SUGGESTED RESEARCH STUDIES ON THE RATIONAL DESIGN AND SPECIFICATION OF MOTORCYCLE TIRES

Transportation Safety Department

Calspan Corporation

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INTRODUCTION

Over the past several years, Calspan Corporation's efforts on two-wheel vehicles have included both analytical and experimental studies and have dealt with a variety of design and performance questions. One of the aspects of special interest has been that of tire requirements - the subject of this note.

Calspan's activities in the analysis and evaluation of single track vehicles began in 1969 with the development, internally, of an eight-degree-of-freedom mathematical model of bicycle dynamics. This model has, over the ensuing years, been expanded and used for developing computer simulations for both bicycles and motorcycles.

Our first externally sponsored work in two-wheeled vehicles was for the National Commission on Product Safety. The purpose of this study was to identify and measure the critical design parameters associated with motions in the vertical plane and the handling qualities of bicycles (Ref. 1).

Early in 1971 Calspan performed its first study for the Schwinn Bicycle Company. This program was concerned with the further development of Calspan's two-wheeled vehicle simulation and the use of the simulation in determining the influence of design parameters on bicycle stability and control (Refs. 2 and 3).

While this work was going on we carried out a second program for the government - in this case for the Bureau of Product Safety of FDA/HEW. The program was concerned with the safety performance of tricycles and mini-bikes (Ref. 4).

Our first externally sponsored work on motorcycles was performed for the Harley-Davidson Motor Company. In this program a sophisticated computer simulation for motorcycle dynamics was developed from the earlier internally supported work. The simulation was used to investigate the influence of several motorcycle characteristics on weave instability at high speed (Ref. 5).

This initial effort for Harley-Davidson has been followed by several others. We performed a study during the fall of 1973 of the weave phenomenon as it applied to a particular prototype design. The next group of studies performed for Harley-Davidson included performance tests of tires on our advanced Tire Research Facility, (TIRF), full-scale validation testing of the FLH 1200 motorcycle and continued computer simulation studies. Recently we have conducted an additional tire test program for H-D and are currently doing another weave phenomenon investigation on the computer (Refs. 6, 7 and 8).

As in the case of our motorcycle work our bicycle work for Schwinn continued after the initial 1971 program. A second major study was completed in 1973. The study involved experimental work, analytical effort, and computer simulation. It was during this program that initial effort was put into developing simplified linear theory tools for two-wheeled vehicle analysis (Ref. 9).

Also completed in 1973 was a comparative evaluation of the Schwinn Continental and Continental-based Sprint bicycles. Our most recent program with Schwinn included the simulation of a transient handling task, parameter variation studies, bicycle tire testing and an investigation of bicycle frame flexibility (Refs. 10 through 13).

In all of the above work Calspan's computer simulations of bicycle and motorcycle dynamics have figured prominently. Relevant material on these and other aspects of Calspan's two-wheeled vehicle work can be found in three Calspan publications in the open literature (Refs. 14-16).

Most recently, we have completed a study of motorcycle response characteristics and handling qualities for the NHTSA in conjunction with its general program for improving the accident avoidance capabilities of these vehicles. This work involved both simulation and full-scale experimental approaches, the measurement of motorcycle physical characteristics and tire performance data, and the analysis of machine-rider interactions. The outputs of this study are, to a large degree, the background for the new research which is suggested here (Ref. 17).

Throughout these studies, the need for tire performance data and for a clear understanding of the complex interactions of the tire and machine parameters has been evident. The purpose of this note is to describe some of the information which has been accumulated and to outline new work which is needed to provide a rational basis for design and selection of motorcycle tires.

TECHNICAL DISCUSSION

As indicated in the Introduction, Calspan Corporation has conducted several research programs in recent years involving acquisition of motorcycle tire performance data. The results of this work have led to the identification of certain desirable characteristics in tires and the recognition of areas where more information is needed in order to assure good matching of tire-motorcycle characteristics. Through the next few pages, examples of available information are presented. These are followed by discussions of pertinent tire characteristics and their influence on motorcycle system design and performance.

