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16. Abstract

This report describes a study of motorcycle handling qualities, involving both transient and steady-state directional stability and control properties, and the development of test procedures suitable for the evaluation of these properties. The approach used in the study consisted of the application of both experimental (with one machine) and simulation techniques (with six motorcycles) for the identification of the significant physical properties and performance measures with which to characterize the machine's accident avoidance capabilities. Emphasis was placed on evaluating the input-output relationships for the group of motorcycles in a series of constant speed-variable radius (hence, variable lateral acceleration) runs covering a range of cornering capability which encompasses normal operation. The primary test used for evaluating transient maneuvering and rider-vehicle interaction characteristics was the single lane change. Supporting activity involved testing of nine motorcycle tires in eighteen configurations to obtain side force performance data developed through slip angle and inclination angle; measurements of the physical characteristics, including all pertinent dimensions and masses and moments of inertia of major assemblies, for all machines; development of a special-purpose lightweight instrumentation system employing telemetering techniques (enabling the measurement of such variables as applied steering torque and rider lean angle); and the application of simplified analytical models of motorcycle response to provide some insight regarding motorcycle stability and control. Results of this initial handling

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study indicate that substantial differences in the values of several performance parameters (for example, steady state control gains) exist among various motorcycle designs and that tire performance characteristics play a very significant role in the determination of these parameters. It is concluded that the results of the study provide a firm foundation of information on several important aspects of motorcycle behavior and have identified special areas where additional study is required.

FOREWORD

This report describes the work performed by Calspan Corporation for the National Highway Traffic Safety Administration under Contract No. DOT-HS-4-00976. The period of performance of this work was from 28 June 1974 to 30 June 1975. Mr. Donald C. Bischoff was the Contract Technical Manager for NHTSA; Mr. Roy S. Rice acted as Project Engineer for Calspan. Engineering and technical support was provided by members of Calspan's Transportation Safety Department: Mr. James A. Davis (full-scale tests), Mr. Donald W. Hess (motorcycle physical measurements and test instrumentation), Mr. Dennis T. Kunkel (simulation). The authors gratefully acknowledge the cooperation of the staff of the Calspan Tire Research Facility (TIRF) under Mr. K. D. Bird.

The complete report on this work is in two volumes:

Volume I	Technical Report
Volume II	Appendices

This is Volume I which describes all phases of the work. It also contains a brief summary and recommendations for continuing studies of motorcycle handling.

This report has been reviewed and is approved by:

Edwin A. Kidd, Head
Transportation Safety Department

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SUMMARY

Descriptions of the work and discussions of the results of this program are covered in two documents - the final technical report and a separate set of appendices. Observations, results, and conclusions are presented throughout various sections of these volumes together with supporting information and numerical data. This brief summary has been prepared to put the accomplishments of the program in the proper context of its objectives and to highlight specific results and conclusions pertaining to motorcycle accident avoidance characteristics.

In view of the far-reaching objectives of the study - to devise test procedures and performance parameters for use in quantifying motorcycle accident avoidance capability and to evaluate a sample group of machines by simulation methods - and recognizing the rather sparse body of existing information on the subject, it will be appreciated that the study was conducted as a broad initial attempt to identify suitable approaches in several areas. Thus, the program involved review and evaluation of test procedures (as adaptable for use with motorcycles from passenger car practice); identification of objective performance parameters (particularly with respect to differences between motorcycles and passenger cars); analysis of full-scale testing instrumentation requirements (to minimize influences on vehicle response characteristics); application of simulation techniques (including specification of input data requirements, rider representations, and compatability with test procedures); and study of the potential for establishing correlation between the performance characteristics and accident-avoidance capability. In spite of the need for this broadband treatment, significant progress has been made toward achieving the overall goal of improved understanding of motorcycle handling characteristics.

The program methodology consisted of four basic tasks, each with associated analytical effort. These tasks were:

1. Test procedure development
2. Motorcycle characteristics measurement

3. Full scale testing
4. Simulation testing

The development of suitable test procedures was based on current automobile test techniques, with emphasis on devising a few representative maneuvers from which effective discrimination among machines appeared to be practical. Adaptability of these procedures to both full scale testing and to the Calspan motorcycle simulation was an important criterion. The motorcycle characteristics measurement task was performed chiefly in support of the simulation study requirements, but important side results, such as the development of a source of motorcycle tire performance data, were also realized.

Test Procedure Development

Based on previous studies of two-wheel vehicle dynamics at Calspan and elsewhere, it was clear that the necessary contribution of the rider to motorcycle stability over a portion of the operating envelopes of these machines would require special approaches to separate rider and vehicle effects in testing operations. On the other hand, it was considered to be very important to identify some straightforward performance parameters of the motorcycle alone which could be measured (or computed from relatively easily-measured variables). A type of steady-state directional control test was therefore selected. Such tests can be performed in several versions. All provide basically the same information (control gains, response gradients, variation with test conditions such as speed) but differ in selection of independent and controlled test variables. For the purposes of this program, a constant speed test, covering a range of lateral acceleration by traversing circular arcs of different radii, was adopted.

Because of the strong rider-motorcycle interaction mentioned above, a true handling test (i.e., one that involves the man-machine system in a closed loop sense) was also sought. A single lane change maneuver, which represents a regularly-encountered real-life riding situation, was selected. This general maneuver provides a convenient means for investigating various operating conditions (by changing course geometry); it can be reasonably well-controlled to minimize data scatter; it is effective in discriminating among riders (especially at the limit); and the significant test variables are easily measured.

Motorcycle Characteristics Measurement

This task involved two major activities--tire performance testing and the measurement of the physical characteristics of a selected group of motorcycles. Six motorcycles, covering a range of size and type, were chosen for study. These were:

(1) Honda CB 125
(2) Kawasaki F-11
(3) Honda CB 360G
(4) Yamaha 650 XS-2 (1972)
(5) Norton Commando 850 Roadster
(6) Harley Davidson FLH-1200 (Electraglide)

The primary physical properties of these machines were measured for use as input data for the simulation. The measurements included the fundamental dimensions such as wheelbase, rake angle, mechanical trail, and wheel size; weight and mass distribution values for the total vehicle and main assemblies; and selected moments of inertia of the whole machine and major parts. A torsional pendulum method was used for the measurement of the inertia properties.

Tire performance characteristics were measured on Calspan's flat belt testing machine (TIRF). All runs were performed under dry surface conditions at a test speed of 30 mph for a small range of normal loads at recommended inflation pressure. The primary test variables were slip angle (up to 8 degrees) and inclination angle (up to 28 degrees). Measurements of three forces and three moments on each of nine tires were made and these data were then converted for use in the simulation in terms of:

Normalized cornering stiffness (a measure of side force as a function of slip angle)

Normalized camber thrust coefficient (a measure of side force as a function of inclination angle)

Pneumatic trail (a convenient representation in the simulation for front tire aligning torque effects)

Full Scale Tests

The principal features of the full-scale test work were:

1. All tests were performed with a single motorcycle - a new Honda CB 360G which was equipped with instrumentation and Calspan's lightweight telemetry package.

2. Testing was performed to each of the two procedures previously described by a single experienced rider with emphasis on operation in the speed region about 40 mph.

3. All tests were performed under dry conditions on a high coefficient of friction surface. Approximately 115 test runs were performed.

The purposes of this phase of work were to evaluate the procedures with respect to their ability to provide repeatable performance data, to produce reference information for evaluation and validation of the simulation results, and to demonstrate the performance of new measurement methods. Regarding this last point, it was of particular interest to determine whether effective isolation of the various control inputs--steer angle and torque as opposed to rider lean angle--could be achieved.

Simulation Studies

This phase of work utilized an existing mathematical model and digital computer simulation of single track vehicles, developed earlier at Calspan, for the evaluation of the group of six motorcycles previously cited in the two test procedures. The principal features of the simulation are:

1. The motorcycle-rider combination is modeled as an eight degree-of-freedom system accounting for the six rigid body motorcycle motions, the steer degree of freedom, and a rider lean angle motion.

2. The model is not restricted by small-angle approximations and nonlinear tire characteristics can be included.

3. The simulation includes a rider stabilization and control model for closed-loop performance studies.

4. Output data is available in both printed and plotted form, with access to many performance variables (e.g., tire forces, slip angles) which are not conveniently measured in full-scale tests.

Results and Conclusions

This initial study of motorcycle handling characteristics involved investigations of several aspects of the problem across a broad front of evaluation methodology. Although it has not been possible to demonstrate definitive performance requirements for improved accident-avoidance capability, the program has identified several promising avenues of approach and has developed an initial information base of performance parameters for motorcycles in lateral-directional motion.

The major accomplishments of the study were:

1. Development of a steady state directional control test procedure with which to evaluate the principal performance response parameters. This procedure has been demonstrated in full-scale tests to be suitable for motorcycles, to produce repeatable data, to discriminate among effects of different control inputs, and to be highly flexible for studying performance in any operating regime. Simulation results with this procedure indicate good discriminatory capability to differentiate among machines.

2. Preliminary evaluation of a lane change maneuver as a method for investigating rider-motorcycle interaction. Limited results show that the measurements of steering inputs and rider lean angle are useful adjuncts to the basic success-failure and speed metrics in this test which should be applicable to separating rider technique effects from motorcycle response. More work is needed on this procedure, in both full-scale testing and simulation, to define best ways to employ it in accident-avoidance capability studies.

3. Compilation of baseline information on motorcycle physical characteristics and tire performance that has not previously been available. These baseline data (especially the inertial properties and tire performance) encompass a wide range of machines and can be used for other studies (perhaps using simplified analytical methods) of additional performance characteristics.

4. Identification of the very significant role of tire characteristics in motorcycle response. In particular, the sensitivity of the response parameters to camber thrust coefficient (with respect to absolute value and to any differences between front and rear tires), the importance of pneumatic trail to steer torque requirements, and the initial categorization of steer requirements at trim may be cited.

5. Demonstration of the capability of the currently available simulation of two-wheel vehicle dynamics to produce useful results on motorcycle

performance characteristics. Although it is clear that certain improvements in the model are essential for broad application to studies of motorcycle accident-avoidance capability (e.g., addition of suspension effects, addition of braking and acceleration capability, rider model improvements), the simulation has been shown to yield reasonable representations of motorcycle-rider behavior in selected applications.

There is great temptation to recommend a long list of next steps to be taken toward acquiring a firm understanding of motorcycle accident-avoidance capability. More work is needed in the areas of combined cornering and braking, fixed and free control instabilities (the so-called wobble and weave modes), and operation at low skid number conditions. On the other hand, it seems appropriate to consolidate the preliminary findings of this study and it is therefore recommended that consideration be given to a program which would extend the experimental work to cover several motorcycles over a broad range of operating conditions in the two procedures developed in this study. These conditions should include at least speed range, tire design and operating factors, and rider variability effects. Concurrent upgrading of the simulation should be included. This approach would be aimed at isolating those factors which may contribute to controllability problems so that the values of the performance parameters developed in the study reported here can be applied in an accident-avoidance capability context.

1. INTRODUCTION

With the increasing interest in and use of motorcycles in the United States, concern has grown regarding the safe operation of these vehicles. The National Highway Traffic Safety Administration (NHTSA) has responded to this concern with the promulgation of Federal Motor Vehicle Safety Standards (FMVSS) numbers 108, 122, and 123 which treat requirements for lighting, braking, and controls, respectively. It is also sponsoring research in other aspects of motorcycle performance; the study described in this report is concerned with an investigation of the accident-avoidance capabilities of motorcycles. Particular emphasis is placed on the lateral-directional control properties of these vehicles and the objective evaluation of response characteristics and handling quality.

The overall objectives of this program were:

1. To develop a set of motorcycle accident avoidance test procedures and to define the meaningful objective response parameters that can be used to quantify accident avoidance capability.

2. To evaluate the accident avoidance capabilities of a representative sample of motorcycles using the accident avoidance test procedures in a computer simulation.

These specific objectives aside, the program was conceived originally as a ground-breaking first effort - to acquire initial accident avoidance data on existing motorcycles that would provide a firm base for future research in such areas as vehicle dynamic responses, braking and acceleration performance, combined cornering and braking, anti-lock brake systems, the influence of crashworthiness modifications on accident avoidance capabilities and, of course, improved accident avoidance test and evaluation methods.

The approach used in meeting the above objectives consisted of performing full-scale experiments with a single representative motorcycle in two basic test procedures - constant speed cornering and a lane change maneuver - which were developed for this purpose. The results of these tests were used to evaluate the utility of selected performance parameters and for validation of the Calspan digital computer simulation program of motorcycle dynamics which was used to investigate the characteristics of five additional machines.

Following this introduction, the report is composed of several sections describing the various phases of the program. Section 2 contains a brief discussion of the background of the motorcycle stability and control problem, emphasizing the lack of available test procedures for evaluating performance. The principal features of the approach used in the study, involving both simulation and full-scale testing, and the primary results of these efforts are described in Section 3. This section also contains outlines and summaries of various sub-tasks which are described in detail in appendices. Section 4 contains a summary of conclusions and gives recommendations for exploitation of the work. A list of references is given in Section 5.

Four appendices are provided in a separate volume. They include:

(1) detailed descriptions of the two test procedures;
(2) details of the measured tire performance characteristics;
(3) representative plots and time histories from the full-scale tests;
(4) plotted outputs from the simulation studies.

2. BACKGROUND

Before discussing the various phases of the study, it will be useful to give a brief background description of the general problem of motorcycle handling characteristics. Since before 1900, various researchers have attempted to formulate mathematical models of the lateral-directional characteristics of two-wheel vehicles. Many of these early efforts resulted in rather elegant mathematical descriptions but they suffered from inadequate numerical information on various components (most notably, tires) or were simplified by neglecting terms or treating only the steady-state for mathematical tractability. Later studies, during the 1950-1970 period, overcame some of these difficulties in the representation of the vehicle but these treated the rider as only a passive element in the system. Since 1970, increasing interest in two wheel vehicles has led to a broader attack on the problem and has resulted in a capability to investigate the dynamics of the rider-machine system. Among the most useful descriptions of the current state-of-the-art are papers by Sharp on the motorcycle only (Reference 1), Weir on the rider-vehicle system based in part on Sharp's vehicle model (Reference 2), and Roland on the closed loop rider-bicycle system in a path-following maneuver (Reference 3). Reference 3, incidentally, contains a short bibliography of earlier work.

In the context of the subject of this program - motorcycle accident avoidance capabilities - it is important that several fundamental differences between two-wheel and four-wheel vehicular stability and control characteristics be understood. These include:

1. Whereas the automobile driver provides little contribution to system stability with most configurations, the motorcycle rider must compensate for the inherent roll instability of the two wheel vehicle for acceptable performance to be achieved.

2. The automobile driver (at constant speed operation) has only the steering wheel for lateral-directional control; the motorcycle rider, on the other hand, utilizes both steering and body lean (center-of-gravity shifting) to effect control.

3. An associated consideration with item 2 is that position control (i.e., steering wheel displacement) is suitable for representing most driving operations with an automobile and response characteristics may be referenced to this mode of control with reasonably complete coverage.* In fact, most automobile response parameters (e.g., yaw rate gain) are determined under fixed position control conditions. Considering just the steering control responses, torque input is probably more significant than steering position (displacement) for the motorcycle because the extremely small values of displacement which are generally employed provide inadequate control cues.

4. The automobile depends primarily on tire slip angle for the generation of side force for path control (although camber effects may be significant in obtaining the desired degree of understeer). Most of the side force developed in motorcycles comes from inclination angle effects (camber thrust) with slip angle effects (and, by extension, steer angle and vehicle side-slip effects) being used only to

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* Certain operations involving steering wheel returnability and "feel" (as a cue near limits of performance) are not covered by these parameters.

trim the vehicle. Thus, it is important that the camber thrust characteristics of the tires be accurately determined.

5. Aside from possibilities of instability which are relatable to component degradations, the reasonably-designed automobile (one which understeers over its complete operating range) avoids two stability problems which may be present in otherwise acceptable motorcycles - wobble (oscillation of the steering assembly about the steer axis with respect to the frame) and weave (a combined roll-yaw oscillation of the whole machine). These free-control problems (in actuality, weave can also occur with fixed control at high speed) have not been specifically-investigated in this program but they must be recognized as potential difficulties in design.

With the above as a foundation on which to base an approach to accident-avoidance capability evaluations, coupled with an almost complete lack of any formalized test procedures for such evaluations, the study was developed along a path which was aimed at defining reasonable testing techniques and meaningful performance parameters and then applying these procedures in full-scale tests (one machine) and simulation (five additional motorcycles) to demonstrate applicability.

3.0 METHODOLOGY

Since the approach used in this program involved a number of separate activities, it is convenient to discuss each phase individually before presenting the collective results of the experimental tests and simulation studies. This section is therefore divided into several subsections which treat specific areas of interest.

3.1 Motorcycle Selection

A group of six motorcycles were selected for the simulation studies to provide a broad range of size, weight, and type of machine so that any trends in the performance characteristics relatable to these factors might be identified. One of these was purchased for use in the full-scale test work; the others were obtained for short periods of time so that measurements of the physical characteristics needed as input data for the simulation could be made.

Each of the motorcycles selected for this task are representative of a segment of the motorcycle population with similar design parameters which determine their handling performance. The selection was based not only on the population distribution, but also on the desire to include for analysis those motorcycles with unique properties that might contribute to their handling characteristics. However, only cycles which are licensable for street use (thus eliminating motocross and road racing cycles as well as minicycles and mini-bikes) were considered.

Important parameters for consideration in the selection of a representative sample were weight, frame design, front and rear suspension characteristics, tires, weight distribution, and specific power output. The motorcycles of concern range in weight from 150 to 700 lbs. and in power from less than 10 to over 70 horsepower. For the most part, front suspension is by oil-damped telescopic shock abosrbers; at the rear there is usually a spring/shock combination constrained by a trailing arm. Three basic types of tires are used: trials, universal, and ribbed. The trials tire is a combination on/off road type, with large, evenly spaced square lugs for adequate traction on surfaces ranging from soft dirt to paved roads. The universal tire has a finer, shallower tread intended more for street use and the ribbed type has principally circumferential grooves and is meant strictly for use on the street.

These characteristics can be used to divide the motorcycle population into groups from which a representative member of the group was selected. The selections are described below.

Heavyweight street --

This is the upper limit of the weight category, and includes cycles such as Harley-Davidson FLH-1200 Electraglide which are designed especially for long distance and high speed touring. Due to its size and the common use of add-on accessories such as windshields and saddlebags, it has high aerodynamic drag. The use of large wheels and tires and a heavy suspension components contribute to a high upsprung weight.

Superbike --

These are the cycles whose prime design goals are acceleration and top speed. They are relatively lightweight (400-500 lbs.) but have engines rated at 60-70 horsepower; they present a unique opportunity to investigate high speed characteristics and the effect of high rear wheel torque under acceleration.

The Norton 850 Commando Roadster is a desirable selection for several reasons. It is the lightest cycle in its class and has its engine, swing arm, and rear wheel assembly isolated from the frame by rubber bushings. Low unsprung weight and long travel suspension may be partly responsible for its good handling reputation.

The Yamaha XS2-650 (1972) on the other hand, is said to have stability and ground clearance problems. The analysis of two different motorcycles in the same class may provide further insight into handling characteristics.

Intermediate street --

This group is typified by the motorcycle eventually purchased for test, the Honda CB 360. It is of medium weight (350 lbs.) and has adequate power, rider comfort, and maneuverability for both touring and urban traffic.

Dual Purpose - Street/Trail --

This designation applies to the whole range of cycles designed to be used for both dirt and street riding. Most of them are very much alike, in that a compromise in handling between a purely street machine like a CB 360 and an all-out motocross racer, ridden exclusively on hilly dirt courses, is made. To accomplish this, a fair amount of adjustability is built into the suspension. Most of these cycles have rear springs which are adjustable for pre-load and some also feature adjustable front forks to set rake and trail. Trials tires are used almost exclusively. The F-11 250 Kawasaki is a typical example of this group. One unique feature of this type of cycle is high ground clearance, which is needed to protect the engine from damage but leads to a higher than average center of gravity.

Lightweight street --

These cycles are close to the intermediates in overall size but may weigh as little as 200 lbs. and have engines rated at around 10 HP. Thus their torque reaction under acceleration is less and their speed range more limited than most of the larger cycles. Because of their light weight, handling is affected to a greater extent by the rider's weight and motions during riding. The Honda CB 125K1 is one of the more popular members of this group.

To summarize, the selected motorcycles were:

Honda 125
Kawasaki 250
Honda 360
Yamaha 650
Norton 850
Harley Davidson 1200

3.2 Motorcycle Physical Measurements

Simulation data input requirements call for the numerical values of a set of physical characteristics of the motorcycle which describe its geometrical layout and its mass and inertia properties. Although some of this information is available from manufacturer's publications, most of these data (especially the important moment of inertia parameters) had to be measured at Calspan. The results of these measurements are given for each machine in Tables 1 through 6.

Many of the characteristics could be simply measured as linear or angular dimensions or weights and need not be described in detail here. The determination of moments of inertia of principal elements of the machine (as well as the values for the complete motorcycles) were made using a torsional pendulum method as indicated in the photographs, Figures 1 and 2.

