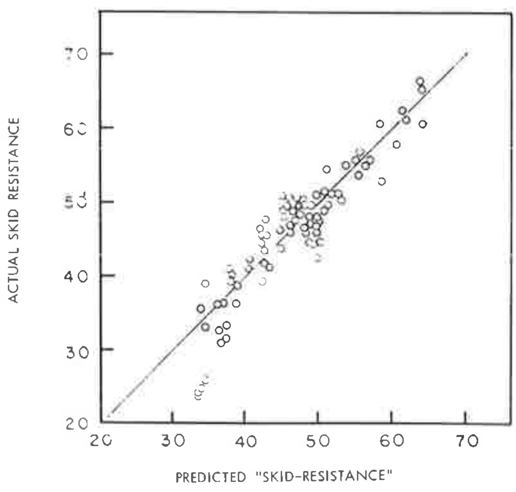

Figure 7. Combined resilience and hardness as predictor of wet skid resistance.

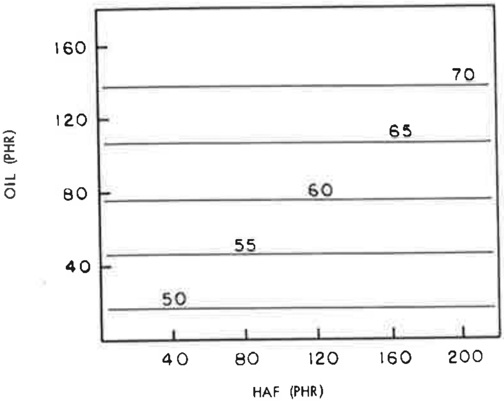

Figure 8. Friction of SBR compounds on a standard road surface as a function of oil and black (HAF) in parts per hundred rubber in the compound. Numbers on the lines are "skid resistance" units.

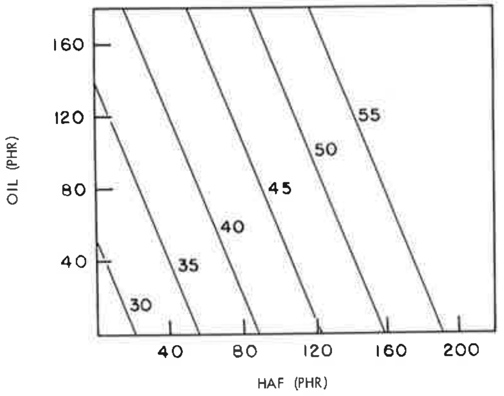

Figure 9. Friction of polybutadiene compounds on a standard road surface. Numbers on the lines are "skid resistance" units.

Figure 5 shows that modulus (hardness) is poor as a predictor alone. Predicted values are those obtained from a least-squares fit of the data. Figure 6 shows that resilience is much better in predicting relative wet friction, and finally Figure 7 shows that, taken together, they give a very high accuracy of prediction. The correlation coefficient for these data is over 0.90, indicating that 80 to 90 percent of the variance in the data is accounted for by hysteresis and modulus.

Glass transition temperatures of rubber and of oil may limit the friction coefficients obtainable from any given combination. The difference between glass transition temperature and service temperature and the form of the damping curves as a function of temperature are related to resilience at the speeds important for skid resistance.

We can show quite clearly by Figures 8 and 9 that the entire composition must be considered, rather than individual components alone. The figures show effects of variation in composition of tire tread stocks made from two commonly used elastomeric materials on wet friction on an actual road surface. With the first material, SBR (Fig. 8), the filler has a negligible effect on skid resistance over a wide range of concentration. This is because of the coincidence that carbon black changes the two important physical properties in opposite directions so as to balance their overall effect on skid resistance. Figure 9 shows that friction of the much more resilient polybutadiene is affected by carbon black as well as by oil, because in this instance carbon black changes the hysteresis of the mixture so much more markedly than it does hardness that it has a significant effect on wet friction.

SUMMARY

1. Friction on road surfaces arises from deformation and abrasion components which can be separated quantitatively by laboratory tests.
2. Slippery surfaces have a high percentage of deformation component.
3. Hysteresis and hardness of tread stock compounds predict skid resistance on slippery roads with a high degree of accuracy.
4. The second-order transition temperature sets practical limits on friction coefficients that can be obtained for a given rubber. However, major compounding ingredients (oil and black) change the hysteresis and modulus of tire rubbers in different ways, so the compound must be considered as a whole.

ACKNOWLEDGMENTS

The work reported here was done by E. M. Bevilacqua and E. P. Percarpio at the Corporate Research Center of UNIROYAL in Wayne, New Jersey, in cooperation with the Development Department of the United States Rubber Tire Company.

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Design for Safety

HARRY M. KEEN, Manager, North American Tire Development Group, Dunlop Tire and Rubber Corporation

•SAFETY has of late been more in the public eye than usual, but this is no new matter as far as the tire makers are concerned. Although concern for safety has been universal it will be appreciated that different needs and concepts exist in different countries as to how the maximum safety level is best achieved.

We believe, however, that the biggest single contribution that tire makers can make to improved safety is in the area of skidding in the wet. Adhesion in the dry is not now really a major tire problem, and structural failures are hardly a direct cause of accidents to any significant degree (not that there is inactivity in these fields—the reverse is the case). But it is wet hold that we think should be the major field for action. As an international company, we are finding this to be the case worldwide.

At this juncture it should be noted that, although the title of this article is "Design for Safety," it has not been found completely possible to separate this subject from the allied subjects of tread rubber compounds, types of pavement, and aquaplaning. There are too many interactions involved to allow this to be possible.

The main factors involved in wet grip are given in Table 1, with an assessment of their level of variability shown in the column on the right. A higher figure shows a high variability and hence a greater potential for improvement. These data were produced in England some years ago but it is felt that they are still very relevant today. It will be observed that tread design, road surface, water depth, speed, and braking systems are all very important factors, and it will probably be conjectured that their analysis with that of the interactions involved will be complex. This has indeed proved to be the case, and it has taken many years of work, on the proving ground and in the laboratory, and a great deal of thought by many people to arrive at the conclusions which will now be summarized.

Aquaplaning was once a theory and subject of controversy, but it is now a proven fact with very practical implications of a far-reaching nature. Figure 1 shows a side view of the contact area between the tire and ground under flooded pavement conditions. It demonstrates the three-zone theory of tire/road contact that was first put forward by V. E. Gough of our company in 1959. Although aquaplaning was once considered to be a rare case of doubtful relevance to everyday conditions, this is no longer the case and its mechanism and the theory involved are acknowledged to be very pertinent to most cases of wet skidding.

Zone 1 in Figure 1 is the zone of bulk water displacement, and here the tread design effect is predominant. Zone 2 is the thin water film zone. Here pattern is still effective, but pavement and tread compound effects also appear. In the third zone, tire/road contact is substantially dry; tread rubber and pavement effects are the most important, with tread design playing a subordinate part.

Figure 2 shows very simply the main features of tread design that are important. The smooth tire section is shown at the top of the diagram, and section B shows a simple ribbed pattern with circumferential grooves. These grooves are important in zone 1 of Figure 1, i.e., in the bulk removal of water. The small slots, knife cuts or sipes in section C of Figure 2 are the design elements concerned with breaking through the thinner film of water shown in zone 2 of Figure 1. In zone 3 of

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TABLE 1

FACTORS INFLUENCING EFFECTIVE BRAKING FRICTION BETWEEN TIRE AND WET ROAD
(100 mph Maximum)

Factor	Level of Variability Due to Factor Considered
Tire:	
Tread pattern design	Up to 4:1
Tread materials	Up to $1\frac{1}{2}$:1
Patterned tire vs smooth tire	Up to 8:1
Road:	
Road surface characteristics	Up to 5:1
Water depth—film 0.05 in. to 0.30 in.	Up to 3:1
Vehicle:	
Speed—reduction due to an increase in speed from 30 to 80 mph	Up to 10:1
Braking system—perfect non-locking system vs locked wheel braking	Up to 3:1

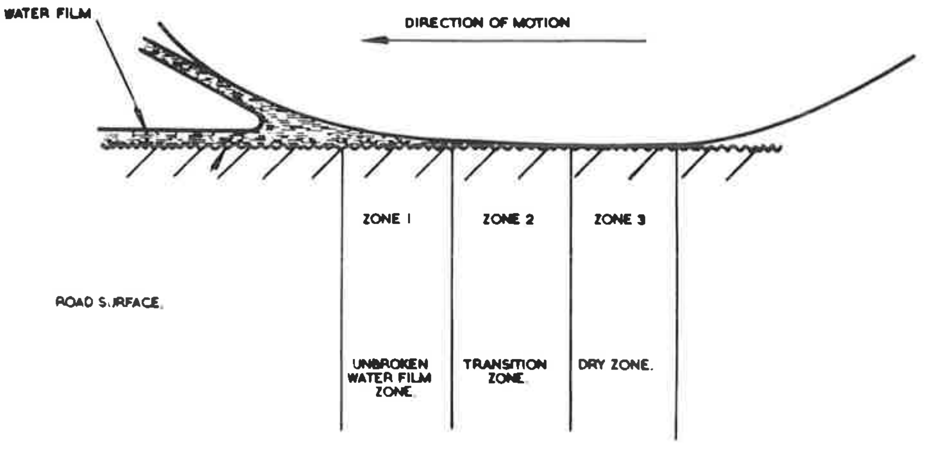

Figure 1. The three zones of the contact area of a tire.

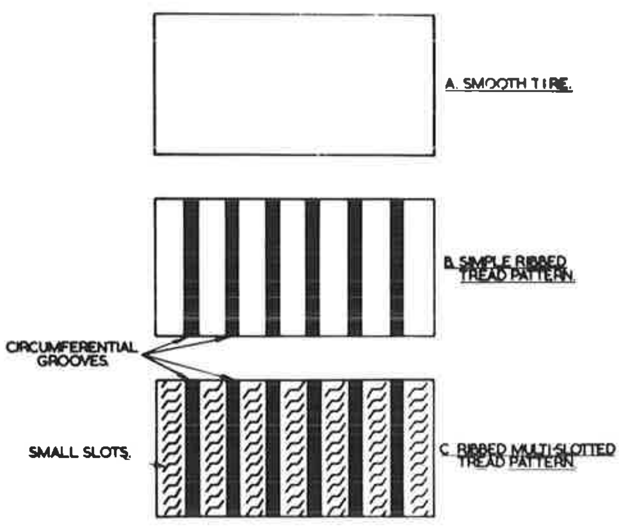

Figure 2. Main features of the experimental tread patterns.

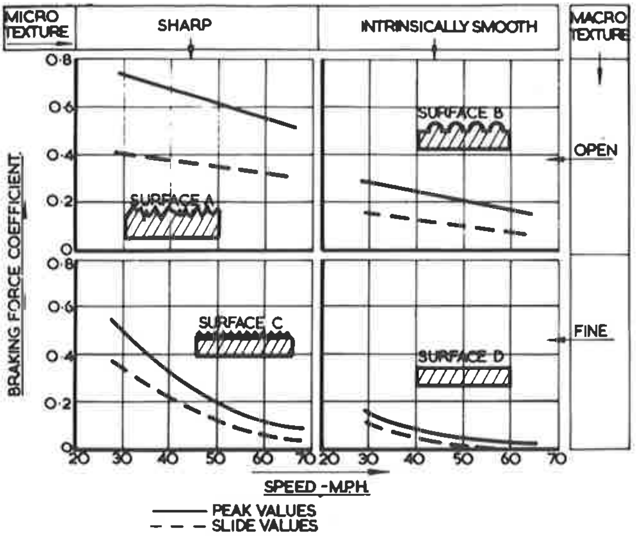

Figure 3. Effect of road surface—smooth tire.

Figure 1 it has been noted that the contact is substantially dry and that the tread rubber comes into its own. But even here it is the tread design that dictates how much tread rubber is in contact with the ground and hence still affects the adhesion.

It at once becomes clear that requirements for the three zones may oppose each other. For instance, zone 1 requires numerous wide grooves, but zone 3 calls for a closed pattern to give the greatest possible amount of rubber in contact with the ground. Hence, a compromise is required. This may also be necessary to preserve other essential tire properties such as tread life, good vehicle handling, and transient stability, all of which are dependent on tread design as well as on other factors.

Our laboratories have, over the past few years, carried out a very full evaluation of adhesions in the wet. This work has been performed on test tracks with actual vehicles, supported where necessary by work on laboratory test machines. The variables studied have included tread patterns, tread compounds, types of pavements, speed variations up to 80 mph, and braking conditions. The last variant entailed measuring peak adhesion values with the tire just rolling and adhesion values with the tires fully sliding.

It will probably be easier first to describe the findings on a smooth, polished surface. We have known for a very long time (since 1925-1930) that such a surface is the most sensitive to tread pattern design and compound variations. For this reason, such a surface has been selected for the bulk of tire development testing.

Using, therefore, a smooth, polished, flooded surface, the following conclusions were reached:

1. At high speeds, tread pattern characteristics dominate tire performance.
2. At all but the slowest speeds, the simplest type of pattern is vastly better than a smooth tire.
3. A modern pattern (one with numerous well-designed grooves and a multiplicity of knife cuts on the ribs) shows less loss of adhesion with increasing speed than any other type.
4. Under the conditions described, the type of tread rubber has relatively less effect than the tread design. An improved compound gives a straightforward improvement in braking adhesion, this improvement being nearly independent of speed.

It should be noted most carefully that this statement concerning the relative importance of compound and design must not be taken out of context. For designing a tire to give the maximum in wet grip under all conditions of road, speed, etc., they would rank about equal. Certainly both are key safety features.

The above findings will be found to agree closely with the three zone concepts mentioned previously.

To illustrate road effects, Figure 3 should be studied. This shows results obtained under flooded pavement conditions with smooth tires. Smooth rather than patterned tires are chosen at this stage to eliminate the main design interactions.

Figure 3 shows braking coefficients plotted against speed for four typical types of surface. The solid lines show peak braking coefficients, and the dotted lines show

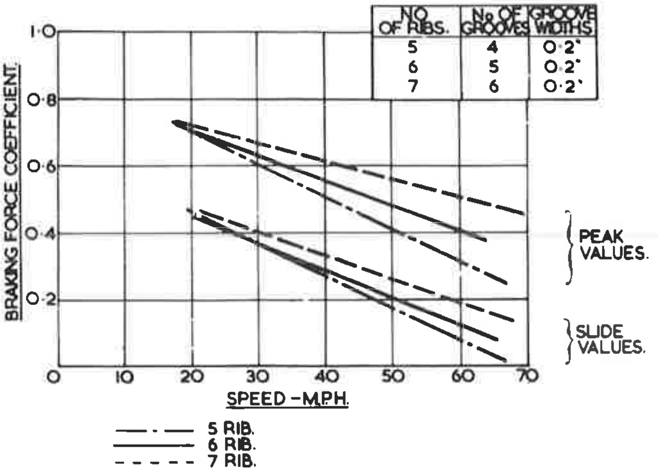

Figure 4. Comparison of tread patterns with four, five, and six drainage grooves.

coefficients obtained with the tires sliding. The two road surfaces in the upper half of the diagram are both open-textured, with a sharp micro texture on the left and a polished macro texture on the right. The lower graphs are for close-textured surfaces, again with a sharp micro texture on the left and polished macro texture on the right.

Thus, surface A (upper left) combines the good drainage of open texture with the good frictional properties of a sharp micro texture. Conversely, surface D (lower right) has poor drainage from close texture, and poor frictional properties from polished macro texture. The other surfaces are obviously intermediate in properties.

As would be expected, surface A is by far the best with the highest brake coefficients and surface D is by far the worst. Again, the other surfaces are, as expected, intermediate.

The results from the full series of tests, where both the tread design and the tread compound were varied for each type of pavement, lead to the following conclusions:

1. Friction on the worst types of surfaces at high speeds is more associated with the removal of water than with compound types. At the risk of being repetitious, it should be noted again that this statement does not denigrate at all the place of the compound in tire development where we want the best performance for all conditions.

2. Tread pattern design has most effect on the closed type of surface such as C or D, but it does not compensate for the deterioration of road surface by polishing.

3. Tire pattern has least effect on open-textured, polished surfaces. This may be partially because the grooves in an open road surface, unlike the grooves in tread patterns, may retain water and feed it into the contact patch.

4. Open-textured surfaces give adhesion coefficients that are less dependent on speed than do closed-textured surfaces.

The above dependence of tread pattern effect on the type of pavement is of very great practical importance. Measurement of pavement friction by trailer and standard tires is under consideration by official bodies, as is the extension of this principle of tire testing.

The most scrupulously careful consideration should be given here before final decisions are reached. Without meticulous care in specifying the surface, tire testing could become of little meaning. For other reasons we selected driven-vehicle testing in place of trailer testing

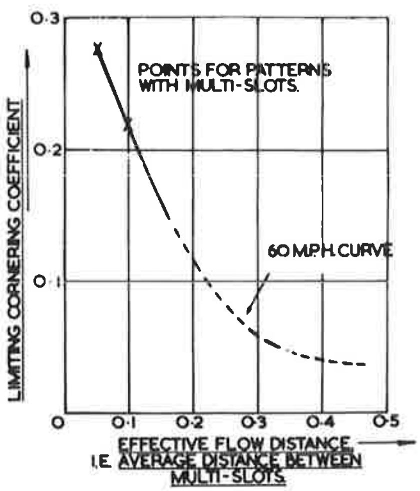

Figure 5. Limiting cornering coefficient vs average distance between tread slots.

for our development work a long time ago, as we found the former method to be more realistic.

Consider now the tread design in more detail. We prefer circumferential groove designs to block designs for the following reasons:

1. They are less liable to uneven wear than are block designs, and we have found that what is known as heel and toe wear can, on blocks, assist in initiating the water wedge and hence can facilitate slipping.

2. Water can flow more easily through straight or nearly straight grooves than through channels between irregularly spaced blocks.

3. The continuous ribs associated with continuous grooves are stiffer than blocks and hence distort less in the contact patch. Remember that a design can function as a water remover only in proportion as its grooves or channels remain open in the contact patch where the water is.

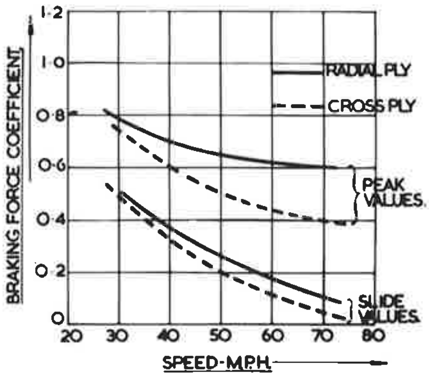

Figure 6. Comparison of production radial ply and cross ply tires; braking carried out on smooth, wet asphalt.

So, having established a preference for grooves, we should consider how many we need. This is illustrated in Figure 4, which shows a plot of braking coefficients against speed. This shows that as the number of grooves is increased from 4 to 6, keeping the groove width constant meantime, the adhesion improves both for peak and slide values. Here results for the 4-groove tire are chain dotted; for the 5-groove tire, solid line; and for the 6-groove tire, plain dotted. The corresponding numbers of ribs in the designs are 5, 6, and 7 respectively.

The importance of groove design having been shown, let us next consider knife-cuts or multi-slots. Figure 5 is a plot of limiting cornering coefficient against average distance between slots in the tread pattern. As will be easily seen, there is a strong correlation, adhesion reducing rapidly as the distance between slots increases and hence the number of slots decreases.

As well as tread design, tire construction can have a significant effect. As previously mentioned, to function in the wet a pattern must not be unduly distorted in the contact patch. Now the radial ply tire has the least distortion of all types due to the high modulus of the tire laterally caused by the rigid breaker. And, as Figure 6 shows, it does in fact have an advantage in grip over the cross ply tire. In this graph of braking coefficient against speed, the dotted lines are cross ply tire results and the solid lines show results from the equivalent radial ply tire. There is a clear advantage for the latter both for peak and for slide values.

Now, it may be asked, what have been the practical results? All the data obtained have been used continuously in our new pattern and compound development work. The result has been that tires are now being supplied with up to 50 percent better stopping power and 50 percent better cornering power in the wet than tires that were being made a decade ago. Under fully flooded conditions, on smooth surfaces, we can now achieve braking coefficients in excess of 0. 50. This figure has often been quoted as marking the line between safety and the reverse. It can therefore be claimed, with some justification, that the latest tires are approaching a position where they are as safe in the wet as in the dry.

More recently we have turned our attention to the problem of truck tires. Here there has long been a discrepancy between truck and automobile behavior. Work in this field has been basically similar to that on passenger tires and we have found that, by pattern improvement, we can almost halve the stopping distance. If we add the effect of compound improvement, we can produce tires which, on flooded roads, can stop a truck in distances equivalent to those in which cars can stop.

Finally the future—what has to be achieved? Work is currently in progress on safety improvements in all three of the aquaplaning zones. We want to be able to deal with more water more quickly, to wipe the ground more completely dry in the second zone by better knife-cuts and more of them; we want further compound improvement to grip the ground better in the dry zone.

We want tires that are safer and that are felt to be safer by the driver. Safety in the wet is not only a question of stopping and cornering; tires must also handle safely when passing another vehicle at 60-70 mph. To help make the safe tire universally desired, it must be improved in other respects—better handling, better transient stability, longer safe tread life—and it must still retain a good boulevard ride.

We would hope that improvement in pavement surfaces would go together with improvements in tires. The first objective should be to eliminate the bad surfaces. A 10 percent loss of adhesion on a good surface does not have the impact on safety that the same percentage loss on a poor surface has. A gain of 0. 05 braking coefficient on a poor surface can have a better effect than double that gain on a good surface. So no radically new development is needed for this initial step.

These I am sure are the areas for attack, and these will be our targets for the future. If we can make the same kind of impact in the next few years that has been made in the past, we may all have done well indeed.

Friction and Slipperiness

W. E. MEYER, Professor of Mechanical Engineering and Director, Automotive Safety Research Program, The Pennsylvania State University

•THIS discussion is limited to aspects of the tire-pavement friction problem in which hydroplaning does not take place, either because the water layer on the pavement is too thin, or the drainage channels permit ready escape of the water from the contact area, or the speed is low. Under these conditions friction is almost entirely due to adhesion and hysteresis losses in the tread rubber. Wear of the tire or of the pavement involves insignificant contributions to the energy exchange in friction, certainly under wet conditions, and will therefore be ignored here. The pavement is considered as being perfectly rigid.

THE NATURE OF RUBBER FRICTION

The adhesion component of friction is due to the making and breaking of atomic junctions between the rubber and pavement surfaces while the hysteresis component is caused by losses within the bulk of the tread rubber. Kummer (1) has shown that both phenomena are different manifestations of the same property of the rubber, namely of its viscoelasticity.

A viscoelastic material can be represented by a system of springs and dampers and, although there is still uncertainty about details of this model, it is not difficult to visualize how bulk deformation of the rubber leads to hysteresis losses and that these are related to the damping properties of the system. Kummer has shown that the making and breaking of the junctions, as the rubber slides over the pavement, involves essentially the same processes as occur in bulk deformation. First, the surface molecules of the rubber form junctions with those of the pavement. Then, as the sliding continues the molecules are stretched until the junctions finally break, and the molecules spring back. Thus we are dealing here with a deformation process of the same general nature as that which leads to the hysteresis losses.