To date, some 30 motorcycle tires have been tested on Calspan's Tire Research Facility (TIRF) to obtain a variety of performance data. Since the purposes of all of the tests were not necessarily the same, complete information for comparison purposes is not available at this time, but the ranges of design parameters and operating conditions are sufficient to illustrate trends and indicate nominal performance characteristics. The tire design parameters covered are:

Diameter (inches):	16 to 21
Width (inches):	2.75 to 5
Tread:	ribbed, universal, trials
Manufacturer:	5

Operating conditions covered are:

Inflation pressure (psi):	16 to 31
Speed (mph):	up to 90 mph (most tests were performed at 30-35 mph)
Normal load (lbs.):	125 to 700
Surface condition:	dry (limited wet surface data are also available)
Slip angle range (deg.):	+1 to -8
Inclination angle range (deg.):	up to 50

The primary performance measurements which were made are the three forces (traction, side force and normal load) and the three moments (overturning moment, rolling resistance moment, and aligning torque) in the standard SAE tire coordinate system. In addition, measurements of relaxation length and radial and lateral force runout were made in some cases. The basic measurements were then used for computing the performance characteristics of interest - cornering stiffness (C_α), camber thrust stiffness (C_γ), and pneumatic trail, for instance.

In the applications to date, we have had no occasion to analyze these data in the broad sense of an evaluation of the motorcycle tire state-of-the-art. For the purposes of this note, however, we have made some preliminary checks to determine ranges and trends of performance characteristics. These show values of cornering stiffne s coefficient (C'_α) ranging from .11 to .33 lbs/deg/lb and of camber thrust fficient (C'_γ) from .006 to .025 lbs/deg/lb. Values of pneumatic trail range as little as .4 inches up to nearly 2.0 inches. Relaxation lengths fro o 8 inches have been measured. Other interesting relationships are sh n in the following figures.

Figure 1 shows a typical motorcycle tire carpet plot as obtained on Calspan's Tire Research Facility (TIRF). In this case, the test variables of interest are slip angle (α), inclination angle (γ), and total side force (F_y) - all measured at a constant value of normal force (F_z). These data may be transformed into values for cornering stiffness coefficient (C'_α, equal to $F_y/\alpha/F_z$ computed about the $\alpha=\gamma=0$ point) and camber thrust coefficient (C'_γ, equal to $F_y/\gamma/F_z$ computed about the $\alpha=\gamma=0$ point). For the data shown, these computed values are $C'_\alpha = .18$ and $C'_\gamma = .0155$ with dimensions of lb/deg/lb.

Figure 2 shows distributions of the side force performance coefficients for the three tire tread types, independent of tire size. The coefficients, however, do reflect nominally rated load and recommended inflation pressure conditions (based on the motorcycle manufacturer's recommendations). The high C'_α values for the ribbed-type tire shown are typical for lightly loaded front tires on small machines. Note the apparently low value of C'_γ for the trials-