The item to be measured is suspended from a ten foot long rod of circular cross section which is rigidly mounted at its upper end. The item is set into an oscillation in a plane normal to the axis of the rod. Knowing the size and material of the rod and the natural frequency of oscillation of each item, its moment of inertia can be determined. The torsion rods used were calibrated with bodies of known moments of inertia and the results thus obtained agreed with the theoretical calculations within 1%.

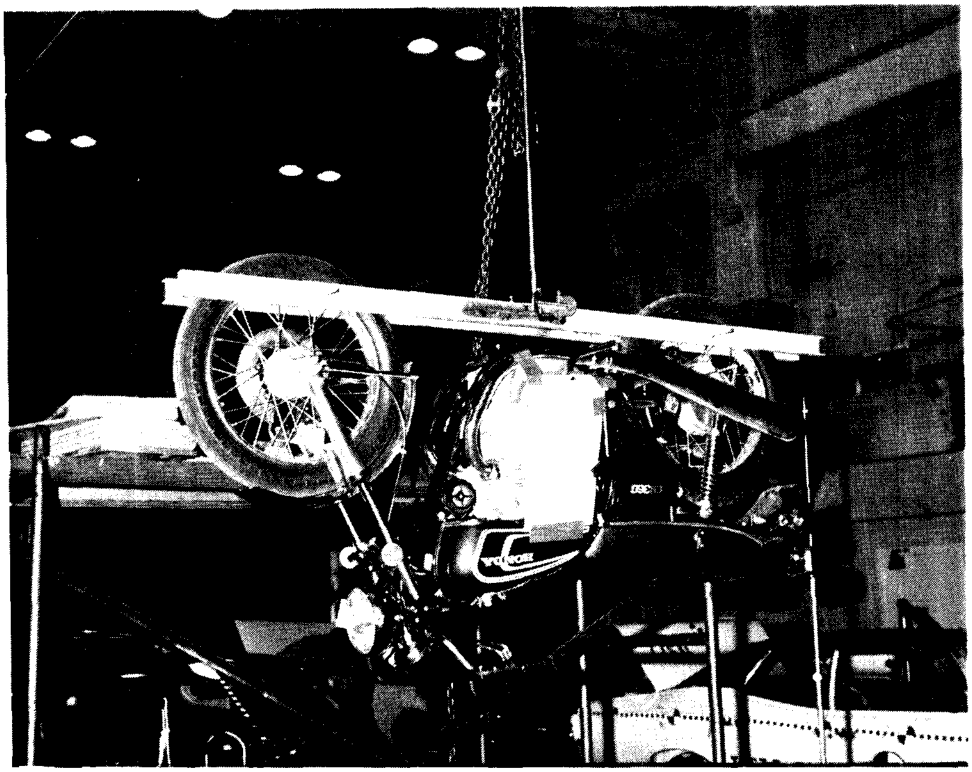


Figure 1a MEASUREMENT OF YAW MOMENT OF INERTIA (I_{ZZ})

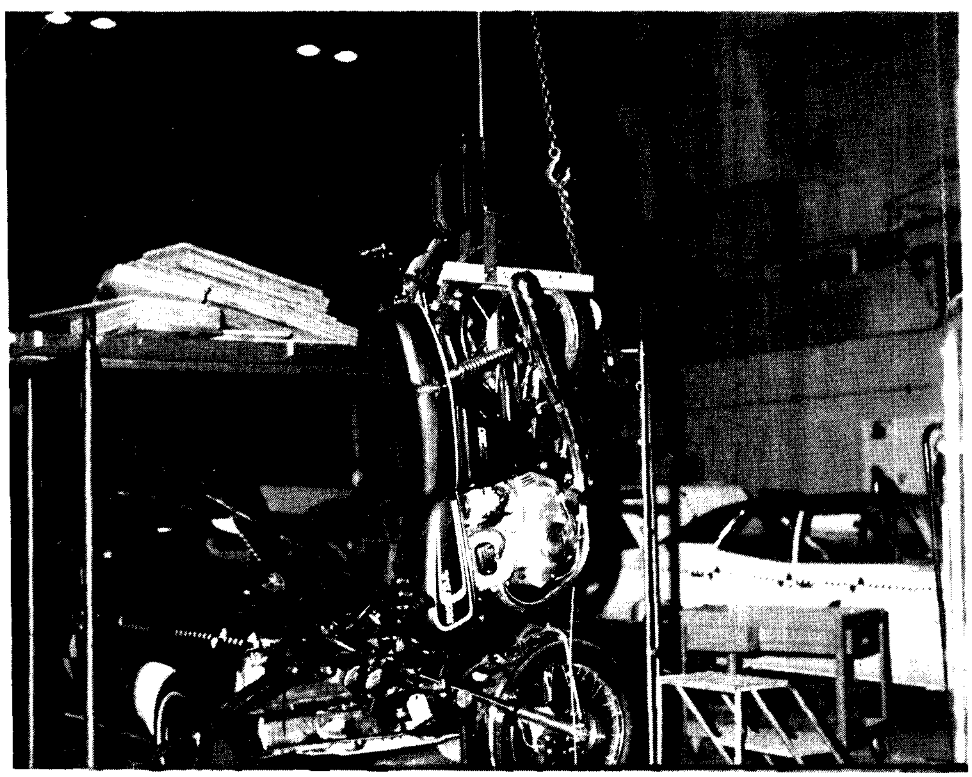


Figure 1b MEASUREMENT OF ROLL MOMENT OF INERTIA (I_{XX})

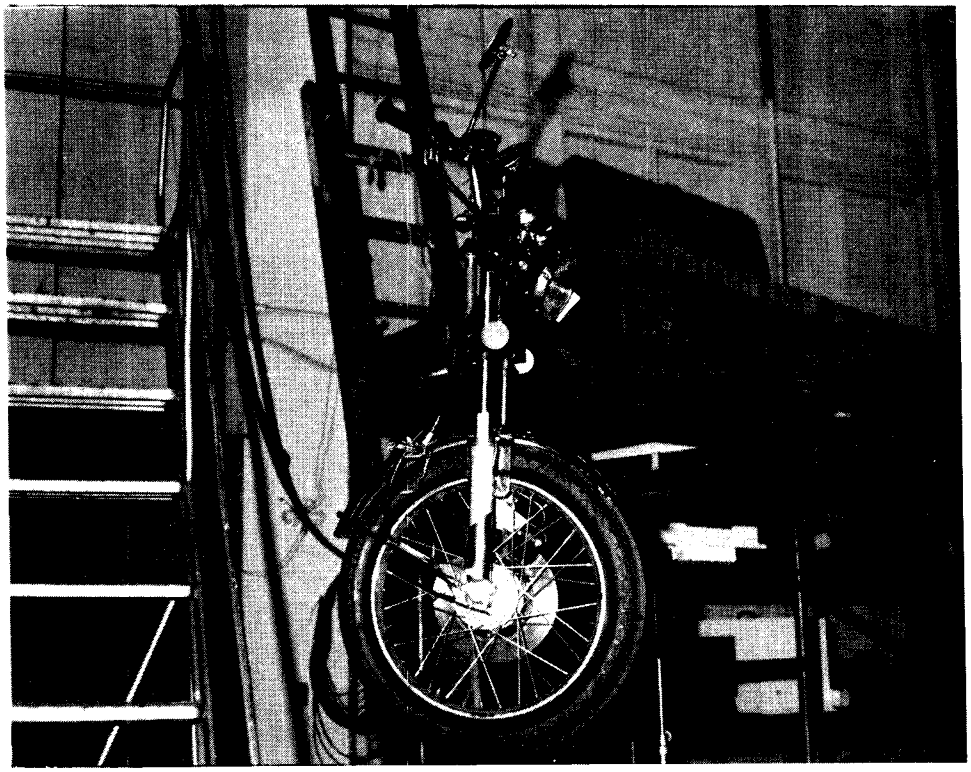


Figure 2a MEASUREMENT OF I_{ZZ} OF FRONT ASSEMBLY

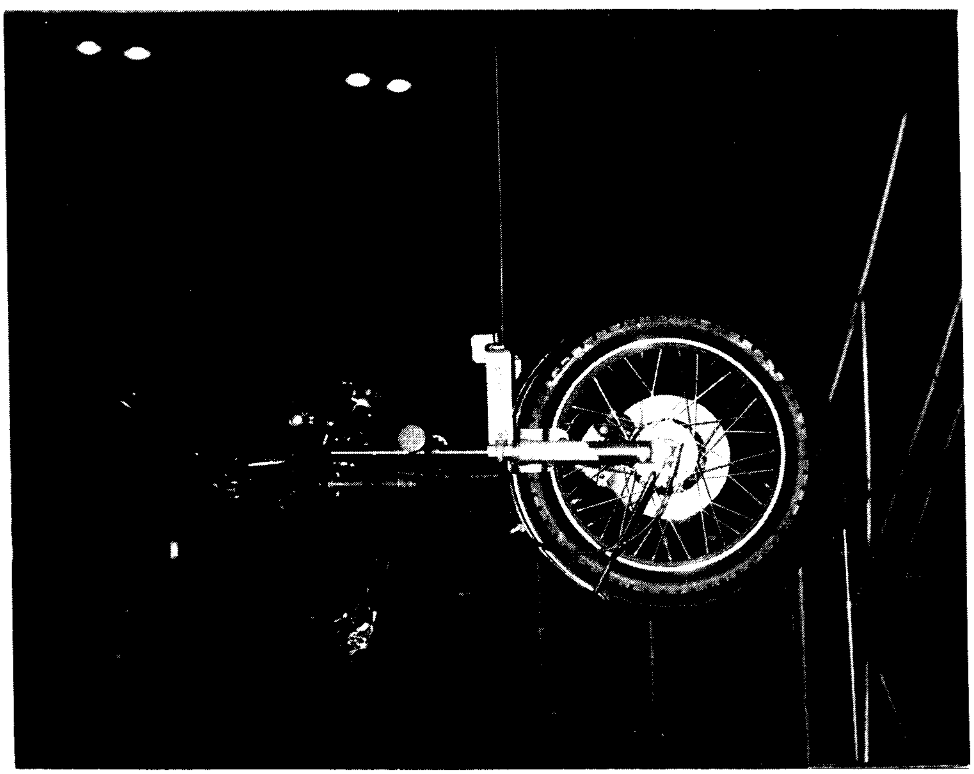


Figure 2b MEASUREMENT OF I_{XX} OF FRONT ASSEMBLY

TABLE 1

MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Honda 360G

1.	Wheelbase	53.3	in.
2.	Seat Height from Ground	31.9	in.
3.	Front Tire Size	3.00 - 18	
4.	Rear Tire Size	3.50 - 18	
5.	Front Tire Outside Diameter	24.8	in.
6.	Rear Tire Outside Diameter	25.8	in.
7.	Fork Tube Angle	61.75	Degrees
8.	Fork Tube Offset	2.67	in.
9.	Weight of Rider	149	lbs.
10.	Front Wheel Load without Rider	169	lbs.
11.	Rear Wheel Load without Rider	203	lbs.
12.	Front Wheel Load with Rider	207	lbs.
13.	Rear Wheel Load with Rider	314	lbs.
14.	Weight of Front Wheel and Tire	24.3	lbs.
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	68.6	lbs.
16.	Front Suspension Ride Rate	114	lbs./in.
17.	Rear Suspension Ride Rate	211	lbs./in.
18.	Distance of Total Motorcycle C.G. from Ground	18.1	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	2.67	in.
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	12.7	in.

TABLE 1

MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire	4.02	lb-in-sec^2
22.	I_{xx} of Front Assembly	34.67	lb-in-sec^2
23.	I_{zz} of Front Assembly	5.80	lb-in-sec^2
24.	I_{xx} of Total Motorcycle	82.3	lb-in-sec^2
25.	I_{zz} of Total Motorcycle	260	lb-in-sec^2

TABLE 2

MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Honda 125

1.	Wheelbase	48.0	in.
2.	Seat Height from Ground	29.7	in.
3.	Front Tire Size	2.75 - 18	
4.	Rear Tire Size	3.00 - 17	
5.	Front Tire Outside Diameter	24.1	in.
6.	Rear Tire Outside Diameter	23.7	in.
7.	Fork Tube Angle	62.8	Degrees
8.	Fork Tube Offset	2.37	in.
9.	Weight of Rider	146	lbs.
10.	Front Wheel Load without Rider	89.8	lbs.
11.	Rear Wheel Load without Rider	114	lbs.
12.	Front Wheel Load with Rider	124	lbs.
13.	Rear Wheel Load with Rider	229	lbs.
14.	Weight of Front Wheel and Tire	12.2	lbs.
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	47.5	lbs.
16.	Front Suspension Ride Rate	50	lbs./in.
17.	Rear Suspension Ride Rate	100	lbs./in.
18.	Distance of Total Motorcycle C.G. from Ground	16.9	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	.88	in.
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	12.3	in.

TABLE 2

MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire	2.75	$lb\text{-}in\text{-}sec^2$
22.	I_{xx} of Front Assembly	21.2	$lb\text{-}in\text{-}sec^2$
23.	I_{zz} of Front Assembly	3.74	$lb\text{-}in\text{-}sec^2$
24.	I_{xx} of Total Motorcycle	39.4	$lb\text{-}in\text{-}sec^2$
25.	I_{zz} of Total Motorcycle	138	$lb\text{-}in\text{-}sec^2$

TABLE 3
MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Kawasaki F11 250

1.	Wheelbase	54.6	in.
2.	Seat Height from Ground	32.1	in.
3.	Front Tire Size	3.00x21	
4.	Rear Tire Size	4.00x18	
5.	Front Tire Outside Diameter	27.68	in.
6.	Rear Tire Outside Diameter	26.42	in.
7.	Fork Tube Angle	60.0	Degrees
8.	Fork Tube Offset	2.45	in.
9.	Weight of Rider	150	lbs.
10.	Front Wheel Load without Rider	116	lbs.
11.	Rear Wheel Load without Rider	156	lbs.
12.	Front Wheel Load with Rider	155	lbs.
13.	Rear Wheel Load with Rider	267	lbs.
14.	Weight of Front Wheel and Tire	22.0	lbs.
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	60.0	lbs.
16.	Front Suspension Ride Rate	60	lbs./in.
17.	Rear Suspension Ride Rate	330	lbs./in.
18.	Distance of Total Motorcycle C.G. from Ground	21.5	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	0.40	in.
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	14.5	in.

TABLE 3

MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire	4.95	$lb\text{-}in\text{-}sec^2$
22.	I_{xx} of Front Assembly	34.1	$lb\text{-}in\text{-}sec^2$
23.	I_{zz} of Front Assembly	5.80	$lb\text{-}in\text{-}sec^2$
24.	I_{xx} of Total Motorcycle	63.3	$lb\text{-}in\text{-}sec^2$
25.	I_{zz} of Total Motorcycle	242	$lb\text{-}in\text{-}sec^2$

TABLE 4

MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Yamaha XS2, 650

1.	Wheelbase	55.8	in.
2.	Seat Height from Ground	30.5	in.
3.	Front Tire Size	3.50 x 19	
4.	Rear Tire Size	4.00 x 18	
5.	Front Tire Outside Diameter	27.0	in.
6.	Rear Tire Outside Diameter	27.6	in.
7.	Fork Tube Angle	61.8	Degrees
8.	Fork Tube Offset	2.18	in.
9.	Weight of Rider	151	lbs.
10.	Front Wheel Load without Rider	207	lbs.
11.	Rear Wheel Load without Rider	249	lbs.
12.	Front Wheel Load with Rider	244	lbs.
13.	Rear Wheel Load with Rider	363	lbs.
14.	Weight of Front Wheel and Tire	28	lbs. (est.)
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	70	lbs. (Est.)
16.	Front Suspension Ride Rate	75	lbs./in. (est.)
17.	Rear Suspension Ride Rate	280	lbs./in. (est.)
18.	Distance of Total Motorcycle C.G. from Ground	19.0	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	2.18	in. (Est.)
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	13.5	in. (Est.)

TABLE 4 (Cont.)

MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire	5.0	$lb\text{-}in\text{-}sec^2$
22.	I_{xx} of Front Assembly	45.0	$lb\text{-}in\text{-}sec^2$
23.	I_{zz} of Front Assembly	7.0	$lb\text{-}in\text{-}sec^2$
24.	I_{xx} of Total Motorcycle	125	$lb\text{-}in\text{-}sec^2$
25.	I_{zz} of Total Motorcycle	417	$lb\text{-}in\text{-}sec^2$

Table 5

MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Norton 850 Commando

1.	Wheelbase	56.8	in.
2.	Seat Height from Ground	32.8	in.
3.	Front Tire Size	4.10x19	
4.	Rear Tire Size	4.10x19	
5.	Front Tire Outside Diameter	26.52	in.
6.	Rear Tire Outside Diameter	26.46	in.
7.	Fork Tube Angle	62.47	Degrees
8.	Fork Tube Offset	2.94	in.
9.	Weight of Rider	144	lbs.
10.	Front Wheel Load without Rider	180	lbs.
11.	Rear Wheel Load without Rider	216	lbs.
12.	Front Wheel Load with Rider	229	lbs.
13.	Rear Wheel Load with Rider	315	lbs.
14.	Weight of Front Wheel and Tire	29	lbs. (est.)
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	70	lbs.
16.	Front Suspension Ride Rate	73.0	lbs./in.
17.	Rear Suspension Ride Rate	252	lbs./in.
18.	Distance of Total Motorcycle C.G. from Ground	19.8	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	2.59	in.
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	14.0	in.

Table 5 (Cont'd.)

MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire (est)	5.20	$lb\text{-}in\text{-}sec^2$
22.	I_{xx} of Front Assembly (est.)	42.0	$lb\text{-}in\text{-}sec^2$
23.	I_{zz} of Front Assembly (est.)	6.50	$lb\text{-}in\text{-}sec^2$
24.	I_{xx} of Total Motorcycle	107	$lb\text{-}in\text{-}sec^2$
25.	I_{zz} of Total Motorcycle	381	$lb\text{-}in\text{-}sec^2$

TABLE 6
MOTORCYCLE PHYSICAL CHARACTERISTICS

Motorcycle Harley Davidson FLH 1200

1.	Wheelbase	61.5	in.
2.	Seat Height from Ground	28.6	in.
3.	Front Tire Size	5.10x16	
4.	Rear Tire Size	5.10x16	
5.	Front Tire Outside Diameter	26.40	in.
6.	Rear Tire Outside Diameter	26.40	in.
7.	Fork Tube Angle	61.8	Degrees
8.	Fork Tube Offset	1.44	in.
9.	Weight of Rider	150	lbs.
10.	Front Wheel Load without Rider	300	lbs.
11.	Rear Wheel Load without Rider	490	lbs.
12.	Front Wheel Load with Rider	339	lbs.
13.	Rear Wheel Load with Rider	601	lbs.
14.	Weight of Front Wheel and Tire	41	lbs.
15.	Weight of Front Assembly (Handlebars, front fork, fender, wheel and tire)	128	lbs.
16.	Front Suspension Ride Rate	130	lbs./in. (est.)
17.	Rear Suspension Ride Rate	450	lbs./in. (est.)
18.	Distance of Total Motorcycle C.G. from Ground	17.9	in.
19.	Perpendicular Distance from Steer Axis to Front Assembly C.G.	1.90	in.
20.	Distance from Front Assembly C.G. to Wheel Center Along Line Parallel to Steer Axis	17.9	in.

TABLE 6
MOTORCYCLE PHYSICAL CHARACTERISTICS (Contd.)

21.	I_{yy} of Front Wheel and Tire	7.20	$lb\text{-}in\text{-}sec^2$
22.	I_{xx} of Front Assembly	69.0	$lb\text{-}in\text{-}sec^2$
23.	I_{zz} of Front Assembly	16.4	$lb\text{-}in\text{-}sec^2$
24.	I_{xx} of Total Motorcycle	226	$lb\text{-}in\text{-}sec^2$
25.	I_{zz} of Total Motorcycle	1000	$lb\text{-}in\text{-}sec^2$

3.3 Tire Tests

Performance tests on representative original equipment tires for each of the six motorcycles were made on Calspan's Tire Research Facility (TIRF). The configurations in which the tires were tested are listed in Table 7.* The principal factors in the program were:

- Inflation pressure - according to manufacturer's recommendation
- Normal load - two conditions were tested:
  (1) nominal value with a 200 lb. rider and
  (2) 120% of the nominal value
- Slip angle range - sufficient to cover all reasonable operating conditions; assumes symmetry of performance for ± values of slip angle.
- Inclination angle range - full range of the tire test facility (without modification), assumes symmetry of performance for ± values of inclination angle.

The following measurements were made:

three forces and three moments } vs. slip angle (α) and inclination angle (γ)

(1) at nominal front tire load and inflation pressure,
(2) nominal rear tire load and inflation pressure,
(3) nominal front tire pressure and 120% load and
(4) nominal rear tire pressure and 120% load

for α = +1, 0, -1, -2, -4, -6, -8 deg.
γ = 0, 10, 20, 28 deg.