The damping characteristics of viscoelastic materials are strongly frequency- and temperature-dependent. At a given temperature, damping will be at a maximum at a definite deformation frequency of the bulk and of the surface molecules of the rubber. If sliding speed is related to frequency, it is not probable that the adhesion component would peak at the same speed at which the hysteresis does, and indeed it does not. The adhesion peak occurs at sliding speeds of around 0.1 mph and the hysteresis peak at 1000 or more times this value.

Relating friction quantitatively to the damping characteristics of the rubber is a complex undertaking. It requires separating adhesion and hysteresis. Theoretically this can be done by using a perfectly smooth surface in one case and a perfectly lubricated, rough surface in the other. In practice this is quite difficult to do and usually can only be approached. Another difficulty is the temperature dependence of both damping and friction, particularly since the energy expended is converted into heat of which a significant portion goes into the rubber. Much of our research is directed toward obtaining answers to these problems, particularly for the conditions which prevail in the case of a tire sliding on a pavement.

One important characteristic of the damping properties of viscoelastic materials is the fact that the damping peak shifts to another frequency without changing its magnitude

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as the temperature changes. By this method, it is possible to obtain the effect of a wider frequency range than can be provided by the test equipment at hand. Explaining friction in terms of deformation frequency implies that the adhesion and deformation peaks of the friction curve should behave as the damping peaks do. For selected conditions, at the adhesion maximum, this has been demonstrated to hold true (2). Preliminary evidence indicates that it is also true for the hysteresis peak (3), although we have not been able to reach the necessary sliding speeds as yet.

PRACTICAL CONSEQUENCES OF THE FRICTION THEORY

Although we now understand the most important aspects of the mechanism of rubber friction more or less in a qualitative manner only, a number of practical applications to the tire-road friction problem are possible. The tire presents, of course, a much more complex situation than a simple rubber block does. One manifestation of this is that a sliding tire exhibits the adhesion peak at higher speeds than a rubber block. This is caused by the temperature increase which occurs in the contact area. A temperature increase causes the damping and, therefore, the friction peaks to occur at higher speeds. When the tire is slipping, the peak occurs at still higher apparent rates of sliding in the contact area. This can be explained by the discrepancy between the sliding speed computed from the measured wheel slip and the true sliding speed. The tread of the tire behaves like the bristles of a brush that is being moved across a small obstacle; on passing over the obstacle the bristles are deflected backward and slide over it at a speed less than that of the brush. Behind the obstacle they snap forward to resume brush speed and their normal position.

Tire performance is also influenced by tire construction and inflation pressure. These determine the pressure distribution and the parasitic motion of the tread elements in the contact area. On a vehicle, suspension geometry and dynamics superimpose further parasitic motions on those already present in the contact zone.

Normally the skidding or sliding tire operates somewhere between the adhesion and the hysteresis peaks. Although the peaks shift toward higher speeds with increased temperature, the effect of a temperature change on the skid resistance at a given speed cannot be predicted with certainty unless considerable information is available. When the hysteresis contribution is relatively minor, a temperature increase would cause the skid resistance to increase because the tire is operating to the right of the adhesion peak on the descending branch of the total friction curve. The temperature increase causes the peak to shift closer to the operating point; hence the latter is higher up on the curve. When hysteresis is predominant, the opposite will occur. Clearly all kinds of combinations are possible, depending on rubber composition, speed, temperature level and change, and whether the tire is operating on a surface producing high adhesion or hysteresis. The prediction of the temperature effect is further complicated by limited information on what role air, pavement, water and initial tire temperature play.

The temperature dependence of tire friction is of particular importance in friction surveillance programs of highway systems. These usually involve measuring the same pavement at intervals of many months and consequently at different temperatures. Pavement friction is subject to change from many causes. The changes cannot be detected nor long-term trends be ascertained unless individual measurements are normalized for temperature effects. Thus ASTM Method E 274 for skid-resistance measurement by locked-wheel trailer should eventually include a temperature correction procedure. This, however, requires the cooperation of all those agencies which operate skid trailers, if only to determine what the range of the error is if no correction is applied. The same applies of course to all testers, whether using full-scale tires or not.

HYDRODYNAMIC EFFECTS ON TIRE FRICTION

At speeds above 30 mph, hydrodynamic effects begin to make themselves felt. Intrusion of the contact area by water begins. This effect is reasonably well understood. It accounts for the decrease of the friction on wet pavements with speed. We know less about what occurs on a wet pavement at lower speeds where friction is still speed-dependent. Though the bulk of the water has been displaced from the contact area, are there small fluid wedges being formed on individual asperities of the pavement as has been suggested? Is a hydrophobic surface to be preferred to a hydrophilic one? Different opinions exist on this point. There are other questions which require answers before we fully understand the mechanism of tire-pavement friction.

PAVEMENT FRICTION MEASUREMENT

Skid-resistance control is primarily a safety measure, but is skid resistance really the parameter which governs the frequency of out-of-control accidents on wet pavements? Wheels are locked after an emergency has arisen, but loss of control can occur because rolling wheels can no longer transmit the forces which are imposed on them. Therefore it may well be just as important to know what the maximum force is that a tire can transmit in slip as when it is locked. Pavement characteristics do influence the ratio between the two friction values.

We are planning to learn more about the characteristics of slipping tires and are therefore modifying our road friction tester which up to now was capable of measuring locked-wheel friction only. We decided that we should measure in transient slip, that is, as if gradually more braking force is being applied. In fact we plan to do just this and let the wheel pass the critical slip (at which friction is at a maximum) and release the brake before or after the wheel has locked. We believe we have a solution which will permit us to obtain the momentary friction force directly, without having to compute it after the test.

MINIMUM SKID-RESISTANCE REQUIREMENTS

For the time being, however, only skid-resistance data are available to highway engineers and skid resistance is all that agencies will be able to measure for some time to come (and this may well remain the best method for pavement surface characterization). The question arises: what skid-resistance values make a pavement safe or unsafe and what minimum values should be tolerated? The obvious solution is to go to accident data for an answer and this has been done here and in Europe. Actually, accidents are statistically rare occurrences (particularly those of a specific type) and, except for selected projects, accident reports are quite unreliable at the present state of the art.

We therefore looked at whether or not it would be feasible to derive minimum skid-resistance requirements from the needs of traffic. One may reason that the minimum skid-resistance requirements are those which permit normal traffic under normal conditions to move safely. For instance, one can postulate that pavement skid resistance is acceptable if it permits the maximum decelerations which are used habitually by drivers in the absence of an emergency. Similarly, one can use lateral accelerations for defining the frictional requirements on curves. Since on wet pavements skid resistance is strongly speed-dependent, speed is a most important parameter in this approach and the minimum requirements will vary with the prevailing traffic speeds.

We believe that by taking this approach we have been able to arrive at minimum skid-resistance values which, if adhered to, will make the nation's highways on the average considerably safer than they are now. A comparison with available accident vs skid-resistance data indicates this (4). Nevertheless, even though our approach may rest on a firmer basis than derivation from accident data alone, more solid data on the characteristics of normal traffic are needed. How do drivers approach a stop sign? What decelerations are used on limited-access highways? And so on.

THE POLISHING OF PAVEMENTS

I have touched earlier on some problems connected with the measuring of skid resistance, but if a standard for minimum skid-resistance values would be adopted, how would an agency responsible for complying with the standard go about assuring that the standard is met?

Of course, pavements with skid-resistance values below the prescribed standard can or must be resurfaced. This method, even with the most lenient standards, can become quite expensive if the new surface loses its skid resistance rather rapidly again.

Pavements are polished by traffic. The rate at which different aggregates polish varies, and the eventual polish at which the pavement stabilizes varies. Empirically each highway department has a fairly good idea about which available aggregates polish more and which less. It is, however, important that we learn which properties make a mineral a poor or a good risk for use in a surface course so that compliance with a standard can be predicted and cost comparisons between different available solutions can be made.

Before procedures of this type are feasible we need to know a great deal more about pavement polishing than we do now. Polishing is the consequence of wear, although the relationship between the two is not necessarily a constant one, even for a single material. It is influenced by all sorts of factors. For instance, studded tires may wear down a pavement, but they can increase its skid resistance. In fact, every winter rejuvenates the pavements in the northern states to varying degrees, whether studded tires are permitted or not. Even a long-lasting rain can raise the skid resistance of certain pavements by a measurable amount.

Traffic, as such, does not polish a pavement. We have run a tire against a drum to which aggregate particles had been glued and found virtually no polishing as long as no abrasive was applied. An abrasive is a prerequisite for polishing. We use a carefully selected and tightly controlled abrasive for our laboratory wear tests and obtain results which are in general agreement with field experience.

We are, however, not sure if the abrasive which we are using is realistic in combination with all pavement materials. To make the correct selection we should know more about the characterisitcs and the sources of the dust on the highways. The nature of the dust changes with the weather and the seasons, and this change may account for the observed variations of the skid resistance.

THE POLISHING PROCESS

Studies on the wear of mineral aggregates have shown that wear produced by a sliding rubber block causes scratches and pits on the flat surfaces of the mineral particles. The amount of wear is not clearly related to any single characteristic, but the hardness of the mineral is an important factor.

Interestingly, minerals are worn by an abrasive consisting of the same material. A very fine polish can result from this combination if the abrasive particles are small. Not much roughening occurs if subsequently coarser particles are introduced, but when the particles are harder than the aggregate they cause rapid roughening. Much more needs to be known before the wear and polishing processes on the highway are fully understood and can be described in quantitative terms.

A parallel line of investigation deals with the problem of how the various properties of individual aggregate particles influence friction. One such property is the microroughness of that portion of the particles which comes into contact with passing tires. There are indications that above a certain microroughness friction is independent of roughness, while below a critical value the friction decreases with decreasing roughness (when the surface is wet). We have been able to confirm this under laboratory conditions. One difficulty we encountered is that we did not find a satisfactory way of describing or measuring microroughness so that we have to depend on defining surface polish by the size of the abrasive used to produce it. In terms of abrasive size, the critical polish (above which friction is independent of it) is about 40 microns.

A major unexplored area is that of the relation between friction and aggregate particle shape and particularly the shape changes which the particles undergo as they wear.

Once we understand how traffic exposure changes pavement skid resistance we can postulate what reconditioning methods must accomplish. It is conceivable that aggregates which tend to polish to unacceptable skid-resistance levels might still make surface courses which are acceptable from the economical as well as the safety standpoint, provided low-cost reconditioning methods can be developed.

ALLOCATION OF IMPROVEMENT POTENTIAL

Of course, the entire burden of providing traffic with adequate friction does not fall on the pavement alone. Tire design can be improved to give better frictional performance by minimizing tread movement, by making the pressure distribution in the contact area more uniform, by tread design, and by choosing rubber compounds which maximize the adhesion and the hysteresis components of friction on all surfaces. Vehicle design enters the problem via suspension geometry and the vibrational characteristics of the entire vehicle. Similarly, steering geometry and the cornering characteristics of the vehicle influence available and necessary friction.

In the light of the present potential for technological progress in tires and vehicle design, it appears that pavement surfaces can make a greater contribution to an increase in tire-pavement friction. Surface courses which retain high skid resistance over long periods of time are now being laid down in various portions of the United States. In the last analysis this is a matter of using a good aggregate with the correct particle-size gradation.

When desirable materials have to be transported to the construction site over long distances and reconditioning methods are not available, periodic resurfacing may still be the most economical long-range solution. It is, however, important that a state have an inventory of its accessible supplies of skid-resistant materials. If the supply is limited, steps should be taken to prevent its use for purposes other than surface courses.

CONCLUSION

I hope I have been able to highlight the most important aspects of the pavement slipperiness problem and to show how far our knowledge has progressed. Much remains to be done before we can derive reliable design procedures for surface courses which are optimum in performance, life and cost. To this end we must fully understand the mechanisms of rubber friction, of the tire-pavement contact, and of the polishing process. This is no small task and contributions from many sources will be needed to accomplish it.

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Road Surface Texture and the Slipperiness of Wet Roads

A. J. HARRIS, Ministry of Transport, British Road Research Laboratory

The texture required of a road surface, so that it shall be as resistant to skidding as possible, is harsh for low speeds and harsh and large-scale for high speeds. The function of the texture is to assist drainage of the water to achieve dry contact as quickly as possible and maximum deformation of the tire tread surface by the asperities of the road surface. This is achieved by easy (large) flow channels and by sharp (harsh) asperities generating high pressure. These conclusions are illustrated in an examination of how the skidding resistance of actual surfaces varies with speed, and how rubber hysteresis increases friction. Aquaplaning is also considered. How suitable textures are being obtained in the United Kingdom and the researches relevant to this subject being planned or in progress at the Road Research Laboratory are discussed.

•FOR this paper, surface texture does not mean the composition of the surface—so much binder, sand, etc.—but the geometrical form of the road surface, that is, the shapes of the asperities large and small that make contact with the tire tread, or deform it, and the channels in between them. The purpose of the paper is to present the views of the British Road Research Laboratory on the importance of the texture thus defined and to outline its plans for research in this field.

TYPE OF TEXTURE REQUIRED

The view of the Road Research Laboratory is that all roads require a harsh texture when wet and that high-speed roads require a coarse texture as well. When speeds are low, for example, town roads restricted to 30 mph, a coarse texture is not required. A road surface is said to be harsh when the fine-scale asperities are angular with sharp points or edges, so that it feels somewhat like sandpaper to the touch. The type of surface that is undesirable feels smooth or polished to the touch even though it may contain large-scale, rounded asperities.

The reason for requiring these types of texture is, first, to facilitate the removal of water from the tops of the asperities so that as far as possible contact can be made between them and the tire tread and, second, to ensure that, in making such contact or even when approaching it, the asperities shall deform the tread by generating high pressures. The high pressures not only assist in the process of water removal, they also ensure that the deformation of the tread is such as to give rise to the frictional force due to the hysteresis of the tread material, the so-called hysteresis friction as distinct from the adhesional friction. Frictional forces are produced effectively only if there is dry contact or deformation of the tire tread. Dry contact produces adhesion and hysteresis friction, deformation produces hysteresis friction only.

Figure 1, an ink contact print, shows the areas of actual contact between tire and road in a static condition, and shows clearly (the white areas) how much larger the drainage system is on a coarse surface. From the print alone it would be expected that the tread pattern can add little to the drainage effectiveness of a sufficiently coarse

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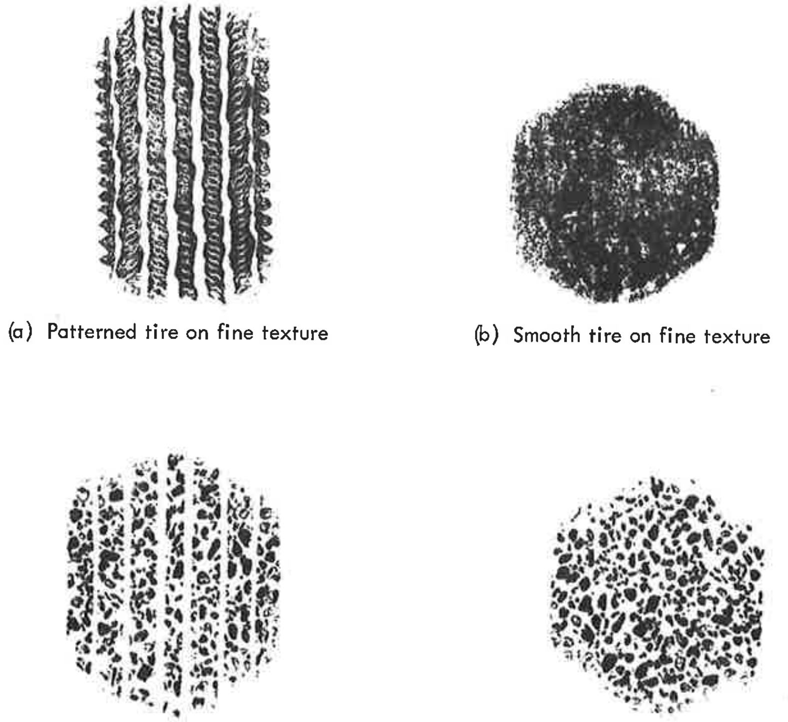

(a) Patterned tire on fine texture

(b) Smooth tire on fine texture

(c) Patterned tire on coarse texture

(d) Smooth tire on coarse texture

Figure 1. Points of contact between tire and road.

surface, and this is found to be the case. Patterned and smooth tires perform very similarly on such surfaces, and a smooth tire is as good as a patterned one or even better.

The conditions in the contact area are illustrated diagrammatically in Figure 2, where a tire is shown advancing in a thick film of water. The bulk of the water

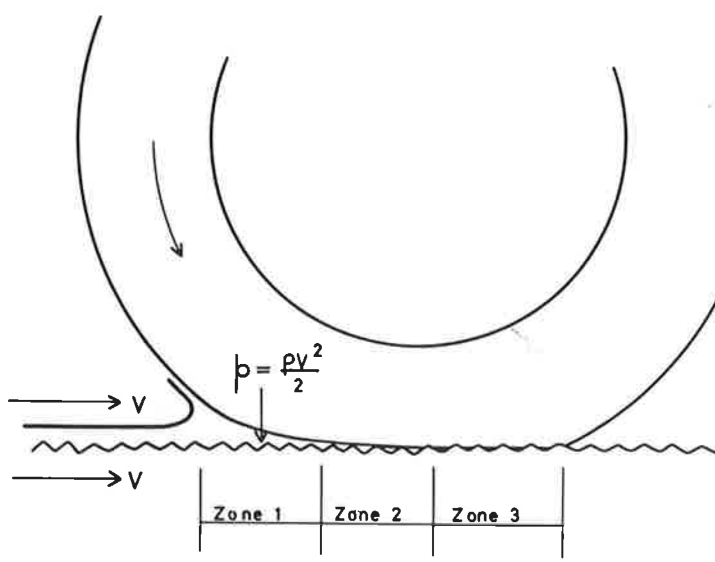

Figure 2. Displacement of water by tire in successive zones.

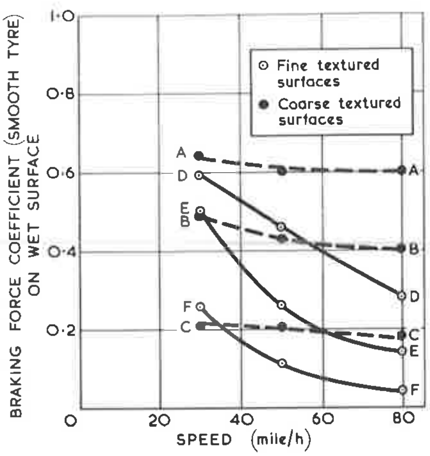

Figure 3. Change in skidding resistance with speed on six surfaces on the Road Research Laboratory test track.

is displaced in zone 1 by the dynamic pressure generated in the water. To the first order this pressure depends on the speed but not on the water depth, so that as far as pressure goes thick films are as easily displaced as thin ones. The total thrust of the water on the tire increases with the thickness of the water, although the pressures remain of the same order. However, the viscosity of water prevents it from being swept away entirely, and the tire is left descending on a much thinner layer in zone 2. If there is time for it to squeeze out all the water it can, zone 3 is formed, where maximum contact and friction are achieved and the water carries none of the load. Clearly, coarseness and harshness of texture would be effective almost entirely in zones 2 and 3. As speeds increase and the time for expelling the water diminishes, the boundaries of the zones move backwards. There is less and less contact and less and less friction. Finally if the dynamic pressure appropriate to the vehicle speed exceeds the pressure which normally exists under the tire and supports it (very approximately equal to the internal pressure, the inflation pressure), only zone 1 remains and the tire is supported on a relatively thick water film. The tire is then said to be in a state of dynamic aquaplaning. The thinner the water layer the larger the part played by viscosity and probably by turbulent energy dissipation in the water and the more the behavior may be expected to depart from the simple conditions just described.

EFFECT OF TEXTURE ON FRICTIONAL COEFFICIENTS

The effects of coarseness and harshness on the coefficient of skidding resistance are shown in Figure 3. The relatively flat curves showing a slow falloff with speed are for coarse surfaces, that is, for good drainage. The swiftly descending curves are for fine-textured surfaces, that is, for poor drainage. However, some surfaces of each class have considerably higher coefficients than others in the same class. These are surfaces which are harsh rather than polished. It is to be noted that the coefficients at 30 mph can put surfaces in a very different order of merit from coefficients at, say, 80 mph if the textures of the surfaces are not similar. At 30 mph it is the harshness which largely determines the coefficient, while at 80 mph the scale of the texture is becoming much more important. A measurement of friction at 30 mph together with a knowledge of the texture would give a fair idea of what could be expected at higher speeds.

HIGH SPEEDS, DEEP WATER AND AQUAPLANING

High speeds or thick layers of water tend to make more difficult the problem of water removal, i.e., causing the load to be supported directly by the surface and not through the water. Figure 4 shows the much lower coefficient obtained in 1 in. of water than in 0.007 in. The rapid descent (between 30 and 40 mph) may be due to the approach of dynamic aquaplaning.

An example of the effect of drainage alone, although it is drainage in the tire tread rather than in the road surface, is shown in Figure 5. This

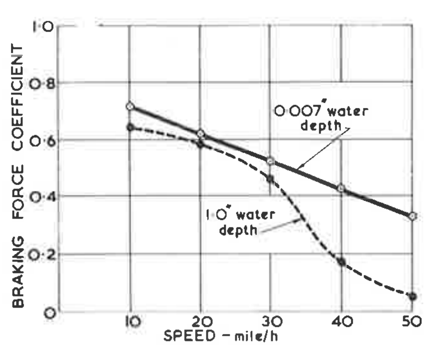

Figure 4. Effect of water depth on the results of locked-wheel braking tests on a smooth surface with a patterned tire.

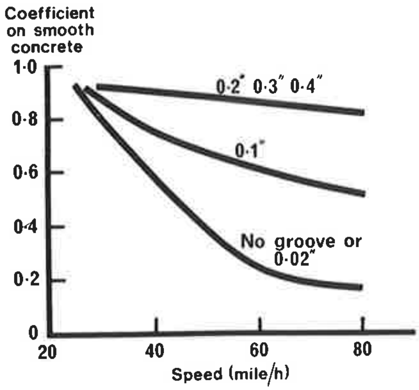

Figure 5. Effect of tire drainage grooves of different widths.

shows the peak braking force coefficient for longitudinally ribbed tires, which differed only in the separation between the ribs of the tread. If the grooves were mere knife cuts, the coefficient was almost the same as for an uncut tire. Grooves 0.1 in. wide gave a much better performance than no grooves, and grooves 0.2 in. wide gave very good results. No further improvement was evident if the grooves were made still wider. It is also clearly shown that increases in drainage which produced little effect at 20 or 30 mph were of great importance at 70 or 80 mph. All this is in agreement with the fact that the percentage falloff in coefficient between 30 and 80 mph correlates to a considerable extent with the texture depth, the simple measure of coarseness of texture.

