# EXPERIMENTAL STUDIES OF TIRE SHEAR FORCE MECHANICS --

## A SUMMARY REPORT

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This summary report is a digest of findings from an experimental investigation of the mechanics of tire shear force generation under general conditions of steering and braking. The investigation was conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan under the sponsorship of the Office of Vehicle Systems Research of the National Bureau of Standards.

## INTRODUCTION

In operation, the tire is required to carry a vertical load, absorb bumps and shocks without failure, be durable, and provide lateral and longitudinal traction forces. In severe vehicle maneuvers related to accident avoidance, the lateral and longitudinal tire forces are extremely important. These forces are determined by an exceedingly complex set of events which take place in the contact patch between tire and road. To date, there is no complete or totally satisfactory model of tire shear force generation. Recently, however, three simplified theoretical analyses of the mechanics of tire traction under steering and braking conditions have been performed [1,2,3]. The derivative mathematical models, which agree qualitatively with each other and with experimental data, express the longitudinal and lateral forces on a given surface at fixed vertical load as functions of longitudinal and lateral slip (slip angle).

During a severe maneuver, the longitudinal slip, slip angle, and vertical load of a vehicle's tires vary widely and hence cause great variation in the longitudinal and lateral tire forces. How these forces develop determines whether the vehicle turns and stops under control, spins, or skids straight ahead. The tire shear force representation developed by HSRI has been incorporated in a comprehensive vehicle simulation and employed to quantitatively analyze the influence of tire traction characteristics on vehicle behavior [1]. This simulation has also been used to evaluate the influence of anti-lock braking control systems on vehicle directional stability [4] and to study the limits of vehicle response to steering and braking inputs [5]. Clearly, the degree of validity of the developed tire model has obvious and important implications relative to the accuracy of these simulation results.

Under NBS Contract No. CST-928-5, HSRI has gathered and analyzed a comprehensive body of structured data on the development of tire shear forces over a wide range of operating conditions. The data were obtained using two complementary pieces of test equipment: a laboratory-installed flat bet tester (FBT) permitting precise control of test conditions at low speed, and a vehicle-towed mobile tire tester (MTT) providing a capability for over-the-road measurements at realistic highway speeds. Complete descriptions of these two tire testers appear in Ref. 6. A detailed account of the conduct and findings of the experimental program will appear in a subsequent publication.

The purpose of this report is to provide a concise summary of the experimental findings and to make specific recommendations for future research directed towards the development of a scientific basis for the characterization and specification of tire traction performance.

## SUMMARY OF EXPERIMENTAL RESULTS

### A. Combined Slip and Slip Angle Data from the Mobile Tire Tester

The mobile tire tester provides the unique capability of on-the-road measurements of tire shear forces under combined slip and slip angle operation at highway speeds. The data presented here was obtained by lowering a tire onto the road at a fixed slip angle and varying the test wheel speed from free rolling to lockup by an electro-hydraulic control system. Each of the curves presented in Figures 1-10 is the average of five replications. They have been selected from a much larger set of curves to illustrate the type of results obtained.

Dry Concrete Data. Figure 1 shows the results obtained for a belted bias tire with a forward MTT speed of 30 mph, with the tire set at 0°, 1°, 2°, 4°, 8°, and 16° slip angles. The great influence of slip angle on longitudinal force, that is, braking force in the wheel plane, is apparent. As the slip angle is increased, the peak of the longitudinal force versus slip curve occurs at higher values of slip. At high slip angles the peak longitudinal force is obtained at lockup. The large reduction in lateral force caused by increasing longitudinal slip can be seen in Figure 1.

Figures 2 and 3 show similar results for a radial tire and a cross bias tire. For both of these tires, as with the belted bias tire, the lateral force falls off with increasing slip and the peak of the longitudinal force versus slip curve becomes less pronounced as slip angle increases.

Since the data in Figures 1 through 3 were collected on different days with varying temperature and humidity and on different sections of roadway, they do not constitute an appropriate basis for quantitative comparisons of tire qualities. Further, the three tested tires differ in tread compounds and tread patterns, as well as in carcass construction. The data are intended only to illustrate qualitative variability in tire shear force performance. In Figure 4, the 0° and 16° slip angle data for all three tires have been plotted on the same graph to emphasize the wide range of results possible.

For the radial tire and the belted bias tire, the form of the tire force curves does not change with velocity. For the cross bias tire, a lower peak and a higher sliding longitudinal force were obtained at 50 mph than were obtained at 30 mph. This result is illustrated in Figure 5.

