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HIGH FRICTION INTERACTIVE AIRCRAFT TIRE-RUNWAY SYSTEMS

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HIGH FRICTION INTERACTIVE AIRCRAFT TIRE-RUNWAY SYSTEMS

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Abstract

The principle of utilizing geometric interaction between runway asperities and tire pattern design is discussed, and a theoretical basis is presented for substantial enhancement of frictional effects by this process. Test data confirming this is given. First order analytical expressions are given for the increased friction coefficients and for the engagement distances required. High speed friction data on a 7.00 x 8 aircraft tire is presented confirming this. Example design geometries are shown for the tire tread groove pattern, and designs and materials are discussed for the asperity grid and its attachment system.

I. Introduction

The tread pattern of the present day aircraft tire represents a compromise between two factors, wear and resistance to wet skid. The role of the familiar tread grooves in this type of tire is simply that of expelling water from the contact patch as the tire rolls in a wet environment. As the area of the tread grooves becomes larger, the number of landings which can be obtained with a given tire decreases because the net surface area available for contact during the touch-down and braking portion of the landing process also decrease. Thus one might say that the geometry of aircraft tires is a balance between these two requirements.

During the process of rolling under wet conditions the aircraft tire depends for its traction characteristics on the ability of the tread grooves to channel water out of the contact patch, so that the tops of the tread lands may sink quickly and come into reasonably intimate contact with the runway surface, similar in principle to the action they undergo under dry conditions. The braking traction is generated between the tops of the tread lands and the runway surface by virtue of the shear forces there. Obviously, in some situations where water depth is so great or speed so high the contact between the tread lands and the runway surface cannot be effected in sufficient time as a point on the tread moves through the contact patch. Under these conditions the available tractive forces drop to almost zero. This is called hydroplaning and is a well known phenomenon in high speed tires.

All of the braking traction normally available in an aircraft depends on the presence of shear forces between the tread lands and the runway surface. In this paper we attempt to introduce a different concept for aircraft braking, namely the use of normal or compressive stresses in order to effect the braking of an aircraft. This is achieved by purposely introducing a geometric pattern of positive asperities on the runway surface capable of beneficially interacting with a similar negative asperity pattern molded into the tread surface of an aircraft tire, in such a way that the basic water expulsion characteristics of the tread grooves are not appreciably changed.

II. Principle of Operation

We attempt to utilize as a basic principle the concept of a geometrically regular pattern of asperities purposely formed onto the surface of a runway. We attempt to introduce the principle of interaction between this asperity pattern and a similar negative pattern of depressions molded into the surface of an aircraft tire in such a way as to leave undisturbed the basic water expulsion characteristics of the tread grooves. One important characteristic needed for this type of design is its ability to last throughout the life of the tire and to be relatively free from weathering and environmental degradation. For this reason we choose to make negative depressions in the tread pattern of the tire, along with positive asperity protrusions on the runway surface. This combination clearly has practical advantages over its opposite counterpart, as can be seen from considerations of tire wear, noise and the maintenance of clean depressions.

Given a negative pattern of depressions in the tire surface with a matching positive pattern on the runway surface, one has a meshed system with gear-like characteristics capable of substantially greater tractive force than equivalent unmeshed surfaces, provided that register or geometric engagement may be assumed between the two patterns. To maximize the likelihood of this in cases where vehicles have variable direction, we use an essentially square pattern of individual protrusions on the runway surface corresponding exactly to a pattern of negative depressions molded into the tread surface of the tire. This is shown in Fig. 1. We call this an interactive tire-runway system.