Dynamic aquaplaning requires a certain depth of water depending on the surface texture and the tire tread. In England we do not regard aquaplaning of this type as a very serious danger on our roads in the water depths commonly encountered. On airfields it may be quite a different matter. On roads, the water depth rarely exceeds about 0.1 in., except of course in puddles where the water is standing. The impression has been given that complete aquaplaning takes place on ordinary wet roads at a definite speed depending on the inflation pressure of the tire. This may be so in deeper water, but we have found it impossible to produce complete aquaplaning on our test track at Crowthorne at depths approaching 0.1 in. except with smooth tires on our smoothest surfaces. With good modern tread patterns quite high coefficients are still obtainable at 2.5 times the aquaplaning speed. Figure 6 shows such a result. The peak coefficient is very adequate and there is no sign of aquaplaning at about 130 mph.

Our view, at the Road Research Laboratory, is that the dynamic type of aquaplaning should be rare. It is a real danger but should occur only in special conditions and can ordinarily be eliminated by a good surface texture, a good tread, and prevention of puddles. Viscous support of the tire has been recognized for many years as a cause of low friction. We should think that lowered friction due to this cause on fine-textured and polished surfaces was more likely to be a significant cause of accidents at the present time. Skidding accidents were found to become frequent enough for the sites to be regarded as accident black spots at places where the sideway force coefficient at 30 mph fell below about 0.4. Fortunately a good surface texture is able to limit this danger under most conditions in England. Very heavy rainfall may, of course, present greater problems in other places.

It is of interest in connection with Figure 6 that the coefficient does not appear to increase at very high speeds. Rising coefficients have been obtained at the Road Research Laboratory but only on coarse surfaces and with a different technique from that used to obtain the results shown in Figure 6. These coarse surfaces can apparently be harsh or polished and the tires that were used showed severe signs of heating and wear. It has been suggested that hysteresis friction could increase in this manner owing to the greater speed of sliding; it is therefore of interest that Figure 6 does not show it even at the high speed attained.

There is a very large difference between the peak and the sliding coefficients in Figure 6. In

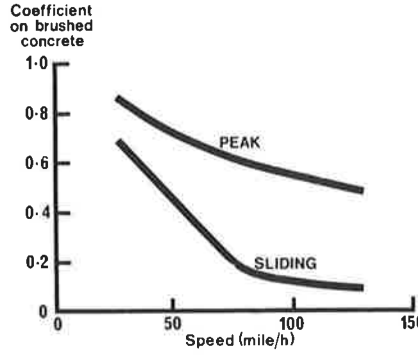

Figure 6. Braking force coefficients up to a high-speed, patterned tire.

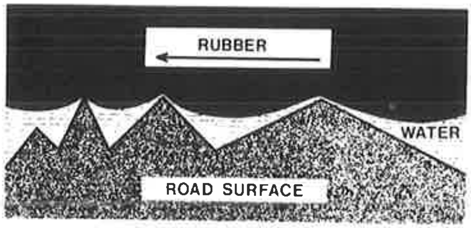

Figure 7. Contact, and deformation of tread, at tops of asperities.

normal driving, friction would be available up to the peak value, and the driver might therefore not realize that if he locked his wheels in an emergency he would experience a very large drop in friction. This emphasizes the need for some device on the vehicle to make wheel locking impossible.

HYSTERESIS FRICTION

In order to get a useful contribution from the hysteresis component of friction one cannot use a smooth surface but must have a texture that will deform the tread rubber at the asperities. This deformation can occur with dry or lubricated contact as shown in Figure 7. The frictional force comes from the pressure difference between the two sides of the asperities when the rubber rebounds less vigorously than it is displaced. It can clearly exert these pressures through a water film if necessary, but the smaller the asperities in relation to the film thickness the smaller their effect will be. Small asperities can be swamped in a way that larger ones will not.

Angularity, steep slopes, sharp edges and points (all that go to make a surface harsh) increase the hysteresis friction. The scale of the asperities is relatively unimportant in itself, but small ones will be swamped in a thin film of water which large ones might penetrate. On the tops of large asperities, where the pressures are likely to be high and water films, if present, very thin, small asperities should still be effective. The coarse, supposedly non-skid, surfaces that turned out to be quite slippery failed because the tops of the large asperities became polished and lost their harshness. Such surfaces, although slippery enough to be unsuitable for roads, do not give the extremely low coefficients which fine-textured surfaces can give. The only way to prevent or reduce polishing is to use a stone which is resistant to it.

PRODUCTION OF DESIRABLE TEXTURES

Large-scale textures are obtained in bituminous surfaces by the use of large aggregate directly in the mix or as a closely packed layer of precoated chippings rolled into the top of a fine-textured asphalt. Some idea of the textures that are attainable can be gained from a number of surfaces that have been in use for over three years on a fast road that carries about 12,000 tons a day. A macadam had a texture depth of 0.06 in., an asphalt with precoated chippings and a surface dressing had texture depths of about 0.07 in. A high-stone-content asphalt, which had failed to maintain an adequate surface because the stones became too embedded, had a texture depth of 0.012 in.

Concrete roads may be given a coarse texture by brushing when new or by cutting grooves when old. In England, concrete is being brushed much more severely than formerly, and an average texture depth of 0.030 in. and a minimum of 0.025 in. are being required.

When concrete is grooved, the direction of grooving is unimportant at, say, 30 mph but can be very important at high speeds. Locked-wheel braking force coefficients at 80 mph on a concrete airfield were about 0.2 on the untreated surface, almost the same in the direction of the grooves, and about 0.6 perpendicular to the grooves. The water depth was about 0.010 to 0.020 in. in these tests, the water tending to drain into the grooves.

Having chosen a method of construction which will give a texture of the right kind, one aims to keep it harsh by the use of stones that resist polishing. In England, stones from each quarry are periodically tested for what is known as their polished-stone value. Roads and sections of roads have been classified into groups according to the severity of polishing expected and the likelihood of skidding, and stone of a sufficiently high polished-stone value is required to be used according to the group concerned. The levels of polished-stone value thus laid down are not obligatory standards, but they are largely effective in that the Ministry of Transport will not approve a scheme unless the levels are adhered to.

Where a road surface consists largely of stone, there is quite a good correlation between the polished-stone value of the stone concerned and the skidding resistance as measured by the sideway force machine or the British pendulum tester.

RESEARCH TRENDS AND POSSIBILITIES

The Road Research Laboratory is following a number of different lines of research in relation to surface texture. Attempts will be made to produce freely draining surfaces which will become no more than damp when it rains. Such surfaces are easy to make, but they tend to close up if heavily trafficked, to disintegrate in frost, or to become filled with silt. It is expected that organic growth may occur in the interstices and contribute to clogging up the drainage. One length of this type of concrete road has been laid, and it is planned to lay a series of experimental lengths in bituminous materials. Not only would such surfaces eliminate the possibility of aquaplaning, they would also to a large extent eliminate the splashing nuisance.

Because there is not likely to be available enough stone of the highest polished-stone value, work is being started on artificially treated aggregates. A calcined flint, heat treated to turn it white, has been found to be among the very best materials for resisting polishing. In view of this, the heat treatment of other aggregates is to be investigated.

Methods of brushing and raking concrete are being studied. As already mentioned, texture depths of 0.030 in. are now being required for motorway construction. The new coarser surfaces have given good resistance to skidding when new, but not a great deal is yet known about the rate at which they will polish. Polishing and wear are certainly taking place fairly rapidly in some cases. Investigation of grooving techniques and the rate of wear is also taking place.

An investigation is being continued in which the best texture for high-speed roads is being sought by directly correlating the skidding accident record of lengths of road with their texture and skidding resistance. Studies are also being made of the relation between texture and hysteresis and of the geometrical characteristics of the texture that are associated with the most effective surfaces.

One of the main purposes of this symposium is to indicate areas where research might usefully be encouraged and I should like to suggest, besides those aspects just mentioned, further theoretical and experimental investigations of the dynamics and physics of the tire-road interaction. The theoretical investigations of the past have mostly been based on very simplified models of the processes involved. It may be that a fuller understanding of what is going on may suggest new lines of practical progress. Those contributing to this symposium from the theoretical side probably have a number of suggestions to offer already.

ACKNOWLEDGMENT

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Tire Hydroplaning and Its Effects on Tire Traction

WALTER B. HORNE, NASA Langley Research Center, Langley Station, Hampton, Va.

This paper first discusses the buildup of fluid pressures in the tire-ground footprint region of wet pavements that can lead to three distinct types of traction loss; namely, dynamic hydroplaning, viscous hydroplaning or thin-film lubrication, and the reverted rubber skid. The paper then discusses how pavement surface texture, pavement water depth, tire tread design, vertical load, and tire inflation pressure affect fluid pressure buildup in the footprint. Finally, two promising methods for alleviating fluid pressure buildup are discussed. These methods are pavement grooving and air jets placed in front of tires.

•WHY is it that skid-type accident rates of both highway vehicles and landing aircraft are much higher during operation on wet pavements than on dry? The answer is that traction characteristics are different and that wet pavements are more slippery than dry pavements. In the past, however, many wet skidding accidents of aircraft were blamed on faulty piloting techniques by the aircraft pilot concerned. Actually, recent research on wet skidding accidents points the main blame for these accidents on a little-understood wet pavement hazard called tire hydroplaning over which the pilot has little or no control. A similar situation faces the automobile driver. Although he does have more control over his speed, he still may be unaware of actual reductions in friction which may occur as a result of wet conditions, especially on smooth, curved pavements.

Tire hydroplaning is usually defined as the condition which exists when a film of water or other contaminant is present in the footprint and separates the tire from the pavement surface. The development of fluid pressures in this water film, which causes hydroplaning to occur, is extremely complicated and depends on many pavement, fluid, tire, and vehicle parameters. It is the purpose of this paper to discuss the effects and variations of fluid pressure which, acting separately or in concert, produce hydroplaning and to point out the parameters of importance. The paper also discusses certain vehicle, tire, and pavement design techniques which can be used to alleviate hydroplaning effects on vehicle traction.

THE ROLLING TIRE

When an unbraked freely rolling tire runs into stationary water on a flooded smooth-surfaced pavement, both viscous and dynamic water pressures can be produced in the tire-ground contact region (Fig. 1). The data in this figure were obtained by recording the water pressures generated in a tread groove and on an adjacent tread rib as an aircraft tire rolled across a water-covered smooth-surfaced pressure plate. The dynamic water pressure results from the stagnation pressure developed at the tire-water interface across the width of the tire at the operational speed. Its effect creates the initial pressure rise shown by both tread and groove water pressures in Figure 1.

Paper sponsored by Committee on Surface Properties—Vehicle Interaction and presented at the 46th Annual Meeting.

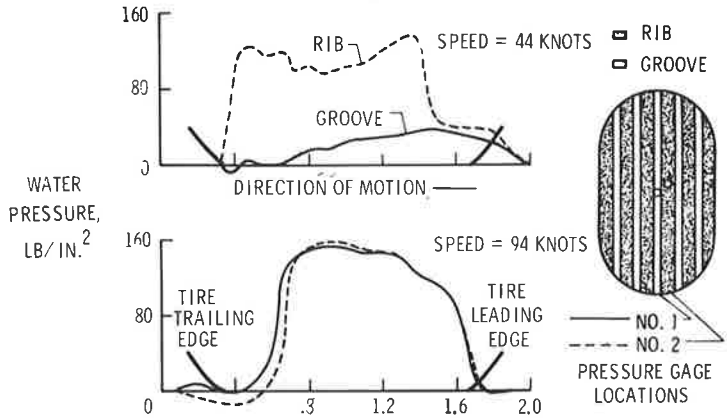


Figure 1. Fluid ground pressure signatures (water depth = 1.0 in.; tire pressure = 90 psi).

The viscous pressure is created by the inability of the rubber in the tread rib to puncture and displace the very thin and viscous residual film left on the smooth pavement after the majority of the water encountered has been displaced or squeezed out from under the tire. The pressure in the water film under the rib, in this case, must rise to the magnitude of the local tire-ground bearing pressure acting on the tread rib because of the tire vertical load. This effect is indicated by the much higher water pressures developed on the tread rib toward the rear of the footprint in Figure 1. Note that under these conditions, the pressure in the groove is correspondingly lower.

By definition, hydroplaning must occur at any speed where the combination of dynamic and viscous water pressures balance the tire-ground bearing pressure over the tire footprint. When this occurs, the tire is lifted off the pavement and rides on a water film. Research indicates that when dynamic water pressures predominate in the footprint, this speed is predicted by the simple relation $V_P = 9\sqrt{p}$, kts, or $V_P = 10\sqrt{p}$, mph, where V_P is the hydroplaning speed, and p is the inflation pressure in pounds per square inch.

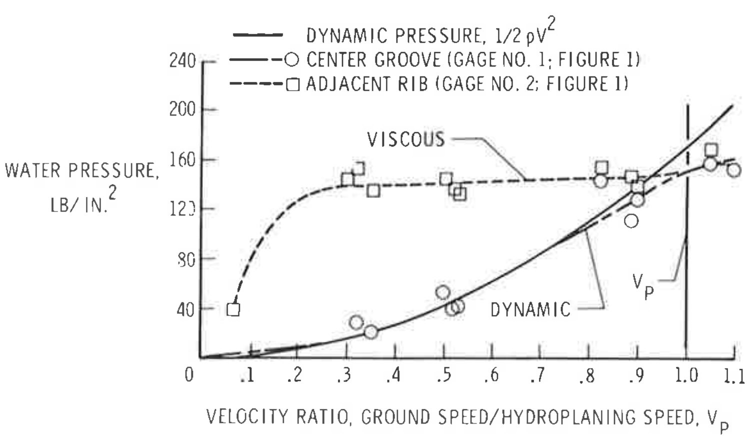
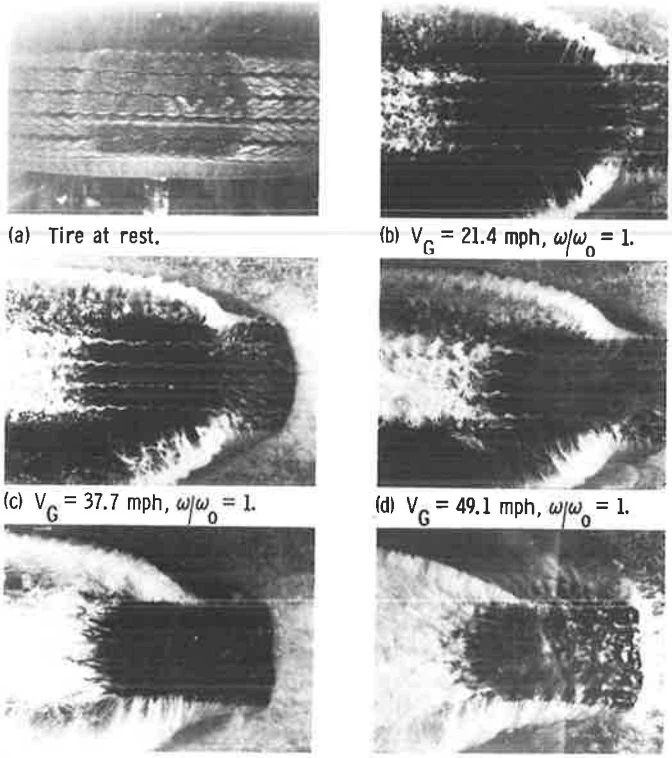


Figure 2. Variation of peak water pressures in rolling tire footprint (water depth = 1.0 in.; tire pressure = 90 psi).



(a) Tire at rest.

(b) $V_G = 21.4$ mph, $\omega/\omega_0 = 1$.

(c) $V_G = 37.7$ mph, $\omega/\omega_0 = 1$.

(d) $V_G = 49.1$ mph, $\omega/\omega_0 = 1$.

(e) $V_G = 59.2$ mph, $\omega/\omega_0 = 0.245$.

(f) $V_G = 77.3$ mph, $\omega/\omega_0 = 0.425$.

Figure 3. Photographs of typical production-type tire taken through glass plate (water depth = 0.4 in.; vertical load = 835 lb; yaw angle = 6°; direction of motion, left to right).

The data presented in Figure 2, which contrasts the viscous (rib) pressures with the dynamic (groove) pressures, show that the equation in the preceding paragraph is not appropriate for the case when viscous pressures predominate in the footprint (for example, a smooth tire on wet ice). These data show that viscous pressures build up much more rapidly with ground speed than dynamic pressures. Thus viscous hydroplaning will occur at much lower speeds than dynamic hydroplaning unless viscous pressures are alleviated by pavement texture or tire tread design.

The progressive development of hydroplaning with speed on an automobile tire rolling across a flooded glass runway surface is shown in Figure 3.

THE SKIDDING TIRE—DRY PAVEMENTS

The ability of a tire to develop traction on dry pavements depends to a great extent on whether the tire is rolling or sliding on the pavement. This is illustrated by the data presented in Figure 4 where braking and sideways friction coefficeints are plotted against slip ratio. (Slip ratio may be defined as the ratio of the difference between the vehicle speed and the braked-wheel speed to the vehicle speed.) In this figure, a freely rolling unbraked wheel has a slip ratio of zero while a fully skidding wheel (locked wheel) has a slip ratio of 1.0. These data were obtained by rolling an automobile tire at a yaw angle of 8° to develop a cornering or side force and then applying the wheel brake. The vehicle speed for the tests was 30 mph, and the tests were conducted on a dry concrete pavement.

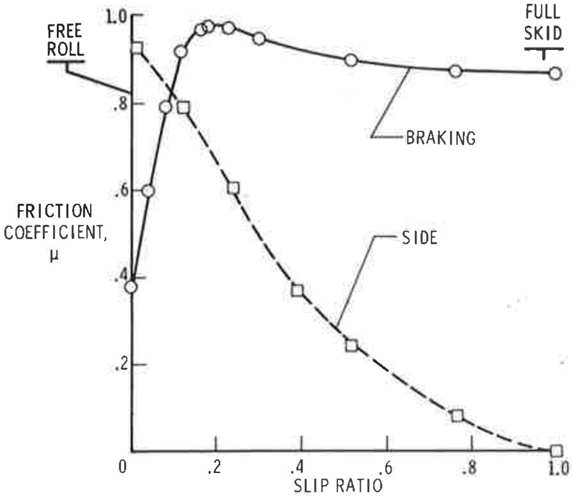


Figure 4. Effect of braking on tire side force capability (dry concrete; speed = 30 mph; yaw angle = 8°).

Consider the dry braking curve in Figure 4. The results show that, as the wheel brake is applied, the braking friction coefficient rises quickly to a peak value at 0.20 slip ratio and then decreases to a lower value at full skid or slip ratio of 1.0. It should be noted that the slip ratio indicated for braking friction to rise to peak value (0.20) is believed to be an apparent slip ratio caused by tire elasticity which allows the tire to windup torsionally about the wheel under the influence of the applied tire-ground drag load. Once the slip ratio for peak drag is exceeded, the tire starts to slip or slide on the pavement with increasing velocity until at slip ratio of 1.0, the relative skidding velocity between tire and ground equals the vehicle velocity.

Figure 4 also indicates that the capability of a tire to develop side or cornering forces is greatly affected by the condition of the tire, that is, whether it is rolling or sliding. For example, it will be noted in Figure 4 that side friction coefficient values decrease rapidly toward zero once the slip ratio for peak braking friction coefficient is exceeded. The lesson to be learned here is that a completely locked or full skidding wheel has no steering capability whatever, a tire cannot develop any side or cornering force if the wheel is locked, and drastic losses in side force can be expected if the wheel slip ratio substantially exceeds the incipient skidding (peak) value. These facts point with favor toward the use of anti-skid or anti-wheel-locking devices in vehicle braking systems to prevent total or partial wheel lockups and insure adequate tire cornering or side force capability during heavy wheel braking. Also, it is noted that cornering capability is preserved if the anti-skid system operates on the front side of the μ-slip curve rather than on the back side as is current practice with aircraft anti-skid systems.

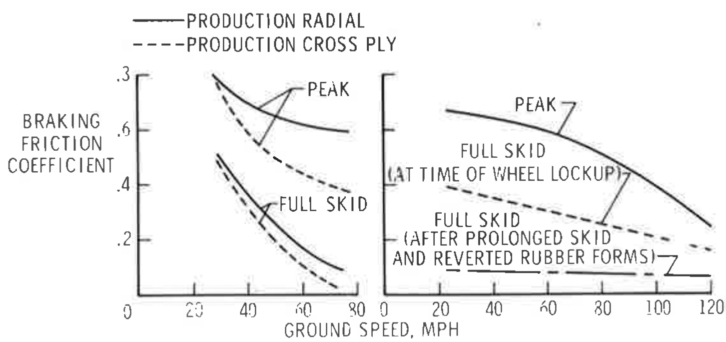


Figure 5. Comparison of tire rolling (peak) and tire locked (full skid) braking friction coefficients.

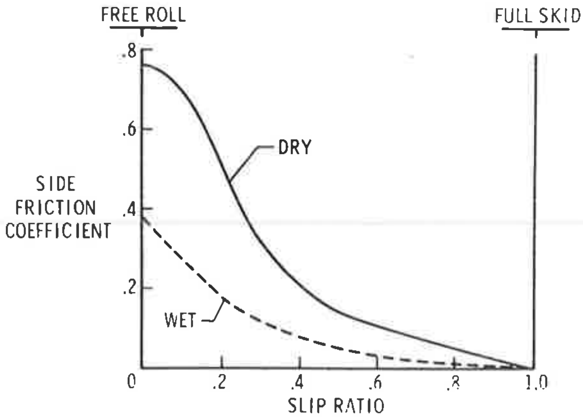


Figure 6. Effect of braking on tire side force capability (concrete surface; speed = 30 mph; yaw angle = 4°).

THE SKIDDING TIRE—WET PAVEMENTS

Results of tests have shown that when tires are allowed to skid under partial or total locked-wheel conditions on wet pavements, the friction coefficients obtained are substantially lower than the peak values obtained when the braked rolling tire just starts to skid. This is illustrated by the braking friction coefficient curves shown in Figure 5 for both automobile and aircraft tires. Tire side force capability also is greatly reduced when the wheel operates in a partial or total slip condition on wet pavements (Fig. 6). The relative importance of the various factors which contribute to this decrease in friction coefficient with slip ratio on wet pavements is not yet fully understood. The very interesting study performed recently by the Royal Aircraft Establishment at Farnborough, England, of a tire rotating on the inside wetted surface of a transparent perspex drum illustrates a point which may be significant in this regard. Motion pictures taken of the tire footprint through the transparent drum surface in the RAE study show quite clearly that the rotating tire allows incoming water to readily pass through or drain from the rear of the footprint. On the other hand, when the tire stops rotating on the drum surface, water inflow and outflow from the tire footprint greatly diminishes. The water, now essentially trapped in the sliding footprint, tends to circulate in left- and right-hand vortices (Fig. 7).

It is also believed that the fact that water can be trapped and carried along in the skidding tire footprint as the locked wheel and tire slide across the wet pavement has a significant effect on the phenomenon called reverted rubber skid.