Wet Surface Conditions. The mobile tire tester carries a supply of water and has a pump and nozzle system for wetting the road ahead of the test tire. The nozzle opening is changed

| S | Fy@4°/1000 |
|---|---|
| 0 | .6 |
| .2 | .4 |
| .3 | .29 |
| .5 | .17 |
| 1.0 | .09 |

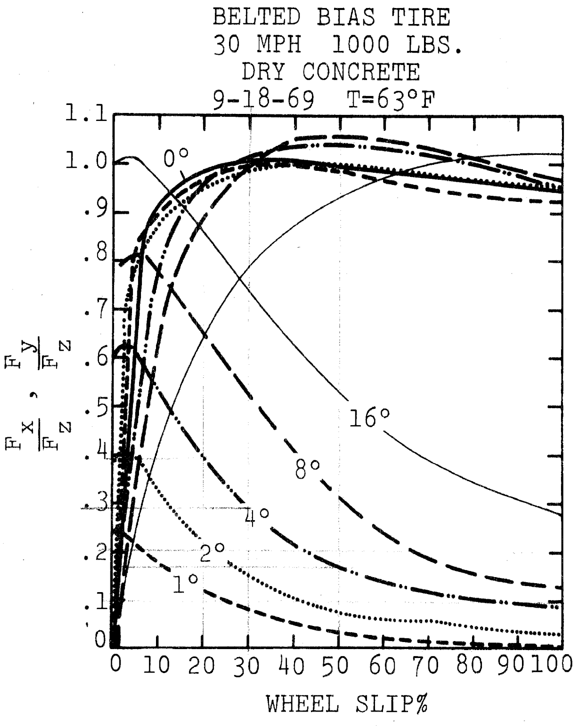

BELTED BIAS TIRE
30 MPH 1000 LBS.
DRY CONCRETE
9-18-69 T=63°F

Figure 1

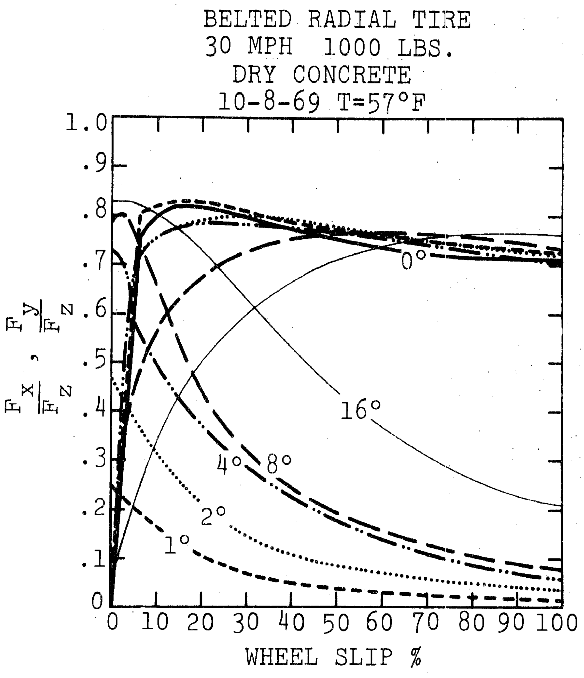

BELTED RADIAL TIRE
30 MPH 1000 LBS.
DRY CONCRETE
10-8-69 T=57°F

Figure 2

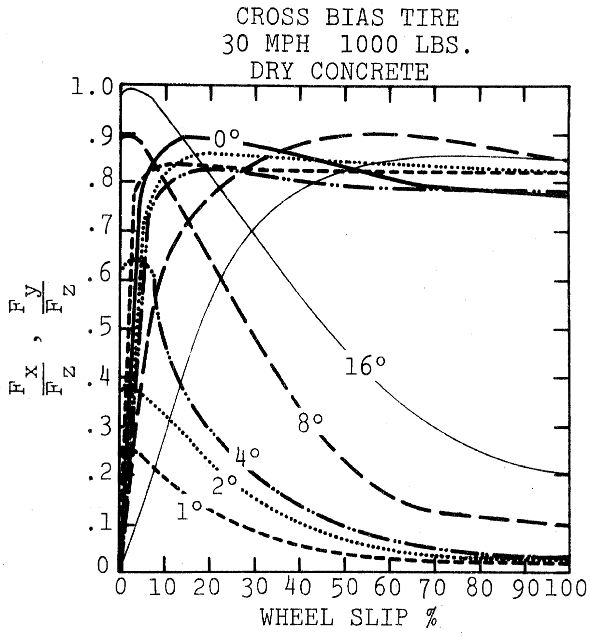

CROSS BIAS TIRE
30 MPH 1000 LBS.
DRY CONCRETE

Figure 3

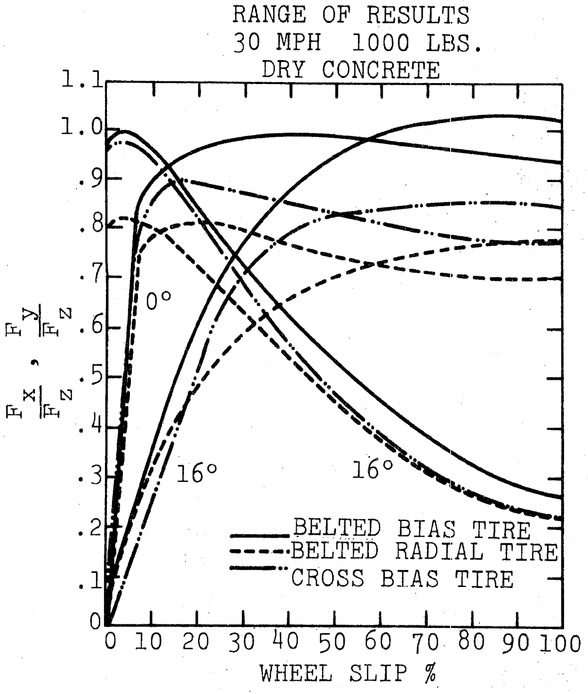
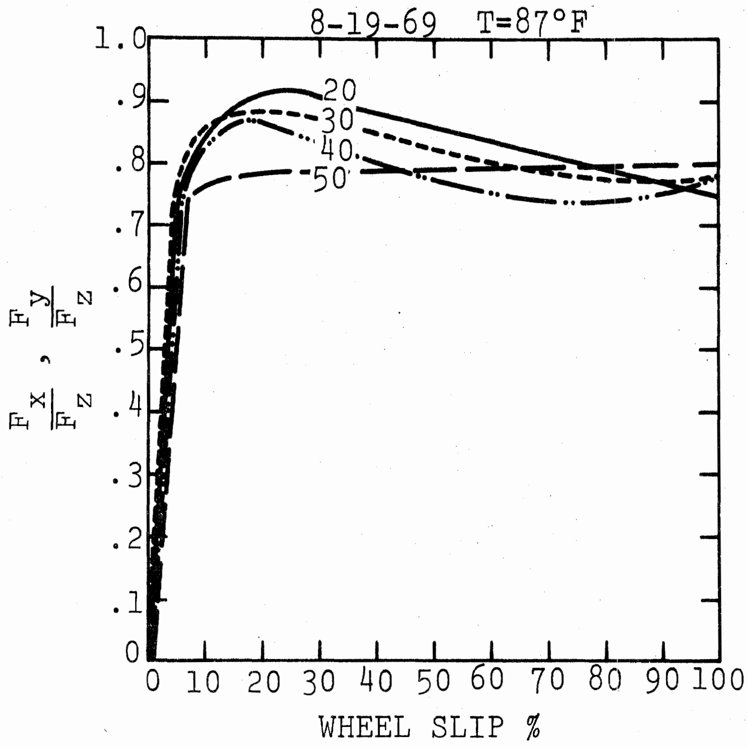

RANGE OF RESULTS
30 MPH 1000 LBS.
DRY CONCRETE

Figure 4



CROSS BIAS TIRE
0° 1000 LBS.
DRY

Figure 5

with test vehicle speed to lay water to a depth of about 0.02". Data for each of the three types of tires operating on wetted concrete are shown in Figures 6, 7, and 8.

As expected, the peak longitudinal force on the wet road is lower than on the dry road, though the loss is only 10 to 15%. The falloff of longitudinal force beyond the peak is much more pronounced on the wet concrete surface than on the dry concrete. The lateral force at zero slip reaches a maximum at a slip angle of 16° or less on the wet surface. In general, the same type of performance was obtained on the wet concrete as on dry concrete, with the exception that the longitudinal force falls off more rapidly with slip.

Figure 9, like Figure 4, is included to show the wide range of results obtained for the three different tires.