*Data on the Harley-Davidson tires were available and these tests were not repeated.

TABLE 7

TIRE TESTING - NORMAL LOADS AND TIRE PRESSURES

Tire No.	Tire Size	Application	Test Loads (lbs)	Test Pressure (psi)
1	2.75-18	Honda 125 Front	125 150	26
2	3.00-17	Honda 125 Rear	230 275	28
3	3.00-18	Honda 360 Front	210 250	26
4	3.50-18	Honda 360 Rear	315 380	28
5	3.50-19	Yamaha Front	240 290	23
6	4.00-18	Yamaha Rear	360 430	28
7	3.00-21	Kawasaki Front	155 185	24
8	4.00-18	Kawasaki Rear	265 320	31
9	4.10-19	Norton F & R	215 260	24

A sample data plot as generated by the TIRF system is shown in Figure 3. Note that this plot differs from the usual carpet plots of tire performance (in which normal force is included as an independent variable) by showing the slip angle and inclination angle effects on side force at a nominally constant value of normal force. This form of presentation is very convenient (and useful) for representing tire data for two-wheel vehicles for which camber thrust is important and load transfer effects are small. Additional data in this form are given for all tires in Appendix B. This appendix also contains complete listings of all measured tire performance data from these tests. In addition to side force information which is of primary interest, these listings contain rolling resistance, aligning torque, and overturning moment data as well.

For use in the simulation, the test data have been reduced to simple representations of normalized cornering stiffness, normalized camber thrust coefficient, and effective pneumatic trail for the normal loads at the tires used in the studies. These data are summarized in Table 8. A third order term modifying the cornering stiffness coefficient at higher slip angle values was also determined but, in light of the small slip angles actually used in the test maneuvers, this effect is of little importance. The values for the performance characteristics given in the table may be defined as follows:

Normalized cornering stiffness (C_α): the change in side force (F_y) between plus and minus 1 degree of slip angle at the nominal value of normal load (F_z) and zero inclination angle.

$$C_\alpha = \frac{F_y\ (\alpha=-1) - F_y\ (\alpha=+1)}{2F_z}$$

Normalized camber thrust coefficient (C_γ): the change in side force between zero and +10 degrees of inclination angle at the nominal value of normal load and zero slip angle.

$$C_\gamma = \frac{F_y\ (\gamma=+10) - F_y\ (\gamma=0)}{10F_z}$$

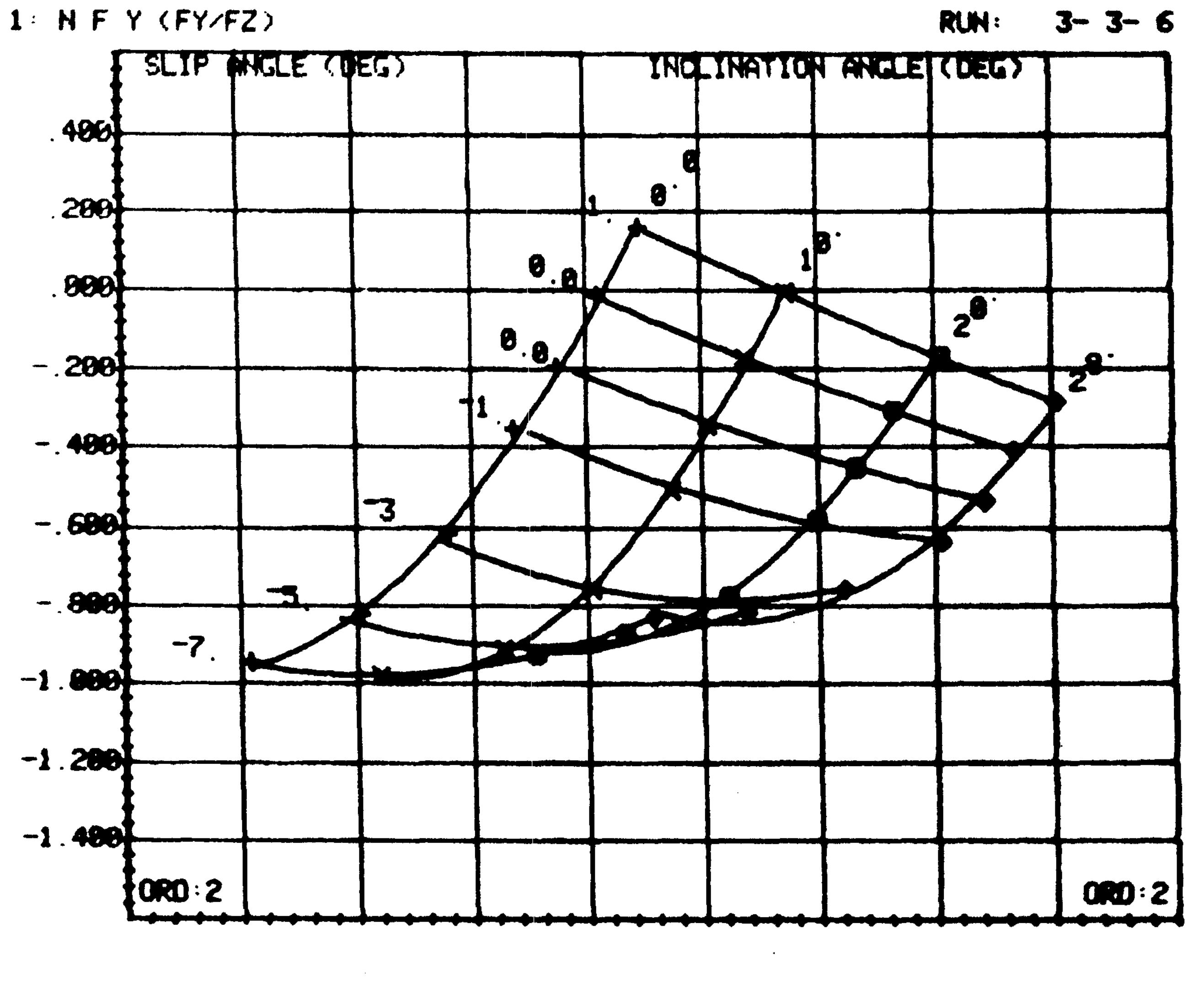


FIGURE 3: TYPICAL TIRE TEST PLOT

VEHICLE	MFR.	LOCATION	SIZE	TYPE	NOMINAL TEST LOAD - lbs.	NORMALIZED CORNERING STIFFNESS lbs/deg/lb	NORMALIZED CAMBER THRUST lbs/deg/lb	PNEUMATIC TRAIL (inches)
HONDA 125	DUNLOP CARLISLE	F R	2.75x18 3.00x17	RIBBED UNIVERSAL	140 260	.33 .18	.019 .015	.52 --
HONDA 360	BRIDGE- STONE	F R	3.00x18 3.50x18	RIBBED UNIVERSAL	210 360	.29 .18	.016 .016	1.02 --
KAWASAKI 250	DUNLOP	F R	3.00x21 4.00x18	TRIALS TRIALS	165 310	.195 .17	.009 .010	.45 --
YAMAHA 650	YOKOHAMA	F R	3.50x19 4.00x18	RIBBED UNIVERSAL	270 390	.25 .185	.0175 .0155	.68 --
NORTON 850	DUNLOP	F R	4.00x19 4.00x19	UNIVERSAL	240 350	.243 .215	.0095 .010	.54 --
HARLEY-DAVIDSON 1200	GOODYEAR	F R	MT90-16T	UNIVERSAL	380 610	.245 .15	.015 .021	.83 --

TABLE 8: NOMINAL TIRE PERFORMANCE CHARACTERISTICS

Pneumatic Trail (t): the longitudinal offset of the point of application of the side force from the center* of the tire contact patch - a measure of self aligning torque (M_z). The value was determined at low side force as an average of both slip angle and camber angle effects.
(α between $\pm 1°$ and γ between zero and 10°)

The effects of these characteristics on motorcycle performance will be discussed in more detail in the section on results (Section 3.3) but a few observations on trends may be stated here. Based on this relatively small sample (10 tires) -

1. C_α decreases with normal load; C_γ is relatively independent of load.
2. Trials-type tires are inferior to other types in side force generating capability.
3. Motorcycle tires have C_α values which are slightly higher in general than automobile tires.
4. Values of C_γ ranged from .009 lbs/deg/lb. to .021 lbs/deg/lb. The lower values do not provide sufficient side force in steady-state cornering and must be augmented by the development of tire slip angles; the higher values produce a surplus of side force at this condition** and opposing side force must be generated with slip angles of opposite sign.
5. The values of pneumatic trail should be considered as reasonable approximations. This approach is a convenient method for characterizing the aspect of aligning torque for motorcycles

*Defined as a point contained in a transverse vertical plane passing through the wheel axle.

**Theoretically (and somewhat simplistically), the roll moment equation of motion for motorcycles will be balanced at a_y (lat. acceleration) = tan ϕ (roll angle). For small roll angles, the camber thrust coefficient should be about 1/57.3 (.0175) for balance.

(since it can be directly added to the mechanical trail term in the equations of motion) but it should be appreciated that pneumatic trail is not single-valued over the complete operating envelope of the tire.

In summary of this phase of the program, 18 performance tests on a group of tires have been made to obtain values of the pertinent characteristics needed for simulation studies of motorcycle lateral-directional stability and control. These tests were similar to those performed on automobile tires (with added emphasis on inclination angle characteristics, however) and results are given in similar form. As will be discussed later, certain parameters may need to be investigated in greater depth and with more precision because of the special nature of their influence on motorcycle response. Nevertheless, these data are believed to provide a good foundation of information on the general performance characteristics of motorcycle tires which has utility beyond the application to this study.

3.4 Test Procedure Development

In attempting to define suitable test procedures with which to determine first-order performance differences among motorcycles, emphasis was placed on investigating lateral-directional control characteristics at nominally constant speed. It is recognized that braking characteristics are not covered in this approach, but it was believed that extension of the simulation studies to include detailed investigation of this aspect of performance would have compromised the degree to which the directional control characteristics could be studied - given the limited resources of the program.

The following factors were used in defining the test procedures:

Compatability with simulation

- for validation purposes
- modification requirements
- cost of operation
- dependence on rider model

Full-scale test operation

- coverage of performance range
- instrumentation and equipment requirements
- test area
- control input coverage
- cost of testing
- test safety

On the basis of these considerations, two procedures were identified for use in this program. One was to be concerned with the determination of basic steady state control response characteristics; the other was to involve rider-vehicle interaction effects under transient maneuvering conditions. The recommended versions of these two procedures are described in detail in Appendix A. In order to facilitate understanding of the results of the study, various aspects of the procedures are briefly discussed below.

Emphasis was placed on outlining a basic stability and control test which would yield first order directional control characteristics of motorcycles. The procedures used for automobile evaluations, which are described in SAE XJ 266*, were studied for possible adaptation to motorcycle testing. Each of the four general methods - constant radius, constant velocity, constant throttle, and constant steer angle - offers some specific advantage but each needs to be modified for motorcycle work.

The primary purpose of this test is to measure the steady-state control gains or sensitivities of the vehicle. These control parameters can then be used as a means to discriminate among designs. The principal problems with the approach are concerned with -

*Proposed Recommended Practice SAE XJ 266 - Passenger Car and Light Truck Directional Control Response Test Procedures.

(1) minimizing the effect of rider technique on the results (i.e. a true vehicle response type of test)
(2) differentiating among the types of control inputs available (i.e., steering angle, steering torque, and rider lean)

These two factors tend to make motorcycle testing of this kind more difficult than automobile testing.

The parameter of special interest is lateral accleration gain as given in three forms:

(1) position control sensitivity - the fixed control response of lateral acceleration to steering angle
(2) torque control sensitivity - the lateral acceleration response to a steering torque input
(3) rider lean control sensitivity - lateral acceleration as a function of the rider's lean angle with respect to the machine.

It is desirable that these parameters be determined over a fairly broad speed range so that any operating conditions of reduced stability (or instability) is identified. In effect, the test should be aimed at determining conditions at which the operational safety of the machine might be compromised or would impose severe demands on the rider for compensation.

On the basis of a belief that 40 mph is a reasonable test speed, the recommended procedure calls for operation at this nominal speed over a series of circular arcs from about 250 to 700 feet. (See Figure 4)

Various forms of a lane change maneuver were considered for use as the primary transient handling task in the program. It was intended that this maneuver provide baseline information for rider skill differentiations as well as motorcycle performance discrimination. After reviewing several versions

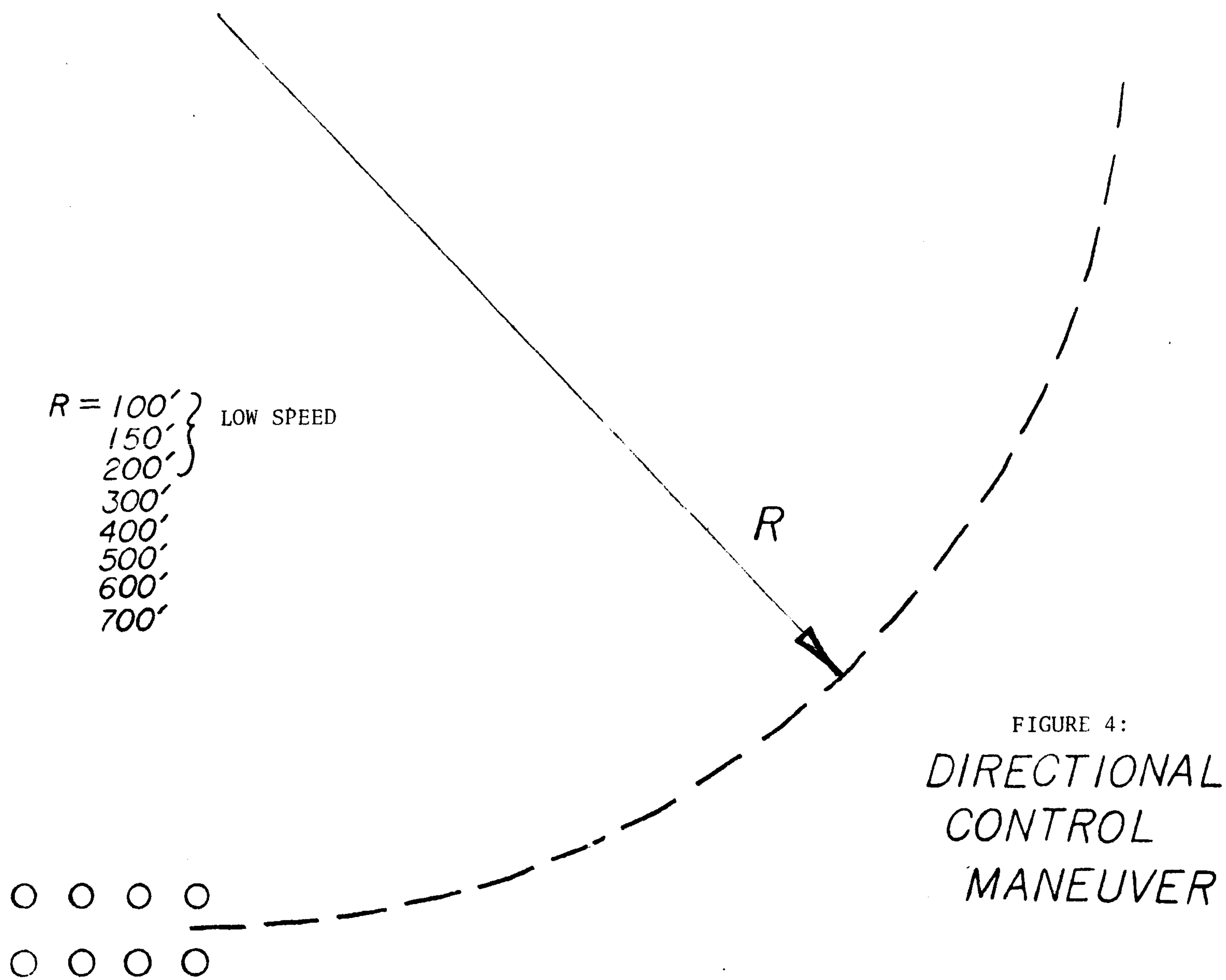


FIGURE 4: DIRECTIONAL CONTROL MANEUVER

of this maneuver (single and double lanes, variable geometry and dimensions, etc.), a single lane change procedure that is believed to address each of the requirements was adopted. A general outline of the test course is shown in Figure 5. The rationale for its selection is:

1. The single lane change represents a maneuver frequently performed by cyclists on the road. By varying the longitudinal distance over which the fixed lateral displacement can be developed, it provides for a range of speeds to be investigated. It calls for the rider to apply both steer and lean control inputs and offers a means for comparing both stability and controllability characteristics.

2. It is compatible with present capabilities of the simulation (i.e., it is initiated from a trimmed straightahead condition) and affords a good basis for validation of transient behavior. Run times for individual test points can be kept to less than 5 seconds for good test effectiveness.

3. In previous applications of a similar technique to automobile evaluation, this method was found to offer reasonable discriminatory power for both vehicle and operator. Certain problems with this type of procedure have been experienced by the ISO in using a simple speed metric but the use of several additional performance parameters (actual control inputs, other motion variables, and failure mode information) is expected to improve its applicability.

Preliminary tests were run to determine reasonable values for the parameters of the maneuver, namely speed and longitudinal and lateral displacement of the entrance and exit lanes. (Δx and Δy of Figure 5). It was decided that Δy should be set at 12 feet to represent typical highway dimensions. Investigations of speed and Δx were guided by several criteria:

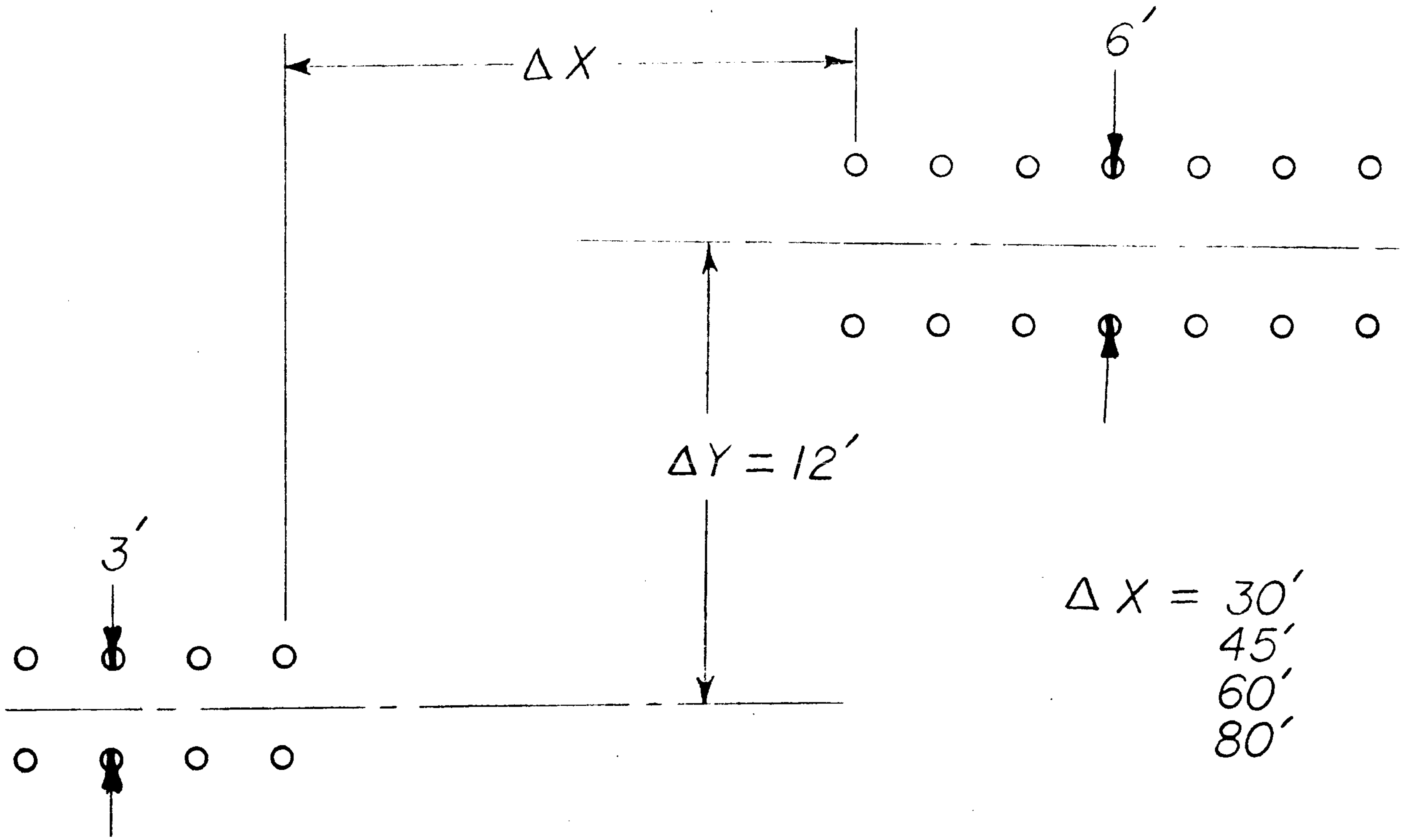


FIGURE 5:

LANE CHANGE MANEUVER

- A maximum speed should be chosen such that resultant lateral accelerations and motorcycle roll angles are well within safe limits of operation based on the drivers judgment.
- Δx should be large enough so that variations in the point at which the rider initiates the maneuver do not dominate test repeatability.
- Δx should be small enough so that maximum speed through the maneuver is well defined. For example, during the initial tests, with $\Delta x = 80$ ft., it was found that the speed used to negotiate the maneuver varied widely.