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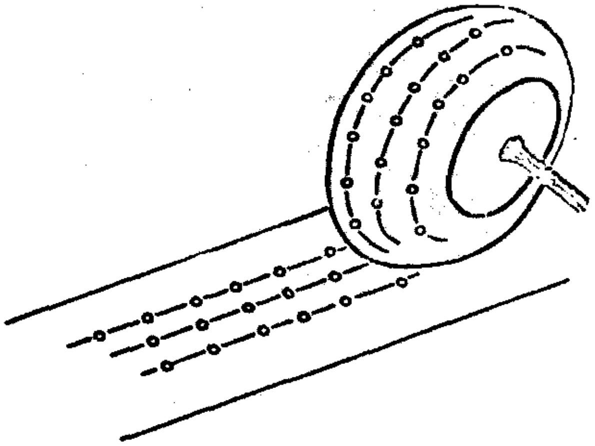
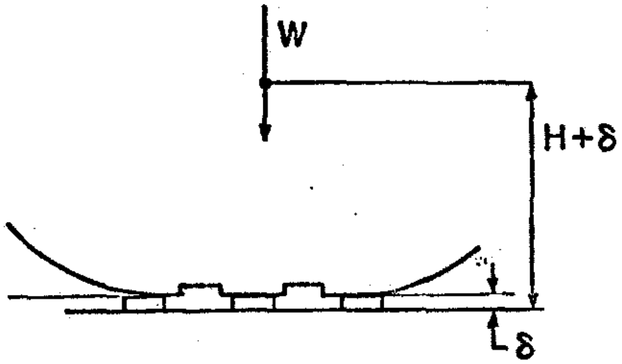


Figure 1. Schematic View of Tire and Roadway with Matching, Interacting Patterns.

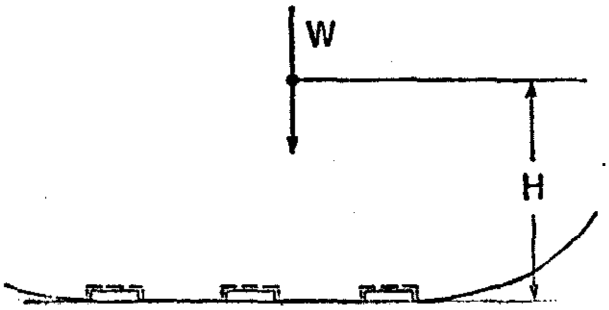
A major problem with the concept illustrated in Fig. 1 is that of assuring proper register between the protrusions on the runway and the corresponding depressions in the tire pattern. One cannot be assured that the two sets of patterns will be in alignment when the patterned tire first meets the patterned runway. A study of this problem has been one of the major objectives of this research. Its solution may be more readily conceived by consideration first of the two possible states of running as illustrated by Fig. 2. In Fig. 2a is shown the tire running out of register with the protrusions, with the axle height given by H + δ, where H is the loaded radius of the tire and δ the height of the protrusions. In Fig. 2b the same tire is shown now running in register with the protrusions, with the axle height being the loaded tire radius H. Fig. 3 illustrates the potential energy associated with these two states, and showing that the state of lower potential energy is associated with the tire running in register as shown in Fig. 2b. This would imply that under conditions of sufficient randomness, such as are normally encountered in the running of a tire on a runway, the tire would tend toward the lower energy state i.e., complete alignment of the protrusions and depressions. Based on such reasoning, one may postulate the following principle:

> Given a geometric pattern of protrusions and a matching geometric pattern of depressions, one on the surface of the tire and one on the surface of a runway, the rolling tire will seek engagement of the two patterns by virtue of the fact that the engaged state is a state of lower energy level.

While this concept seems theoretically sound, it needs to be substantiated by direct experimental evidence.



(a) Tire Running Out of Register.



(b) Tire Running In Register.

Figure 2.

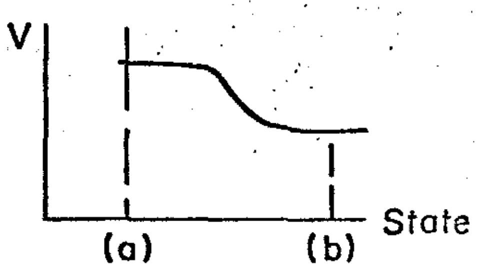


Figure 3. Potential Energy of Tire Running Out of and In Register.

III. Theory of Friction Effect

A theoretical approximation for the value of the friction force obtainable with an interactive tire-runway system can be obtained using energy concepts as a basis. Consider the tire under braking traction as shown in Fig. 4. The tire in this mode acts as an elastic spring, since its fore-aft stiffness is a well known tire property and may be measured readily. Let this fore-aft spring rate be denoted by k

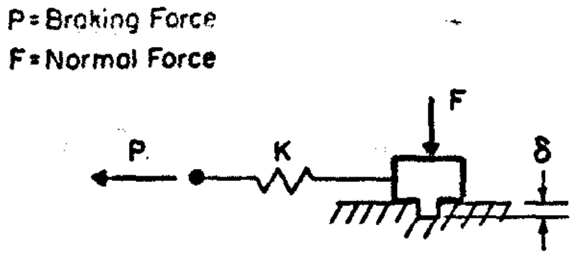


Figure 4. Forces Acting on Engaged Protrusion.