BELTED BIAS TIRE
30 MPH 1000 LBS.
WET CONCRETE
9-18-69 T=63°F

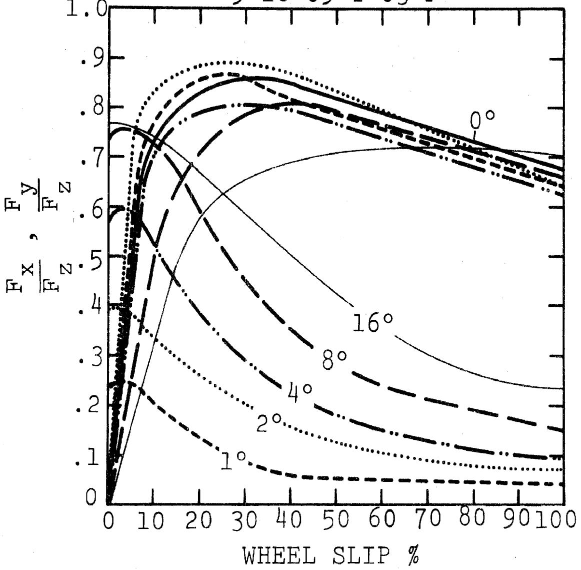


Figure 6

BELTED RADIAL TIRE
30 MPH 1000 LBS.
WET CONCRETE
10-8-69 T=57°F

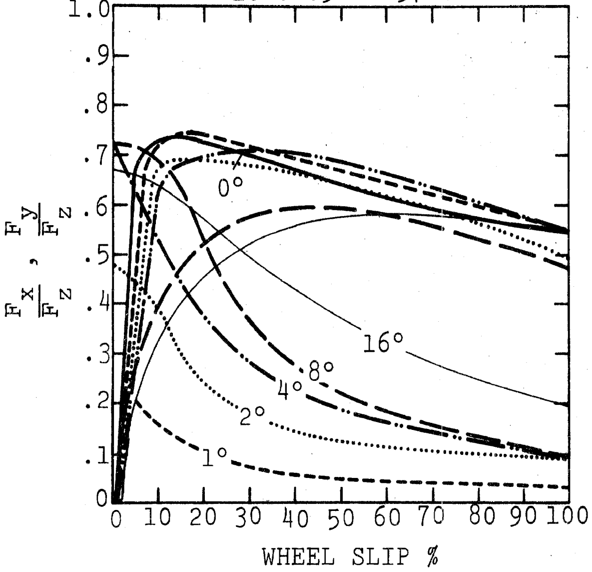


Figure 7

CROSS BIAS TIRE
30 MPH 1000 LBS.
WET CONCRETE

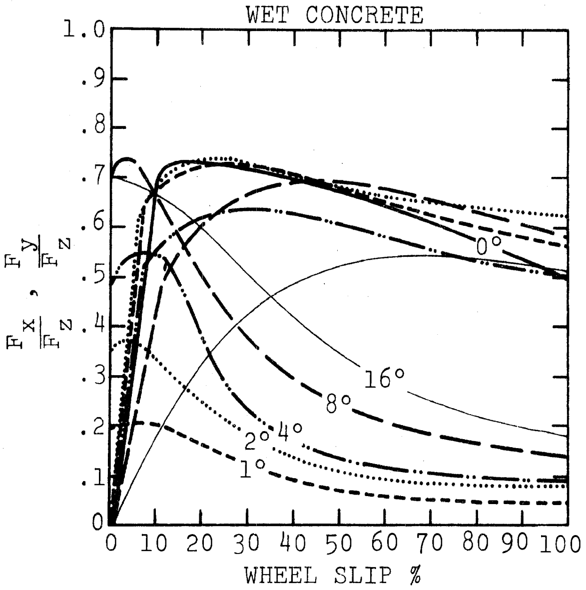