These two procedures are, in some sense, a complementary set. The response characteristics determined in the directional control tests are presumed to have some bearing on the operating conditions for which the lane change can be successfully accomplished. These relationships may be concerned with magnitudes of input control levels, limitations associated with the performance envelope of the test machine, or dynamic compensation required of the rider. For the purposes of this program, most of the tests (both full-scale and simulated) were performed at a nominal test speed of 40 mph and lateral accelerations up to .5g.

3.5 Instrumentation and Data Acquisition

During the full scale test work data were acquired using Calspan's PCM (Pulse Code Modulation) telemetry system. Figure 6 shows the major components of the PCM telemetry system. The following summary describes the principle features of the system components:

1. An Aydin Vector Model MMP60 PCM Encoder that can accept as many as 32 channels of analog data. Six channels were utilized in the experimental program. The unit measures about 2" x 2" x 2". (Fig. 6a-1)

2. The encoder serial PCM signal is fed to an Aydin Vector Series TI202 VHF transmitter which broadcasts the signal via a stub antenna. (Fig. 6a-3)

   Signal range is line-of-sight and is adequate for work on Calspan's VERF. The unit measures about 1" x 2" x 4".

3. An Arnold Magnetic Model ASL-A28/1-AA 12 volt to 28 volt power supply feeds the on-board encoder and transmitter. The unit measures about 2" x 4" x 4"; all on-board components, taken together weigh less than 10 lbs. (Fig. 6a-2)

4. At the ground station the transmitted signal is detected by a Clarke Instruments Model 167-E receiver, the output of which is a serial PCM signal. This signal can be put either on magnetic tape for permanent storage or later playback or fed to a decommutator. (Fig. 6d)

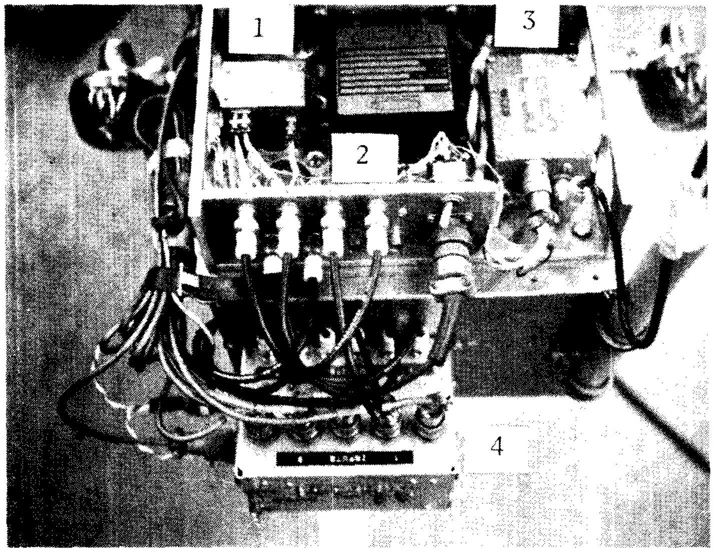
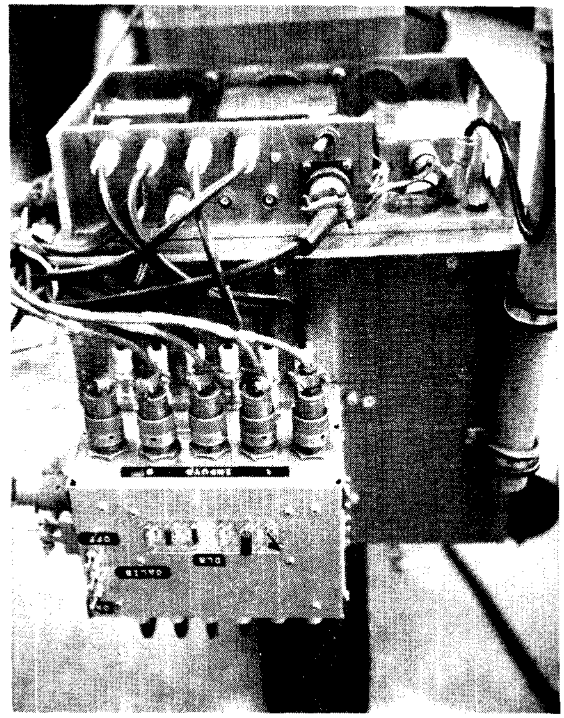


Figure 6a
(1) PCM Encoder, (2) Power Supply, (3) Transmitter, and (4) Sensor Amplifiers



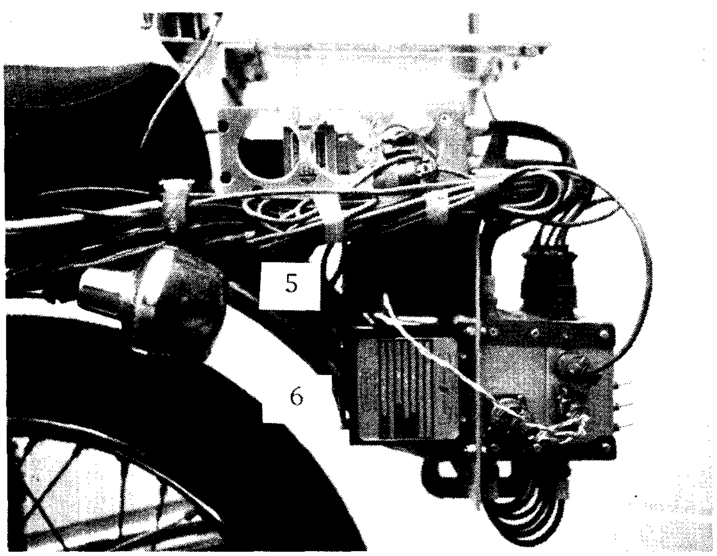


Figure 6c
Sensor Power Supplies

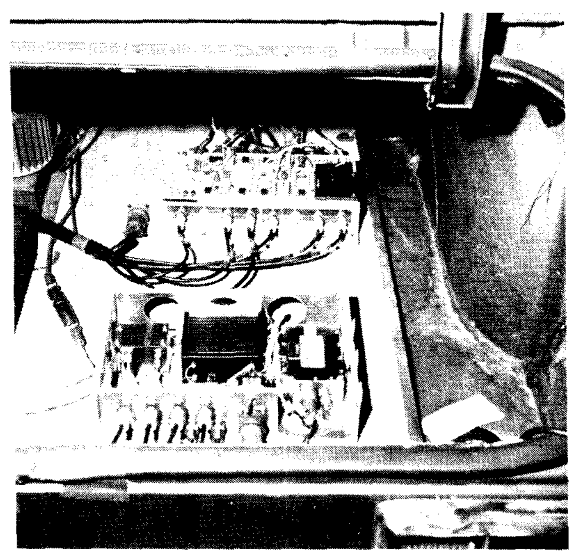


Figure 6d
VHF Receiver, Channel Selector and PCM Decommutator

Figure 6. PCM TELEMETRY SYSTEM

5. Aydin Monitor Model 1023A PCM Decommutator which has one analog output channel and 31 digital output channels. The six remaining data channels to be used are then fed to digital-to-analog converter. (Fig. 6d)

6. Aydin Monitor Model 758 Channel Selector/DA Converter. The 6 channel output of this unit and the single channel from the decommutator can be displayed on a strip chart recorder for real-time data acquisition capability.

Characteristics of the control input and motion sensors are given in Table 9. Photographs of these sensors as installed on the motorcycle are shown in Figures 7a-d. Figure 6c shows the locations of the power supplies for these sensors.

A complete schematic of the motorcycle data acquisition system is shown in Figure 8. For this program the output of the D/A converters was fed directly to a strip chart recorder and not stored on magnetic tape.

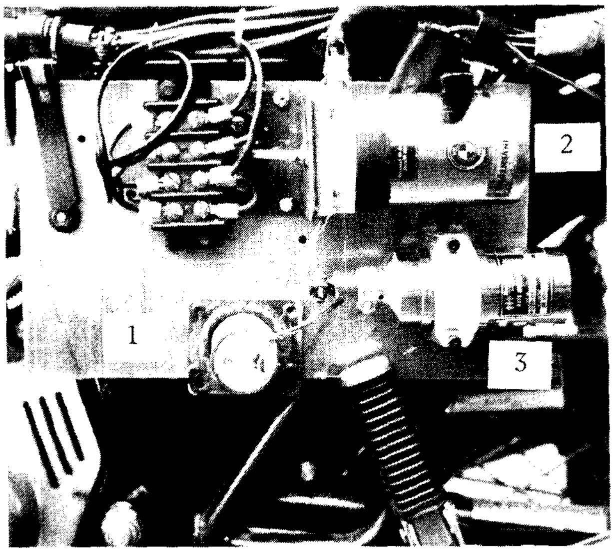


Figure 7a
(1) Lateral Accelerometer, (2) Roll Angle Gyro, (3) Yaw Rate Gyro

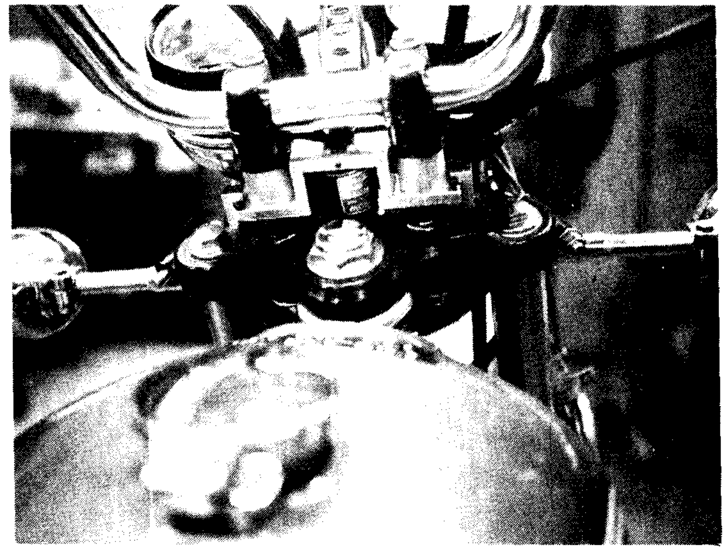


Figure 7b
Steering Torque Transducer

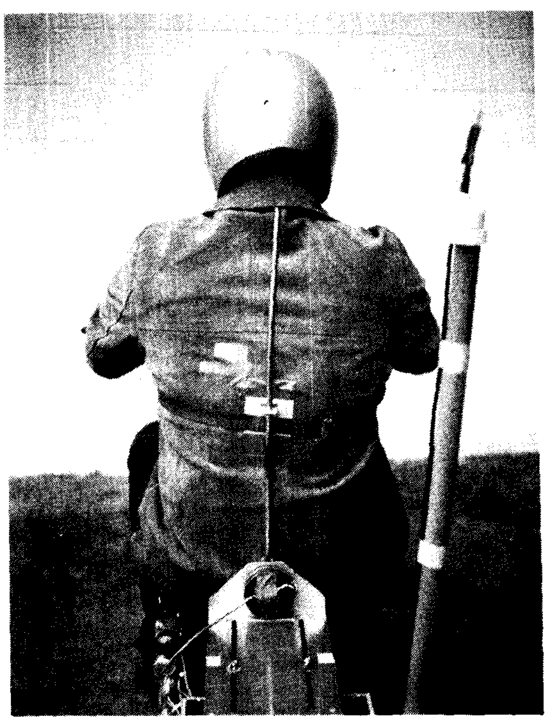


Figure 7c
Rider Lean Sensor

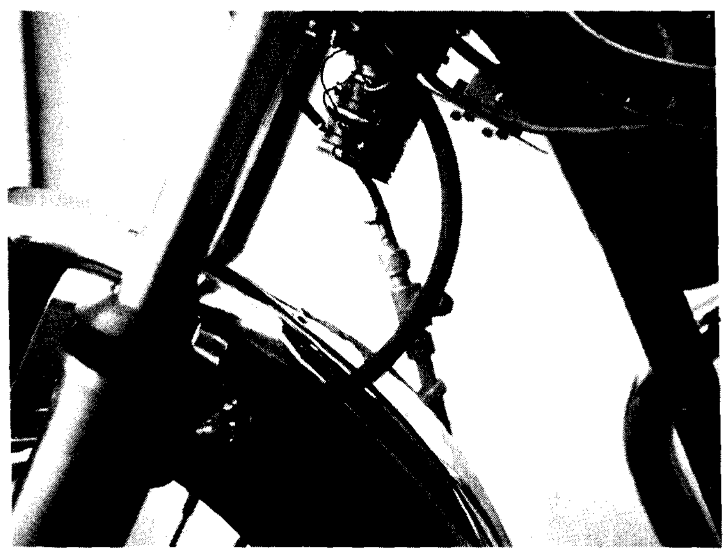


Figure 7d
Steer Angle Sensor

Figure 7. INPUT AND MOTION SENSORS

TABLE 9

INSTRUMENTATION CHARACTERISTICS

Function	Instrument	Manufacturer	Measurement Range	Accuracy
Yaw Rate	Rate Gyro	Humphrey	± 30 deg/sec	2%
Roll Angle	Free Gyro	Humphrey	± 175 deg	2%
Steering Angle	Precision Rotary Potentiometer	Denver-Amsco	± 90 deg	0.2%
Steering Torque	Torque Transducer	Lebow	± 20 lb-ft.	1%
Lateral Acceleration	Linear Accelerometer	Gianinni	± 4 g	2%
Rider Lean Angle	Precision Rotary Potentiometer	Helipot	± 90 deg	0.5%
Speed	DC Tachometer Generator	Servo-Tek	0-60 mph	0.1%

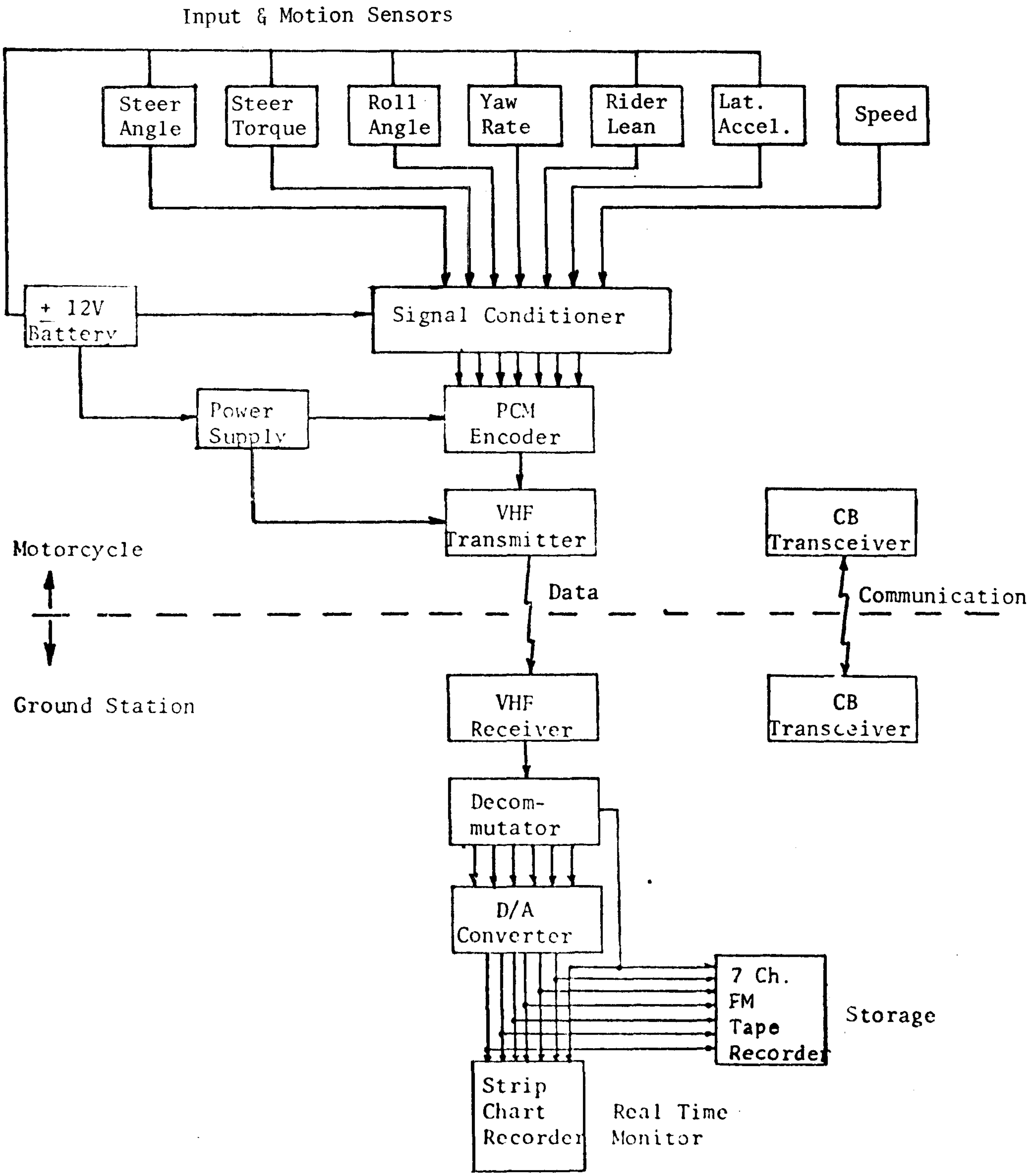


Figure 8. MOTORCYCLE DATA ACQUISITION SYSTEM

3.6 Simplified Analytical Methods

During the development of the test procedures, primarily with regard to identifying performance parameters of significance, the use of simplified steady-state models of two-wheel vehicle response characteristics was relied upon to give first order indications of the discrimination potential of the tests. This brief discussion of the approach, which is based on previous studies performed at Calspan (Reference 5), is intended only to demonstrate its general utility; nevertheless, it has proven to be very helpful in explaining some of the observed performance patterns in the experimental and simulation results.

This simplified analysis is based on linearized (constant coefficient) equations of motion for four degrees of freedom--lateral translation, yaw rotation, and roll rotation of the rigid body rider-motorcycle system and rotation of the front wheel-handle bar assembly about the steer axis. Forward velocity is treated as a constant. These equations can be solved simultaneously to yield various response ratios (transfer functions), including those involving rider lean angle if it is treated as simply an effective externally applied roll torque.

Without getting into the background and development of these expressions, they are of the following general form -

$$\frac{a_y}{\delta} = \frac{V^2/\ell \left[\cos\sigma + \frac{C_{\phi F}}{C_{\alpha F}}\sin\sigma - \frac{Z_F t - W_s f}{Mhg}\left(\frac{C_{\phi R}}{C_{\alpha R}} - \frac{C_{\phi F}}{C_{\alpha F}}\right)\right]}{1 + \frac{MV^2 (a\,C_{\alpha F} - b\,C_{\alpha R})}{\ell^2 C_{\alpha F} C_{\alpha R}} + \frac{V^2}{\ell g}\left(1 + \frac{i_T}{MRh}\right)\left(\frac{C_{\phi R}}{C_{\alpha R}} - \frac{C_{\phi F}}{C_{\alpha F}}\right)} \qquad (1)$$

where:

a_y = lateral acceleration

δ = steering angle

T = steering torque

V = velocity

ℓ = wheelbase

M = total mass (machine + rider)

Z_F = front wheel normal force

W_s = steering assembly weight, $M_s g$

t = trail

f = steering assembly mass offset

h = system center-of-gravity height

R = wheel radius

i_T = wheel moment of inertia about spin axis (both wheels)

g = gravitational constant

σ = rake angle

$C_{\alpha\ (F,R)}$ = tire cornering stiffness (front, rear)

$C_{\phi\ (F,R)}$ = tire camber stiffness (front, rear)

This expression (for position control lateral acceleration gain) appears much like that for the simplified automobile. It includes, however, the effect of rake angle and the roll-camber influence - in the $\left(\frac{C_{\phi R}}{C_{\alpha R}} - \frac{C_{\phi F}}{C_{\alpha F}}\right)$ term. This latter effect is one of the most important contributors to the motorcycle's stability and control characteristics.

This simplified approach was employed in several brief analyses of special interest. These analyses include:

1. First order evaluations of steady-state performance parameters. The results indicated that the selected set of motorcycles spanned a wide range of position control characteristics--from the lightweight Honda 125 at the oversteer end to the heavyweight Harley-Davidson, which has understeer characteristics approaching those of a small car. These evaluations were later confirmed by the simulation results. A typical output plot from these analyses is shown in Figure 9.