The energy stored in the tire by virtue of the braking force P is given by

$$E = \frac{1}{2} k \left(\frac{P}{k}\right)^2 = \frac{1}{2} \frac{P^2}{k}$$

The work done in dislodging the protrusion of height δ and raising the normal force F a distance δ, which is the mechanical equivalent of completely disengaging the two patterns, is

$$W = F \cdot \delta$$

Equating these gives

$$P = [2kF\delta]^{1/2} \qquad (1)$$

This is the tractive force associated with lifting the normal force F a distance sufficient for disengagement of the pin with a corresponding depression. Under conditions of a certain amount of randomness it will represent the maximum force available to the tire on the runway. It does not depend on the ordinary shearing forces of surface contact between the tire and the runway but rather on the normal compressive forces between the sides of the pin and the sides of the corresponding depression. In order to account for the usual friction coefficient available between the tire and the runway, one must add a tractive force to Eq. (1) in order to account for this additional friction effect. This gives a more complete value for the maximum tractive force available in the form of Eq. (2):

$$P = \mu_o F + [2kF\delta]^{1/2} \qquad (2)$$

where μ_o is the inherent friction coefficient between the two materials.

Eq. (2) may also be rewritten in terms of the usual notation of a friction coefficient, defined as the ratio of the tractive force P to the normal force F. This gives

$$\mu_{effective} = \mu_o + [2k\delta/F]^{1/2}$$
$$= \mu_o + \mu_{interaction} \qquad (3)$$

While this formulation is admittedly approximate, it is interesting to examine the asperity heights necessary to obtain various levels of friction coefficients on a runway surface. In doing this, it should be noted that generally speaking the second term of Eq. (3) is the dominant term which controls the major fraction of the available friction coefficient in wet or inclement conditions. This term involves a ratio of the tire fore-aft stiffness to its vertical load. While there is no fixed value for this ratio, examination of the tire stiffness data available in the literature seems to indicate that generally speaking the tire fore-aft stiffness increases as the tire rated load also increases. Therefore it would be expected that over a wide range of tire sizes the ratio k/F would remain more or less the same order of magnitude. This is confirmed by some approximate calculations which are shown in Table 1.

The three tires chosen in Table 1 were selected because sufficient data about them was available and, in cases of the first two, experimental measurements on effective friction coefficients will be presented later in this paper.

The effective depth of the depressions in the tire will change as the tire tread wears, just as the groove area of the tire also decreases with wear. This means that the effective friction coefficient will decrease somewhat as the tire progresses from the new to the fully worn state. This is a factor in assessing the value of this process, but the deterioration of effective friction coefficient should be no more severe than the deterioration of water expulsion capabilities since both depend on exactly the same phenomena.

The calculations given in Table 1 show that very modest asperity heights are sufficient to provide quite large additional friction coefficients. For example, the 7.00 x 8 tire can be provided with an additional friction coefficient of nearly 1.0 by use of asperity height of only 3/16 of an inch, which is not much larger than is normally available on a rough open graded asphalt surface. A more conventional full-size tire such as 30 x 11.5-14.5 can be provided with additional friction coefficient of 1.0 by use of asperity height of 0.8 inches, provided it is placed in a regular pattern. This is