Figure 8

RANGE OF RESULTS
30 MPH 1000 LBS.
WET CONCRETE

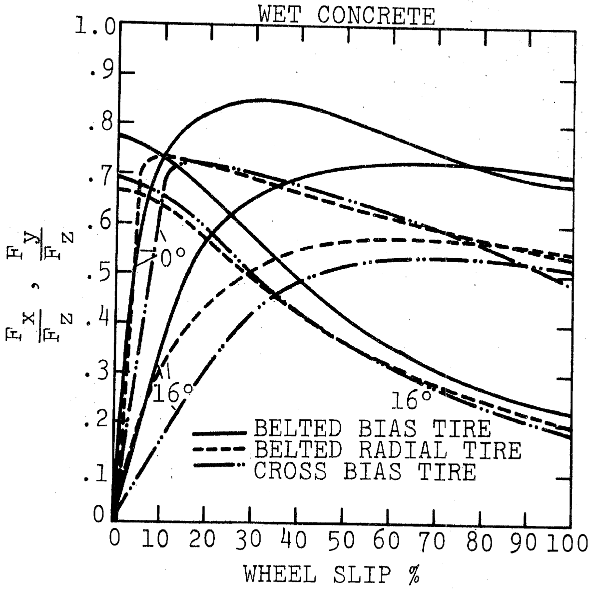
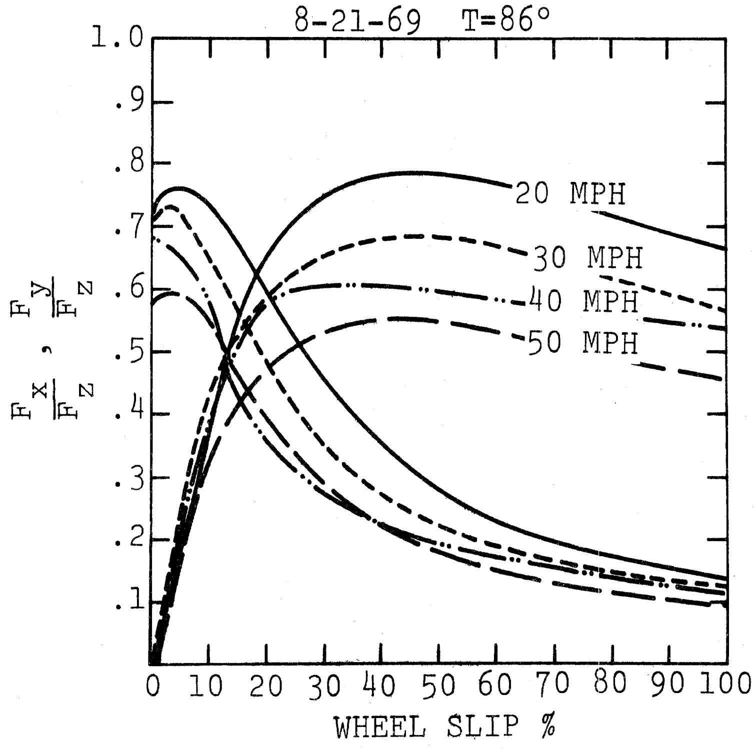


Figure 9

Typical data illustrating the influence of velocity on wet surfaces are presented in Figure 10. Similar results were obtained for all three types of tires.