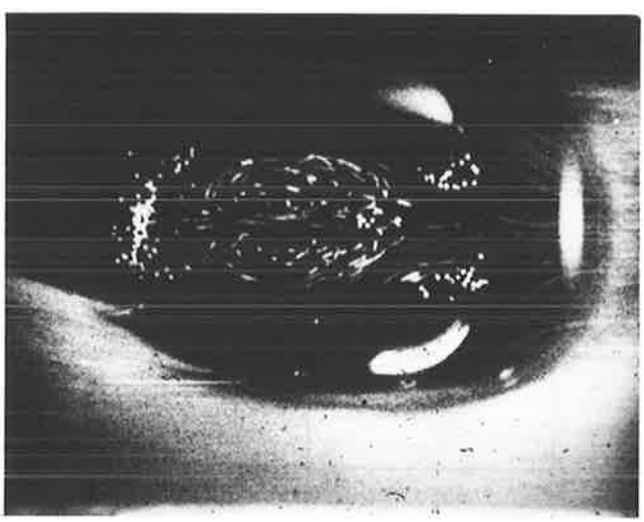


Figure 7. Trapped water circulating in the fully skidding footprint (tire pressure = 30 psi; water depth = 6 mm; drum speed ≈ 82 fps).

LEFT MAIN AND NOSE TIRE TRACKS

RIGHT MAIN TIRE TRACKS

MAIN LANDING GEAR TIRE WITH REVERTED RUBBER SKID PATCH

Figure 8. Hydroplaning accident—wet runway; 4-engine jet transport.

Reverted Rubber Skid

This phenomenon is named for the appearance of an aircraft tire after this type of skid occurs on wet pavements. The tire shows a patch of rubber that has the appearance of having been heated to the point that the surface rubber has melted and has reverted to the uncured state. This type of phenomenon occurs after a prolonged wheel skid, and once started, results in very low tire-ground braking friction which persists down to very low speeds (Fig. 5). It has been suggested that the braked tire's contact with the wet pavement may produce enough heat to turn the water, which is trapped and carried along in the tire footprint, into steam. Also, results of calculations show that, under the pressures involved, the steam would be hot enough to melt the rubber in the contact patch. It has also been suggested that this patch of soft, tacky rubber could produce a seal that would further entrap steam and water which would enable the tire to ride on a cushion of steam. Thus, the distinctive white marks left on wet pavements by reverted rubbers skids, in contrast to the black streak left on the pavement by dry skids, may be the result of the pavement in the tire path being steam-cleaned. Fortunately, as far as highway safety is concerned, this phenomenon has been noted thus far only during high-speed aircraft landings where the tire pressure is much higher than for automobile tires. An example of the white streak, reverted rubber, skid is shown in Figure 8.

TECHNIQUES FOR ALLEVIATING TIRE TRACTION LOSSES FROM TIRE HYDROPLANING

Viscous Pressures Predominating—Viscous Hydroplaning

Viscous fluid pressures in the tire-ground contact zone of rolling tires build up with speed to the dangerous levels required for hydroplaning only when water-covered pavements are smooth or smooth acting, when contaminants considerably more viscous than

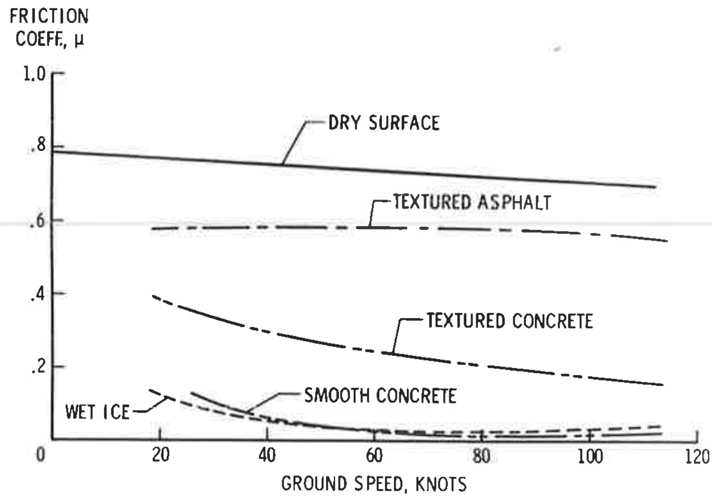


Figure 9. Thin film lubrication (damp runway; smooth tread; p = 140 psi).

water coat pavements, or when the tire enters a locked-wheel skid. It is important to point out that only slight amounts of precipitation, such as from a heavy dew which coats the pavement with a thin film of fluid, can produce this effect. This type of traction loss is illustrated by the very low peak braking coefficients developed by a smooth tread aircraft tire during braked rolling on damp smooth concrete and wet ice (Fig. 9). This figure also shows that providing the pavement with a surface texture is an excellent method for alleviating this condition. As previously mentioned, another effective method for alleviating viscous pressure buildup in the footprint is to provide the tire with an efficient tread design. The cornering data shown in Figure 10 for automobile tires having smooth, grooved, and grooved and siped tread designs illustrate this point, particularly at the low speeds where dynamic effects are small.

The large decrease in traction suffered when braked rolling tires enter a full skid on wet pavements was illustrated by the data presented in Figures 5 and 6. This type

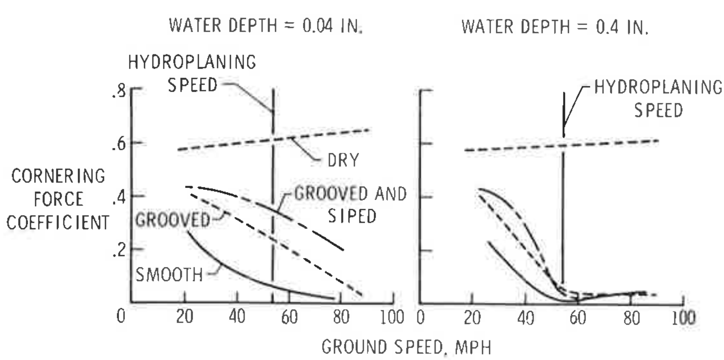


Figure 10. Viscous and dynamic pressures predominating (smooth concrete; yaw angle = 6°).

loss can be eliminated only by preventing the locked-wheel skid from occurring and suggests advantages to be gained from the use of anti-skid techniques or devices to prevent the wheel from locking up.

Dynamic Pressures Predominating—Dynamic Hydroplaning

Dynamic fluid pressures in the rolling tire-ground contact zone build up with speed to dangerous levels only when pavements are critically flooded. The depth of water on the pavement required can vary considerably depending on the particular combination of tire tread design and pavement surface treatment under consideration. Smooth tires operated on smooth pavements require the least water depth, while grooved tires operated on open-textured or grooved pavements require the greatest water depths for tires to dynamically hydroplane. Figure 10 shows that tread grooves improve tire traction when the water depth is less than the tread groove depth (0.04-in. water depth). This benefit is lost when the water depth exceeds the tread groove depth (0.4-in. water depth).

Several relatively new techniques offer great promise as a means of alleviating dynamic hydroplaning effects on tire traction by providing better fluid drainage in the tire-ground contact zone. For example, porous pavements are currently under study in England and elsewhere. A thin but porous wearing course is laid on top of an existing pavement. This construction allows the water trapped in the footprint to drain through the pavement itself as well as through the drainage channels provided by the tire and pavement surface texture.

Another very promising technique is to groove the pavement (Figs. 11 and 12). The pavement grooves provide additional drainage channels in the tire-ground contact zone and greatly increase water drainage from under the tire.

The use of air jets (Fig. 13) placed in front of aircraft tires to remove standing water on the pavement by means of an air blast also shows promise. Preliminary studies have been performed on automobile tires, aircraft tires, and full-scale aircraft. The results of these studies indicate that air jets are effective in removing standing water from the front of the tire and substantially increase tire traction on flooded textured pavements.

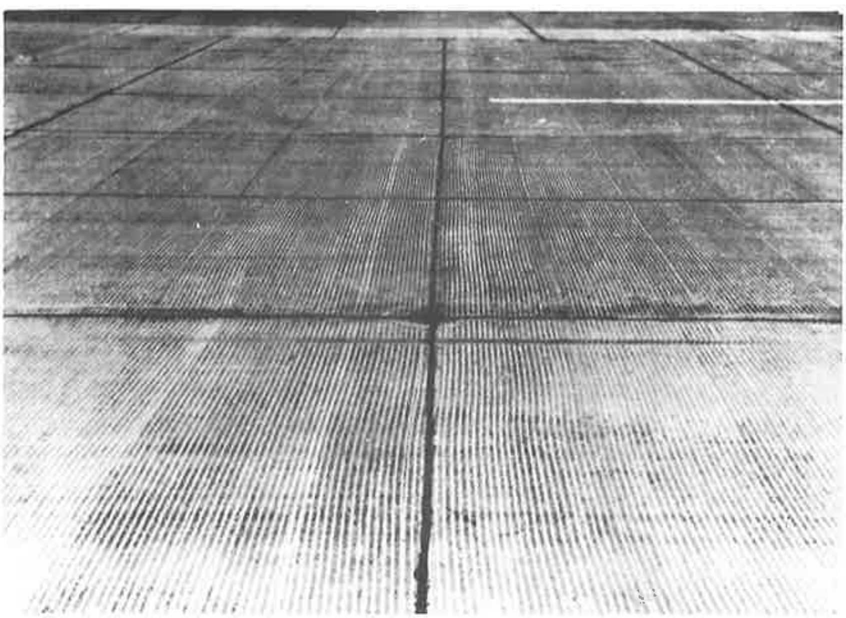


Figure 11. English grooved concrete runway (transverse grooves $\frac{1}{8}$ in. x $\frac{1}{8}$ in. on inch centers).

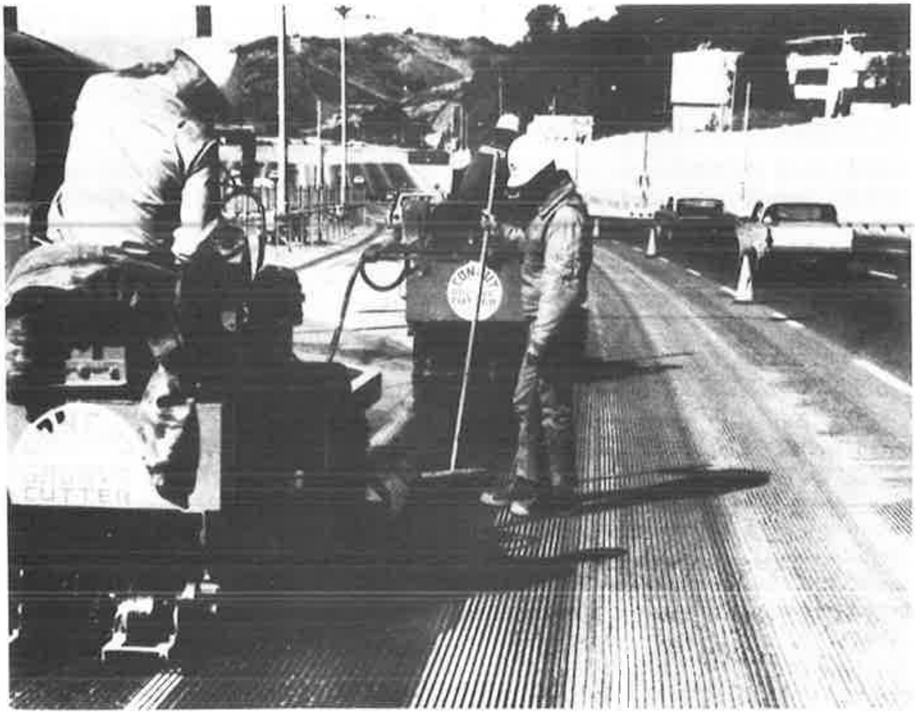


Figure 12. Longitudinal grooving—California highway.

Steam Pressures Predominating—Reverted Rubber Skid

Available results indicate that the extremely hazardous reverted rubber skid condition can be eliminated by preventing the tires from locking up. In this regard, the fact that many different aircraft equipped with anti-skid devices have suffered reverted rubber skid-type accidents points to the need for improving these devices for operation under low tire-ground friction conditions. At the present time, the only means

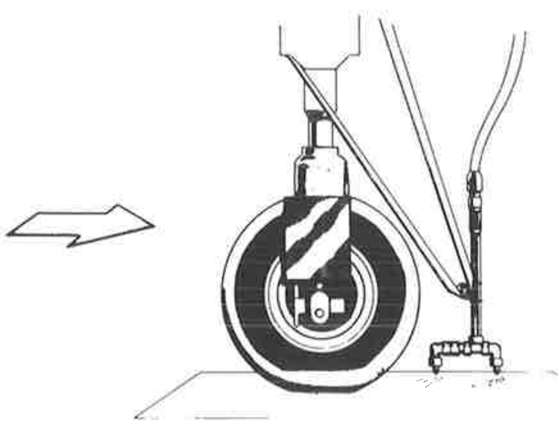


Figure 13. Arrangement of air jets.

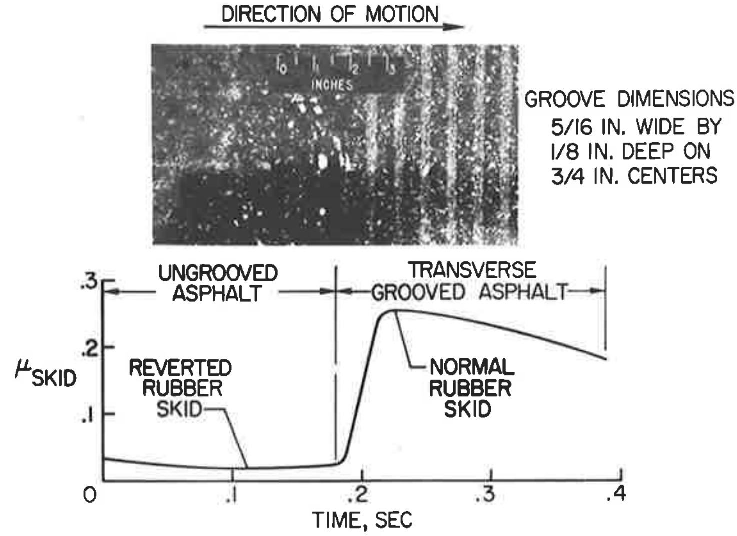


Figure 14. Effect of transverse grooves on reverted rubber skid (32 x 8.8 aircraft tire; ground speed = 77 knots; F_z = 16,000 lb; p = 250 psi; water depth = 0.1 to 0.2 in.).

known to alleviate the low friction conditions produced by a reverted rubber skid once it has fully developed on a tire is to substantially increase the effective pavement texture, such as by transverse pavement grooving. The effectiveness of pavement grooving in the alleviation of the reverted rubber skid condition is well demonstrated by comparing the friction coefficients for grooved and ungrooved asphalt shown in Figure 14.

CONCLUDING REMARKS

The research results described in this paper point out several tire, pavement, and vehicle operating conditions under which both aircraft and ground vehicle safety during operation on wet pavements are greatly degraded. The more important of these are the smooth or badly worn tire, pavements initially provided with too little texture or worn smooth or polished from traffic, the locked-wheel skid, and driver-pilot technique.

If highway safety is to be improved, then:

1. Smooth tire and smooth-acting pavements must be identified and rejected for vehicle and highway usage. For example, operation on highways with smooth tires can be controlled or prohibited as is presently being done in the State of New York and several European countries. Criteria and evaluation techniques are vitally needed to detect surfaces which are potentially slippery when wet so that the surface can be renovated by pavement grooving, surface additives, or resurfacing before skidding accidents start to occur.

2. Efforts should be made to reduce the catastrophic losses in tire cornering and braking ability that occur during partial or complete locked-wheel skids. Driver education can help in this regard, but the need to incorporate effective anti-skid or anti-wheel-locking devices in vehicle braking systems is clear.

3. It is believed that an educational program to alert the automotive public to important hazards of wet road driving will substantially reduce skidding accidents and improve safety.

Measuring Tire Friction Under Slip With the Penn State Road Friction Tester

HERBERT DOMANDL, Research Associate in Mechanical Engineering, and
W. E. MEYER, Professor of Mechanical Engineering, Automotive Safety Research Program, Pennsylvania State University

Skid resistance measurements remain the most practical method for characterizing the frictional properties of highway pavements. Friction measurements with tires operating under slip are, however, needed for research purposes. The adaptation of the Penn State road friction tester, which was originally designed for measuring skid resistance with a full-scale tire, to the measurements of tire-pavement friction under slip is described. The method employed consists in gradually retarding the test wheel by an adjustable brake actuating system and measuring the forces in both horizontal arms of the test wheel parallelogram suspension. By electric addition of these forces and measuring vehicle speed and test wheel velocity the complete friction vs slip relationship of an individual test cycle is obtained.

•FRICTION studies of the tire-road interaction are essential to a better understanding of what happens to a vehicle in certain maneuvers. Experimental approaches under real road conditions are a necessary supplement to laboratory investigations and theoretical studies.

Friction is usually described by its coefficient, that is, the ratio of the friction force to the load of the bodies sliding on each other. The friction force in the tire-road contact area is highly dependent on a variety of factors, particularly temperature, sliding speed, surface texture and rubber composition, making its reliable and reproducible measurement rather difficult.

The friction forces measured at the tire-road interface give information about the performance of the tire and about the frictional properties of the pavement under stated conditions. This paper is concerned primarily with the latter use of tire-pavement friction data and therefore tire variables will not be considered.

SKID RESISTANCE

The simplest approach to the study of the frictional properties of the tire-road interface is to lock the tire and measure the friction force developed by the skidding tire. This procedure is used by highway departments to survey the frictional characteristics of pavements for the purpose of monitoring the condition of surface courses, scheduling resurfacing operations, etc. A standardized method for this purpose is available as ASTM Method E 274.

This test, however, simulates the frictional behavior of a pavement as it is seen by a skidding vehicle, a mode of operation which should be avoided at all cost because no control can be exercised over the directional movement of the vehicle while the tires are locked. It is preferable that the tire, when braking, driving or cornering

Paper sponsored by Committee on Surface Properties—Vehicle Interaction and presented at the 47th Annual Meeting.

forces are applied to it, continue to roll. Under these conditions, the tire is said to operate under slip because a certain amount of sliding is superimposed on the rolling mode whenever the tire transmits a force. As long as the tire only slips, directional control is maintained, and greater forces can be developed as well.

FRICTION UNDER SLIP

From theory and experiments, we know that the coefficient of friction of tire operating under slip is highly dependent on the amount of slip and that the maximum coefficient occurs at about 10 to 20 percent (the "critical slip"). The ratio between the coefficients at critical slip and during skidding is not constant, but depends on texture and microroughness of the surface and other factors. The relation between slip and skid coefficients and the processes controlling them are discussed in detail by Kummer and Meyer (1).

It is not the intent of the authors to promote at this time the measurement of slip resistance as a means of characterizing pavements for the purposes of the highway engineer. It is arguable that skid resistance is more significant from the safety standpoint than slip resistance, on the grounds that it is most important that a vehicle come to the quickest possible stop once it is out of control. On the other hand, one can take the stand that the critical slip resistance is more important because it defines the point up to which the vehicle will remain under control. Be this as it may, the purpose of this paper is to describe an apparatus for the measurement of tire-pavement friction under slip to enable us to carry out research to determine, among other things, the relationship between skid resistance and slip resistance.

Measuring Friction Under Slip

Several approaches to the measurement of tire friction under slip are possible and were considered. The method chosen simulates in the most realistic way the transient behavior of a braking tire and has the further advantage that it could be applied to our existing tester (2) with a minimum of changes. The chosen method has the additional advantage of fairly straight-forward conditions in the tire-pavement contact area. Therefore it is particularly suitable for research purposes.

Basically, the method consists in decelerating the test tire at a controlled rate and measuring friction force and slip during this process. A rapidly responding measuring and recording system is required. In this manner the friction coefficient over the entire slip range can be obtained from a single test cycle.

The Penn State Road Friction Tester as a Slip Tester

The concept described has been used to convert the Penn State road friction tester (1) from a skid into a slip tester. The tester, whose design dates back to 1958 (3), was built with some thought to its eventual adaptation to other studies on tire-road interaction than those concerned with skidding tires. Several changes and improvements have been made in the intervening years, but these did not change its operating mode or performance (4).

As a skid tester it has been used during the past four years by the Pennsylvania Department of Highways for regular pavement surveys throughout the state and by the University for research purposes. Its performance compares favorably with that of other testers (5).

DESIGN CRITERIA

All measurements should be direct to avoid errors and accuracy losses through computation or the application of corrections. It should be possible to calibrate the measuring system statically in order to keep the calibration procedure simple and permit frequent checks.

In keeping with the objective of creating a research tool, easy modification of the test cycle should be possible. This means that one should be able to modify the rate of brake application as well as alter the point at which the brake is released.

Figure 1a. The Penn State road friction tester.

The instrumentation system should allow measurement at normal travel speeds on all highways. All sensitive components should be protected against the environmental hazards to which they might be exposed on the road. The system should give meaningful data of adequate accuracy without making the equipment more sophisticated or expensive than absolutely necessary.

Basic Design

The Penn State road friction tester (1) consists of a $^3/_4$-ton truck as the towing vehicle with a single-wheel trailer attached to it (Fig. 1). The vehicle carries a 250-gal tank and a pump to deposit a film of water in front of the test wheel. The engine drives an air compressor and an oversize 12 VDC generator which through a 550 W inverter provides 115 VAC cycle power to the instruments.

Trailer Design

The heart of the tester is the trailer. Since it is of the single-wheel type it can be attached to a crossbeam at the rear of the towing truck in any desired relation to the

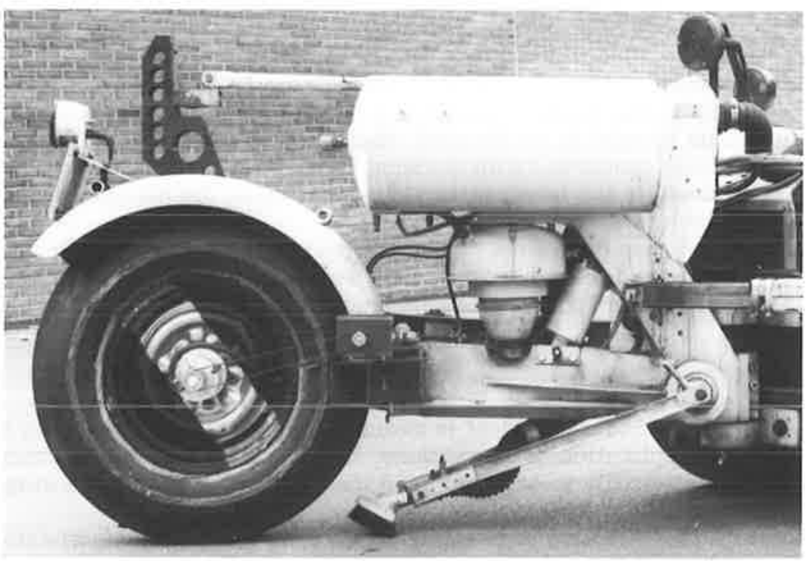


Figure 1b. The trailer with test wheel.