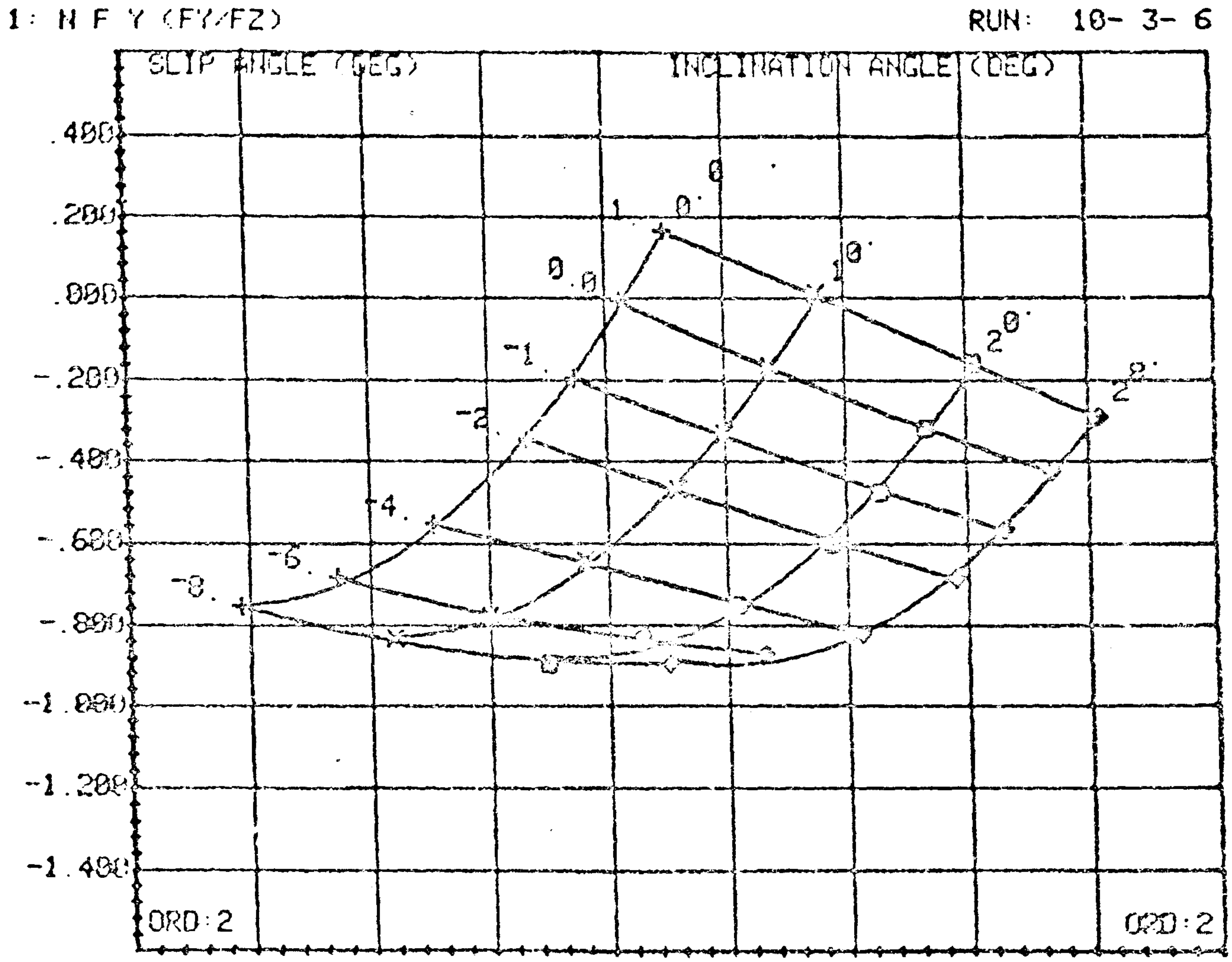
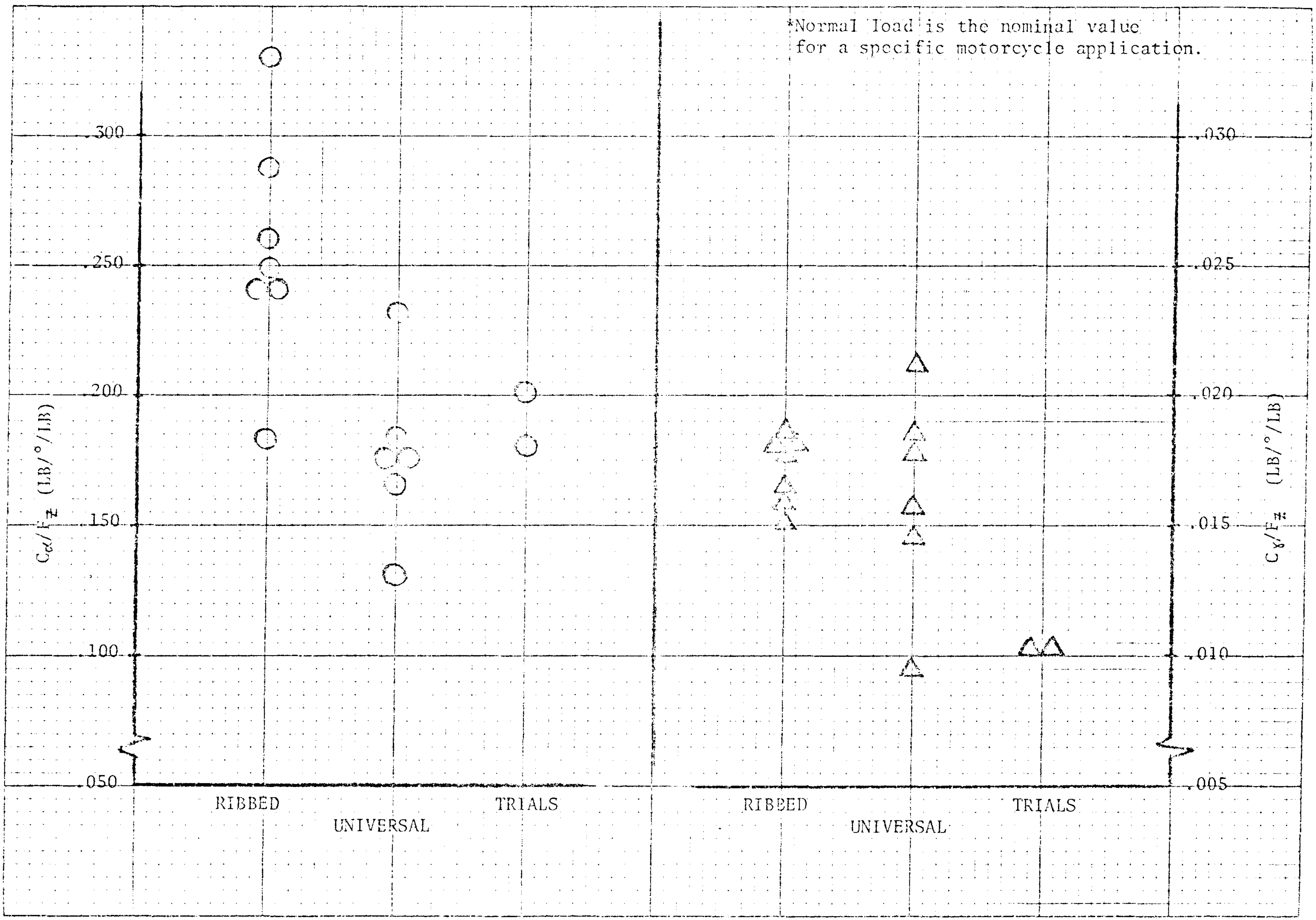