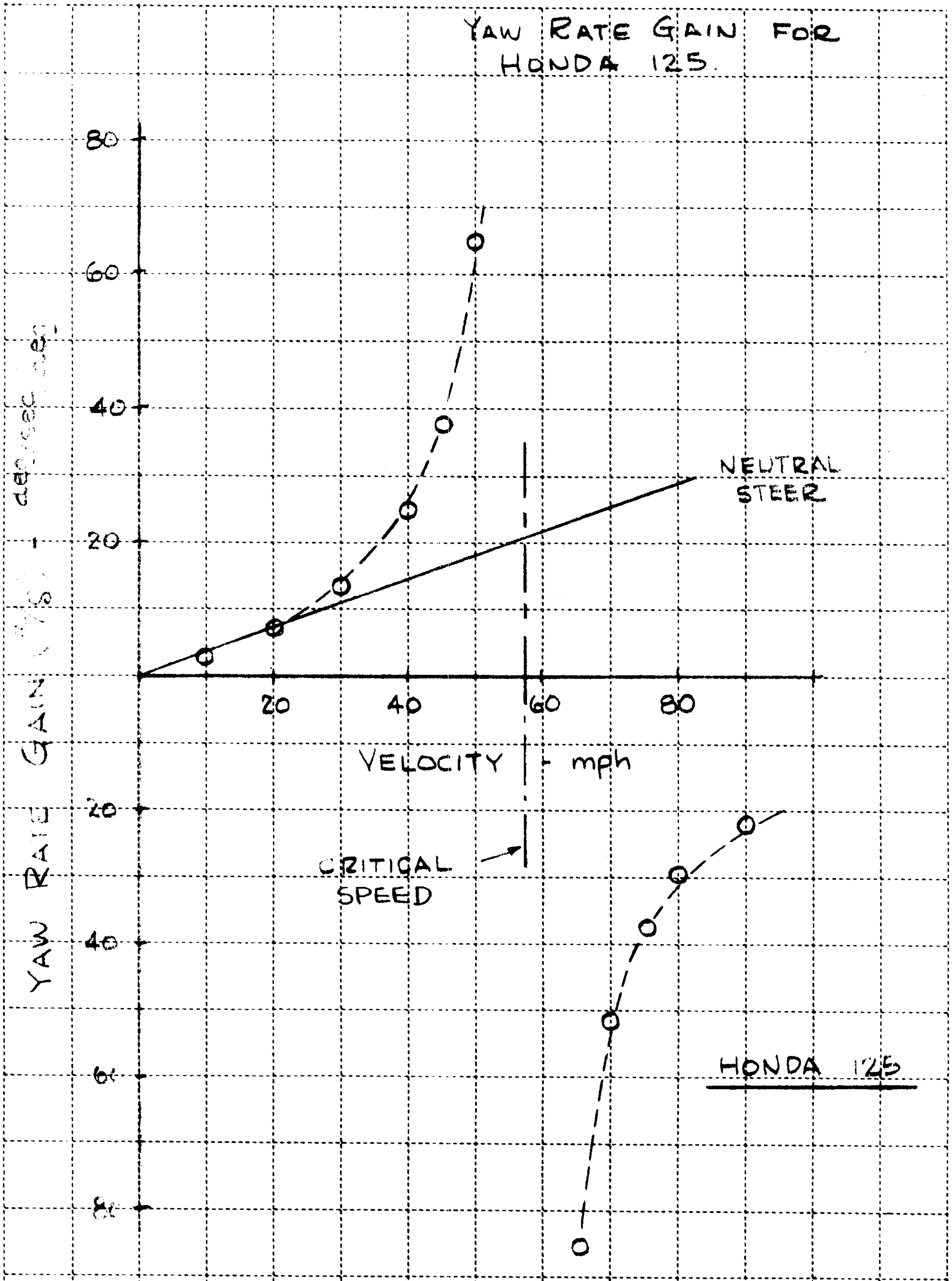


Figure 9: TYPICAL SIMPLIFIED ANALYSIS RESULTS

2. Investigation of the effect of rider lean angle and the roll-camber steer term on the performance parameters. The simplified theory was used to develop the skid pad equation for the motorcycle -

$$\delta + \frac{C\alpha\phi}{C\sigma}\,\Theta\phi_R = \frac{\ell/R + (kC_{\alpha\phi} - \frac{ho}{Co})\,Ay}{C\sigma} \qquad (2)$$

Where:

δ = steer angle about the fork axis

Φ_R = rider lean relative to the frame

$C_{\alpha\varphi} = \frac{C_{\phi F}}{C_{\alpha F}} - \frac{C_{\phi R}}{C_{\alpha R}}$ ($C\ \phi$ F,R are tire camber stiffnesses)

$C\sigma \cong \cos\sigma - \sin\sigma\,\frac{C_{\varphi F}}{C_{\alpha F}}$ (σ is the complement of the fork tube angle)

θ = a rider lean angle gain that determines how much roll moment per unit lean (relative to the motorcycle frame) is obtained.

k = a term related to moments of inertia, it is $\cong 1$

ho = static margin = $\frac{bC_{\alpha R} - aC_{\alpha F}}{\ell\ (C_{\alpha F} + C_{\alpha R})}$

$Co = \frac{C_{\alpha F}C_{\alpha R}}{(C_{\alpha F}+C_{\alpha R})W}$

ℓ = wheelbase

The interesting points that can be made are:

- For zero rider lean (ϕ_R is pos. clockwise looking forward), the motorcycle is similar to the 2df car except that the apparent Ackermann angle (steer angle required as V $\rightarrow$0 at constant radius) is $^{\ell/R}/C\sigma$ instead of ℓ/r - clearly a fork angle effect.

- The understeer/oversteer factor, K, is

$$K_{mc} = \frac{k\,C_{\alpha\varphi} - \frac{h_o}{C_o}}{C_\sigma} \quad \text{instead of} \quad K_{car} = \frac{-h_o}{C_o}$$

Again the fork angle effect is present but the term $k \; C \alpha \phi$ is similar to an "add on" steer effect in a car. In fact, it can be shown that the term is identical in effect to roll camber in a car.

- The influence of rider lean, ϕ_R, is to change the apparent Ackermann angle but not the understeer factor, K. The Ackermann angle is given by (from equation 2):

$$\delta_{A} \Big|_{A_{y=0}} = \frac{\ell/R - C_{\alpha\varphi}\Phi_R \, \Theta}{C_{\sigma}}$$

Positive lean (into the turn) will either increase δ_A or decrease it depending upon the sign of $C \alpha \phi$. (C_{σ} and Θ are always positive).

3. A convenient form for investigating torque input requirements is:

$$T = (F_{yF} \, t_1 + M_s f a_y + \frac{i_F}{R} \, Vr \sin \sigma) \cos \phi$$
$$- (F_{zF} \, t_2 + W_s f) (\sin \phi + \delta \sin \sigma) \qquad (3)$$

where

T	= applied steering torque
F_{yF}	= front wheel side force
t_1	= total effective trail (mechanical plus pneumatic)
M_s	= steering assembly mass, $\frac{W_s}{g}$,
F_{zF}	= front wheel load ($-Z_F$ in eq. 1)
f	= steering assembly mass offset
a_y	= lateral acceleration
i_F	= front wheel moment of inertia around spin axis
R	= wheel radius
r	= yaw rate

σ = rake angle

v = velocity

ϕ = roll angle

δ = steer angle

t_2 = mechanical trail

This expression [Eq. 3] may be simplified if one is interested primarily in the "on-center" characteristics of motorcycles by using the small angle approximations, cos ϕ = 1 and sin ϕ = 0 . Applying a few approximations to the general equation [a_y (g units)$\approx\phi$ (rad); $F_y \approx F_z \phi$; and $M_s f a_y \approx W_s f \phi$], further simplification is possible. Then,

$$T \approx F_{zF} (t_1 - t_2) + a_y \frac{i_F}{R} \sin \alpha$$

$$- \delta \sin \sigma \quad (F_{zF} t_2 + W_s f) \tag{4}$$

This equation demonstrates the importance of the value of pneumatic trail ($t_1 - t_2$) in the determination of steering torque requirements. Note that the first two terms require torque application in the same direction as steering displacement; the third term (arising from steering head rake) provides an aiding torque. For the special case in which pneumatic trail is zero on a neutral steer machine ($\delta = \ell\rho$, where ρ is curvature of the turn), an expression for the speed at which the rider-applied torque is zero can be derived. This speed, which is called the inversion speed, is -

$$V = \left[\frac{\ell R \ (F_{zF} t_2 + W_s f)}{i_f \cos \sigma} \right]^{1/2} \tag{5}$$

To summarize this brief discussion, the simplified constant coefficient model of the motorcycle appears to be a useful tool for achieving some insight into the performance characteristics of these machines. Although it was applied to only a few specific analyses in this program, it can be an important adjunct to the more sophisticated nonlinear simulation model for preliminary analysis of motorcycle performance.

3.7 Simulation Description

In this subsection, the characteristics of Calspan's motorcycle simulation program are discussed in general terms to demonstrate its capability to treat various operating condtions and control modes. The description of the mathematical model on which it is based is quite brief; it is described in more detail in Reference 4.

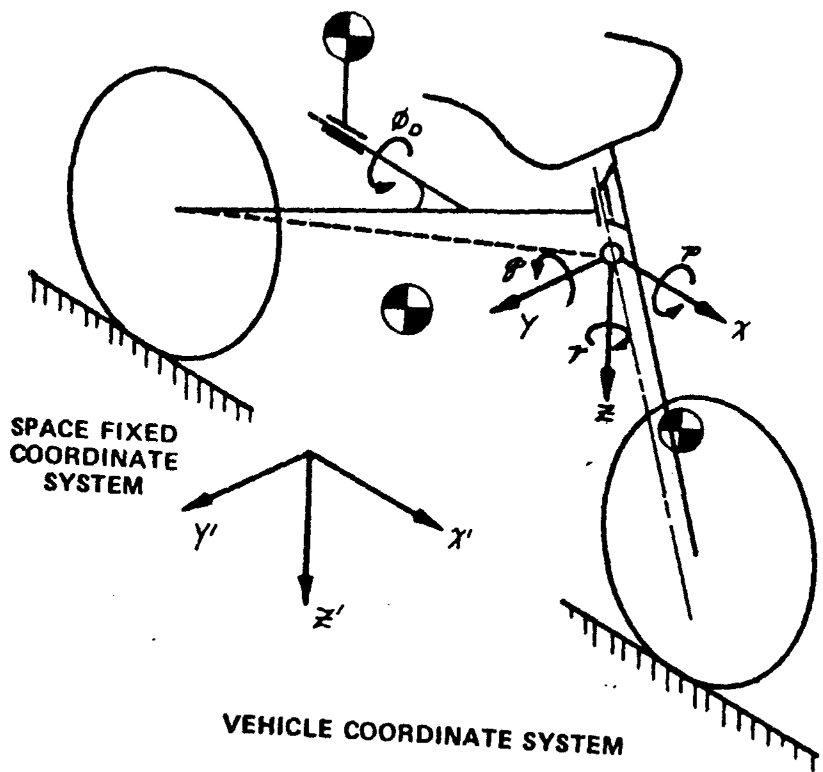
The vehicle-rider model is a system of three rigid masses with eight degrees of freedom of motion: six rigid-body degrees of freedom of the rear frame, a steer degree of freedom of the front wheel, and a rider lean degree of freedom (see Figure 10). The basic physical parameters of the vehicle which are included in the mathematical analysis are shown in Figure 11, where Θ_F is the rake angle of the steer axis and δ is the steer angle of the front wheel about the inclined steer axis. The symbols M_D, M_R, M_F represent the masses of the rider, the rear wheel and frame, and the front wheel and steering fork assembly, respectively.

The analysis is based on the following assumptions:

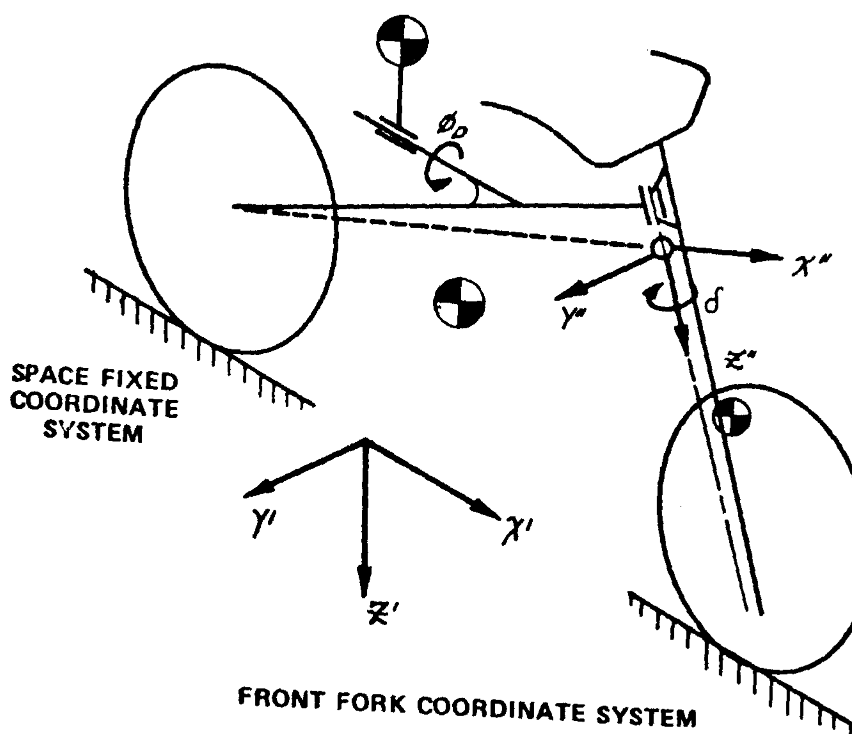
(1) The mass distribution of the vehicle is assumed to be symmetrical with respect to the vertical-longitudinal plane through the geometrical center of the vehicle. Thus, the X-Y and Y-Z products of inertia are assumed to be zero. X-Z products of inertia and all moments of inertia of each rigid mass are included.

(2) The vehicle is assumed to be moving through still air on a flat level surface. The aerodynamic drag, the front to rear weight transfer due to aerodynamic drag, and the pitching moment, aerodynamic lift, and steer moment due to windshield aerodynamic drag are included as approximations.

(3) A driving thrust on the rear wheel is included to overcome the aerodynamic drag. Thus, the vehicle is initially moving at constant speed. Front tire rolling resistance is assumed negligible.



VEHICLE COORDINATE SYSTEM



FRONT FORK COORDINATE SYSTEM

Figure 10. Two-Wheel Vehicle Model

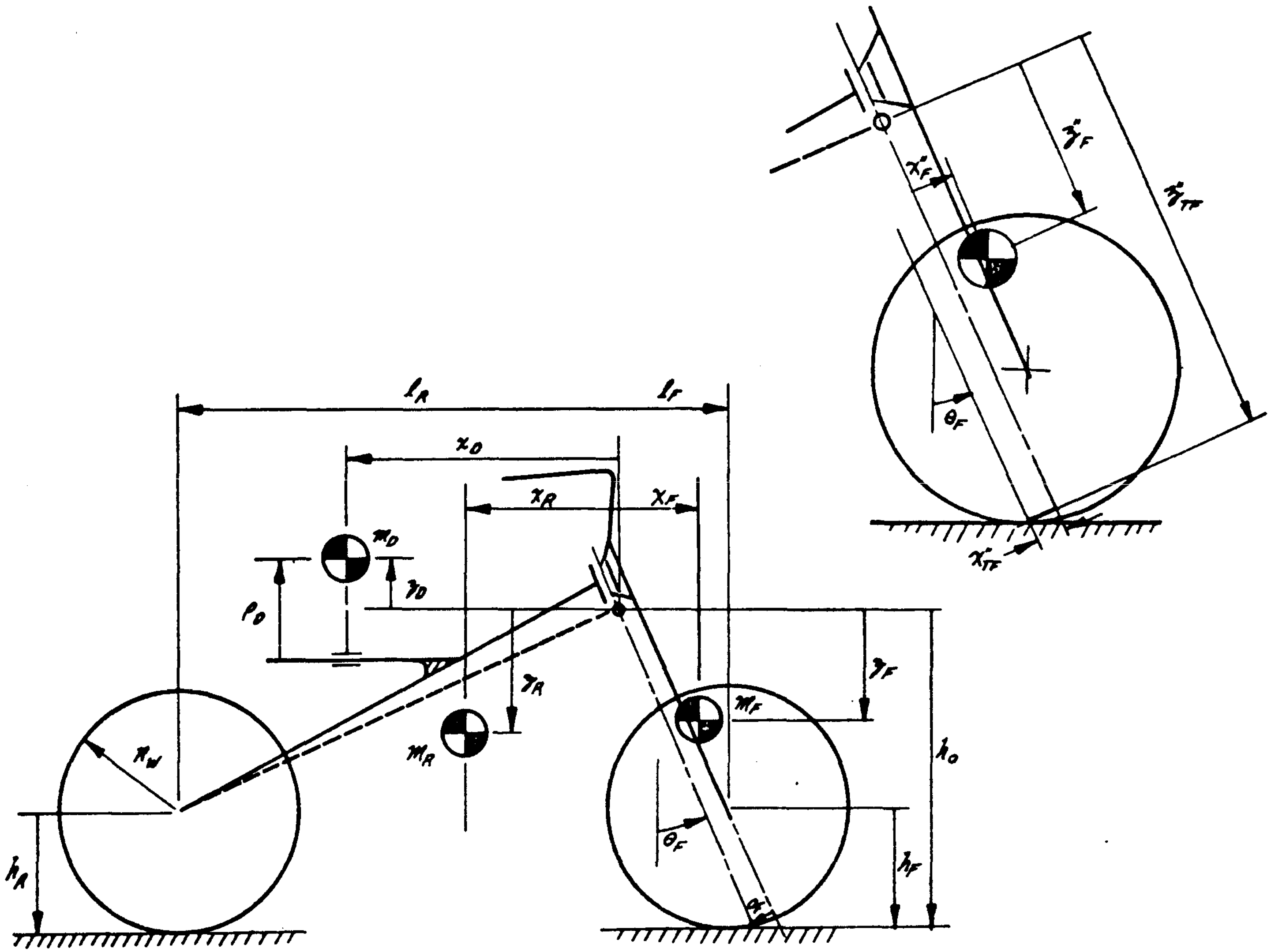


Figure 11. Characteristic Dimensions of Motorcycle Model

(4) Tire lateral forces as functions of slip angle, inclination (camber) angle, and vertical load are modeled independently for front and rear tires.

(5) External torques acting about the steer axis include the moments due to the lateral and vertical tire forces, tire aligning torque, and a couple due to the aerodynamic drag force on the windshield. The gyroscopic moments of the wheels and engine are included.

(6) Viscous steering damping is included between the front assembly and the rear frame.

(7) The axis of rotation of the engine is assumed to be transverse with the direction of rotation of the engine the same as that of the wheels.

To analyze the handling of a two-wheel vehicle in the nonlinear region of operation, the equations of motion are written in complete nonlinear form. All inertial coupling terms between the rider, the front assembly, and the rear frame are included. The digital computer simulation program for this analysis solves the equations of motion for prescribed rider control inputs and/or disturbance inputs and produces time histories of the resultant vehicle motions.

The simulation program, consisting of twelve subroutines, uses approximately 200 K bytes of core storage when run on an IBM System/370 Model 165 computer. The output processor program uses approximately 160K bytes of core storage.

Over one hundred input variables are required by the simulation program. These data include forty-six vehicle parameters: dimensions, weights, moments of inertia, tire side force coefficients, aerodynamic coefficients, etc.

The digital computer simulation program consists basically of the application of a modified Runge-Kutta step-by-step procedure to integrate the equations of motion. The integration step size is a variable although a value of 0.01 second is generally used. The solution of up to 10 seconds of simulated real time may be obtained with a step size of 0.01 second. Solution output is obtained from a separate output processor program which can produce time histories of as many as 36 variables (translational and angular positions, velocities, accelerations, tire force components, etc.) in both printed and plotted format.

The general form of the rider control model is shown in Figures 12 and 13. This model involves a roll stabilization loop and a path-following guidance loop which are connected through a simple human operator transfer function to the vehicle dynamics model. The basic form of control, for both stabilization and path-following, assumes matching actual roll angle of the system with a "command roll angle"--a rider-generated term which corresponds to a desired lateral acceleration. Details of this model are described in Reference 3.

It will be helpful for putting the results of the simulation studies with the directional control test procedure in perspective to give a brief discussion of the rider-motorcycle stabilization loop. Its functioning, as employed in most of the runs, is diagrammed in Figure 14. Note that rider lean effects are absent in this figure. Except for a special set of runs specifically aimed at evaluating the influence of rider lean on control input requirements (which will be discussed later), this mode was deliberately inhibited by forcing the rider to remain in-plane with the motorcycle. Thus the rider-controlled loop closures are through applied steer torque in response to sensed roll motion of the machine.