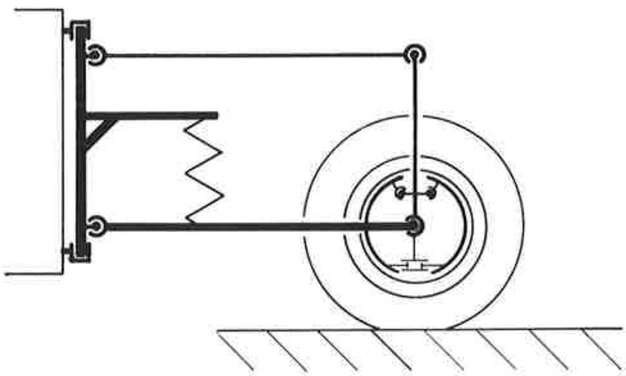


Figure 2. Trailer principle.

towing vehicle. The truck can therefore travel in the normal manner in a traffic lane, but measurements can be made in either wheel track or between them by changing the point of attachment of the trailer. The trailer consists basically of a wheel with brake, suspended on a horizontal arm pivoted to the towing vehicle and loaded through a spring abutting against the vehicle structure (Fig. 2). The spring, in effect, transfers part of the towing vehicle weight to the test wheel. By using an air spring the test wheel loading can be changed from the cab while the vehicle is in motion.

When the test wheel brake is applied, the friction force developed between tire and pavement produces a reaction torque at the brake. The brake mounting plate is free to rotate on the wheel axis, but is restrained by the upper horizontal arm pivoted vertically above the pivot of the main arm (Fig. 2). The suspension arm and the restraining arm are so dimensioned and attached that they form the long sides of a parallelogram.

The Test Wheel in the Slip Mode

When the brake is so applied that the wheel does not lock, the wheel will rotate at a lower velocity than that of free rolling. We say that the wheel operates with "slip." Slip is usually given as a percentage, obtained in the present case as

$$s = \frac{V-R\omega}{V} \times 100 \quad (1)$$

where (with consistent units)

V = vehicle speed
R = effective tire radius (see Fig. 3)
ω = angular velocity of the test wheel

The coefficient of friction is

$$f = \frac{F}{W} \quad (2)$$

where (Fig. 3)

F = force at the tire-pavement interface
W = vertical load on the test wheel

Instead of coefficient the somewhat more convenient term "friction number" may be used:

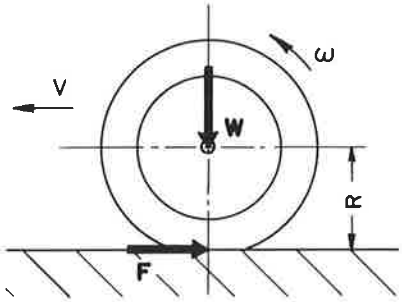


Figure 3. Forces acting on the test wheel.

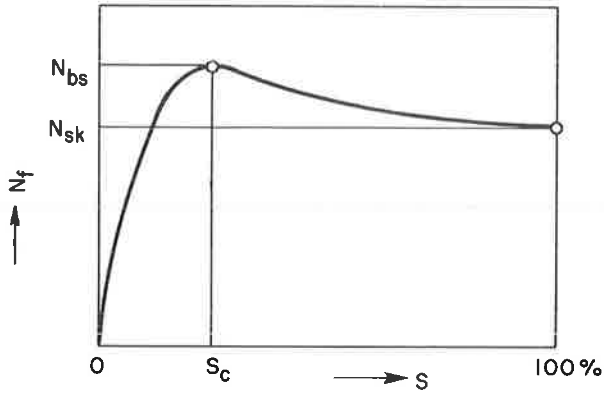


Figure 4. Friction number vs slip.

$$N_f = 100f = 100\frac{F}{W} \quad (3)$$

A dictionary definition of "coefficient" states that "it is an unchanging ratio measuring some given effect or property in given conditions." In the case of tire-pavement friction, the description of the "given conditions" would be quite lengthy. To circumvent this problem one can agree on a set of conditions as they are specified in ASTM Method E 274 for the case of the locked wheel (100 percent slip) by defining the conditions under which the skid number N_{sk} is to be measured. Slip (brake or drive slip) numbers can be defined similarly. For the present purpose the maximum friction coefficient which occurs at slip s_c (the critical slip) will be called the brake slip number N_{bs} (Fig. 4). Except for the fact that the wheel is operating in the slip mode, the conditions of ASTM Method E 274 apply.

MEASUREMENT OF TIRE-PAVEMENT FRICTION

According to Eq. 2 the friction coefficient is proportional to the friction force as long as load W is constant. To obtain F any reaction force proportional to it may be measured. Under transient conditions, however, all reaction-forces in the parallelogram also contain a certain amount of inertia forces due to the deceleration or acceleration of the test wheel. Their effect can be neutralized by summing the forces in the two horizontal links of the parallelogram (Fig. 5):

$$D = \frac{I}{e}\frac{d\omega}{dt} + \frac{R}{e}F + \frac{x}{e}W \quad (4)$$

$$E = -\frac{I}{e}\frac{d\omega}{dt} - \left(1 + \frac{R}{e}\right)F - \frac{x}{e}W \quad (5)$$

where

- I = moment of inertia of the rotating masses
- e = length of the brake torque arm
- t = time
- x = displacement of the tire footprint center due to F relative to its static location

By addition:

$$E + D = -F \quad (6)$$

As can be seen from Eq. 6, all influences due to pure moments and purely vertical forces on the measured friction force are automatically eliminated.

This means that by measuring the forces acting along the axes of the two arms the force at the tire interface can be obtained by simple summation and without regard to changes in wheel inertia or deceleration. Thus by decelerating the wheel a record of instantaneous slip and of the corresponding friction force (or coefficient of friction or friction number, if the wheel load remains constant) can be obtained without complex data processing.

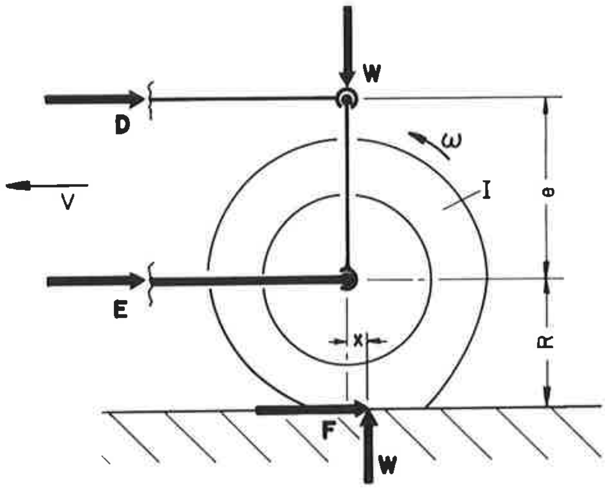


Figure 5. Forces on the trailer.

Measuring System

To measure the friction force F (or the friction coefficient) directly as the sum of forces E and D in the horizontal links of the trailer without additional computation, transducers of equal sensitivity are necessary. The main arm itself is used as mechanical part of the transducer for force E (Fig. 6) by measuring with strain gages attached to it the bending moment acting on it in its horizontal plane. This moment is due to the offset which puts the suspension arm pivot in the wheel plane. The gages are placed in the horizontal neutral plane of the main arm as close to the test wheel as possible to minimize influences from incidental side forces. To obtain maximum sensitivity the cross section of the main arm has been reduced as much as strength considerations permit.

Force D in the upper horizontal restraining link is also measured by strain gages. They are bonded to the tension side of a bar in which D induces a bending moment due to its offset to the neutral plane of the bar (Fig. 6). The offset can be adjusted to give the transducer the same sensitivity as the main arm has. Both strain gage bridges are combined to form a single one in such a way that the combined output is now directly proportional to the sum of the two forces and therefore to the friction force F. The bridge is operated with a carrier frequency of 20 kc and the output is amplified and recorded by a dry-writing Century Model 444 oscillograph.

The latter also records the output of a track wheel driven DC generator to indicate the vehicle speed (which is kept constant during a test). In addition, the test wheel speed is recorded. The wheel drives an impulse generator which produces 100 pulses per revolution. The output frequency, which is proportional to the angular velocity of the test wheel, is fed through a frequency-to-analog converter and an amplifier to the oscillograph.

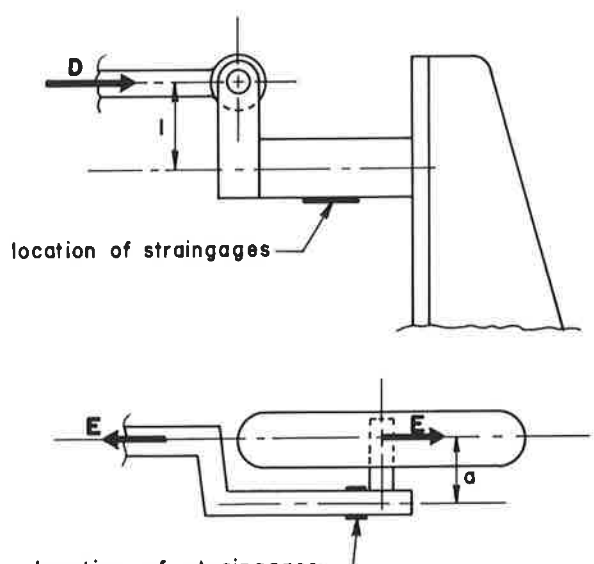


Figure 6. Force measurement.

TEST CYCLE CONTROL

The test wheel brake is a standard automotive hydraulic drum brake. The hydraulic system is pressurized by a pneumatic booster (2). Pneumatic system pressure is admitted to the booster by a solenoid valve which is controlled from the cab. By inserting an adjustable throttling valve in series with the solenoid valve the rate of brake application can be controlled and thereby the rate of increase of the slip.

When the critical slip has been reached, the friction force will be at its maximum. The brake force continues to increase, but the friction force decreases. The test wheel goes rapidly to 100 percent slip. Operating the wheel in the locked condition for any length of time may be undesirable, at least on high-friction surfaces, because it can cause tire flat-spotting. Flat spots would introduce noise into the force signal.

To control wheel lock, either limiting it to a predetermined period of time or preventing it altogether, the signal from the test wheel driven impulse generator is used to de-energize the brake system solenoid. This causes the brake to be released.

Several modes of operation can be achieved:

1. The brake can be actuated by a cycle timer at constant time intervals and be released automatically by the control system or the cycle timer.
2. The release signal can act as an override. In this case, the brake is actuated each time the test wheel speed increases above the setting point of the release control. Because of time delay in the control system and with a corresponding setting of the release point, the test wheel can be made to run up completely between individual test cycles. If only the friction at the critical slip is to be determined the release point can be so adjusted that complete spin-up does not occur.
3. Manual actuation and release is, of course, possible at any time.

For skid testing, the brake release can be bypassed. This permits the test wheel to be held in the locked condition until equilibrium at the tire-pavement interface has been attained. Thus the tester can be used to make skid-resistance measurements in accordance with ASTM Method E 274.

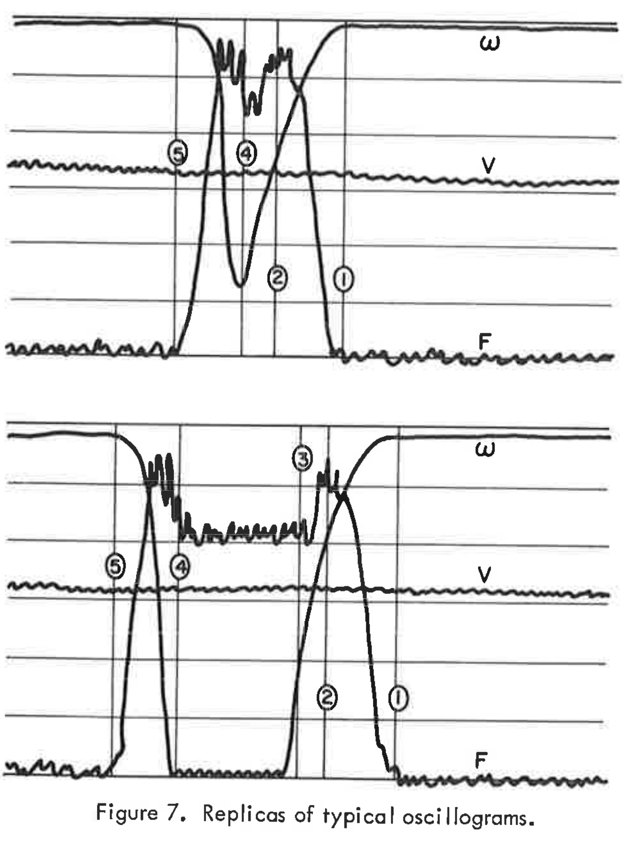


Figure 7. Replicas of typical oscillograms.

CALIBRATION

The static calibration procedures for wheel load and friction force used with the skid-resistance measurements are still applicable (2). To determine whether or not the indicated force is independent of wheel deceleration the wheel is raised off the ground—a lift cylinder which is a permanent part of the tester (2) makes this a simple matter—and with the vehicle at rest the test wheel is spun up by suitable means. The wheel is then permitted to run free and the brake is applied. No force signal should be generated as the wheel is decelerated.

Vehicle and test wheel speed are calibrated by driving a known distance at constant speed and measuring the time needed to traverse this distance.

TYPICAL RESULTS

In Figure 7 two typical oscillograms are reproduced. They are to be read from right to left. Vehicle speed, V, test wheel angular velocity, ω, and friction force, F, are recorded.

At point 1 brake application begins: the test wheel velocity begins to decrease slowly and the friction force increases. At point 2 the critical slip has been reached: the friction force is at its maximum. The test wheel velocity now decreases rapidly and the friction force decreases again.

At point 3 in the lower oscillogram, the test wheel velocity has become zero: the wheel is locked and the tire slides along the pavement. At point 4 dumping of the air from the brake application system allows the test wheel to spin up again. In the upper oscillogram this occurs before the wheel has come to a full stop. At point 5 the test wheel has regained its original velocity. The vehicle speed has remained constant throughout the cycle.

Scales are not given in Figure 7 for any of the variables because the intent is to show the results which are typically obtained. By filtering, most of the noise can be eliminated from the recorded signals. Since, however, a transient process is being recorded, filtering must be used with caution to prevent erroneous results. In skid testing there is, of course, no such limitation.

CONCLUSION

Although only a limited number of tests have been made so far, it is evident that the adaptation of the Penn State road friction tester to the measurement of tire-pavement friction in transient slip has been successful.

The conversion will be useful in many aspects of tire-pavement friction research where laboratory and theoretical studies require verification under real road conditions. The data which we are planning to obtain will also clarify how skid number and brake slip number are related (1) and to what extent the one can serve in the place of the other where safety is concerned.

ACKNOWLEDGMENTS

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Preliminary Report on Skid Resistance of Linseed Oil-Coated Concrete

W. L. KUBIE, L. E. GAST and J. C. COWAN, Northern Regional Research Laboratory, U. S. Department of Agriculture, Peoria, Illinois

•ANYONE who has read the American Society for Testing and Materials (ASTM) Special Technical Publication No. 366 (1) knows that there are many ways to measure skid resistance of road surfaces. Data are comparatively easy to collect, but their interpretation is sometimes difficult. During the past several years, we have collected data and gained some information and experience in coating concrete with linseed oil and in measuring skid resistance. A coating of linseed oil properly applied imparts resistance to freeze-thaw cycles and to salt for both air- and nonair-entrained concrete made with portland cement. Our studies on the skid resistance of the linseed oil-coated concrete are reported in this preliminary paper.

Initially, we undertook studies on our own parking lot with a static tester and, later, with a British portable (BP) tester (2). In 1966 and 1967, we arranged with Districts 3 and 4, Illinois Division of Highways, to carry out skid-resistance tests with the BP tester. Attempts to coordinate our testing with the BP tester, and testing with the Portland Cement Association (PCA) trailer on suitably oiled areas, were successful for only a limited period in 1967. Although these tests are preliminary in nature, we believe that a report of our findings will guide others working with linseed oil as a coating for concrete.

EXPERIMENTAL

Materials and Methods

Compounds used were the National Flaxseed Processor Association (NFPA) anti-spalling compound and a linseed oil emulsion developed at the Northern Laboratory (NU). The NFPA compound contains equal volumes of boiled linseed oil and mineral spirits (3). The NU emulsion compound is prepared from equal volumes of soil and water mixtures (4). The emulsion contains 50 volume percent of a mixture containing 97 percent of boiled linseed oil and 3 percent of saturated tallow alcohols and 50 volume percent of a water phase containing 0. 37 percent sodium hydroxide and 0. 03 percent dipicolinic acid and water 99. 6 percent (by weight). Characteristics of the NFPA solution and the NU emulsion are given in Table 1.

Application of Coating

The NFPA and NU compounds were applied by several procedures: paint brush for small areas, portable spray tank for somewhat larger areas, and spray bar rigs mounted behind trucks for bridges and roadways.

When a brush was used on squares on a closed section on an Interstate road, the compound was measured out for a given area and applied much in the same manner as painting. A 3-in. pig bristle brush of good quality was used. A DeVilbiss[1] MBC paint

[1]Mention of firm names or trade products is made for information only and does not constitute endorsement by the U. S. Department of Agriculture over other firms or similar products not mentioned.

Paper sponsored by Committee on Surface Properties—Vehicle Interaction and presented at the 47th Annual Meeting.

TABLE 1
CHARACTERISTICS OF LINSEED OIL "COMPOUNDS"*

Property	NFPA Solution	NU Emulsion
Pounds of oil per gallon	3.85	3.85
Density		
Grams per cc	0.854	0.958
Pounds per gallon	7.12	7.98
Viscosity (Brookfield at 25 C, 60 rpm)	9	11
pH	—	11.5

*NFPA = National Flaxseed Processors Association.
NU = Northern Regional Research Laboratory.

sprayer was used on our north parking lot and sidewalks. This portable sprayer operates satisfactorily with both NFPA and NU compounds at 35 to 40-psi air pressure. A measured amount of material was sprayed over a given area.

Bridges and roadways were coated with spray bar rigs mounted on small carriage wheels behind trucks. The rigs varied from location to location. Width of spraying bar varied from 6 ft to ones that covered one lane on an Interstate bridge including gutter and sidewalks. Compound was sucked by gear pump from a 55-gal drum mounted on the truck. Some rigs had wind shields on each side of bar, but others did not. The pumps usually supplied the material to the spray rig at about 40 psi.

The sand used in these tests was furnished by the State and passed their specifications for fine aggregate. The fly ash was furnished by the Chicago Fly Ash Company. Sand and fly ash were spread on test squares from different hand shakers specifically made for the purpose. Sand was spread on bridges by a workman standing on a truck and throwing the sand from a shovel in an arc.

Generally, the NFPA compound and our NU emulsion were applied to previously uncoated areas at the rate of 0.025 gal per sq yd and then at the rate of 0.015 gal per sq yd for a total oiling of 0.04 gal per sq yd or approximately 0.16 lb of oil per sq yd. Additional information on the procedures for oiling is given elsewhere (3-8).

Measurement of Friction

The coefficient of friction between rubber and concrete was determined in selected areas of the NU parking lot by drawing a box over the surface by means of weights and pulleys (static tester). The bottom of the box was covered with a piece of gasket rubber ¼ in. thick, 5¼ in. wide, and 8 in. long. Coefficients were measured at 16 different places in each area (four times at each of four weights). The weight of the box empty was 666 g; with added weights, it was 1,166, 1,666, and 2,166 g. Measurements were made before and after wetting the surfaces with a thin film of water.

Measurements were also made with a BP tester (2), developed by the British Road Research Laboratory. It is a pendulum instrument. All measurements were made with a British rubber pad. Each value reported in this paper represents an average of at least five determinations, sometimes 10 or more.

The PCA trailer was used in a few tests. This trailer, described in Dillard and Mahone's monograph (1), measures the drawbar pull with both wheels locked. During some tests on dry but coated concrete about 2 to 4 hr after oiling, it was necessary to adjust the brakes because the load at 40 mph was too great for the brakes to hold.

The values reported by all three methods are the coefficient of friction multiplied by 100.

DISCUSSION AND RESULTS

Previous reports (3-8) show that linseed oil in mineral spirits and linseed oil emulsions soak rapidly into concrete. How much oil concrete can absorb depends on a number of factors. Among these are roughness of the concrete and previous treatments of the surface. Smooth, highly troweled surfaces absorb much less than rough, broomed surfaces. Often previously oiled surfaces will absorb less than unoiled. Older concrete appears to absorb less oil than new concrete.

Since we knew that concrete improperly or freshly coated with linseed oil can be slippery, we determined the skid resistance of coated concrete that had weathered for a considerable period. Sections of our north parking area at NU were selected for these tests since coated and uncoated areas were available. Two to three years after

TABLE 2

SKID RESISTANCE OF COATED CONCRETE AFTER AGING VALUES AS COEFFICIENT OF FRICTION TIMES 100

NU Parking Lot	Static Tester		BP Tester[a]	
	Dry	Wet	Dry	Wet
Coating 1 NFPA compound[b]	111	95	100	80
Coating 1 NU emulsion	101	92	104	80
Coating 2 NFPA compound[c]	100	92	101	78
Coating 2 NU emulsion	97	90	98	72
Control—uncoated	96	91	108	80

[a]British portable tester.
[b]Coating 1: One coat of linseed oil compound or emulsion at the total oil rate of 0.16 lb per sq yd.
[c]Coating 2: Two coats of linseed oil compound or emulsion at a total oil rate of 0.16 lb per sq yd.

oiling the skid resistance of the coated and uncoated areas was approximately equal (Table 2).

Visual examination of the surfaces suggests that the differences in friction values within the same test procedure are probably caused by differences in the roughness of the concrete and not by any effect of the oil. This observation is true whether measured by the static or BP tester.

Standards of skid resistance for the BP tester are values suggested by the Road Research Laboratory (2). A summary of these standards is given in Table 3.

In another series of tests, four bridges on Illinois Interstate highways were evaluated. Two were tested 6 months and 2 years, respectively, after oiling. The other two bridges had been oiled three times at 2, 3, and 5 years before the test. Data given in Table 4 show that values from the BP tester were high when the bridge decking was dry. When it was wet, bridge 1 rated "good," bridge 2 rated well above "generally satisfactory," bridge 3 was just below "generally satisfactory," and bridge 4 values were slightly lower. No bridge was potentially slippery by the suggested standards. On bridges 3 and 4, we were able to obtain data with the BP tester and the PCA trailer. The values agree well with each other although the PCA trailer gave somewhat higher values in the tests.

These data indicate that properly applied linseed oil has no long-term effect on lowering the skid resistance of concrete below standards set by the Road Research Laboratory. All areas tested in this report would be classified as easy sites.

Initial Coatings on Roadways and Bridges

Three areas were coated and tested. None had received any previous oil coating. Two areas (bridge 5 and roadway) were open to construction traffic only, but the third

TABLE 3

SUGGESTED VALUES OF SKID RESISTANCE FOR USE WITH THE BRITISH PORTABLE TESTER

Category	Type of Site	Skid Resistance on Wet Surface	Standard of Skid Resistance Represented
A	Most difficult sites, such as: a. Roundabouts (cloverleaves) b. Bends with radius less than 500 ft on nonrestricted roads c. Gradients, 1 in 20 or steeper, of length greater than 100 yd d. Approach to traffic lights on derestricted roads	Above 65	"Good"—fulfilling the requirements even of fast traffic, and making it most unlikely that the road will be the scene of repeated skidding accidents
B*	General requirements, i.e., roads and conditions not covered by categories A and C	Above 55	"Generally satisfactory"—meeting all but the most difficult conditions encountered on roads
C*	Easy sites, e.g., straight roads with easy gradients and curves, and without junctions, and free from any features, such as mixed traffic, especially liable to create conditions of emergency	Above 45	"Satisfactory only in favorable circumstances"
D	All sites	Below 45	"Potentially slippery"

*On smooth-looking or fine-textured roads in these categories, vehicles having smooth tires may not find the skid resistance adequate. For such roads, accident studies should also be made to ensure that there are no indications of difficulties due to skidding under wet conditions. All tests were made in wheel trace areas.