FIGURE 1. TYPICAL MOTORCYCLE TIRE CARPET PLOT

FIGURE 2. INFLUENCE OF TREAD PATTERN AT NORMAL* LOAD AND PRESSURE, 30 MPH



type tires (admittedly, only a small sample) and the close grouping of the value for this coefficient for ribbed tires near the theoretical value of the tangent of one degree (.0175). The significance of this value can be seen in the following.

It can be shown that to a first approximation the sideslip angle of the motorcycle body (i.e. frame) is given by:

$$\beta \approx \frac{b}{R} + A_y \frac{W_R}{C_{\alpha R}} \left[1 - (1 + G) \frac{C_{\gamma R}}{W_R} \right] + \varphi_R \, \theta \, \frac{C_{\gamma R}}{C_{\alpha R}}$$

where: β = body slip angle, radians
b = c.g. to rear axle, ft.
R = radius of turn, ft.
A_y = lateral acceleration, g
W_R = rear axle weight, lbs.
$C_{\alpha R}$ = rear tire cornering stiffness, #/rad (negative)
G = a gyroscopic effect, dimensionless
$C_{\gamma R}$ = rear tire camber stiffness, #/rad
φ_R = rider lean angle, rad
θ = rider lean gain, dimensionless

If rider lean is set to zero and the small gyroscopic term, G, is ignored (it is of the order of .05) it can be seen that when $\frac{C_{\gamma R}}{W_R}$ = 1 the slip angle is independent of A_y and takes on a constant positive value, $\frac{b}{R}$. This in turn means that the machine noses out of the turn at all speeds. This arises from the fact that camber thrust provides all of the rear tire side force - no tire slip angle is needed.

Since $\frac{C_{\gamma R}}{W_R}$ is the camber thrust coefficient in #/rad/# the equivalent critical value in degree units is 1/57.3 = .0175.