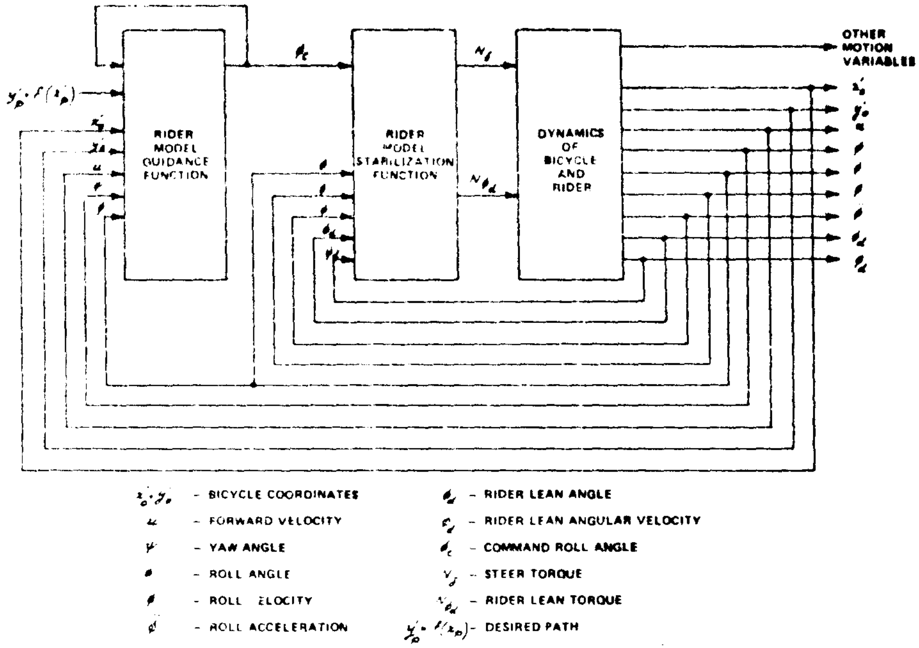


Fig. 12. Block Diagram of Rider Control Model

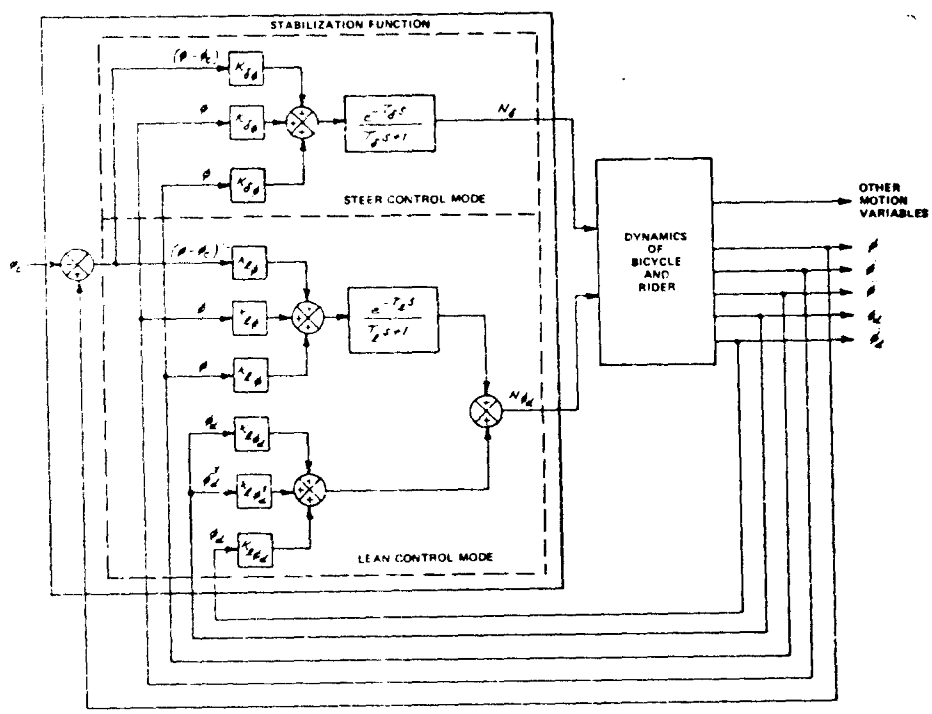


Fig. 13. Block Diagram of Stabilization Function of Rider Control Model

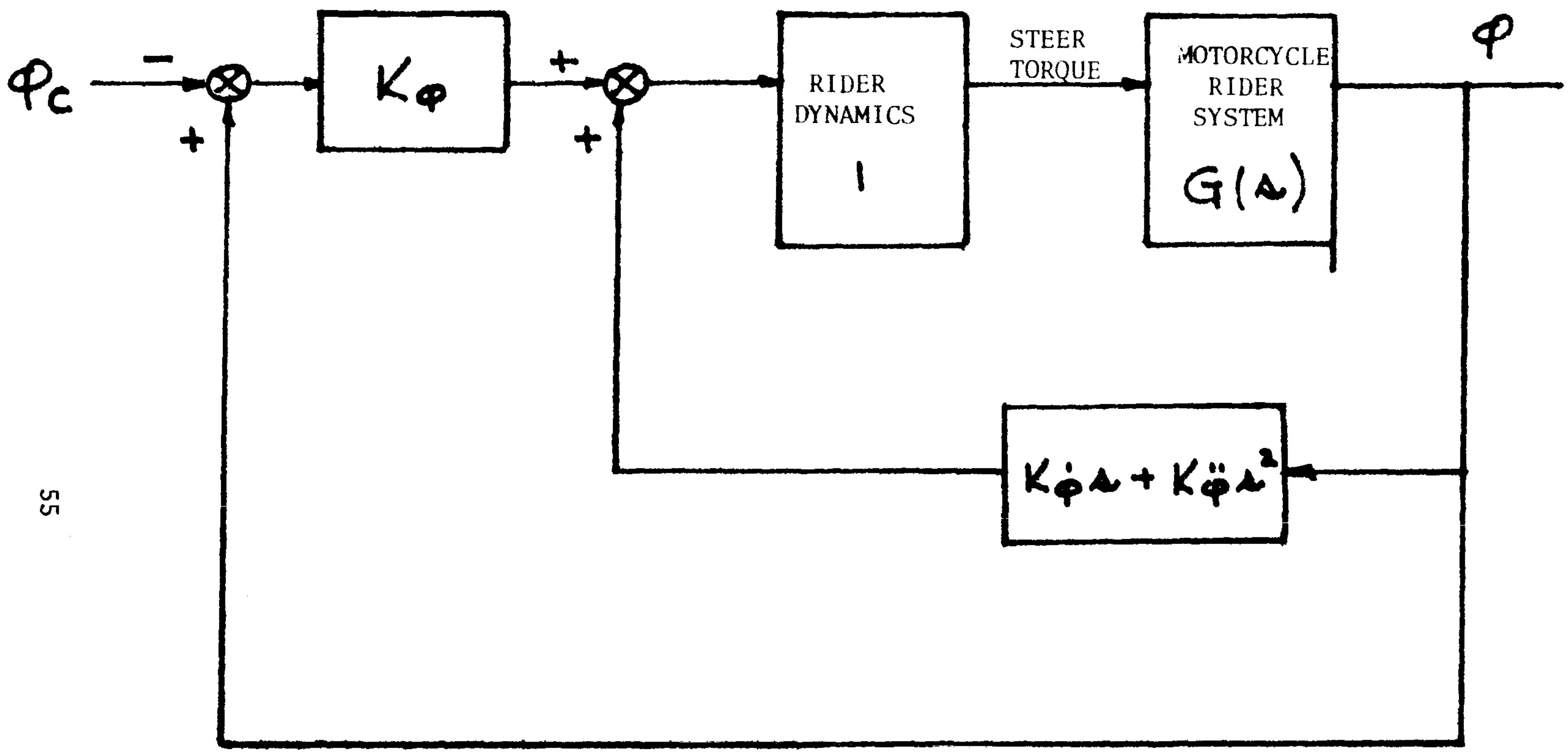


FIGURE 14: MOTORCYCLE STABILIZATION LOOP

In this mechanization, primary stabilization and control is achieved through the comparison of the actual roll angle of the system with the self-generated command roll angle. Derivative terms of the roll motion (rate and acceleration) are used to provide acceptable dynamics. Since there is no free integration term in the feed-forward path of this mechanization, a steady state roll angle error exists in order to sustain the steering torque input required for cornering. For purposes of this discussion, the motorcycle response is simply designated as G(s), a higher-ordered transfer function relating the motorcycle's roll response to steering torque, and rider dynamics are omitted.

The closed loop response of the system can be described by the expression -

$$\frac{\varphi}{\varphi_c} = K_{\varphi}G(s) / G(s)K_{\ddot{\varphi}}s^2 + G(s)\ K_{\dot{\varphi}}s + [G(s)K_{\varphi}-1]$$

At steady state, the expression reduced to -

$$\frac{\varphi}{\varphi_c} = K_{\varphi}G / (K_{\varphi}G-1)$$

Although this indicates a steady state error, φ_c is used only as a reference to achieve a lateral acceleration value in the region of interest. The response of the system can be made stable, fast, and well-damped by appropriate selection of the values for K_{φ}, $K_{\dot{\varphi}}$, and $K_{\ddot{\varphi}}$ in conjunction with the values for the elements of G(s), and the resultant steady-state conditions can be used to evaluate the associated control input and motion output variables of interest. As indicated earlier, these include the applied steering angle and steering torque, tire and motorcycle slip angles, and lateral acceleration, turn radius, and yaw rate values which result. From these, computations of the vehicle response parameters (steady state gains) follow directly, just as in the full-scale test work.

3.8 Results

Numerical results from the experimental and simulation phases of the study are combined in this section. Because of the much broader coverage of the simulation work, enabling the formulation of comparisons among machines, these results are emphasized. They demonstrate a number of interesting points about motorcycle response which are discussed in some detail. The principal results of the test work with the Honda 360 are given in graphical form; they illustrate the type of output information available from the suggested procedures.

3.8.1 Simulation

Approximately 40 runs were made with the simulation program in the two procedures recommended for use in this study. The majority of these were devoted to the evaluation of steady state lateral-directional response characteristics--partly to emphasize the fundamental nature of these parameters and partly because of problems of execution and interpretation of the transient performance task and its results. Time history plots for all runs are given in Appendix C.

Directional Control Test Procedures

For use in the simulation studies, the procedures were adapted for compatability with the simulation program in order to maximize the efficiency of its utilization. For the directional control tests, these adaptations consisted of specifying a run array of several nominal command roll angles at constant speed and restriction of rider lean control to a passive role. This approach allowed for full coverage of the range of lateral acceleration values of interest (but avoided a requirement for path control) and for emphasizing the steer control modes in the analysis.

Typical time histories for the primary input and output variables in the directional control test simulation are shown in Figure 15. The conditions for this run were a speed of 40 mph and a desired (command) roll angle of 25 degrees. This roll angle corresponds to a lateral acceleration of about .5 g. The rider remained approximately in-plane with the motorcycle throughout the

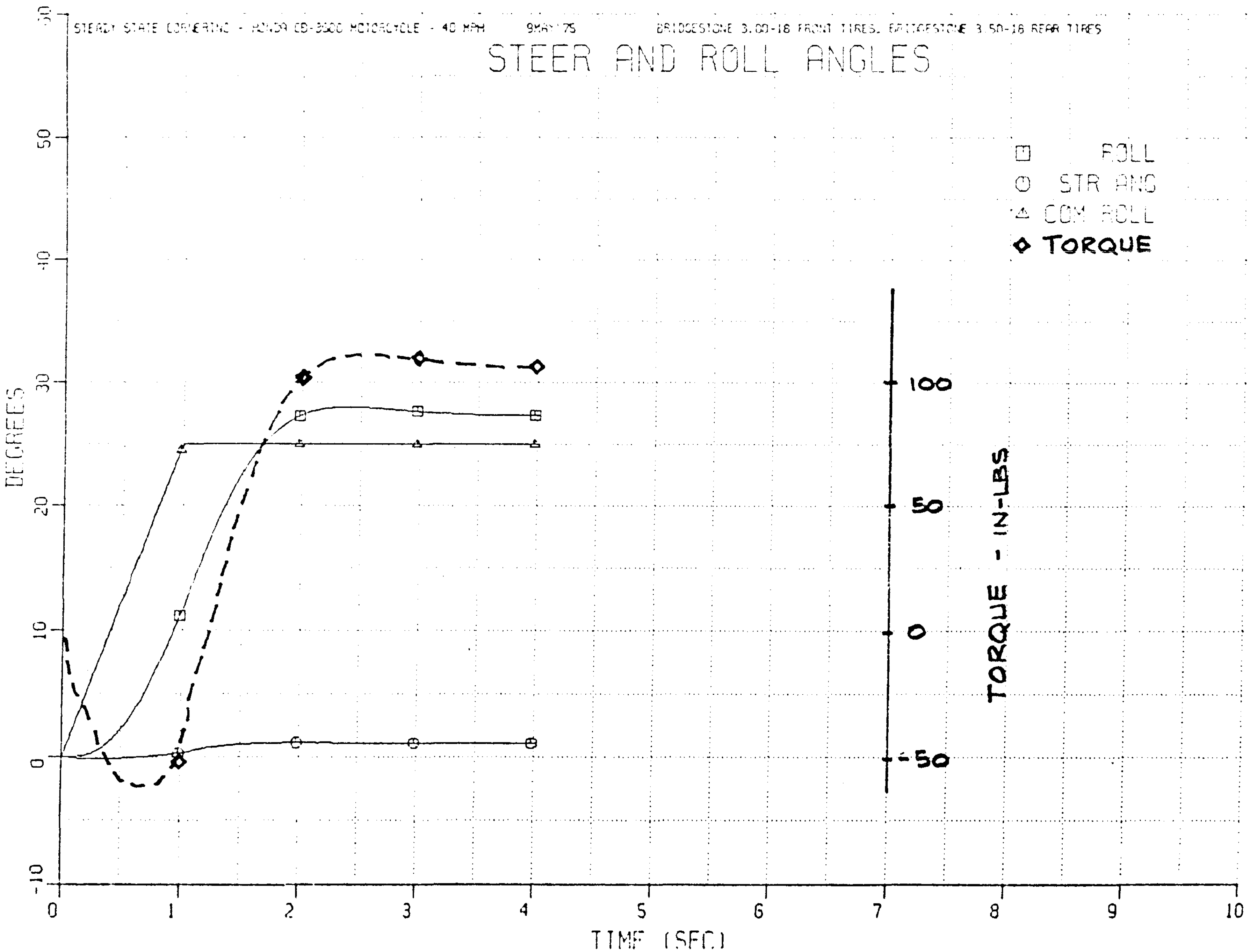


FIGURE 15: SIMULATED DIRECTIONAL CONTROL TEST RESPONSE

run--reaching a maximum of .18 degree (lean-out) early in the maneuver and settling to a steady-state value of .07 degree (lean-in). The response is rapid and well damped at this condition for the rider control model coefficients selected for this maneuver.

The initially-applied reverse steering torque produces a small reverse steering angle. The roll angle (lateral acceleration) builds up to a slight overshoot of the final steady state condition within .7 second of the time at which the command roll angle is established. The offset in actual roll angle from the command value of about 2 degrees is due to the torque requirement without a feed-forward integration term (as explained in Section 3.7). The rider control coefficient values for this run were: K_{φ} = 45 lb-in/deg; $K_{\dot{\varphi}}$ = 20 lb-in/deg/sec and $K_{\ddot{\varphi}}$ = 5 lb-in/deg/sec^2. These values were used with all six machines and produced similar response patterns in all cases at this operating condition.

Results for a series of runs over a range of lateral accelerations for all machines with this test procedure are shown in Figures 16 and 17. These data are reduced in Table 10 to give values for three primary performance parameters at a reference operating condition--40 mph speed, .4g lateral acceleration, 200 pound rider, and recommended tires. The range of data for the Honda 360 shown in the figures was extended to demonstrate the reasonable linearity of the characteristics over the lateral acceleration performance envelope.

In general, the steady state input requirements of steer angle and steer torque tend to be related to vehicle size. However, the Kawasaki steer angle requirements are relatively high and those of the Yamaha low. Steer torque requirements for the Honda 360 and the Norton appear to be relatively high and low, respectively. These patterns are reflected in the values of the performance parameters given in Table 10.* The Yamaha 650 is of particular

*The negative sign associated with the Understeer Factor in Table 10 indicated oversteer.

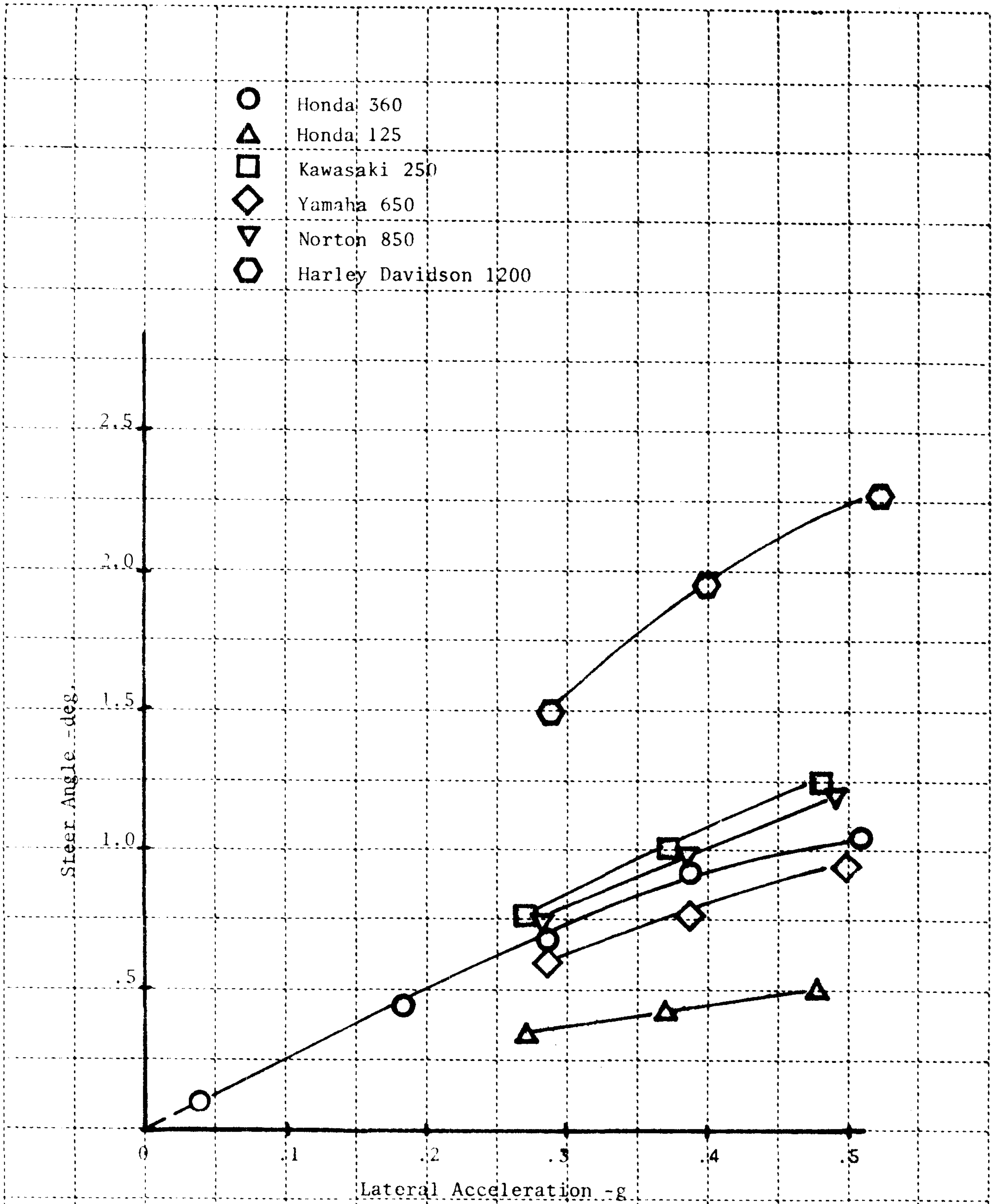


FIGURE 16: SIMULATED DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - STEER ANGLE