TABLE 4

SKID RESISTANCE OF AGED AREAS—BRIDGES ON INTERSTATE

Bridge	BP Tester		PCA* Trailer	Remarks
	Dry	Wet	Wet	
1	95	72		6 months after oiling
2	104	62		2 years after oiling
3	111	54	61	Oiled 2, 3, and 5 years before test
4	114	51	56	Oiled 2, 3, and 5 years before test

*Portland Cement Association.

(bridge 6) was open to traffic. Some of the collected data are given in Table 5. If a limited area is coated with oil, traffic appears to transfer some oil not absorbed by the concrete to the road beyond.

All three areas were potentially slippery immediately after oiling. Where oil was absorbed slowly but the road was open to traffic, the concrete recovered to the initial dry skid resistance within 3 hr and to the initial wet values within 24 hr. At 3 hr the wet values were low but still acceptable by the criteria of the British Road Research Laboratory. Bridge 5 recovered to a "generally satisfactory" rating within 3 hr. With little traffic complete recovery required some time—between 3 days and 2 months, but no data are available within this period. Bridge 6 recovered to "satisfactory under favorable conditions" in 3 hr and to original wet skid resistance in 1 day. The roadway with no traffic recovered slower than the other two areas. It was coated at 40 F. Neither the roadway nor bridge 5 was open to traffic until after wet values for skid resistance had returned to initial values.

Reoiling of Concrete

Reoiling concrete can be done without substantially lowering skid resistance, except for a rather short period after the reoiling. This period varies (Table 6). Again, the amount of applied oil and the traffic conditions appear to be factors in the rate of recovery. The recovery to initial dry skid-resistance values occurred in less than 4 hr. The wet values obtained with the BP tester showed that all three areas recovered to initial values within 24 hr. Bridge 2 received less linseed oil than bridges 3 and 4 and recovered to higher BP test values quicker. Bridge 2 had sanded and unsanded areas. The unsanded areas recovered to initial values of wet skid resistance within 2.5 hr. All three bridges showed some transfer of oil by traffic to the road beyond. Wet test values with the PCA trailer for bridges 3 and 4 were low at 3 to 4 hr and did not return to initial values in 23 hr, although at this time they were approaching initial values. Additional wet tests with the PCA trailer were not feasible then because it was needed

TABLE 5

SKID RESISTANCE OF FRESHLY OILED CONCRETE—BP TESTER VALUES

Area	Before Oiling	Within 30 Min	After 3 Hr	After 3 Days	Subsequent Tests	
					Values	Days
Bridge 5[a]:						
Dry	97	42	102	99	96	60
Wet	76	—	58	60	79	60
Bridge 6[b]:						
Dry	103	38	114	114	117	7
Wet	62	—	46	60	62	7
Roadway[c]:						
Dry	97	35	77	100	—	—
Wet	76	—	52	63	78	19

[a]Bridge was not open to traffic immediately before or after oiling. New road. Two coats of compound at total rate of 0.04 gal per sq yd. Open to construction traffic. No data available between 3 and 60 days.

[b]Bridge was 13 years old. Bridge open to traffic. Oil absorbed slowly. Value at 1 day—wet skid resistance was 63. Two coats at the total rate of 0.04 gal per sq yd.

[c]Roadway was laid same year as oiling. Not open to traffic. Oil applied in two coats at a total rate of 0.04 gal per sq yd. Open to some construction traffic. No data available between 3 and 19 days.

TABLE 6

SKID RESISTANCE OF REOILED CONCRETE[a]

Area	Before Reoiling	Within 30 Min	After 3 to 4 Hr	After 22 to 24 Hr
Bridge 2:				
Dry (BP)	104	50	112	110
Wet (BP)	62	—	58	62[b]
Wet (BP)	58	(47 dry)	61	63[c]
Bridge 3:				
Dry (BP)	111	40	110	—
Dry (PCA)	—	40	68	—
Wet (BP)	54	—	49	55
Wet (PCA)	61	—	37	48
Bridge 4:				
Dry (BP)	114	31	99 (120 at 1.5 hr)	—
Dry (PCA)	—	35	57	—
Wet (BP)	51	—	44	55
Wet (PCA)	56	—	38	50

[a]All bridges were opened to traffic between tests. Linseed oil was applied in one coat at the rate of 0.027 gal per sq yd on bridge 2 and 0.03 gal per sq yd on bridges 3 and 4. Traffic on all bridges transferred some oil to road beyond bridge. Sand was used on parts of bridge 2. These bridges are the same ones reported in Table 4.
[b]Average of oil and sand.
[c]No sand applied.

elsewhere. The rate of change of the wet values between 4 and 24 hr was sufficient to predict that both bridges 3 and 4 would recover their original PCA values shortly.

Use of Abrasive Materials

Sand and other abrasive materials are sometimes used to reduce slipperiness of surfaces. Spreading an abrasive material serves two purposes: (a) it can absorb material on the road that may cause the slipperiness, and (b) it may increase the skid resistance of the surface. Tests were run on bridges that were open to traffic and on small squares closed to traffic (Table 7).

Results given in Table 7 do not show any particular merit in using sand to decrease the slipperiness of linseed oil-coated areas. Sand may assist in removing excess oil. Wet skid-resistance values for sanded areas 3 hr after application of the oil were lower than values for unsanded areas. At 24 hr and at 7 days, most of the sanded areas had recovered to the initial values. Almost all the sand was gone, and visual inspection showed that some oil was carried off or absorbed by the sand in the traffic areas, as well as the areas closed to traffic.

Fly ash in these limited tests does show an advantage at 3 and 24 hr after oiling compared to sand or oil alone. Recovery to original skid-resistance values was achieved. The fly ash darkens the concrete, and it might be objectionable for this reason.

Amount of Oil for Application

The amount of oil that should be applied to a specific area of concrete needs to be studied further. On concrete that has not been previously coated but has set for 28 to 30 days, 0.16 lb of oil per sq yd (0.04 gal of compound per sq yd in applications of 0.025 and 0.015 gal per sq yd) appears to be suitable. The finishing or other surface treatment can vary this amount. In an area finished with a trowel, the desirable

TABLE 7

USE OF ABRASIVE MATERIALS WITH LINSEED OIL—BP TESTER VALUES

Area[a]	Initial	Oil Only			Sanded			Fly Ash		
		3 Hr	24 Hr	7 Days	3 Hr	24 Hr	7 Days	3 Hr	24 Hr	7 Days
Bridge 2:										
Dry	104	112	110	108	112	111	109	—	—	—
Wet	62	61	63	63	57	61	61	—	—	—
Bridge 6:										
Dry	103	120	119	115	112	114	118	—	—	—
Wet	62	53	66	61	44	61	63	—	—	—
Roadway squares:										
Dry	85	92	108	103	81	100	96	74	90	101
Wet	64	56	49	55	63	52	57	65	61	62

[a]Bridges 2 and 6 were open to traffic. Roadway was not. Fly ash darkened the road area considerably. See Tables 5 and 6 for rates of oiling for bridges. Roadway was coated by brush at the total rate of 0.04 gal per sq yd of compound; square 3 X 3 ft were coated.

TABLE 8

EFFECT OF SURFACE TREATMENT ON SKID RESISTANCE VALUES—BP TESTER VALUES

Surface Treatment	Dry	Wet	Remarks
Trowel	76	60	Oil coated 2½ years before with 0.08 lb per sq yd
Broom:			
1	93	83	Oil cured 2½ years before
2	96	77	Oil cured 2½ years before
3	99	80	Wax resin cured 2½ years before
4	100	82	Uncoated
Burlap drag:			
1	108	80	NU parking lot, 3½ years old, uncoated
2	97	76	Interstate, uncoated

amount appears to be less than 0.08 lb of oil per sq yd. Attempts to coat troweled areas at NU with this amount gave slippery spots. Most areas finished with a broom or bag appear to absorb 0.16 lb per sq yd if given sufficient time. Troweled areas do not have as high skid resistance as broomed or burlap-dragged areas. The latter two appear to be about equal in skid resistance, as evidenced by data in Table 8.

Age of the concrete may also be a factor since studies showed that older concrete absorbs oil less rapidly than new concrete. For example, recovery from initial slipperiness was very rapid with our broom-finished NU sidewalks when they were new and initially coated with 0.16 lb per sq yd. When these sidewalks were 2.5 years old, previously uncoated areas were coated with the same amount and appeared slippery. They had not recovered their original skid resistance after 2 months; Table 9 gives BP tester values on the areas that received no previous treatment or were treated with wax resin. In the same table, note that the previously oil-cured sidewalks did recover to approximately the original high skid-resistance values when coated with 0.10 lb per sq yd. Slightly more, or 0.12 lb per sq yd, did not permit rapid recovery.

Rapid recovery was made with either reoiling or new oiling of old concrete where traffic transferred excess oil to the roadway beyond the area of application. Data in Table 10 for heavily traveled bridges 2, 3, and 6 show that 3 to 24 hr was sufficient for recovery to original wet values. Where traffic was light, more than 24 hr was required to attain skid-resistance values equal to the original values before oiling. Although the section of roadway had achieved BP tester values of 61 in 24 hr, which the Road Research Laboratory criteria consider "generally satisfactory," recovery to original skid-resistance values did not occur until sometime between 3 and 19 days.

Other factors may be involved in recovery of skid resistance, such as temperature of the concrete and air above it, wind velocities at and shortly after application of the oil, and dryness of the concrete. Some data related to the effect of temperature are given in Table 11. Note that the roadway had not recovered a dry skid resistance equal to the initial value within 3 hr, but it did recover original dry skid resistance in 19 hr. Procedures need to be developed for determining how much linseed oil should be applied under a given set of conditions, such as a specific concrete area, time permitted for absorption before the road is reopened to traffic when the road is dry, time permitted if the road becomes wet shortly after oiling, and how rapidly the oil is absorbed.

Precautionary safety measures should be taken when operations lead to conditions that are hazardous. The extent of these measures will depend on the conditions. Among

TABLE 9

EFFECT OF AMOUNT OF OIL ON SKID RESISTANCE VALUES—NU SIDEWALKS

Amount of Oil (lb/sq yd)	Wet BP Values		Previous Treatment
	Before Oiling	Two Months After Oiling	
0.16	82	58	None
0.16	80	57	Wax resin 2½ years before
0.10	83	78	Oil cured 2½ years before
0.12	77	58	Oil cured 2½ years before

TABLE 10

EFFECT OF THE AMOUNT OF OIL AND TRAFFIC CONDITIONS ON WET SKID RESISTANCE VALUES

Area	Amount of Oil (lb/sq yd)	Traffic Conditions	Before Oiling or Reoiling	Wet BP Tester Values, Time After Oiling		Subsequent Tests	
				3 Hr	24 Hr	Values	Days
Bridge 2	0.108 (reoiling)	Heavy (sand and no sand)	62	58	62	61	7
		Heavy (no sand)	58	61	63	63	7
Bridge 3	0.12 (previously oiled 3 times)	Heavy	54	49	55	—	—
Bridge 5	0.16 (new pavement, 6 months old)	Light	76	58	60 (3 days)	79	60
Bridge 6	0.16 (first oiling, old pavement)	Very heavy	62	46	63	62	7
Roadway	0.16 (new pavement, 2 months old)	Light	72	52	61	63	3
						79	19

TABLE 11

EFFECT OF TEMPERATURE ON RECOVERY OF DRY SKID RESISTANCE VALUES

Area	Original	After 30 Min	After 1 Hr	After 3 Hr	Temperature, F
Bridge 2	100	46	106	115	66
	105		100	112	
Bridge 5	97	42	—	102	100
Bridge 6	102	43	94	120	61
	103	36	54	116	
Roadway	97	35	—	77	40
				108 (19 hr)	

the more important factors are the amount of oil applied, the temperature of the road, the weather, the age, finish and previous coatings of the concrete, the extent of traffic and the nature of the road area. Highway officials should give consideration as to what the precautionary measures should be. Under ideal conditions, the concrete is slippery for a short period after application, usually less than an hour, and only slightly longer when the pavement is wet. When conditions are less than ideal, these periods of slipperiness as measured by the BP tester and the standards of the Road Research Laboratory are only slightly increased. The time to complete recovery of original skid resistance was extended for varying periods and depended on the conditions.

SUMMARY AND CONCLUSIONS

Linseed oil compounds can be applied to new, old, and previously oiled concrete, and a rapid recovery to original skid-resistance values can be achieved. In a number of tests, dry skid-resistance values were restored within 3 hr. At a low temperature of 40 F, recovery is delayed to sometime between 3 and 19 hr. Wet skid-resistance values on test bridges usually recovered to original values within 3 to 24 hr. Longer recovery times were encountered with wet skid resistances under certain conditions such as low temperatures and no traffic. Since it is possible for a variety of reasons to apply too much oil, highway officials need to consider precautionary measures to reduce hazards. If the road needs to be open to traffic as soon as possible, certain factors need to be considered before oiling: the amount of oil to be applied; extent and nature of area to be coated; temperature of the road; the event of rain; and the age, finish and previous coatings given to the concrete. Procedures that transfer oil from a coated area speed the return of skid-resistance values to original values. A test to determine capacity of concrete to absorb linseed oil compounds is needed.

ACKNOWLEDGMENTS

Appreciation is expressed to the Illinois Division of Highways, particularly to Districts 3 and 4 and to the Research and Development Section whose cooperation made this work possible. We also thank the Portland Cement Association, who loaned us a British portable tester and their skid trailer for some of our tests.

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A Progress Report on the Evaluation and Application Study of the General Motors Rapid Travel Road Profilometer

J. R. DARLINGTON and P. MILLIMAN,
Research Laboratory Section, Testing and Research Division,
Michigan Department of State Highways

This paper is primarily concerned with evaluation of accuracy, reliability, and applicability of the General Motors rapid travel profilometer (RTP) for highway purposes. Details of the measurement system itself are very limited, having been excellently covered in an earlier report by General Motors.

The report comprises four sections: theoretical and experimental accuracy, profile analysis methods, reliability and field experience, and a brief discussion of use of the RTP on Michigan projects.

Comparison study of RTP profiles and precise level survey profiles demonstrates RTP accuracy. Thousands of miles of use have proved the system to be rugged and consistently reliable. Furthermore, field experience has shown the system to be easily usable for determining the surface profile of any type of highway surface. In addition, the magnetic tape medium and FM format of recorded field data permits and facilitates electronic data processing machine computation.

The results and rationale of correlation studies between the RTP index and slope variance (CHLOE), and the RTP and a BPR-type roughometer, are presented and are considerably better than would be theoretically surmised. Also, the frequency reponse of the RTP is compared to various length rolling straightedges and to a BPR-type roughometer and is found greatly superior in this respect to either of these devices.

A considerable portion of the report is devoted to the various methods of profile analysis permitted by the device's output format. It lends itself to analog, digital, or hybrid processing. Power spectral density analysis is investigated and suggested as a superior method of profile analysis and presentation.

•IN February 1963, the Research Laboratory of the Michigan Department of State Highways submitted a proposal to the Bureau of Public Roads under the Highway Planning and Research Program to ". . . study, field evaluate, and determine the applicability to pavement and bridge surface roughness measurements, of the presently evolving (1963) General Motors Corporation, Rapid Travel Profilometer." The proposal was subsequently approved by the Bureau, and the Laboratory proceeded to procure the necessary components and to assemble a system identical to the GM unit.

At the time the proposal was submitted the GM device was still under development. Its evolution, however, had advanced sufficiently to indicate that it would prove to be the first practical, accurate, high-speed road profilometer.

Paper sponsored by Committee on Surface Properties—Vehicle Interaction and presented at the 47th Annual Meeting.

This report includes a very cursory description of the measurement system. The device was in existence prior to this study and has been adequately described by Spangler and Kelly (1), the GM personnel instrumental in its development. This report principally covers an evaluation of the system's profile measuring capabilities and its applicability to highway work.

In theory, the General Motors rapid travel profilometer (RTP) is capable of reproducing a surface profile while so-called rolling straigntedge profilometers, of any practical length, produce distorted profiles. The RTP represents a new concept in profilometry by utilizing inertial principles and hardware to establish its reference plane. Evaluation of this new instrument by the Department has confirmed its theoretical capability and demonstrated that it meets or exceeds expectations. In addition to obvious advantages such as accuracy, speed, and safety, the RTP provides many unexpected, but important, benefits. One example is the provision for adjustable profile filtering prior to power spectral analysis. Another is the flexibility in processing stored field data to enhance or attenuate specific profile features. Magnetic tape profile storage enables direct analog, digital, or hybrid processing and eliminates the need for manual data reduction. RTP attributes of greatest importance appear to be efficiency in use, faithful reproduction of all significant wavelengths, and data storage on magnetic tape.

Correlations obtained between the RTP and other profile devices are discussed and a short summary of RTP applications to Department problems is also included. Prior to presenting a final HRP report on this project to the Bureau of Public Roads, further study will be performed on system accuracy by computing the coherence functions between RTP profiles and closely sampled level profiles. Additional work will be necessary to derive other profile indexes from the RTP data.

Profiles and profilometers have traditionally been described in the spatial domain. In this domain, distance and elevation characterize profile features, while profilometers are usually described in dimensional terms (straightedge length, wheel size, etc.). Analysis of profiles, the RTP, and ride phenomena in general, is greatly facilitated in terms of the frequency domain. This is a viewpoint from which profilometers and vehicles are described by their response to road profile frequencies. Also in this domain, profiles are seen as complex signals with specific statistical properties. The profile's effect on ride can be analyzed by modern frequency domain techniques as explained by Marshall (2) and Bendat and Piersol (3). It will aid the reader to bear in mind the relationships between profile wavelength, vehicle speed, and frequencies induced in the vehicles. For example, a 20-ft wave traversed at 60 mph will produce a 4. 4-cps signal while the same wave traversed at 20 mph will produce a 1. 5-cps signal. This concept, though elementary, is important to an understanding of high-speed profilometry.

Figure 1. Michigan's GMR-type rapid travel profilometer.

RAPID TRAVEL PROFILOMETER

For the benefit of readers unfamiliar with the RTP, or as a review for those requiring it, a brief and greatly simplified system description is given.

Figure 1 shows Michigan's version of the General Motors RTP. The device is relatively simple. It consists of a small truck with a spring-loaded pavement follower wheel mounted underneath. An accelerometer is secured to the truck body at a point directly over a linear potentiometer which is connected between the follower-wheel axle and the vehicle body.

To obtain a surface profile, the system traverses the surface and during the run, potentiometer and accelerometer signals are recorded. If the accelerometer signal is then double integrated to produce a body displacement signal, and this displacement signal is summed algebraically with the potentiometer signal, the resulting signal will comprise the wheel movement, or the surface profile. This assumes, of course, that the accelerometer is linear and of correct frequency response, that all signals are properly scaled, and that the vehicle speed was not so great as to cause the wheel to leave the surface.

Also, at the option of the operator, it is feasible to perform the integration and summing functions as data are being sensed and then record only the profile signal. This approach, however, precludes any further processing with raw data signals and limits the flexibility of processing techniques. This matter will become clearer to the reader as he progresses further into the report.

GLOSSARY

Auto- and Cross-Correlation—These are statistical techniques, which show the correlation of signal amplitude with itself (auto-correlation), or with another signal (cross-correlation), for various distances along the signal.

Bandpass—The term bandpass, applied to a system, refers to its frequency response. Bandpass characteristics are often presented on a graph known as a Bode plot, showing those frequencies that are passed by the system and those which are attenuated or amplified. Such plots appear in Figure 2.

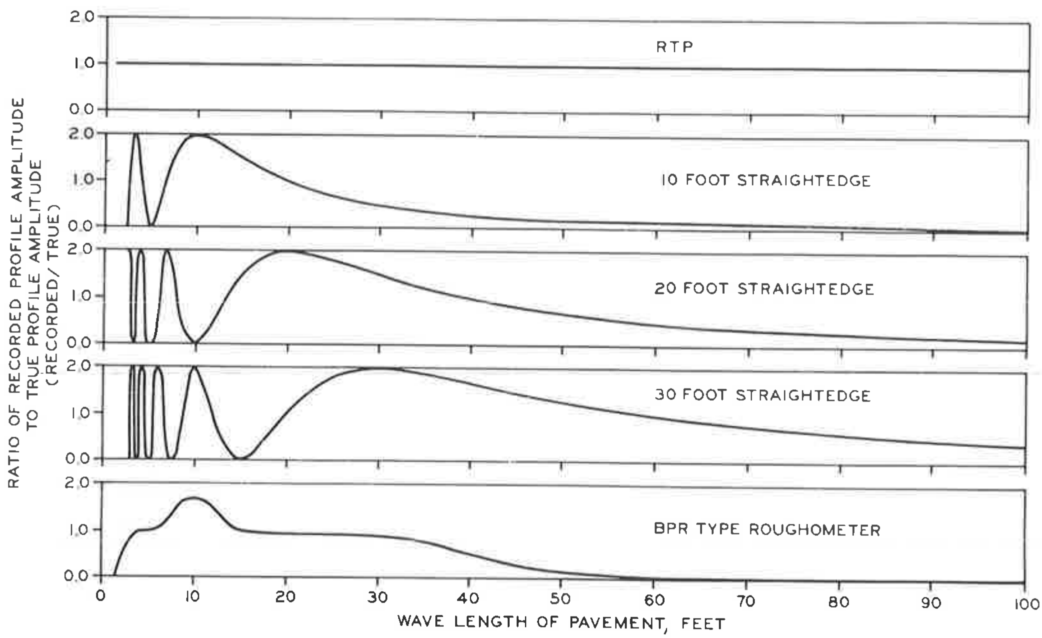


Figure 2. Theoretical differences between RTP, rolling straightedges, and seismic roughometers.

Coherence Function Analysis—A statistical technique that expresses correlation of two signals at all frequencies of interest. Such an analysis would indicate any frequencies not passed by the RTP but present in the precise level profile.

Cross Power Spectral Density Analysis—A technique similar to PSD analysis except that covariance between two signals is used instead of variance for one signal.

Filters—A filter is a process, device or electrical network designed to transmit, block or attenuate specific frequencies of any signal applied to the filter. Filtration used with the RTP can be described by linear, third-order differential equations; hence the terms linear, third order found in the text. Second-order filtration refers to second-order differential equations and so on. Each order implies a certain attenuation rate beyond the filter cutoff frequency, such as 60 db per frequency decade for the third-order filter. In addition to order, the filter type must also be specified. Highpass filters attenuate all frequencies below a certain value and pass all those above. Lowpass filters provide the opposite characteristic. Bandpass filters attenuate frequencies above and below given values and pass all frequencies between.

Filter Center Frequency—This phrase applies to bandpass filters and is that frequency upon which the filter is centered. A typical bandpass filter might be centered at 10 cps and pass all frequencies from 8 cps to 12 cps.