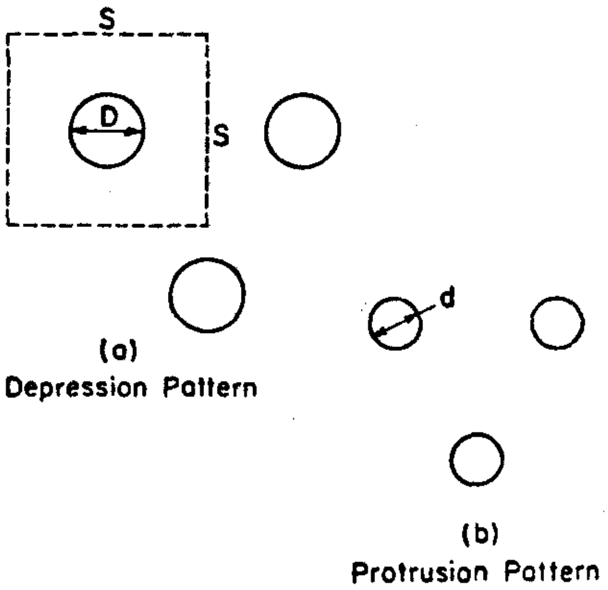
Table 1 Calculated Vales of μ_{Added}

Tire	Load F lbs.	Fore-Aft Stiffness k lbs/in.	Asperity Height δ in.	$\mu_{Interaction}$ (Calculated)
Scale Model of 40 x 12 (4.5" Dia)	40	160	0.08	0.8
7.00 x 8	1100	2500	0.1875	0.92
30 x 11.5-14.5	20,000	13,000	0.8	1.02

not an excessive asperity height and could be tolerated by normal non-patterned tires without damage to them.

IV. Theory of Engagement

Friction coefficients discussed in the preceding section are available only when the protrusion pattern on the runway fully engages the mating depression pattern on the tire surface. While consideration of minimum energy levels indicates that the engagement tends to occur under a state of randomness such as normally would be the case as the tire runs on a runway surface, it is difficult to ascertain the length or distance of runway needed for such engagement. Some very approximate computation on such distance may be performed by consideration of the probability of occurrence of engagement, based on relative area ratios. If a square pattern of spacing s is used for both the depression and protrusion patterns as shown in Fig. 5, then the total area associated with a single element is s^2.



(a) Depression Pattern

(b) Protrusion Pattern

Fig. 5. Square Pitch Protrusion Pattern

That fraction of the net total area which will allow engagement of the protrusion in the depression pattern is illustrated in Fig. 6 as being the area delineated by the location of the center of the protrusion in a circular region of diameter D-d.

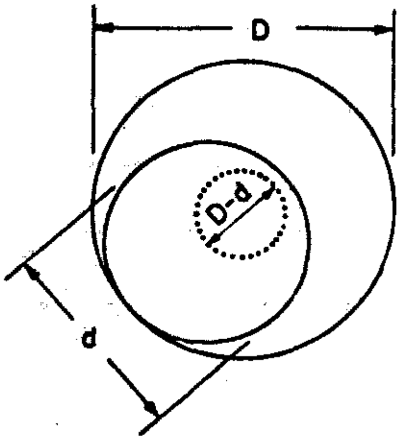


Figure 6. Area of Engagement.

This gives an area of possible engagement equal to $\pi(D-d)^2/4$. This means that the probability of engagement p is given by

$$p = \pi(D-d)^2/4s^2 \qquad (4)$$

The probability of not engaging is given by

$$q = 1 - p \qquad (5)$$

and requires a distance s for decision. The probability of not coming into register at least once under conditions of random placement of the protrusion pattern on the depression pattern is given by q^n, where n is the number of spacings s traversed. This means that the probability of engagement as a function of number of spacings s traveled may be plotted directly, since the probability of engagement is given by

$$P_e = 1 - q^n \qquad (6)$$

The general form of this relationship is given in Fig. 7.

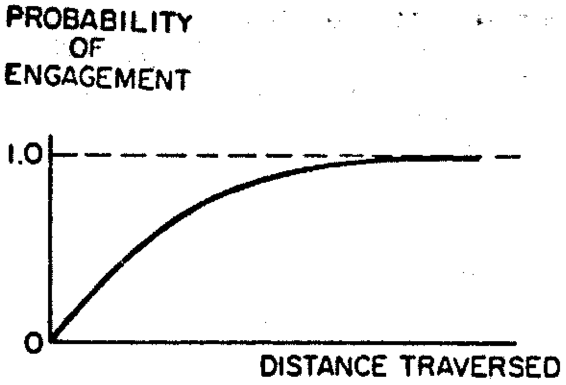


Figure 7. Probability of Engagement vs Distance Traveled.