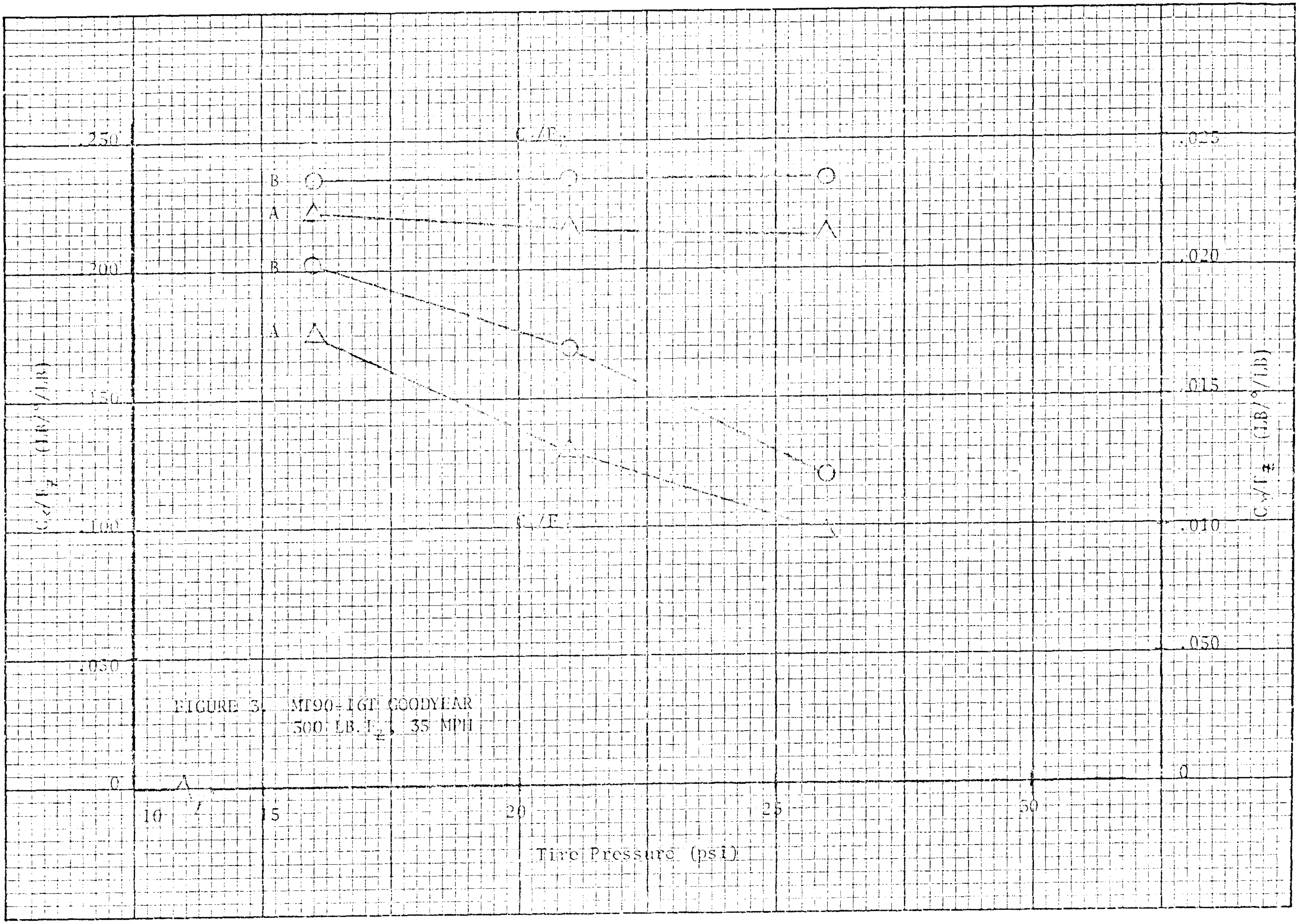


FIGURE 3. MT90-16T GOODYEAR
500 LB. F_z, 35 MPH

The above expression also demonstrates that constant rider lean (ϕ_R) provides a bias on the Akermann value $\frac{b}{R}$; since $C_{\alpha R}$ is negative, positive lean tends to reduce the nose-out body slip angle for the critical camber coefficient case.

The above consideration is one of several that can be examined by use of generalized steady-state expressions for other parameters than β - i.e. - steer angle, roll angle, rider input torque, and rider lean.

Figures 3 and 4 show preliminary examples of some design and operational properties/performance interactions for motorcycle tires that are obtainable from currently available data. Figure 3, showing the effect of tire pressure on the side force coefficients, indicates little effect of this variable on the C'_α parameter (within the test range) but substantial decrease in the C'_γ coefficient with increasing pressure for the test load of 300 lbs. This suggests that over-inflation of motorcycle tires can seriously decrease camber thrust and, in turn, require somewhat higher slip angles (and, therefore, sideslip and/or steer angles) in order to obtain sufficient side force for a given cornering acceleration.