Hybrid Processing Systems—A data processing system consisting of linked analog and digital computers. Analog data can be fed into the analog section of the system from magnetic tape. These data can then be partially processed by analog techniques, such as filtration and simulation. Partially processed data are then moved to the digital section for further processing and digital printout.

Power Spectral Density—A statistical technique which breaks down the total amplitude variance (mean square value) of a signal into variance associated with any specific frequency or wavelength band. Thus, power spectral graphs show the amplitude densities for the wavelengths found in road profiles. A road found to be rough riding, for instance, would exhibit high-amplitude densities at wavelengths known to cause vehicle bounce.

Profiles

Road or Actual—The term road profile has reference to road surface elevation variations. It includes all elevation changes—small surface texture variations up through those changes caused by the curvature of the earth.

Precise Level—These are plots of elevations, obtained from road surfaces with a precise level, rod and target. For evaluation of the RTP, readings were taken at 1 to 5 ft intervals depending on rapidity of change in the surface. Values between the sampled elevations were estimated by simple linear interpolation.

Raw Profile—Refers to RTP transducer data consisting of accelerometer and follower-wheel potentiometer signals recorded on magnetic tape. These data are partially filtered by inherent limitations of the system and will be further filtered when processed by analog computer.

Computed or RTP Profiles—These are finished profiles computed from raw profile data. During this computation the investigator may remove any undesirable long-wave data such as that resulting from pavement design grades, vertical curves or earth curvature. Therefore, the term RTP profile normally means all road surface elevation changes up to some stated maximum wavelength of minimum frequency.

Resolution Bandwidth—Each value on a road profile PSD graph can be considered the result of "looking" at the profile through a narrow bandpass filter. The range of frequencies passed by this filter is called the resolution bandwidth. The PSD spectrum will be increasingly resolved as the filter bandwidth is made smaller, but more profile will be needed to maintain a fixed statistical confidence in the result.

ACCURACY STUDIES

Theoretical Accuracy

In theory, a profilometer of the RTP type should exhibit accuracy superior to that of any other current road profiling or roughness measuring device. It has much greater usable frequency range, being limited on the high end only by the size (6 in.) of the measuring wheel and on the low end by the quality of electronic equipment used. Accuracy of the system is relatively unaffected by vehicle properties such as suspension, tires, and weight changes. Wavelengths of from 3 in. to 1200 ft have been successfully measured and reproduced with the RTP during this study.

Profile resolution with the RTP is primarily a matter of recorder scaling. Obviously, on any conventional recorder, it is not possible to simultaneously obtain a scaling which will sense pavement grade changes of many feet and at the same time resolve small surface bumps. Those familiar with instrument calibration and sensitivity adjustments will immediately recognize that high signals will overload an instrument set at high sensitivity and that low signals will be lost when recording at a low sensitivity setting.

Figure 2 shows the theoretical differences between the RTP and other surface measurement devices. These are amplitude ratio (bandpass) plots for the RTP, 10, 20 and 30-ft rolling straightedges, and a typical BPR-type roughometer. A ratio of output to input amplitude equal to 1.0 indicates no error. Ratios of 2.0 and 0.0 indicate plus and minus 100 percent error, respectively. Analysis for a rolling straightedge on a sine wave profile is given in the Appendix. A realistic combination of spring, mass, and damping factor was used for the theoretical BPR roughometer bandpass plot.

Bandpass plots for slope variance devices (CHLOE) should be similar to straightedge plots with suitable modifications for sense wheel geometry. Validity of this assertion is demonstrated by noting that integration of the slope profile should yield an ordinary straightedge profile. Since length of the device is the determinant of straightedge bandpass characteristics, no improvement in accuracy is gained by taking the profile's first derivative.

Arguments that roads are not composed of pure sine waves and, therefore, would not cause such distortion of straightedge data are not tenable. Distortion would occur in the power spectrum of a straightedge profile taken from a completely random road

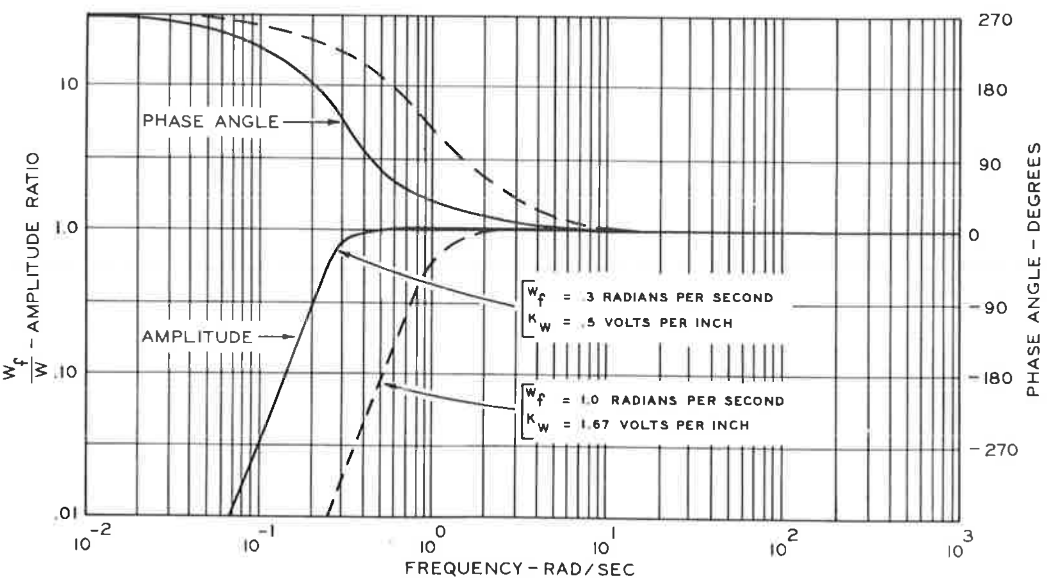


Figure 3. Filter attenuation rates and phase shift.

surface. This would indicate that, on the average, the straightedge would amplify or attenuate random data in a given frequency band just as it did for sine waves.

RTP amplitude ratio does begin to roll off for wavelengths shorter than 3 in. due to the finite size (6 in.) of the measuring wheel. Long-wave reproduction is primarily a function of the quality of electronic equipment used.

Reference Problems

Acceleration and follower-wheel data from the RTP transducers are converted to pavement profile by analog computation. This computation, whether in RTP or laboratory-based computers, inserts an arbitrary reference from which the profile is measured and allows filtration of specific wavelengths.

Analog computation of the profile provides adjustable third-order, high-pass filtration. The purpose of this filtration is twofold. First, reasonable recorder and computer scaling for low-amplitude data does not permit writing the high-amplitude, long-wave data found in most profiles. Consequently, this long-wave information is attenuated by filtration, thus reducing the frequency range but eliminating computer or recorder overload. Second, double integration greatly amplifies small, low-frequency drifts in the electronic system. Filtration of low frequencies eliminates such drift effects and thereby stabilizes the computation process. So-called open loop integration without some filtration is possible only with highly sophisticated equipment.

The filtration process has several effects on RTP profiles. By definition, third-order, high-pass filtration attenuates at a rate of 60 db per frequency decade for frequencies below the filter cutoff point. Thus, as wavelength increases indefinitely, amplitude is reduced to zero. Lag in presenting a wave in the computed profile (phase shift) approaches 270 as the wavelength increases. Figure 3 illustrates both of these characteristics. It should be noted that effects of filtration are also a function of RTP speed. As the RTP speed increases, the frequency sensed from a given surface will increase, i. e., fixed wavelengths are traversed in a shorter time period. Various combinations of RTP speed and filter frequency provide a wide range of profiling options. For instance, by profiling at 68 mph and commuting at 0. 3 radians per second a 1400-ft wave could be reproduced.

Introduction of a mechanical model for the filter used in profile computation will facilitate explanation of the computed profile appearance and reference problems. Third-order filtration of the profile which is inherent in the analog computation circuit can be viewed as a mechanical system into which the profile is fed. For simplicity, a second-order system will be described which behaves similarly to a third-order system but only attenuates at 40 db per decade instead of 60 db. Since the unfiltered profile from RTP transducers is fed into this filter, it is equally valid to view the filter model as actually traversing the profile. The filter model thus replaces the entire RTP and computational system.

The filter model is constructed as follows.

Consider a large mass, say 6400 lb, supported by a spring of 20 lb per foot rate and a viscous damper of ratio 0. 5. A small wheel is attached to the damper and spring opposite the mass. The device is run down the road on this small wheel, and displacement measured between wheel and mass, to yield the profile. The model has a natural frequency of 0. 3 rad/sec, one of the standard filters used in profile computation. If such a device could be built, it would function as a perfectly valid profilometer. As the model rolls along, it is clear that shortwave features will be measured faithfully since plus and minus excursions of the wheel occur too rapidly for movement of the heavy mass. Undesired long waves, on the other hand, will be filtered out since they tend to move the entire system, which results in little relative displacement between wheel and mass.

Explanation of reference and profile appearance problems is now intuitive. It is easy to see that the profile is measured with respect to position of the mass which forms an arbitrary reference plane. Moreover, the road profile may excite the system to oscillate near its natural frequency, thus continuously changing the reference plane. Clearly, position of the reference mass at a given time is a function of all profile

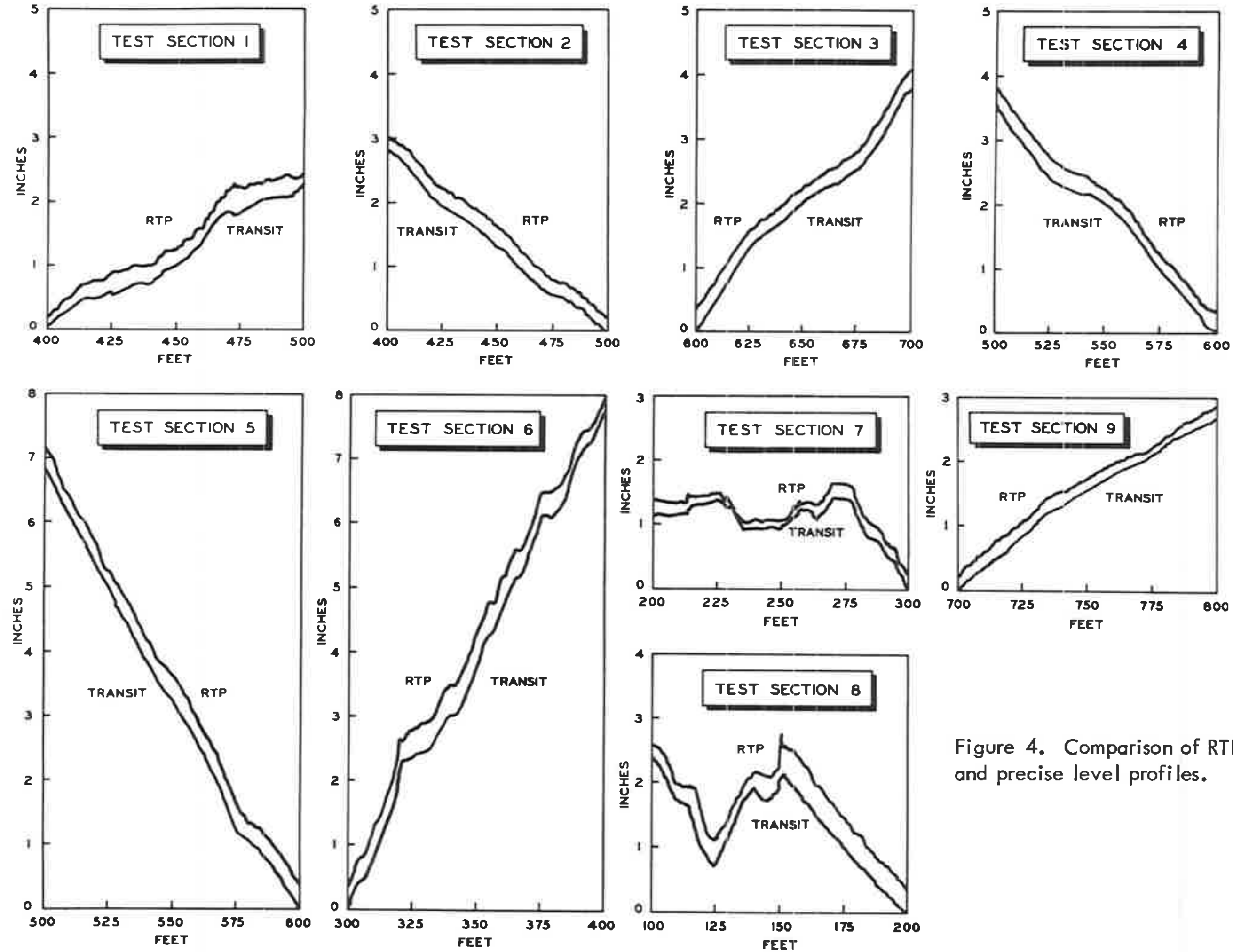


Figure 4. Comparison of RTP and precise level profiles.

previously encountered on the run. This explains the seeming paradox that two different but equally valid profiles can be obtained from the RTP by running a test section in opposite directions. That is, when the model arrives at spot x on the roadway, the position of its reference mass may differ from its position when arriving at spot x from the opposite direction. However, the two profiles can be made to match each other or conform to a fixed transit reference by a process called "tipping," explained in the section on analysis methods. A qualified statement of RTP accuracy would say that the profile is accurate with respect to an arbitrary reference for a given frequency band.

Pre-Test Stabilization Runs

Another problem readily explained in terms of the hypothetical filter model is the need for a stabilizing approach run whenever a profile is taken. Vehicle accelerations causing wide swings in the recorded signals at the start would appear, during profile computations, as violent oscillations of the "filter mass." To prevent this occurrence a short run is necessary before entering the test zone allowing these perturbations to fade. The duration of stabilization run required varies inversely with filter frequency and is thus reducible by proper filter choice. A typical pre-run with a 0.3-rad/sec filter frequency might be 500 ft. At 1.0 rad/sec 100 ft would suffice. In any event, the longest pre-run consistent with possible filtration choices should always be used. It should be noted that profile recorded after a short pre-run would still be accurate; it would merely be measured with respect to a rather unsettled filter model reference. This would cause overloading of the analog computer or recorder not scaled for such large signals.

RTP and Precise Level Profiles Compared

Field tests were set up to experimentally verify theoretical RTP accuracy. RTP profiles were taken on nine 1000-ft pavement test sections of various surface materials and roughness. Precise level readings on these sections were made every 1 to 5 ft, depending on profile detail, and subsequently plotted by digital computer. RTP profiles were computed such that wavelengths up to 100 ft suffered no attenuation or phase shift and several 100-ft lengths from each test section were electronically tipped to match the precise level reference plane (pavement grade). Precise level and tipped RTP profiles were then plotted together for comparison.

Visual inspection of the selected 100-ft lengths (Fig. 4) shows close aggreement between RTP and precise level profiles despite sampling gaps in the precise level data. To statistically quantify the relationship of the two profiles, each pair of traces was sampled at 2-ft increments and a linear correlation computed. Excellent correlation resulted—the 95 percent error intervals (1.96 standard deviations) are very small and slopes are near 1.0 (45°), as desired (Table 1).

Table 1
LINEAR CORRELATIONS BETWEEN
RTP AND PRECISE LEVEL PROFILES

Test Section	Slope	One Standard Error (in.)	Correlation Coefficient
1	0.97	0.050	0.997
2	0.98	0.034	0.999
3	1.00	0.046	0.999
4	0.97	0.031	0.999
5	1.01	0.044	0.999
6	1.02	0.074	0.999
7	0.99	0.056	0.982
8	1.01	0.096	0.986
9	1.05	0.027	0.999

Unfortunately, simple linear correlation of simultaneous points from two or more signals such as these can be misleading in that it may be insensitive to differences in frequency content. Consider two signals, with similar high-amplitude low-frequency trends, such as the profiles in question. If only one of the signals also contained higher-frequency low-amplitude data, correlation might still be good, because high correlation of long waves might obscure or negate the lack of correlation at shorter wavelengths. To preclude this possibility each signal could be filtered to a narrow band of frequencies, and linear

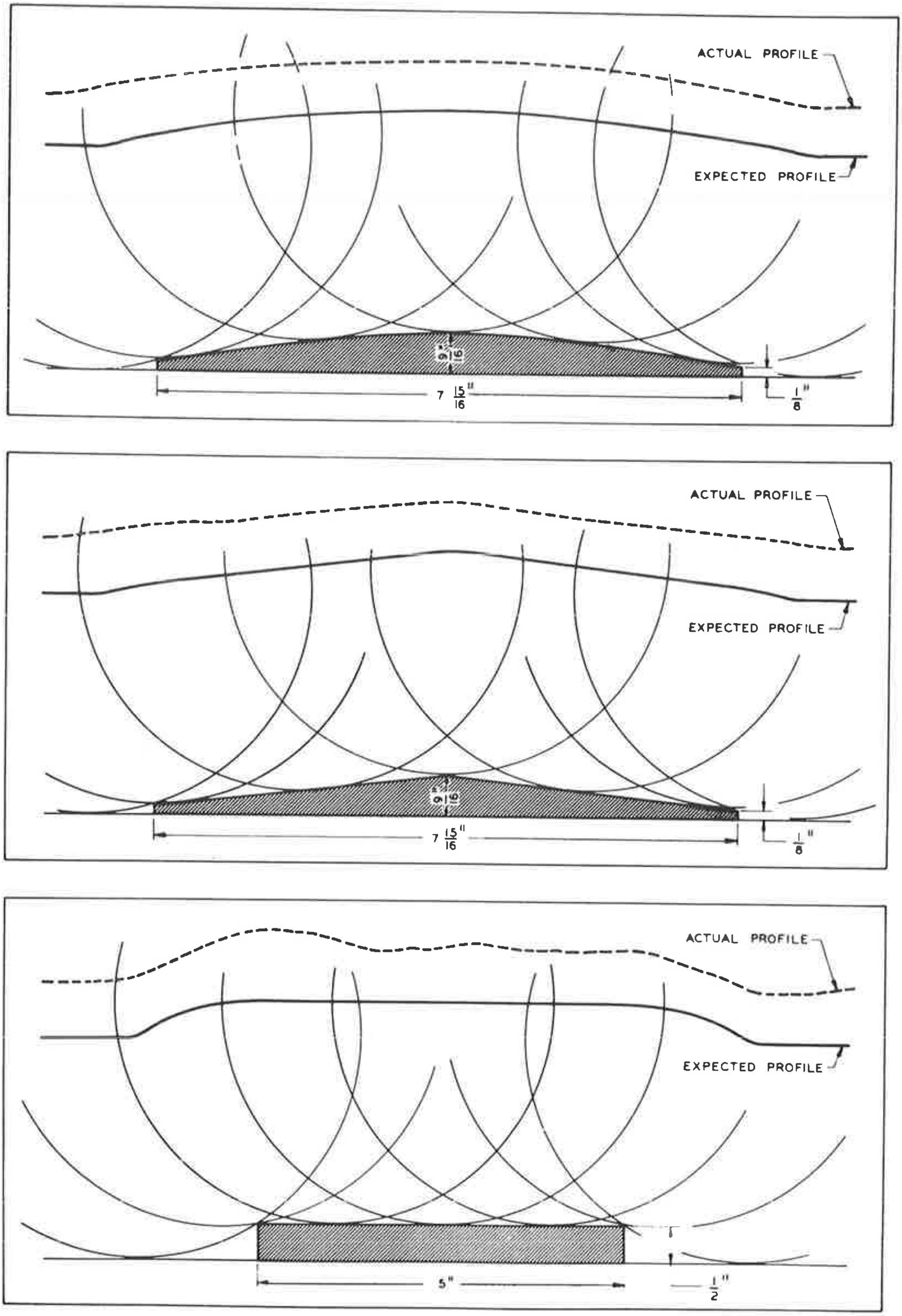


Figure 5. Profiling known waveforms.

correlation of the data would then be more meaningful. One would then consider correlation in each frequency band, e.g., 0-1 cps, 1-2 cps, etc.

A technique which performs such a correlation mathematically is the coherence function. It is a statistical process defined by the expression

$$\gamma_{xy}^2(f) = \frac{| Gxy\ (f) |^2}{Gx\ (f)\ Gy\ (f)}$$

in which Gx (f) and Gy (f) are power spectra for each signal and Gxy (f) is the cross spectra at frequency (f). The result is a graph showing correlation (0 to 1) for all wavelengths in question.

Coherence function analysis of RTP and precise level data is in process but is incomplete at this time. Uniform and closely spaced precise level readings are needed for a test section containing large amounts of data at all frequencies. Sections of precise level profile will have to be digitally tipped to match the arbitrary reference of RTP data, and computer programs will be needed to compute coherence functions from RTP and modified precise level profiles.

Profiling Known Waveforms

Correlations obtained to date confirm the RTP's capability for accurate reproduction of profile wavelengths of 50 to 100 ft. This observation is supported by noting that high correlation is maintained down to any 50-ft region. Although correlation information is lacking for middle wavelengths, several profiles were made of variously shaped shortwave objects. Three waveforms that would be increasingly difficult to profile, the semicircle, triangle and rectangle, were fabricated from steel plates, secured to a pavement surface and then profiled. These three shapes, in the order presented, required increasingly better RTP high-frequency response for faithful shape reproduction. (Frequency response in this sense means ability to pass increasingly intense high-frequency terms found in the Fourier decomposition of these waveforms.) From the results obtained it appears that the mass of the follower arm and wheel is the major limitation to RTP high-frequency response. The metal waveforms were profiled at 12.5 ft/sec since higher speeds caused considerable follower-wheel bounce. Figure 5 shows the expected and actual profiles superimposed. Expected profiles are axle paths of the 6-in. follower wheel over the waveforms. Except for the follower-wheel bounce over the rectangle, agreement of the traces is so close that quantitiative comparison is deemed unnecessary.

ANALYSIS METHODS

Magnetic Tape Recorders

A word about magnetic tape recorders is in order before discussing methods of profile analysis. Most meaningful analysis will require raw data storage on magnetic tape. This is true whether data are computed by the RTO analog package, processed in lab-based analog equipment, or digitized for numerical analysis. Departmental experience indicates that a highly portable IRIG standard FM deck, using 1-in. tape, is highly desirable. It should be of highest instrumentation quality and, for efficient use with digitizers, be capable of at least a four-to-one speed change.

Visual Inspection

An obvious method of profile analysis is visual inspection. Adjustable filtering during profile computation is advantageous for this and other types of analysis. Profiles filtered at high frequency will contain only low-amplitude short-wave detail which can be amplified for greater clarity. At low filter frequency, long-wave high-amplitude features will dominate the profile. As the profile is computed from raw data it can be simultaneously recorded on a spare tape track for subsequent analysis. Information data must be re-recorded with the profile to maintain synchronization.

Since road profiles are normally thought of with respect to a plane perpendicular to gravity, it may be disturbing to find the profile tipped the "wrong way." A gravity reference can be restored by taking precise level shots at intervals equal to the longest unfiltered wave. Computed profile can then be electronically tipped, section by section, to match the precise level points. This is actually a process of reinserting previously filtered low-frequency data.

All of the RTP profiles shown in Figure 4 have been electronically tipped to match the true pavement grades. The Department has found that a two-pen "x, y" plotter is indispensible for visual profile displays of this type. These servo-driven plotters have a large "y" axis range allowing a plot of terrain elevations while retaining considerable surface detail.