V. Flat Plank Experiments

It was felt that the most economical way to obtain experimental data on this concept was to carry out both small scale model experiments and experiments on a small commercial aircraft tire.

Small scale experiments were conducted on a scale model of a 40 x 14 aircraft tire, reduced in size by a factor of approximately eight to an outside diameter 4.5 inches. This tire was manufactured especially for scaled shimmy studies and was made from the same type of cord and rubber used in the full scale tire. It was geometrically similar in all respects and further maintained scaled similarities between the various elastic stiffnesses of the model tire and its full scale prototype.

Several of these tires were modified by forming regular patterns of depressions in their tread surfaces. These were run on a dynamometer wheel which was modified by attaching a regular pattern of positive protrusions on its surface. These latter protrusions were made by casting a series of epoxy plates with the protrusions in them.

Several important results were obtained from the model experiments which influenced design thinking on the larger scale work. These were:

a) The best position for location of the depression pattern is in alignment with the tread grooves in terms of rapid engagement of the two patterns.

b) The best location for the depression pattern is in the tread lands in terms of maximum available friction coefficient.

c) Rapid or almost instantaneous engagement of the protrusion pattern with the tire depression pattern occurred when the roadwheel was brought up to speed and the stationary scale model tire was suddenly brought into contact with it, simulating the landing of an aircraft. High speed photography failed to detect any sliding of the tire over the protrusion surface, and this was confirmed by the absence of abrasion and tearing of the surface of the tire.

Since these results seemed to be encouraging, design work was begun on a 7.00 x 8 aircraft tire in order to examine the feasibility of this concept for a normal commercial tire.

In an effort to simplify manufacture of the protrusion pattern, it was decided to concentrate on a cylindrical protrusion with an essentially square pitch arrangement, with the depressions in the tire surface located on the tread grooves in order to facilitate rapid engagement. Fig. 8 shows the pattern used in the tire while a photograph of the finished tire running on its mating surface is shown in Fig. 9.

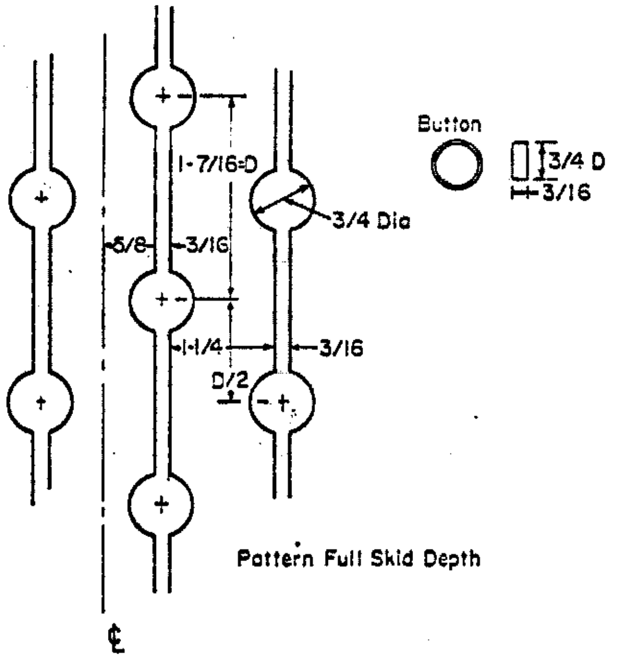


Figure 8. Tread Pattern for 7.00 x 8 Aircraft Tire.

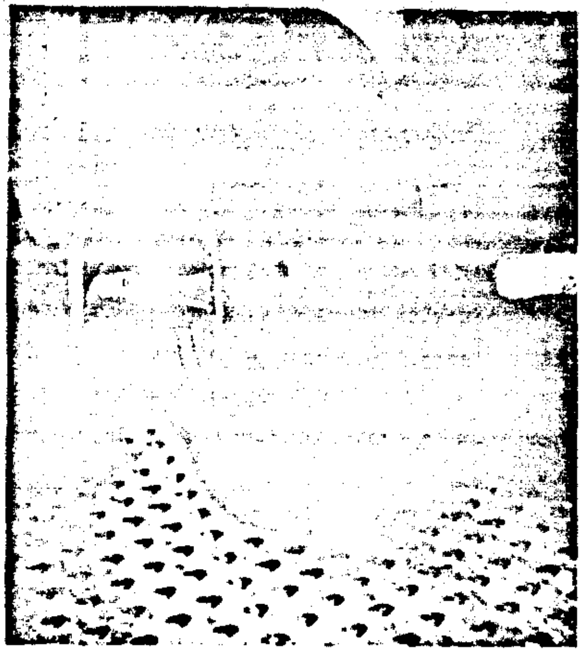


Figure 9. Aircraft Tire Running on Mating Surface.