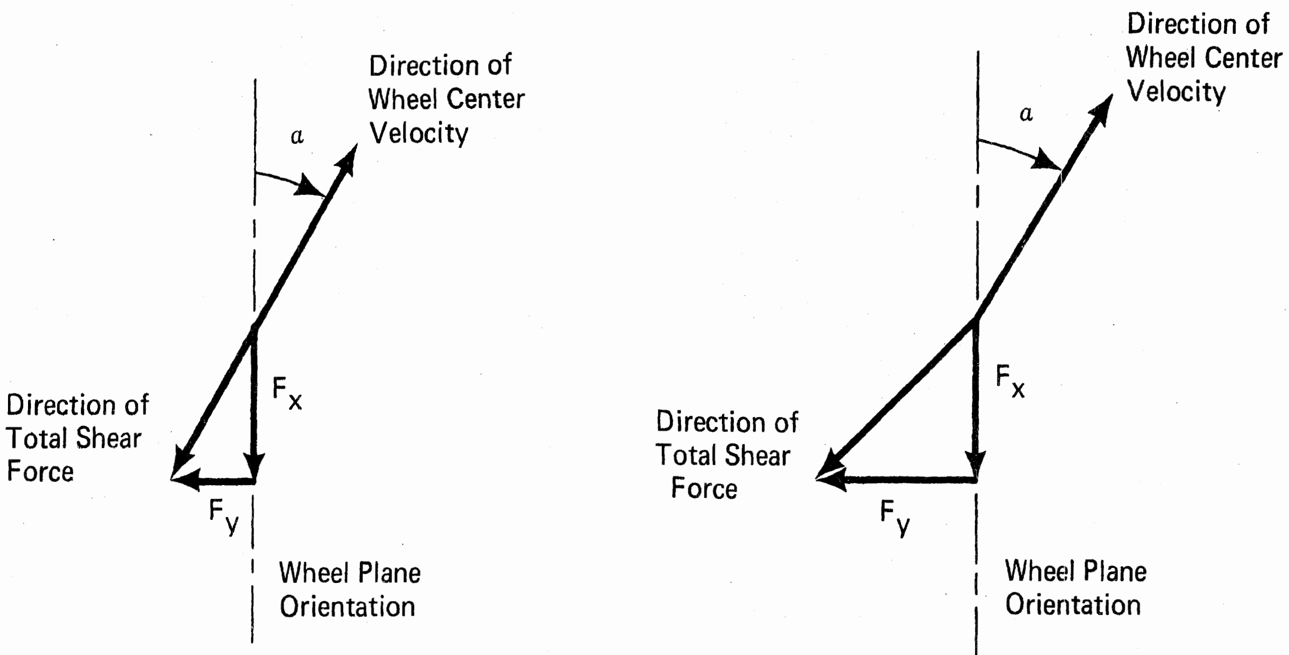


CROSS BIAS TIRE
8° 1000 LBS.
WET CONCRETE

Figure 10

## B. Experimental Results for Locked Wheels

In Part A, experimental data are presented for longitudinal slip, s, ranging from 0 to 1.0 (0 to 100% wheel slip). Locked wheel operation of the tire corresponds to s = 1.0. For the locked wheel condition (at any slip angle $\alpha$), the sliding velocity at every point in the contact patch between tire and road is the same and the direction of sliding corresponds to the slip angle of the tire. If the frictional characteristics of the tire-road interface are isotropic, then the tire shear force will oppose the direction of sliding as shown in Figure 11a. In this case, $F_y/F_x = \tan \alpha$.



a. Isotropic, $\mu=\mu_x=\mu_y$

b. $\mu_x \neq \mu_y$

Figure 11. Directional Characteristics of Tire/Road Friction

If the resultant shear force does not oppose the direction of sliding, then, as shown in Figure 11b, $F_y/F_x$ does not equal $\tan \alpha$. Thus the quantity $F_y/F_x \tan \alpha$ equals 1.0 if the total shear force opposes the direction of sliding and does not equal 1.0 otherwise. Table I is a tabulation of $F_y/F_x \tan \alpha$ values computed from data for locked wheels towed at slip angles of 8° and 16°.

These results indicate that the direction of tire shear force is not collinear with the direction of sliding on a wet surface. This may be due to the tread pattern and the difference between longitudinal and lateral wiping action on the wet road. Clearly, the difference in the direction of shear force between wet and dry roads is very large. On the wet road, $F_y$ is much larger than

## TABLE 1

## RELATION OF THE DIRECTION OF LOCKED WHEEL SHEAR FORCE TO THE DIRECTION OF SLIDING

AVERAGE VALUES, V = 20, 30, 40, 50 MPH; $F_z$ = 1000 LB.

| $\frac{F_y}{F_x \tan \alpha}$ | DRY CONCRETE | WET CONCRETE | WET TRAFFIC PAINT* |
|---|---|---|---|
| CROSS BIAS | .9 | 1.5 FOR 8°<br>1.3 FOR 16° | 2.6 FOR 8°<br>2.0 FOR 16° |
| BELTED BIAS | 1.0 | 1.6 FOR 8°<br>1.3 FOR 16° | 2.4 FOR 8°<br>1.6 FOR 16° |
| RADIAL | 1.0 | 1.3 FOR 8°<br>1.1 FOR 16° | 2.3 FOR 8°<br>1.9 FOR 16° |

$F_x \tan \alpha$, indicating that the ratio of lateral force to longitudinal force is greater on a wet road than on a dry road.

## PARAMETERS FOR CHARACTERIZING TIRE TRACTION PERFORMANCE

One goal of our theoretical and experimental investigations of tire mechanics is to characterize the shear force performance

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*The HSRI test facility at Willow Run Airport has a specially prepared strip of asphalt which has been painted with traffic paint. When wet, this surface has low friction and water does not drain through it easily. Although this type of surface is artificial, it provides a relatively low coefficient of friction which is easy to maintain.

of a tire in terms of a few carefully selected parameters that can be conveniently measured. By means of these parameters, and formulae (characterizing functions) relating them to shear force output, we are attempting to obtain a mathematical description or prediction of performance that is valid over the full range of operating variables.