Figure 4 shows similar side force data as a function of tire section width for 18 inch diameter tires (of different manufacturer for ribbed and universal tread patterns). Here, the C'_γ parameter is relatively unaffected while the C'_α characteristic decreases as width increases. It should be recognized, however, that the normal loads on the tires as tested have also been increased for the greater widths. A plot of cornering stiffness, i.e. C_α, defined as $\partial F_y/\partial\alpha\ \alpha=0$ (the non-normalized C_α parameter) would show a slightly increasing trend with section width.

These preliminary plots are presented merely to illustrate the type of information which can be obtained from available data. Many other combinations of parameters are possible and useful and one of the steps which is recommended later in this note for further research treats the analysis of our available tire performance data in a more comprehensive study than was possible in this initial examination.

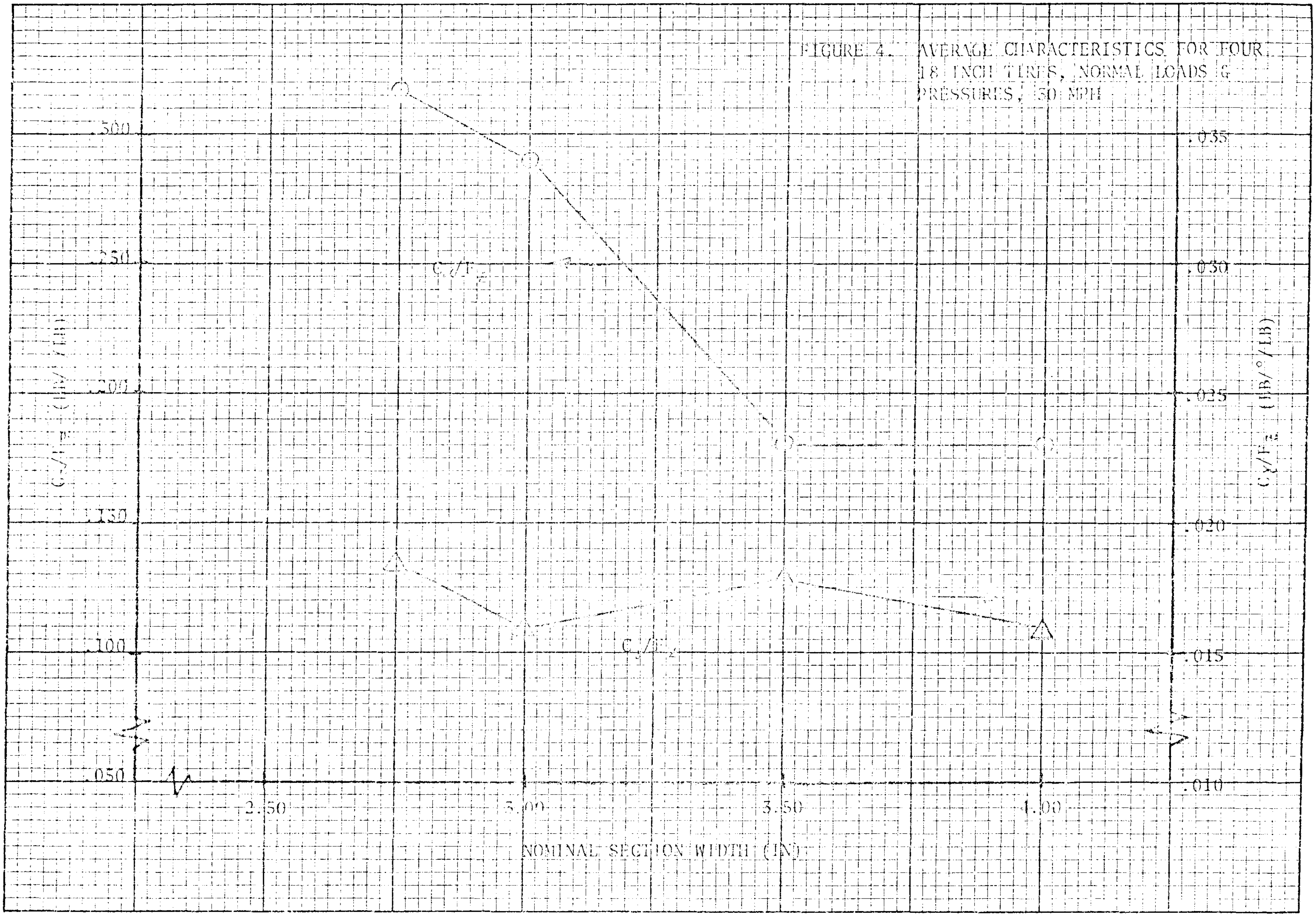


FIGURE 4. AVERAGE CHARACTERISTICS FOR FOUR 18 INCH TIRES, NORMAL LOADS & PRESSURES, 30 MPH

It is important that the role of tire cornering stiffness (C_α) in motorcycle lateral-directional control be understood before examining requirements for suitable tire combinations. For most machines, well over one-half the required side force for cornering is obtained from camber thrust. In fact, on some machines, the side force due to inclination angle (as achieved by the motorcycle in satisfying the roll moment balance requirement in a steady-state turn) may be more than sufficient* for maintaining the turn and would have to be reduced by the development of slip angles producing forces in the opposite direction. In general, for reasonably designed machines under normal operating conditions, the camber thrust developed by the tires will be quite close to that required for cornering so that only very small slip angles (less than one degree) are needed to trim to the desired operating conditions. On this basis, high values of cornering stiffness for motorcycle tires, unlike those for automobiles, are of reduced significance and, similarly, high peak normalized side force performance values (due to slip angle and for dry conditions) provide no substantive advantages.

One of the most important aspects of motorcycle behavior is the variation in the interactions of the tire performance characteristics on the different machines. These variations occur primarily because of the influence of the tire camber thrust on the requirements for the development of tire slip angles to achieve lateral-directional force and moment balance. When the camber thrust from the tires is sufficient to meet side force requirements in cornering, the tire is not required to operate at any slip angle. When the camber thrust is not sufficient, the additional force must be supplied by tire slip angle; when the camber thrust is more than enough, slip angles must be developed which actually reduce the side force to the desired level. This can be demonstrated by the following simplified analysis.