The depression pattern in the 7.00 x 8 tires was obtained by recapping these tires in a mold especially adapted for this purpose. The positive runway protrusion pattern was formed by cutting small cylindrical sections from round steel bar stock and spot welding these to a 20 gage steel sheet, which in turn could be rigidly attached to an ordinary highway surface.

In the first series of experiments to be reported, these patterned tires were run on sheets of the type just described in a flat plank machine where brake force coefficients could be measured accurately under controlled conditions. This machine consists of a fixed instrumented yoke which loads a tire against a translating horizontal bed plane.

Slow speed drag coefficients were measured in this flat plank machine at rated tire deflections. The measurements were carried out on both tires in wet and dry conditions. Due to the short length of the plank, care had to be taken to be sure that the engagement was complete in those tests involving the interaction of depressions and protrusions. These slow speed tests results are summarized in Table 2.

In the first series of experiments, plain and patterned tires are compared on both plain and patterned surfaces. Since the tread compounds are somewhat different in the two tires the results from plain to patterned tire may not be compared directly, but each tire may be observed to react differently on the plain and patterned surface and under dry and wet conditions.

The conclusions which may be drawn from the flat plank drag data are as follows:

1. The patterned tire running on the patterned surface gives by far the highest available friction coefficients of any of the combinations tested, being approximately twice as great as the coefficient obtained with the smooth tire on the same surface.
2. Under conditions of wet traction the interactive tire on the patterned surface shows no loss of friction coefficient. This is the only combination of tire and surface tested which did not show such a loss.
3. From this data we conclude that it should be possible to obtain friction coefficients of the order of one or greater under a substantial speed range using a patterned tire on a patterned surface.

Table 2 Low Speed Peak Coefficients
Steel Surfaces-Flat Plank Data

	Standard Tire		Tire With Depression Pattern	
	Dry	Wet	Dry	Wet
Smooth Runway Surface	0.45	0.37	1.09	0.68
Pattern Runway Surface	0.69	0.55	1.35	1.35

VI. Trailer Experiments

In order to resolve a number of questions concerning the ease of engagement of a patterned tire with a pattern of protrusions on a runway surface, a series of outdoor tests was planned to be conducted at moderate speeds. The apparatus used to do this was a braking trailer designed and built for the University of Michigan by the Texas Transportation Institute. This trailer was towed behind a large truck tractor used for tire testing purposes by the Highway Safety Research Institute at the University of Michigan. The trailer is basically a 3-point device, with a single test wheel and a 2-point hitch at the rear of the tractor. Speeds up to approximately 40 to 50 miles an hour could be obtained with this device. The trailer is equipped with a conventional aircraft brake so that reasonably large brake torques may be applied to the test wheel. A variety of test tire sizes may be accommodated but for purposes of this experiment the 7.00 x 8 tire size was the only one used. This trailer is shown in Fig. 10.

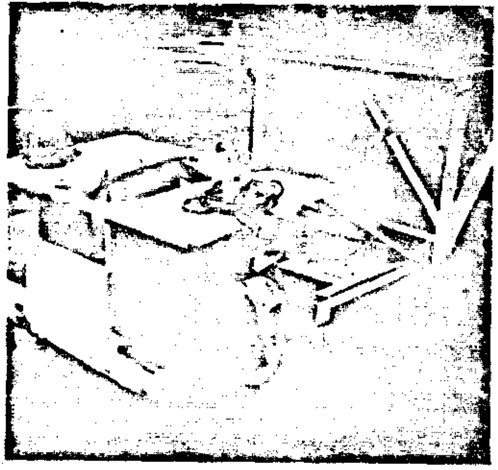


Figure 10. Braking Trailer.