In Ref. 1, the tire is characterized in terms of two elastic parameters, $C_s$ and $C_\alpha$, and a "friction expression." For experimental work, the longitudinal elastic parameter, $C_s$, is defined as the absolute value of the slope of the curve of longitudinal force versus longitudinal slip, s, evaluated at $s = 0$, for the slip angle, $\alpha$, equal zero. Similarly, the lateral elastic parameter, $C_\alpha$, is defined as the absolute value of the rate of change of lateral force with respect to slip angle evaluated at $\alpha = 0$ for $s = 0$. For small values of longitudinal slip and slip angle (lateral slip), the predicted tire forces are independent of the friction expression which is used to compute the maximum shear force intensity between the tire and the road. This expression accounts both for the decrease in braking force beyond the maximum of the longitudinal force versus slip curve, and for a decrease in cornering force at large lateral slip. In our previous study [1], a formula expressing friction coefficient as a linear function of sliding velocity was used to obtain tire shear forces in qualitative agreement with experimental results at large values of longitudinal and lateral slip.

Examination of the extensive data collected during the present study leads to the following conclusions relative to tire characterizing parameters and functions:

(1) The cornering stiffness, $C_\alpha$, and the braking (longitudinal) stiffness, $C_s$, are good parameters for representing tire shear force in the low slip angle and longitudinal slip range, respectively.

(2) A parameter (or parameters) characterizing the longitudinal distribution of normal pressure in the contact patch (different for different types of carcass constructions), is needed to describe characteristic differences in shear force performance observed in the 3° to 8° slip angle range.

(3) A large increase in the vertical load carried by the tire results in a significant reduction in the interfacial friction coefficient. This phenomenon should be studied in more detail. None of the three simplified tire models cited previously treats the influences of vertical load adequately.

(4) The maximum shear force potential at the tire-road interface (friction coefficient) generally varies as a complicated function of sliding velocity and vertical load. A linear function of sliding velocity is adequate for representing the shear forces produced under certain interface conditions.

(5) The longitudinal and lateral tire forces produced at high values of slip on wet surfaces suggest the prevalence of effective longitudinal and lateral coefficients of friction which are unequal in magnitude.

## RECOMMENDATIONS

### A. Work Towards Establishing a Concise Set of Parameters and Characterizing Functions Describing Tire Shear Force Performance Should be Continued

The three models developed in Refs. 1-3 represent a good start towards defining useful parameters and characterizing functions. Based on the research reported here, the test program outlined in Figure 12 is proposed as a means of quantifying tire shear force performance, evaluating specific tire parameters, and refining existing characterizing functions.

| Designation of Test Type | Machine Used | Conditions and Form of Results | Parameters or Characterizing Functions Involved |
|---|---|---|---|
| 1.<br>Determine<br>$C_\alpha$ | FBT | 1. Safety Walk<br>2. Low slip angles, $F_y < .3F_y$ maximum at the $F_z$ used<br>3. 400 lbs $\le \lvert F_z \rvert \le$ 2,000 lbs<br>4. Plots of $F_y$ vs. $\alpha$ at various $F_z$ values | 1. $C_\alpha = \left.\frac{\partial F_y}{\partial \alpha}\right\rvert_{\alpha=0}$<br>and<br>2. $C_\alpha$ vs. $F_z$ |
| 2.<br>Determine<br>$C_s$ | FBT | 1. Safety walk<br>2. Low slip valves such that $F_x < .3\ F_x$ max., e.g., set $F_x$ to $F_z/5$, $F_z/10$, 0, $-F_z/10$, $-F_z/5$, and read slip<br>3. 400 lbs $\le \lvert F_z \rvert \le$ 2,000 lbs<br>4. Plots of $F_x$ vs. s at various $F_z$ values | 1. $C_s = \left.\frac{\partial F_x}{\partial s}\right\rvert_{s=0}$<br>and<br>2. $C_s$ vs. $F_z$ |
| 3.<br>$F_y$ vs. $\alpha$ and $F_z$ | FBT | 1. Concrete slab<br>2. Carpet Plot $F_y$ for $\alpha$ = 2° to 20° and $F_z$ = 400 lbs to 2,000 lbs | 1. A parameter characterizing the pressure distribution |
| $s = 0$ | MTT | 1. Wet and dry concrete surfaces<br>2. $F_y$ for $\alpha$ = 2°, 4°, 6°, 8°, 10°, and 16° at the speeds and loads shown in Chart A | 2. $\mu_y$ vs. $F_z$<br>3. $\mu_y$ vs. $V_s$, wet and dry |
| 4.<br>$F_x$ vs. s and $F_z$ | FBT | 1. Concrete slab<br>2. Carpet Plot $F_x$ for s = 0 to max. possible, $F_z$ = 400 to 2,000 lbs | 1. A parameter characterizing the pressure distribution |
| $\alpha = 0$ | MTT | 1. Wet and dry concrete surfaces<br>2. $F_x$ for $0 \le s \le 1.0$ at the speeds and loads shown in Chart A | 2. $\mu_x$ vs. $F_z$<br>3. $\mu_x$ vs $V_s$, wet and dry |
| 5.<br>Combined<br>$F_x$ and $F_y$ | FBT | 1. Concrete slab<br>2. $F_y$ vs. $F_x$ at $\alpha$ = 2°, 4°, 6°, 8°, 10°, 12°, 16°, 20° for $F_z$ = 400 to 2,000 lbs | 1. Friction rule applied to combined force generation |
|  | MTT | 1. Wet and dry concrete surfaces<br>2. $F_x$ and $F_y$ vs. s for $\alpha$ = 2°, 4°, 6°, 8°, 10°, and 16° at the speeds and loads shown in Chart A | 2. Check on all the other parameters |