*The critical value discussed earlier is the "just enough" condition.

When a motorcycle is in dynamic equilibrium in a turn, the resultant roll and yaw moments and side force must be zero--the sum of the tire forces must equal the centrifugal force; the yawing moments due to these forces at the front and rear tires about the system c.g. must balance; and the roll moment due to centrifugal force must be equalized by the moment produced by banking the vehicle in a turn. As a first approximation:

$$F_y = 0; \; Ma_y = F_{yf} + F_{yr} \qquad \text{(a)}$$

$$M_z = 0; \; a\,F_{yf} = b\,F_{yr} \qquad \text{(b)}$$

$$M_x = 0; \; Ma_y h \cos\varphi = Wh \sin\varphi \qquad \text{(c)}$$

where:

M = mass of rider-motorcycle system

ay = lateral acceleration

Fyf = front wheel side force

Fyr = rear wheel side force

a = horizontal distance between front wheel contact point and system center of gravity

b = horizontal distance between rear wheel contact point and system center of gravity

h = height of system center of gravity above the ground plane

φ = bank angle (roll angle) of the system with respect to vertical

W = rider-motorcycle system weight; Mg.

The values of Fyf and Fyr are functions of the tire performance characteristics and slip and inclination angles. Again, represented in a simplified manner -

$$F_{yf} \quad C_{\alpha F}\left(\beta + \frac{a}{R} - \delta \cos\sigma\right) + C_{\gamma F}\left(\varphi + \delta \sin\sigma\right)$$

$$F_{yr} \quad C_{\alpha R}\left(\beta - \frac{b}{R}\right) + C_{\gamma R}\,\varphi$$

where:

C_α = cornering stiffness, lbs/deg

C_γ = camber stiffness, lbs/deg

β = sideslip angle, deg

δ = steer angle, deg

σ = rake angle, deg

R = turn radius, ft.

$(\beta + \frac{a}{R} - \delta \cos \sigma) = \alpha_F$, front wheel slip angle

$(\beta - \frac{b}{R}) = \alpha_R$, rear wheel slip angle

If the side force requirements are exceeded by the sum of only $C_{\gamma F}$ and $C_{\gamma R}$ with concurrent satisfaction of the roll moment equation (which can be simplified to $A_y = g \tan \varphi$), the front and rear slip angles must be such that forces opposing those due to inclination angle are developed. In effect, β will be small (and in some cases, as shown earlier, the vehicle may be "nosed out" of the turn--even at high speed) and δ is utilized primarily as a trim device (as contrasted to its use as the primary control mechanism in automobiles) to satisfy the yaw moment balance.