The runway surface was formed by fabricating 20 sections, each 8 feet long, of 20 gage steel sheet to which were spot welded small cylindrical steel slugs as previously described. These were welded to the plate using a spacing template for accurate location of the protrusion pattern. This 160 foot long track was then put down on a normal asphalt highway by bolting with lead anchors to the highway.

Two types of tests were conducted. In the first, the intent was merely to measure the distance needed for the tire with depression pattern to come into complete register with the pattern of positive protrusions on the runway. The method for measuring this distance was a particularly simple one. Small flexible plastic capsules of a water soluable paint were bonded to the inside of the depressions in the tire tread pattern, at the bottom of these depressions. This meant that the tire could run normally on the flat runway surface without breaking the paint filled capsules, and further could run out of register on the patterned surface without breaking them. As soon as register occurred, however, the cylindrical protrusion entered the depression far enough to rupture the paint capsule, leaving a definite spot of paint on top of this protrusion. This method proved very effective in measuring the distances needed for engagement. These are compared in Table 3 with the calculated distance based solely upon the geometry of the protrusion and depression surfaces, using Eq. (6). From the comparison of the experimental results and the calculated results given in Table 3, one may conclude:

a) The theory of area probability engagement based upon random contact gives results which are the same order of magnitude as those observed in experiment.

Table 3 Comparison of Measured and Calculated Engagement Distances

Run	Conditions	Measured Engagement Distance	Calculated Engagement Distance Using Eq. 6
1	Dry, zero brake torque	8'	$P_e = 0.99$ Distance = 4'
2	"	12'	$P_e = 0.999$
4	Dry, 400 psi brake pressure	3.1'	Distance = 6' based on
6	Wet, zero brake torque	5.6'	D = 0.75 in. d = 0.625 in.
7	"	2.8'	s = 1.25 in.

b) Engagement takes place more rapidly under wet conditions then under dry conditions.

c) Engagement takes place more rapidly with brake torque present than with brake torque absent.

Test data was obtained on a patterned tire running over this protrusion surface on a day in which rain was constant and heavy. Attempts were made to obtain maximum braking force values by adjusting brake energizing pressures upward until tire locking occurred. In general it is not possible to locate peak forces in this way since the various runs had to be conducted at fixed levels of brake pressure. The results of these tests are given in Table 4, and from that table it may be seen that the patterned tire operating on the wet surface of protrusions gave friction coefficients at least twice as great as those obtained with the same tire operating on wet asphalt. The asphalt in question was a relatively coarse textured asphalt and was judged by feel to be above-average to excellent in its frictional characteristics.

It should be noted that the improvements demonstrated in Table 4 were accomplished by use of a cylindrical depression pattern only 3/16 of an inch high, one that could be incorporated into a relatively small 7.00 x 8 aircraft tire by recapping the tire without changing the tire carcass in any way.

Care should be taken in interpreting the comparison of the calculations in Table 4 with the measured values. The calculations indicate that the friction effect added by the presence of the protrusion pattern is 1012 pounds as indicated in the last column. The influence of the inherent friction coefficient between the tire surface and the wet metal plate at the speeds indicated is not known, but in any event there would be some friction contribution from that source. Therefore it appears that the theory of Eq. (3) would indicate a frictional value somewhat higher than that actually obtained by experiment. Due to the nature of its derivation, Eq. (3) may be thought of as giving an upper limit to the added friction available with the interactive effect.

VII. Tread Pattern and Runway Protrusion Design

The problem of forming the regular geometric pattern of depressions in the surface of an aircraft tire is not a difficult one. The depression pattern proposed here is aligned with the existing groove pattern used to expel water, and should in no way inhibit that function. As a matter of fact, due to the additional open areas present it may actually aid in expelling water in a normal runway surface, so that the pattern used and proposed here may actually be beneficial in regard to wet skid tractive capability when used on normal runway surfaces. It may, however, exhibit slightly greater rates of wear. This is as yet unknown and must wait the results of field trials. There is as yet no satisfactory method of measuring aircraft tire tread wear in the laboratory.