Vertical Loads

|  | 600 lbs | 1000 lbs | 1400 lbs |
|---|---|---|---|
| 10 mph | 0 | + | 0 |
| 30 mph | + | + | + |
| 50 mph | 0 | + | 0 |

+ Required

0 Optional

CHART A

Note: FBT = Flat Bed Tester

MTT = Mobile Tire Tester

$\mu_x$ = Longitudinal Friction Coefficient

$\mu_y$ = Lateral Friction Coefficient

FIGURE 12. A PROPOSED TEST PROGRAM

The proposed test program is divided into five test series. The first two test series are intended to evaluate the low shear force (normal driving) performance of the tire. The next two cover lateral and longitudinal force separately, but involve almost all of the conditions to which a tire is likely to be subjected during severe vehicle maneuvers on a level surface. Finally, combined longitudinal and lateral force characteristics are considered in the fifth category.

The machine used, the test surface, the range of test conditions, and the form of the output data are listed for each type of test. The final column in Figure 12 indicates the parameter or characterizing function which would be evaluated from each particular test.

## B. Attempts Should Be Made to Develop Procedures for Grading Tire Traction Performance in Terms of a Selected Subset of the Parameters and Characterizing Functions Mentioned in Recommendation A

Since tire traction is dependent upon many variables, no one simple parameter or measure would be adequate to equitably rate differences in tires. Those parameters and characterizing functions most important in accident avoidance maneuvers such as a stop, a swerve, and a combined stop and swerve, should be selected for rating tire traction.

Also, since the tire must operate under a wide range of conditions and of input commands, one tire can be superior in some qualities and relatively inferior in others. Thus, again, more than one measure is needed to adequately rate the different types of tire shear force performance.

A proven working set of tire parameters and characterizing functions is not available now. In the last column of Figure 12, a possible set of parameters and characterizing functions is indicated. They are: $C_\alpha$, $C_s$, a parameter for characterizing the pressure distribution; $\mu_y$ and $\mu_x$ as functions of $V_s$ and $F_z$; and a friction rule which applies to combined longitudinal and lateral force conditions.

Means for deducing the pressure distribution parameter and $\mu_y$ and $\mu_x$ from the experimental results have not been developed yet. Use of the proposed approach is highly dependent upon devising simple tests to evaluate the necessary tire parameters and characterizing functions.

### C. Efforts Should Be Made Toward the Development of a Detailed Model to Aid in the Understanding of How Shear Force is Generated by the Tire

In a previous publication [7], Frank and Hofferberth discussed basic philosophical and conceptual considerations of the mathematical modeling of tire traction mechanics. In particular, they distinguished between two basic approaches: (1) a detailed formulation proceeding from a microscopic examination of material properties and mechanics, and (2) a simplified approach employing "physical-equivalent" models on a macroscopic scale (e.g., the stretched string concept). They pointed out the limitations of the simplfied approach, but concluded that the computational difficulties associated with any sufficiently comprehensive detailed model probably ruled out the feasibility of that approach given the analog and digital computer technology of the day (1967). In the short time since, the hybrid computer has been developed into a uniquely powerful tool for solving partial differential equations. The iterative and storage capabilities of the hybrid computer allow time sharing of analog equipment which in turn makes the solution of detailed finite element models of continuous systems practical. It now appears appropriate to attempt to exploit the new hybrid technology to implement a detailed finite element tire model. Such a model (if successfully developed) would provide real insight into the mechanisms of shear force generation and would serve as a useful reference for evaluating simplified representations such as the HSRI model presented in Ref. 1.

## ACKNOWLEDGMENT

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