Analysis Equipment

Any analysis beyond visual inspection will require analog or digital computation, or both. Profile computation can be performed by an optional analog computing package built into the RTP. Analog analysis beyond this level, however, will require a lab-based analog computer of at least the 20-amplifier class. It should be equipped with at least 10 integrators, a comparator, an x^2 unit and a multiplier. Digital computations will require an analog-to-digital converter. This unit need not be very elaborate due to the low frequencies involved. Most digitizers sample very rapidly so that profile playback speeds, of four or even eight times normal, result in efficient use of computer memory and time. Coupled analog and digital computers, called hybrid systems, greatly facilitate profile analysis but are not in widespread use. Choice of analog or digital methods depends, to some extent, on depth of analysis desired.

Single Number Indexes

Profile analysis begins by recasting the data into terms more meaningful than computed profile. The first and least powerful technique is to characterize the profile by a single number index. A particularly dubious index is inches per mile. An analog computer program has been developed to accumulate vertical excursions of the profile. These excursions are summed and divided by test section length to yield the average inches-per-mile index. This index provides little information since it does not relate to particular wavelengths nor does it express the distribution of amplitudes. Digital or analog methods can be used to obtain the average and variance of the profile or its derivatives. Again, these single number indexes provide no information about wavelength content.

It is perhaps more meaningful to obtain these quantities in a narrow frequency band rather than overall frequencies. This can be accomplished by synthesizing a narrow bandpass filter on the analog computer. Profile data are then passed through the filter and any desired index is computed from the emerging signal. This process may be repeated for all frequency bands of interest. An estimate is thus obtained linking each index to a particular wavelength band. Such indexes might be relevant to vehicle behavior or indicate the nature of pavement distress.

Simulation of Other Profile Devices

Assuming correctness of RTP profiles, one can compute actual slope variance, inches per mile, and other indexes directly. There is interest, however, in obtaining these indexes as measured by existing profile devices. Since these devices (BPR roughometers or rolling straightedges) have passbands totally unlike the RTP, it is necessary to synthesize a model of each device in analog or digital terms. RTP profiles are then fed into these models and the appropriate index computed from the emerging signal. Although analog simulation of a BPR roughometer is fairly straightforward, the rolling straightedge is not. Simulation of the latter device on the analog computer requires transport delays to shift the profile to that seen by successive wheels. (Transport delay tape decks or analog computer delay packages are commercially available.) Straightedges are, however, relatively simple to synthesize on the digital computer.

Correlation of the RTP and Other Profile Devices

A shortcut to prediction of CHLOE and MDSH-BPR type roughometer indexes from RTP data was tried with rather unusual results. Twenty-two ½-mi pavement test sections were run simultaneously with the RTP, CHLOE, and roughometer. These sections included good, average and poor riding surfaces on rigid, flexible and overlay pavements. Since the CHLOE slope variance and roughometer inches per mile are numeric indexes, the RTP profiles were converted to inches per mile. Simple linear correlations between RTP, CHLOE, and roughometer indexes are given in Table 2. The good correlations obtained were not expected. How could three devices with radically different passbands, and in two cases differently computed indexes, correlate so well? It was also discovered that the RTP data had been inadvertently overfiltered during processing, thus removing all but the longest waves. Apparently, a frequency band strongly sensed by the RTP was correlating well with the outputs of two devices which very weakly sensed this same frequency band.

This would indicate that intensity of the higher frequencies sensed by CHLOE and the roughometer correlates with intensity of lower frequencies sensed by the RTP. Apparently the intensities of both these bands are higher on rough roads and lower on smooth roads. Under these conditions, any parameter reflecting amplitude dispersion computed from one frequency band will correlate with the same or a different dispersion parameter from the other band. What the correlations very likely show is not an ability to directly predict various indexes from RTP data, but a correlation among various wavelengths in the selected test sections. Such intra-profile correlation, if universally found, would permit indirect prediction of traditional roughness parameters from RTP data.

To validate the above hypothesis would require a major experimental effort. Consequently, the computation of indexes from RTP data is probably most safely done by simulation techniques as previously discussed.

Advanced Analysis

The RTP makes possible new methods of characterizing road profiles in highly meaningful terms. Flat bandpass, ability to pre-filter, and magnetic tape storage are prerequisites to use of high-powered analytical techniques. Such techniques began to appear about two decades ago but their application to highway work has been very limited (4, 5). Known broadly as time-series methods, they include auto- and cross-correlation, power spectral density, cross power spectral density, and coherence functions.

Table 2
LINEAR CORRELATIONS BETWEEN
RTP, CHLOE, AND MDSH-BPR ROUGHOMETER INDEXES

Correlation of RTP in. per mi with:	Pavement Type	Correlation Coefficient
CHLOE, slope variance	Combined Types	0.917
MDSH-BPR, in. per mi	Combined Types	0.830
MDSH-BPR, g's per mi	Combined Types	0.778
CHLOE, slope variance	Flexible	0.907
CHLOE, slope variance	Rigid	0.918
CHLOE, slope variance	Overlay	0.984
MDSH-BPR, in. per mi	Flexible	0.910
MDSH-BPR, in. per mi	Rigid	0.896
MDSH-BPR, in. per mi	Overlay	0.989
MDSH-BPR, g's per mi	Flexible	0.980
MDSH-BPR, g's per mi	Rigid	0.906
MDSH-BPR, g's per mi	Overlay	0.992

Of these, power spectral density analysis currently appears most promising for highway work.

Power Spectral Density Methods

The power spectral density function (PSD) is best described by a possible analog method of computation. Consider a number of narrow bandpass filters of bandwidth B_e' (B_e being resolution bandwidth) selected such that their center frequencies are uniformly distributed over the frequency range of interest. Apply the profile signal as input to this array of filters. Square the output of each filter and accumulate the squared outputs over the profile length. Divide each accumulation by the profile length thereby obtaining the mean variance of each frequency band. Then divide each mean variance by B_e to form an average over the frequencies passed by that particular bandpass filter. These are PSD estimates and form the PSD graph when plotted against bandpass filter center frequencies. The units are amplitude^2/frequency on the "y" axis and frequency on the "x" axis.

In practice, PSD analysis is more complex than its explanation would indicate. Fairly stringent statistical requirements must be met and the profile must be prefiltered. Long-wave, high-amplitude signals present in most profiles have plagued investigators using precise level profiles (6). These powerful signals dominate the PSD analysis obscuring subtle power differences in important regions. Various methods, sometimes called detrending, have been tried to filter out these wavelengths. Such filtering is possible with digital techniques but computer time is heavily consumed (7).

The RTP resolves this problem by automatically filtering out these long waves during profile computation. Filtration of unwanted high frequencies may also be necessary if the profile is to be digitized for PSD analysis. This filtration can also be readily performed on the analog computer prior to digitizing. Recently, several firms have marketed analog devices specifically designed to do PSD and related analysis. This equipment may prove adequate for profile analysis programs and is sufficiently portable to be used in the field.

PSD graphs and estimates for two typical test sections appear in Figures 6 and 7. Each 1-ft sample of an 1812-ft profile was digitized and PSD estimates were then computed for frequencies of 0.01 to 0.25 cycles per foot, in 0.01-cycle increments. This corresponds to wavelengths of 100 to 4 ft. Frequencies above and below these wavelengths were filtered out. Assuming statistical assumptions are met, the estimates from the sample are within 20 percent of the true value for the entire highway 90 percent of the time. The resolution bandwidth was 0.04 cycles per foot. Logs of the estimates were taken and then expressed as percents of the highest value. This provides a plot which remains within the boundaries of the paper but takes maximum advantage of space. It is read with the page in normal position and primarily shows shape of the spectrum.

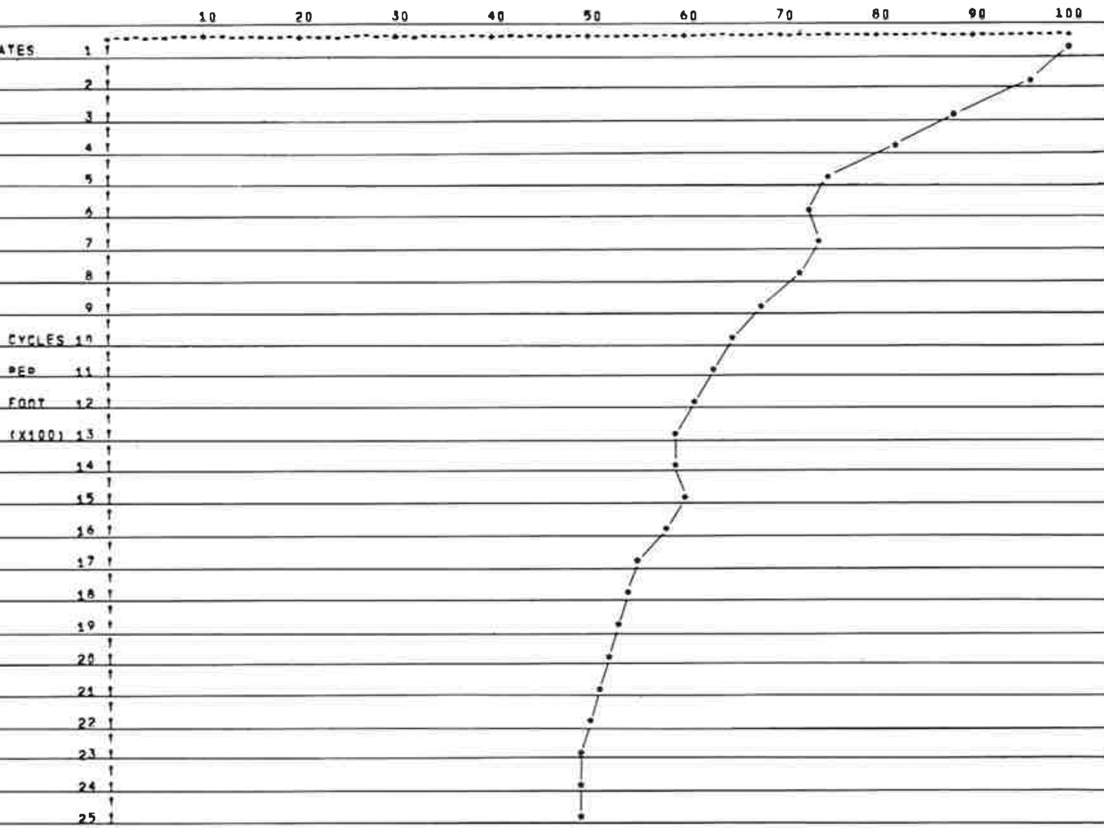
It should be mentioned that when applying PSD techniques to profile analysis, the same problems are encountered that occur in analysis of most random data. As in any other statistical study, the investigator must include a statement of his statistical decisions. Sample length, resolution bandwidth, data bandwidth, and confidence levels—if clearly stated—will enable other investigators to make comparisons with their own work. Length of the profile sample must be chosen to yield stable, reliable estimates of the true power spectrum since shorter samples will produce erratic results. If the sample available is too small to yield reliable PSD estimates, it will not yield reliable estimates of any other type which attempt to characterize the profile. Often, when large samples of profile are taken, a problem known as non-stationarity appears. This is due to changes in the statistical properties of the profile as the sample is traversed. Techniques for analysis of such data have been given by Bendat and Piersol (3). In this connection, it must be noted that if the non-stationarity is bad enough to preclude PSD analysis, any other analysis method will be equally invalid. Random data, at best, are difficult to analyze but PSD techniques, if applicable, offer the only coherent, fully developed method of attack. If PSD analysis cannot be applied, very little can be said statistically about the profile.

ROAD PROFILE, POWER SPECTRAL DENSITY ANALYSIS
MICH STATE HWY DEPT   RESEARCH PROJECT 63F-73

DATE 12-28-67 REEL 001 LOCATION 050

POWER SPECTRAL ESTIMATES

CYCS PER FOOT X100	WAVE LNGTH (FT)	ESTIMATES (SQUARE FEET PER CYC PER FT)
1	100.0	2.72-002
2	50.0	1.46-002
3	33.3	3.20-003
4	25.0	8.82-004
5	20.0	2.14-004
6	16.7	1.74-004
7	14.3	1.80-004
8	12.5	1.33-004
9	11.1	6.40-005
10	10.0	3.48-005
11	9.1	2.15-005
12	8.3	1.42-005
13	7.7	1.11-005
14	7.1	1.14-005
15	6.7	1.16-005
16	6.2	8.03-006
17	5.9	4.66-006
18	5.6	3.89-006
19	5.3	3.55-006
20	5.0	2.87-006
21	4.8	2.19-006
22	4.5	1.73-006
23	4.3	1.48-006
24	4.2	1.45-006
25	4.0	1.43-006



TREND TEST FOR STATIONARITY, N = 12, MEANS 33, MEAN SQRS 19 REVERSES. CHI SQUARE TEST FOR NORMALITY, N = 39, CHI SQUARE = 109.47
SAMPLE LENGTH, 1812 FT, RESOLUTION BANDWIDTH, 0.04 CYCS PER FT. MAXIMUM ERROR IS 20 PER CENT AT 90 PER CENT CONFIDENCE.

Figure 6. PSD graph and estimates for test section one.

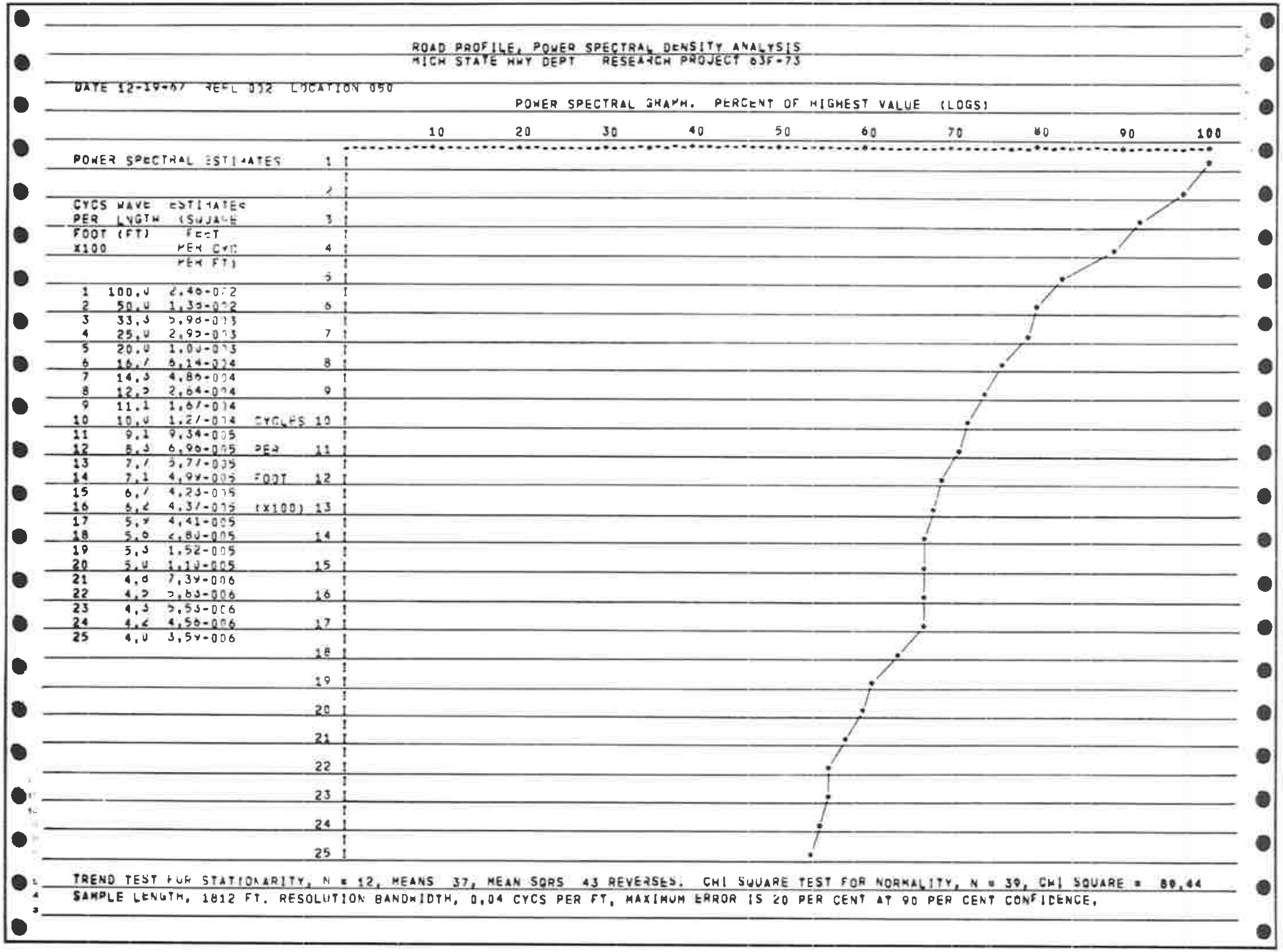


Figure 7. PSD graph and estimates for test section seven.

Uses of power spectral density analyses are too many and varied for inclusion here. Some applications to highway work have been by covered by Hutchinson (4), Quinn and VanWyck (5), and Quinn and Zable (6). PSD and cross-PSD estimates are used in coherence function computations mentioned earlier. An interesting use in determination of vehicle transfer functions by modifying the process is also covered (5, 6).

Miscellaneous Analysis Methods

Two additional types of profile analysis should be mentioned for completeness. Amplitude distributions are easily formed from RTP profiles by analog or digital methods. Such characterization of the profile is not complete since it carries no wavelength information. Usefulnes of this measure probably lies somewhere between indexes and PSD analysis. Another analysis method uses the profile as direct input to a simulated vehicle. Problems of what to do with the output, however, still remain.

RELIABILITY AND FIELD EXPERIENCE

RTP reliability has been fully demonstrated during many miles of profiling. Several minor initial difficulties have been eliminated. Solid-state electronics minimizes instrumentation failures. Several minor improvements have been incorporated and are available in commercial models of the RTP.

A weak link in the system from the reliability and profiling viewpoint is the follower-wheel system. The wheel is subject to wear and despite 300 lb of holding-down force will bounce on sharp rises. Detailed profiles of severely distressed surfaces (faulted joints) are difficult with the present system. Nevertheless, wheel wear is not rapid and sharp obstructions are rare in general profile work.

Field experience has led to several refinements in operating procedures:

1. Ideally, such systems would use a servo-drive tape recorder where tape speed is continuously controlled by vehicle speed. This would eliminate minor vehicle speed variation effects and greatly simplify distance scaling on finished profiles. However, such instruments are expensive and add to system complexity. The Michigan RTP does not include such a recorder. Its tape unit has a number of fixed speeds. To facilitate distance scaling on the finished profiles, it has been found advantageous to operate the vehicle at various fixed speeds such as 50, 25 or 12.5 ft per sec.
2. A detailed operations checklist assures uniform profiling techniques and is a valuable teaching aid.
3. Remote control of profilometer electronics permits one-man (driver) operation where necessary.
4. Magnetic tape dropouts can cause violent perturbations of the "filter mass" and invalidate a test. A device designed by the Laboratory's electronics personnel monitors critical channels during testing, and signals if a dropout occurs. This is a serious problem only when computing the profile from tape.

MICHIGAN RTP APPLICATIONS

Michigan's use of RTP profiles is increasing rapidly. Most analyses to this time have been visual. Advanced analysis techniques will be used in a forthcoming study linking profiles with dynamic axle forces. A digital computer "roughness package" program is being considered. It will compute all possible indexes, power spectra, and other desired profile information. A few examples of initial studies will indicate the diversity of use:

1. A study of 24-hr slab movement recording actual slab curling;
2. A study of blowups clearly showing the cross-section profile;
3. A comparison of hand, transverse and longitudinal bridge deck finishing;
4. Examination of approaches and platforms for an electronic scale project;
5. Profiles of an airport runway to aid in resurfacing operations; and
6. Profiles of a number of experimental pavements as the first of a series of periodic

profiles to study progressive changes. These include pavement variables such as continuous reinforcement, no load transfer dowels, styrofoam-insulated subgrade and asphalt-stabilized subgrade.

CONCLUSIONS AND OBSERVATIONS

1. This study has shown that the General Motors rapid travel profilometer is a rugged, fast, reliable, and easily utilized system for profiling highway road and bridge surfaces. It is superior to any other known highway profilometer in that it provides an accurate, "true" profile of the surface being measured.

2. The magnetic tape recording medium facilitates computer processing. This in turn permits (a) controllable filtering to enhance or attenuate specific profile features, (b) various types of statistical processing, (c) simulation of other surface measurement devices, and (d) calculation of single number numerical indexes for correlation with CHLOE, BPR-type roughometer, rolling straightedges, and other such instruments. Of course, in addition to all these is possible the most common mode of use—visual examination of the profile in areas of interest such as joints, patches, rough areas, and distressed areas.

3. Maximum utilization of the RTP, as with any instrument, requires complete awareness and comprehension of all of its capabilities and limitations. The subtleties of the device and its application are such that potential users should anticipate an extensive familiarization and break-in period. Serious study of the device and the involved concepts will reward the highway engineer with a very valuable tool.

4. To achieve an RTP system of superior accuracy and resolution it is essential that the two transducers, the magnetic tape recorder, the signal conditioning and calibration electronics, and the analog computer all be of highest instrumentation quality.

5. The pavement follower arm and wheel currently constitute the RTP's major limitation to high-speed (50 to 70 mph) operation and thereby high-frequency response. Development of a sensitive non-contacting distance transducer would eliminate this problem and permit profiling of any surface, at any speed.

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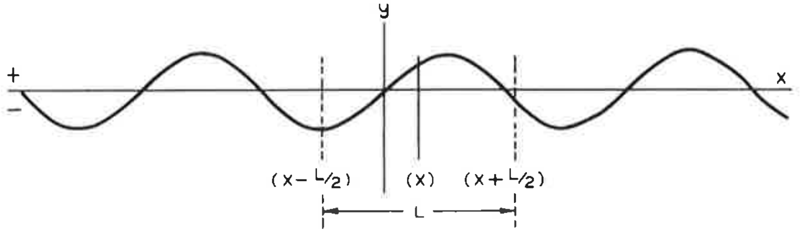
Appendix

Transfer function for rolling straightedges on sine surfaces. Consider the sine wave profile shown:



For displacement of the measuring wheel on a straightedge we have:

$$y = -1/2\,A \sin 2\pi n\,(x - L/2) + A \sin 2\pi nx - 1/2\,A \sin 2\pi n\,(x + L/2)$$

where:

- A = amplitude
- n = number of cycles per foot
- L = length of straightedge
- x = distance in feet

Noting that $\sin(A + B) + \sin(A - B) = 2 \sin A \cos B$ we can write:

$$y = A \sin 2\,\pi nx - A \sin 2\,\pi nx \cos \pi nL, \text{ and}$$
$$y = (1 - \cos \pi nL)\,A \sin 2\,\pi nx$$

If A = 1 ft, $(1 - \cos \pi nL)$ is the output amplitude and also the amplitude ratio or transfer function (T). Inspection of T reveals maxima when the product nL is an odd integer and minima when even. Note that for $n < 1/L$, T ceases to oscillate and descends asymptotically to zero.