Insofar as the runway is concerned, it is clear that it would not be economically possible to manufacture large runway surface areas from metallic constructions such as used here. Their use in this work was simply a matter of convenience in regard to initial development cost. A number of suggestions have been explored for the manufacture of large-scale protrusion patterns which could be used economically in the overrun areas of existing air fields. Perhaps the most feasible suggestion is that of forming a regular grid or lattice work of protrusions from some relatively tough plastic, such as toughened ABS or PVC, and bonding this grid-work surface to the existing runway. The B. F. Goodrich Chemical Corporation has recently developed an extremely high-strength family of toughened acrylic resin adhesives marketed under the name of TAME, and field trials with it have shown that it will retain good bond characteristics over a severe winter cycle. In order to maintain proper geometric spacing, a sheet of plastic could be hot formed and bonded down to the surface quite inexpensively. Fig. 11 shows a photograph of a prototype sheet of the same size as used for the 7.00 x 8 aircraft tire tests. This sheet was formed with the lattice members to provide proper spacing and geometric control only. They are not intended as being structurally functional and could actually be

Table 4 Braking Force Vs. Speed
Patterned Tire Normal Force on Tire 1100 lbs.

Speed, mph	Wet Asphalt	Wet Patterned Surface	Calculation Eq. (3) (See Table 1)
20		1100	
30	450	1000	> 1012
40		900	

considered as disposable. It would not be necessary to bond them to the surface of the runway.

The state of California has used bonded highway center markers and reflectors for some time, and it is recognized that in areas of moderate to mild climate such bonding processes are quite practical with conventional epoxy. It is believed that with the more modern TAME system just mentioned, bonding processes could be carried out successfully anywhere in the United States.

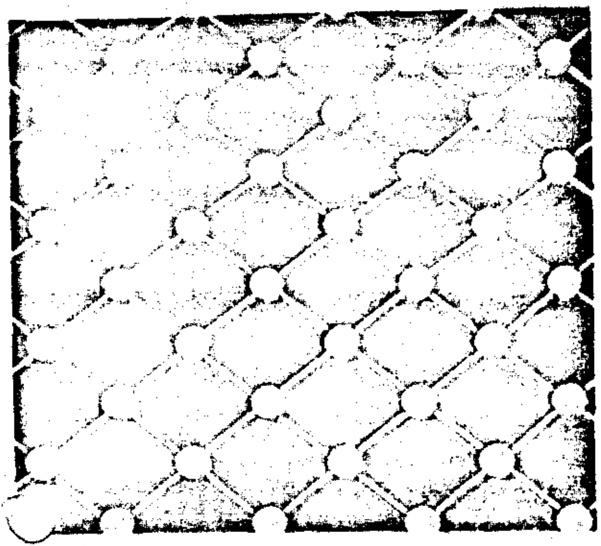


Figure 11. Sample Grid.

VIII. Application

The most important applications for the interaction effect between tire and runway appear to be in those aircraft runway areas where high friction coefficients are very important. Two of these which come to mind immediately are:

- a) Overrun areas at the ends of commercial or military airfield runways.
- b) Landing mats which could easily be formed with such a protrusion surface.

There may be other potential applications where such a high friction surface would be highly desirable, such as a helicopter landing pad on shipboard or other areas where gust, sidewind or ship pitching produces unfavorable aircraft landing conditions.

While the full scale characteristics of such a system in large commercial ces still must be investigated, there does not seem to be any particular advantage to using the interaction system discussed here over an entire airfield runway. Its use appears to be most important in overrun areas where the availability of high friction coefficients under all climatic conditions could be assured. From the data presented, it appears that this could in fact be accomplished and that such a system would be effective in preventing overruns on either military or commercial aircraft. Further developments must await larger scale test work.

IX. Acknowledgments

During the course of this work many associates aided the author immeasurably. I would especially like to thank Richard Dodge, Robert Wild, Richard Larson, Ming Loo and George Nybakken for aid in obtaining tire force data, Herman Steigerwald of Thompson Aircraft Tire Company for manufacturing special tires, Joseph Brusse of Texas Transportation Institute for construction of the braking trailer, and Dr. Dwight Loughborough of B. F. Goodrich Tire Company for the benefit of his many years of tire experience. Finally, particular credit should go to the National Aeronautics and Space Administration from whom funds were obtained for construction of the braking trailer and patterned tires under Grant NGL-23-005-010.