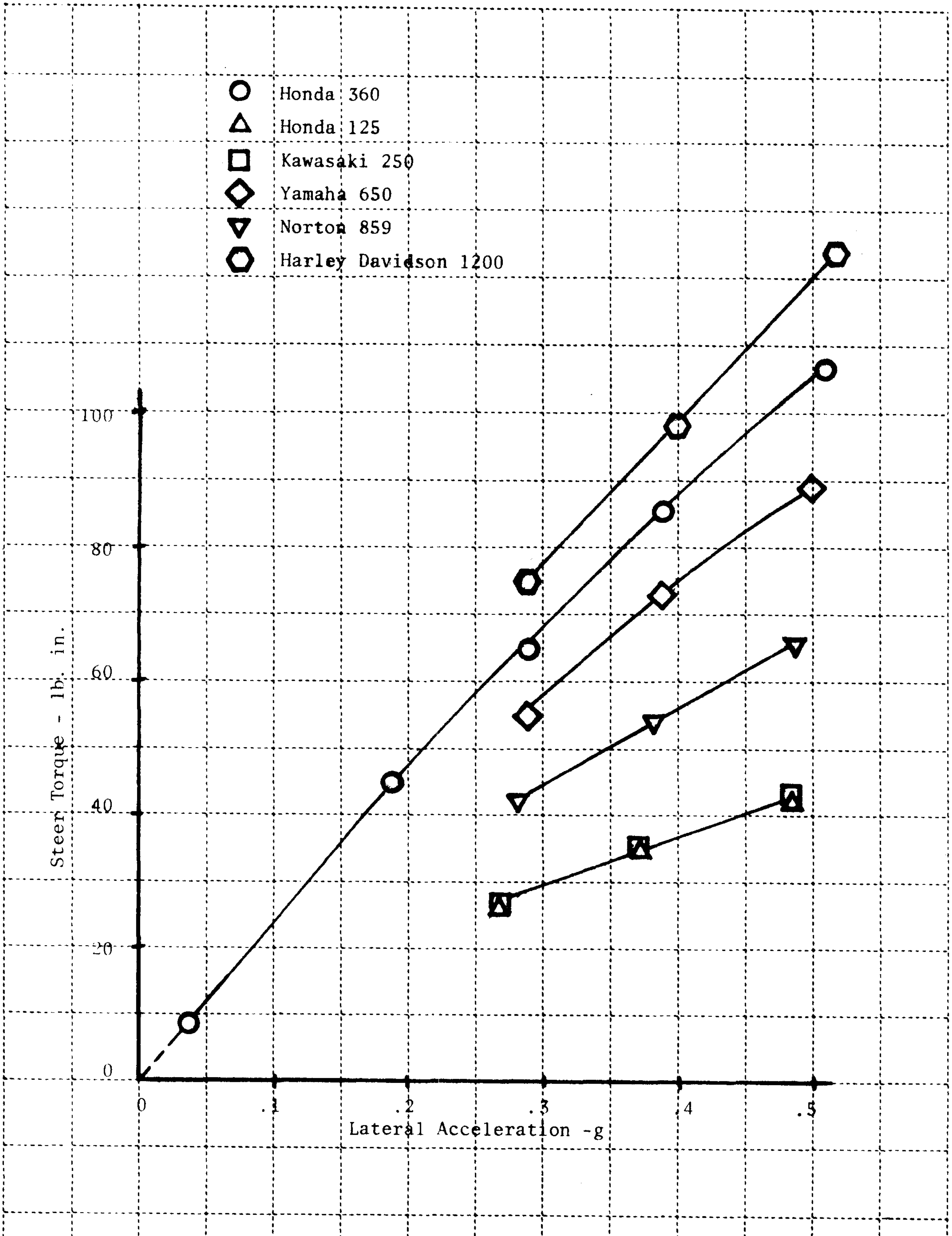


FIGURE 17: SIMULATED DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - STEER TORQUE

VEHICLE	NOMINAL SPEED (mph)	NOMINAL LATERAL ACCELERATION (g)	STEER TORQUE SENSITIVITY (in-lbs/g)	STEER ANGLE SENSITIVITY (deg/g)	UNDERSTEER FACTOR (deg/g)
HONDA 360	40	.4	190	2.3	0
HONDA 125	↓	↓	74	.8	-.9
KAWASAKI 250	↓	↓	76	2.2	+.3
YAMAHA 250	↓	↓	160	1.4	-.5
NORTON 850	↓	↓	114	2.2	+.1
HARLEY-DAVIDSON 1200	↓	↓	216	3.4	+2.2

TABLE 10: SIMULATED DIRECTIONAL CONTROL RESPONSE PERFORMANCE PARAMETERS

interest because of its high steer angle gain and oversteering behavior. The H-D 1200 shows understeer qualities approaching those of a small automobile. The near neutral-steer characteristics of the Honda 360 and the Norton, in view of the generally-held opinion that they are "good-handling" machines, would suggest that values in this range are desirable. The large negative value of the understeer factor for the small Honda is indicative of its low critical speed (as discussed below).

One of the most interesting aspects of motorcycle behavior which can be observed from these results 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.

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 the turn. That is -

$$\begin{aligned} &Fy = 0;\ May = Fyf + Fyr && \text{(a)} \\ &Mz = 0;\ a\ Fyf = b\ Fyr && \text{(b)} \\ &Mx = 0;\ May\ h \cos\phi = Wh \sin\phi && \text{(c)} \end{aligned} \qquad [1]$$

where -

M = mass of rider-motorcycle system

a_y = lateral acceleration

F_{yf} = front wheel side force

F_{yr} = 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 -

$$F_{yf} = C_{\alpha f} \left(\beta + \frac{a}{R} - \delta \cos \sigma\right) + C_{\phi F} (\phi + \delta \sin \sigma)$$
$$F_{yr} = C_{\alpha r} \left(\beta - \frac{b}{R}\right) + C_{\phi R} \phi$$

where:

C_α = cornering stiffness, lbs/deg

C_ϕ = camber stiffness, lbs/deg

β = sideslip angle, deg

δ = steer angle, deg

σ = rake angle, deg

R = turn radius, ft.

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

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

If the side force requirements are exceeded by the sum of only $C_{\phi F}$ and $C_{\phi R}$ with concurrent satisfaction of the roll moment equation (which can be simplified to $A_y = g \tan \phi$), 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, 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.

In all motorcycle configurations which were evaluated, camber thrust provided at least one-half the total side force required for cornering. Some machines, the two Hondas and the H-D 1200, for example, develop sufficient side force by this mechanism, that they operate in a "nosed-out" trim attitude in the region of nominal test speed (40 mph). Others, the Kawasaki and Norton from the test group (which have low camber thrust coefficient values) make up the deficiency by developing tire slip angles through vehicle side-slip and thus trim at a "nosed-in" attitude.

In order to examine effects of speed on the values of the performance parameters, particularly with respect to the existence of a critical speed (in the sense associated with fixed control of an oversteering automobile) and an inversion speed (at which lateral acceleration gain in response to steering torque is infinite), a series of tests were simulated with the two Honda motorcycles. Results are shown in Figure 18 and 21.

Figure 18 shows the variations in the steady state values of steering input angle and torque at various speeds for the nominal lateral acceleration test condition of .4g. The Model 360 is well-behaved in this range--torque requirements increase slightly and the steering angle decreases approximately inversely with $(\text{speed})^2$. This latter relationship is to be expected for a near-neutral steer vehicle, for which δ is proportional to ℓ/V^2 at constant Ay. Note that torque requirements increase however, even though steering angle is reduced. The Model 125 on the other hand is slightly beyond its position control critical speed at 60 mph (the actual value for the steer angle at the data point shown in the figure is -.05 degree) although the torque input value is still reasonable. Operation at this condition under torque control poses no problem, as demonstrated by the time history plots shown in Figure 19, except for the high frequency, small amplitude oscillation in the torque

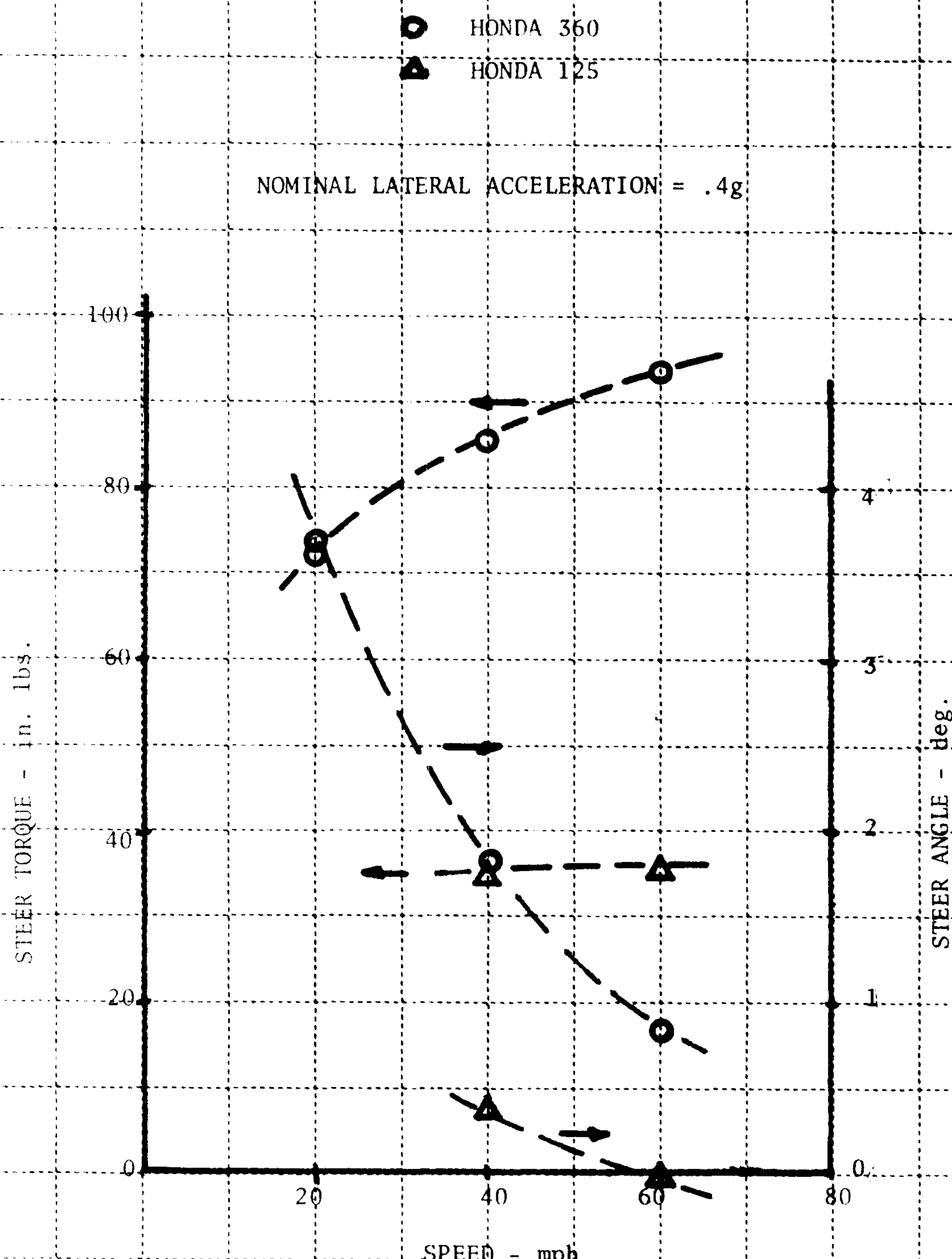


FIGURE 18: DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - SPEED EFFECTS

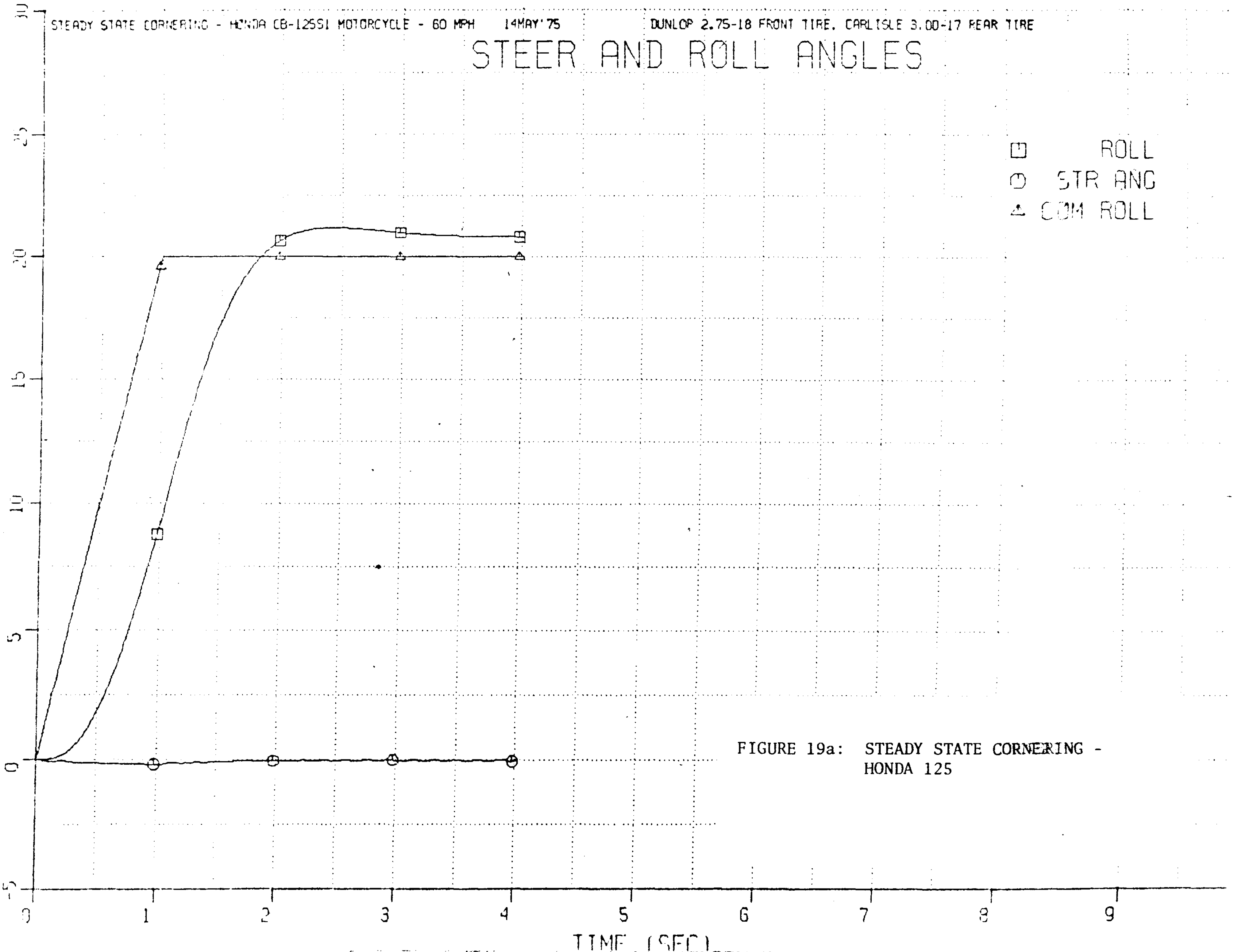


FIGURE 19a: STEADY STATE CORNERING - HONDA 125

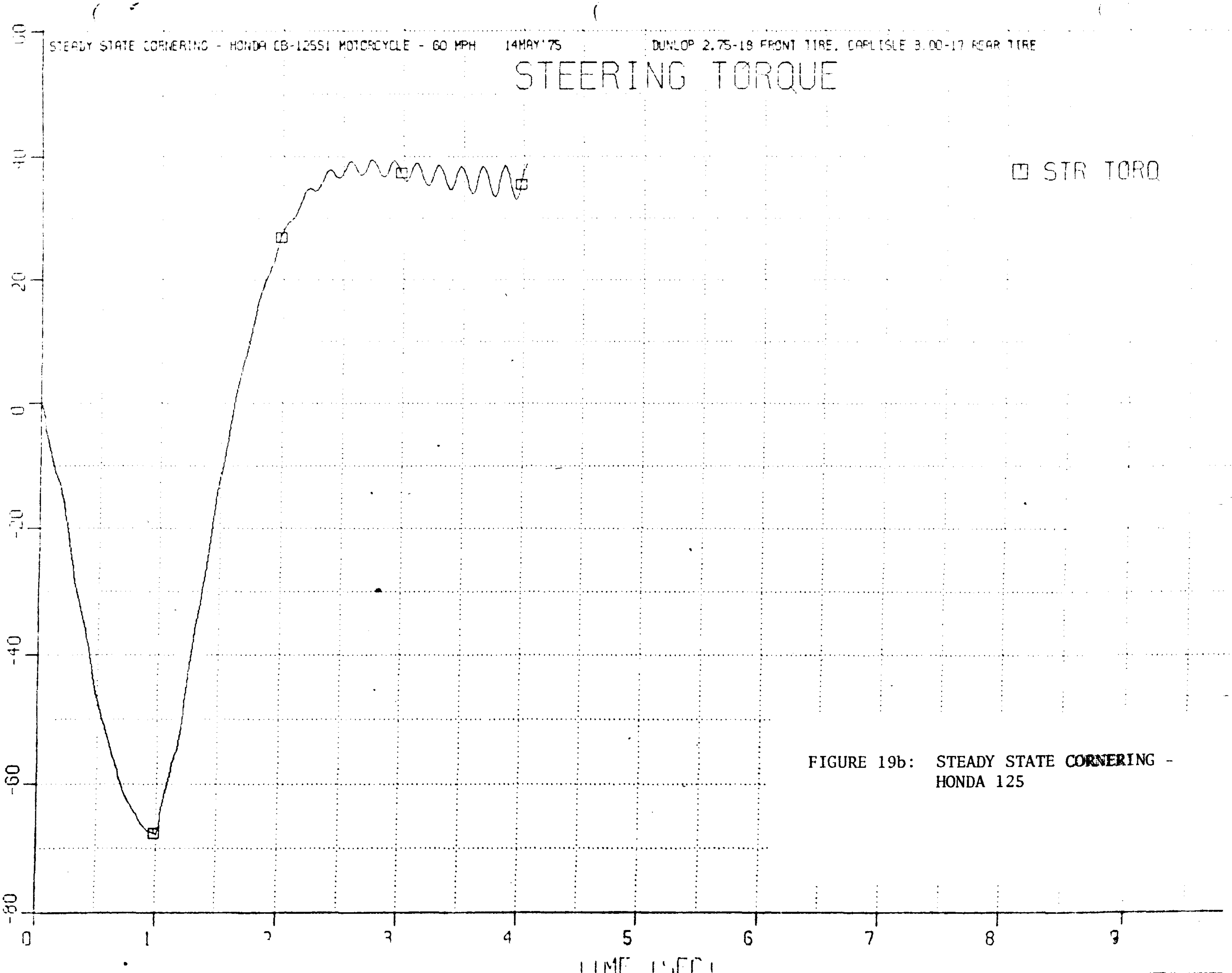


FIGURE 19b: STEADY STATE CORNERING - HONDA 125

trace which begins to build late in the run. Similar oscillations were observed for other configurations under specific conditions (See Appendix C for time histories) and, since the frequency is in the range associated with steering wobble, this condition should be investigated further in later in-depth studies.

The performance of the Honda 360 at "on-center" handling conditions was checked in a short series of runs through a range of test speeds from 5 to 40 mph. These data are shown in Figure 20. Steady state lateral acceleration for these runs was approximtely .04g--representative of a mild path correction in nominal straight-line running. The interesting point to be noted is the inversion of the direction of the applied torque at the low speed condition. This run was also marked by the low damping of the response as shown in Figure 21. This figure may be compared with Figure 15 where, with the same rider model parameters, the response of the machine is rapid and well-damped for a .5g turn at 40 mph.

Although it was not possible to investigate performance at other than the nominal O.E. condition of the motorcycles in any depth, the availability of additional data on tires suitable for use with the Harley Davidson 1200 machine provided a basis for a comparison of tire effects. The results of this comparison are shown in Figure 22. The most striking difference between the two configurations is for the steer torque requirement. The normal configuration (i.e., the one shown in earlier data) has a much higher steer torque sensitivity parameter value (and, therefore, higher torque requirements). This difference is due entirely to the tire characteristics--in particular, the pneumatic trail (aligning torque) difference. Table 11 compares the tire sets for the two configurations.