There are several aspects of tire performance which have been recognized with regard to their relationship to automobile handling but which appear to be of greater consequence to the motorcycle. These include:

1. Tire dynamics - as measured by the response time for the buildup of side force following the imposition of a change in operating condition. It is usually characterized by an equivalent distance of travel termed relaxation length.

2. Tire/wheel nonuniformity - variations in side force as a function of tire (wheel) circumferential position. These produce fluctuating disturbance inputs which may excite resonant motions of the vehicle. In particular, free control oscillations of the steering assembly may be initiated from this source.

3. Camber thrust coefficient - because the motorcycle derives a large portion of its side force from camber thrust, information on this parameter is required up to large angles - in the range of 40-50 degrees. Possible discontinuities or abrupt changes in value are significant.

4. Slip angle/inclination angle relationships - the fixed steer lateral-directional control characteristics of motorcycles are significantly influenced by the parameters $\frac{C_{\gamma F}}{C_{\alpha F}}$ and $\frac{C_{\gamma R}}{C_{\alpha R}}$ and their difference. In fact, this effect (which is equivalent to the roll-camber steer effect in automobiles) is the principal understeer term for motorcycles (which tend to be oversteer on the basis of weight distribution and cornering stiffness values alone). Thus, apparently small variations in the values of the individual coefficients may result in substantial change in the value of the term, $\frac{C_{\gamma F}}{C_{\alpha F}} - \frac{C_{\gamma R}}{C_{\alpha R}}$, and thereby change the under/over steer characteristics of the machine. This can be shown with an example taken from the work reported in Ref. 17. The understeer factor, K, is described by the expression:

$$K = -\frac{h_o}{C_o} + (1 + G)\left[\frac{C_{\gamma F}}{C_{\alpha F}} - \frac{C_{\gamma R}}{C_{\alpha R}}\right]$$

where:

h_o = static margin

C_o = a combined tire performance parameter

G = gyrosocpic effect

$C_{\alpha F}$, $C_{\alpha R}$ = tire cornering stiffness

$C_{\gamma F}$, $C_{\gamma R}$ = tire camber thrust stiffness

Values for the first term were computed for several motorcycles to be in the range of -.01 to -.03 (the negative sign indicates oversteering). Values for the second term ranged from +.01 to +.08, indicating the ability to affect the steer characteristics of the motorcycle significantly by proper selection of tire coefficients.

SUGGESTED STUDIES

In the previous discussion, we have described some of the problems associated with the selection of motorcycle tires to assure good stability and control characteristics of the machine throughout its operating envelope and we have indicated the type of information which is available for their solution. The following brief descriptions outline several study tasks which are aimed at acquiring additional perspective.

1. Tire Data Analyses.

Extend the preliminary analyses described in this note, using currently available data, to define trends and values for interactions of tire design and operational variables. Emphasize the evaluation of camber thrust characteristics and analyze the sensitivity of motorcycle response parameters to changes in these characteristics at front and rear. Among the specific topics to be covered would be the effects of high rear camber thrust capabilities on steering requirements, influences of tire parameters on wobble stability, and variation of pneumatic trail as a function of slip angle magnitude.

2. Tire Performance Parameter Variation Study.

The objective of this work would be to examine in some detail the effects of changes in tire characteristics on the values of performance parameters and stability indices for a single motorcycle design. The approach would utilize the Calspan two wheel vehicle dynamics simulation program supported by constant coefficient analyses. Reasonable ranges in such tire factors as C_α, C_γ, pneumatic trail, relaxation length, and load and their combinations (as functions of front or rear location) would be investigated to determine sensitivity of the machine's responses to these changes. The output of the study would be the identification of critical factors and the definition of allowable variations in these factors which would limit changes in the response characteristics to some selected value.

3. Supplementary Tire Test Program

As noted previously, currently available tire data spans a wide range of design, operating conditions, and performance characteristics but, since the data were acquired on several diversified programs, coverage is incomplete with respect to some factors. For example, only a few trials-type tires have been tested and relaxation length data are not available on most of the tested tires. This work would be aimed at testing a number of tires judiciously selected to provide data to fill in gaps in current information so as to enhance the quality of observed performance trends and interactions. A relatively modest program is suggested for an initial effort - perhaps 20 configurations - with the recognition that more complex interactions (the effect of the different types of wear, which occur at the front and rear locations, on the performance parameters, for example) could be investigated at a later time. Test results would be applied in association with current data to evaluate influences on the performance of motorcycles.

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