The tire performance effect was also studied with the Yamaha 650 in two configurations differing only with regard to rear tire characteristics. A comparison of the tire parameters is shown in Table 12 and the results of the simulated directional control measurements are given in Figure 23. Note the marked differences in input requirements for steady-state control due almost

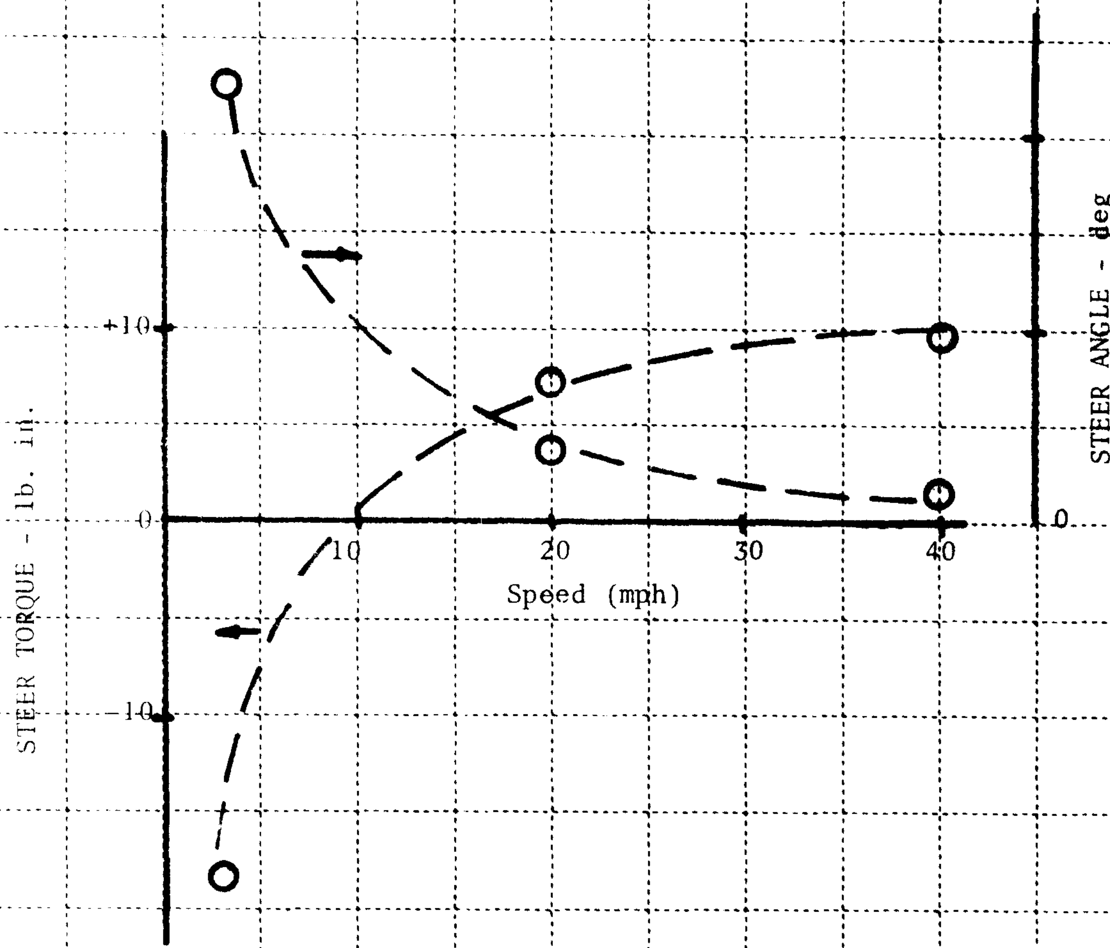


FIGURE 20: DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - ON-CENTER PERFORMANCE (HONDA 360)

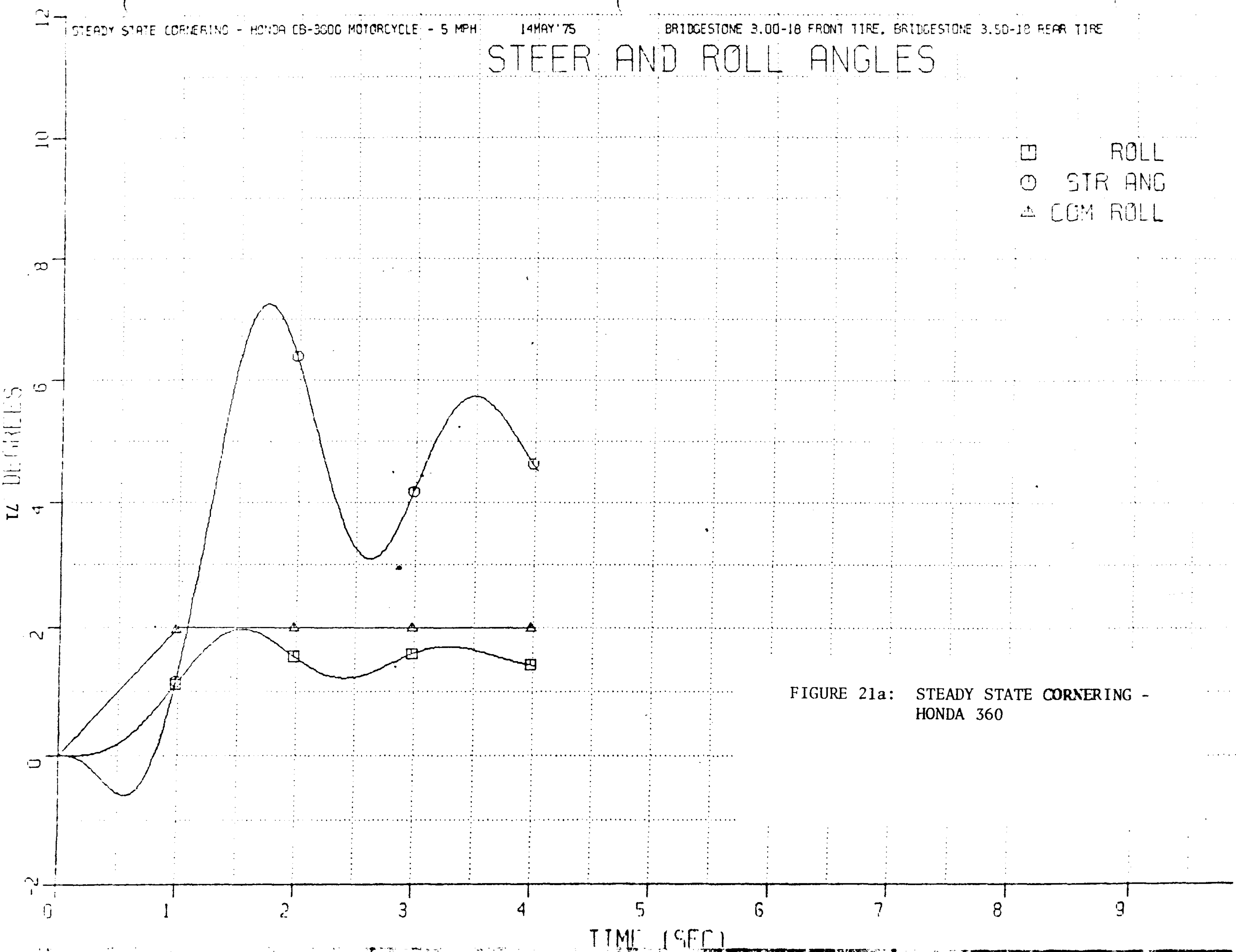


FIGURE 21a: STEADY STATE CORNERING - HONDA 360

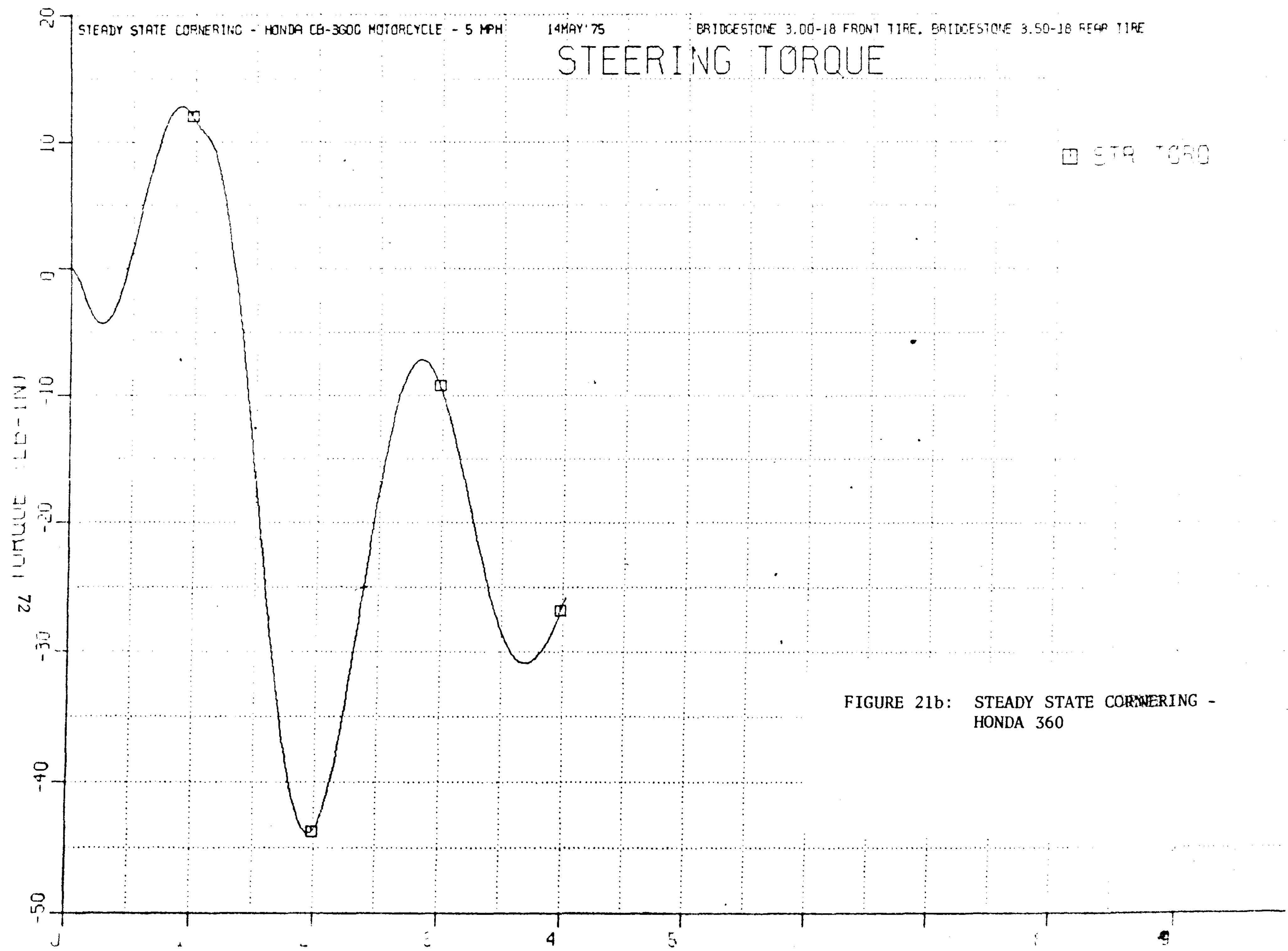


FIGURE 21b: STEADY STATE CORNERING - HONDA 360

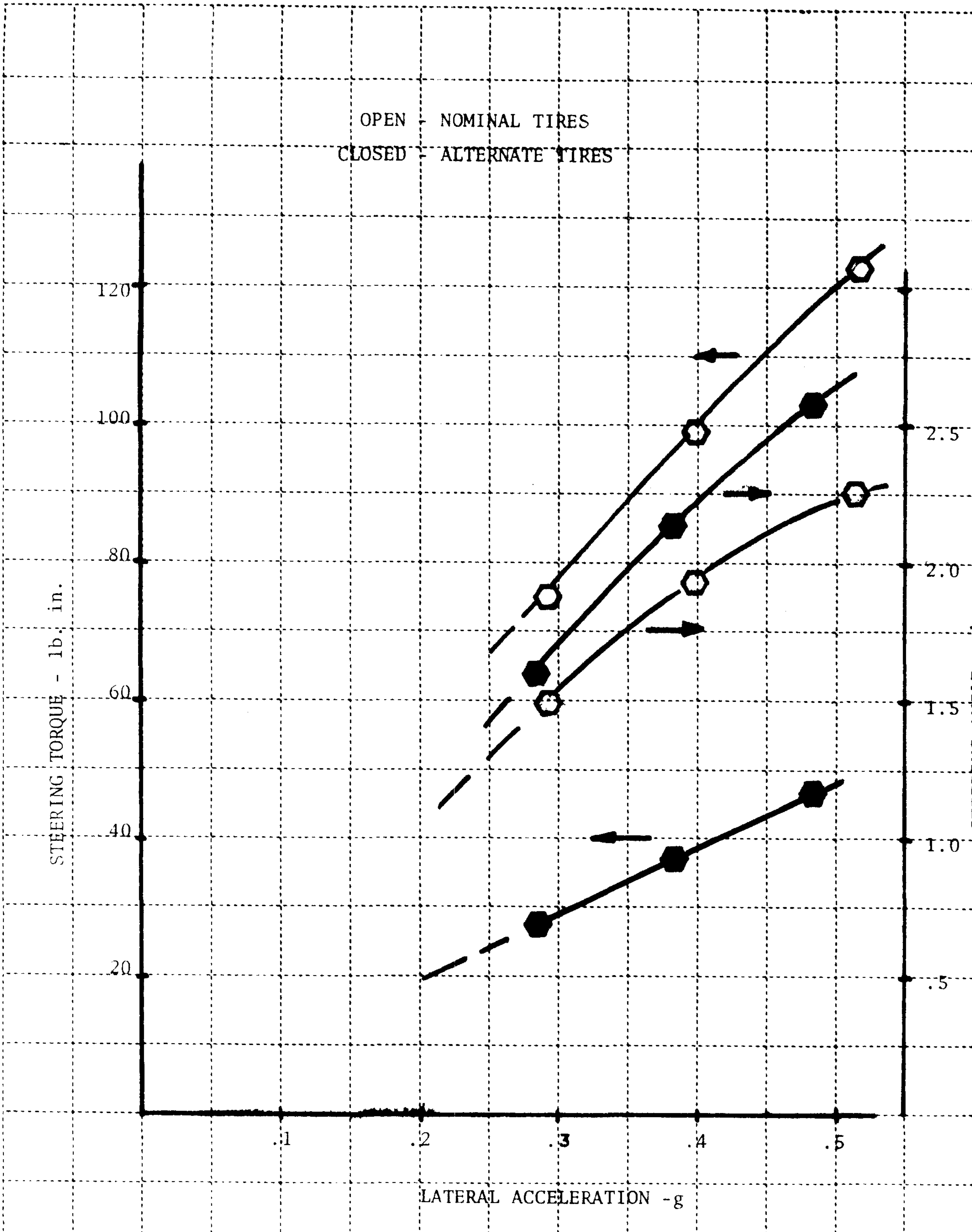


FIGURE 22: HARLEY-DAVIDSON 1200 TIRE PERFORMANCE EFFECTS

TIRE CONF.	NOM LOAD (lbs)	NORM. CORNERING COEFF (lbs/deg/lb)	NORM. CAMBER THRUST COEFF (lbs/deg/lb)	PNEUMATIC TRAIL (inches)
NORMAL				
FRONT	370	.248	.015	.83
REAR	615	.149	.021	--
ALTERNATE				
FRONT	340	.217	.0102	.50
REAR	670	.153	.0195	--

TABLE 11: HARLEY-DAVIDSON TIRE SET COMPARISON

entirely to the difference in the camber thrust coefficients of the two rear tires. With the high C_γ tire, the cornering characteristics are reasonably well-balanced between front and rear; with the low C_γ tire, the deficiency of rear end side force required at a given lateral acceleration must be made up by tire slip angle development. This means increased vehicle side slip angle (β), but, because the front end does not need to be operated at any significant slip angle, the β effect must be reduced by a reduction in the steer angle. In this case (i.e., a mismatched rear tire), position control sensitivity (g/deg) is quite high.

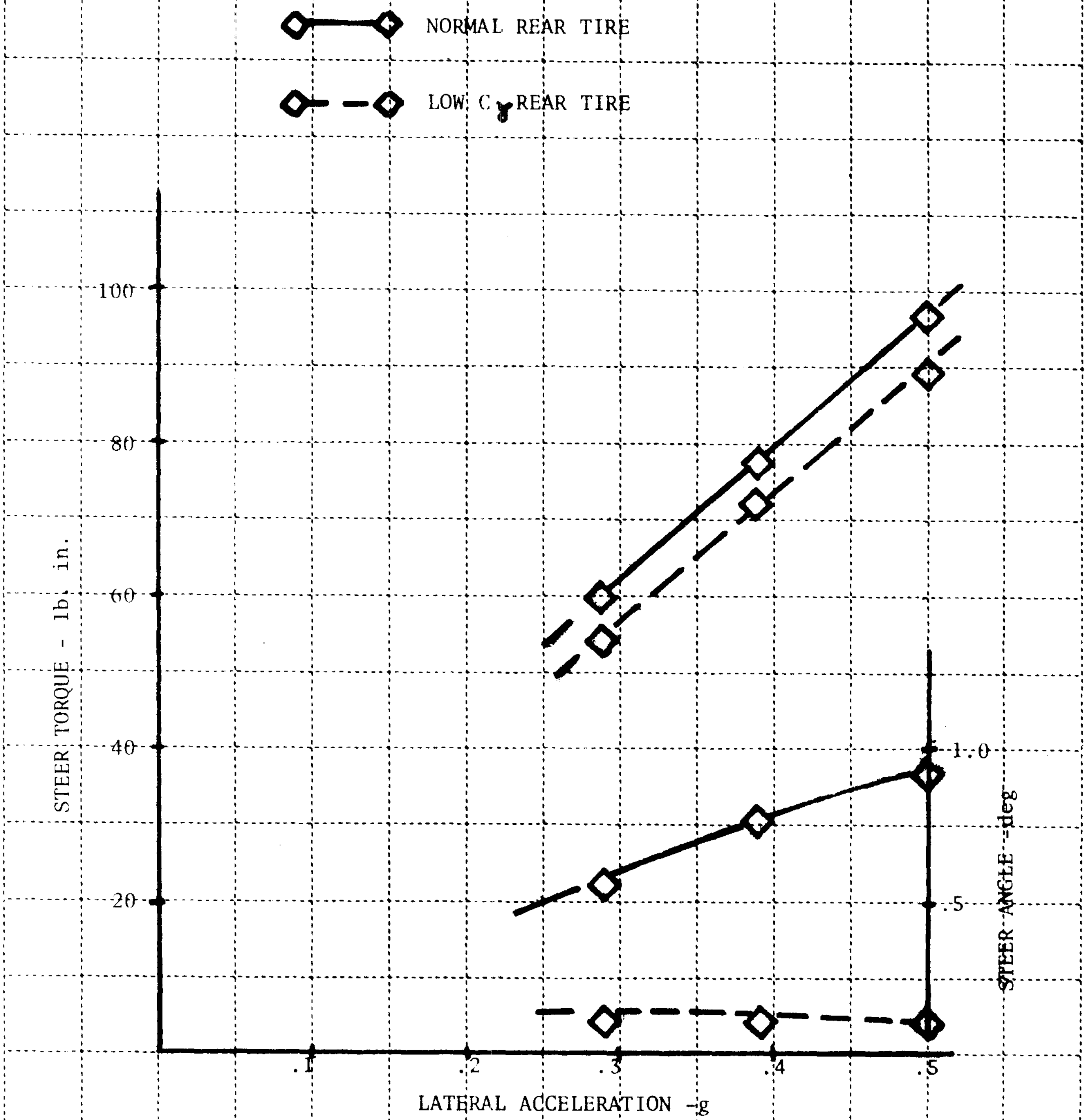


FIGURE 23: DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - TIRE EFFECTS ON YAMAHA

TIRE CONF	NORMAL LOAD (lbs)	NORM. CORNERING COEFF. (lbs/deg/lb)	NORM. CAMBER THRUST COEFF. (lbs/deg/lb)
NORMAL REAR	390	.185	.0155
ALTERNATE REAR	390	.186	.0103

TABLE 12: YAMAHA REAR TIRE COMPARISON

The effect of rider lean angle on motorcycle steady state response characteristics was investigated in a series of 3 runs with the Honda 360 machine. Although the rider lean control mode was inactive in these runs, the rider was coupled to the motorcycle by a torsional spring with adjustable compliance which produced a small range of quasi-steady state rider lean angles for comparison. Attempts to increase this range resulted in divergent rider motions which are not representative of effective closed loop control.

Results are listed in Table 13. In these runs, the rider is leaned into the turn (i.e., at a larger angle with respect to vertical than is the motorcycle) and this results in a small increase in applied steering torque.

RIDER LEAN ANGLE - deg	LATERAL ACCELERATION-g	SPEED - mph	APPLIED STEER ANGLE-deg	APPLIED STEER TORQUE in-lbs	VEHICLE SIDELSIP ANGLE -deg	MAXIMUM REVERSE STEER TORQUE - in-lbs	TIME TO FIRST CROSSOVER (SEC)
.05	.39	40	.91	85.5	.49	49	.67
1.0	.40	40	.91	92	.50	52	.68
3.2	.41	40	.92	98.5	.48	52.5	.69

TABLE 13: DIRECTIONAL CONTROL RESPONSE CHARACTERISTICS - RIDER LEAN ANGLE EFFECT

Transient Handling Maneuver

The transient handling maneuver used for this study was the single lane change as briefly described in Section 3.4. This simulated maneuver requires operation of the complete rider-motorcycle mechanization and initial difficulties with achieving well-damped path-following in the transient portion of the maneuver followed by stable low-error tracking in the exit lane in the simulation prevented completion of all the initial objectives of this phase of work.

As discussed in the section describing the rider model used in the simulation (Section 3.7) several error coefficients are employed in the path-following guidance mode of operation. Successful performance requires that values of these coefficients be properly balanced for compatability with the desired path (as previewed) and predicted course. Optimization of these coefficients and evaluation of the six reference motorcycles was not accomplished in this study but the applicability of the simulation to this maneuver has been demonstrated.

Figures 24a and 24b show plotted time histories of the primary control and motion variables in the maneuver. Figure 25 shows a comparison of an ideal path and actual path for a set of rider model coefficients that produce a well-damped stable execution of the lane change but which show a need for a slightly longer gap (x) distance than desired to achieve the lateral displacement required. This run was made at a nominal speed of 40 mph with the Honda 360 motorcycle normal configuration characteristics and passive rider lean control.

In order to improve the fidelity of the simulation in this application, the following modifications are needed:

1. incorporation of active rider lean control (the capability to do this already exists; but suitable values for the coefficients must be defined)

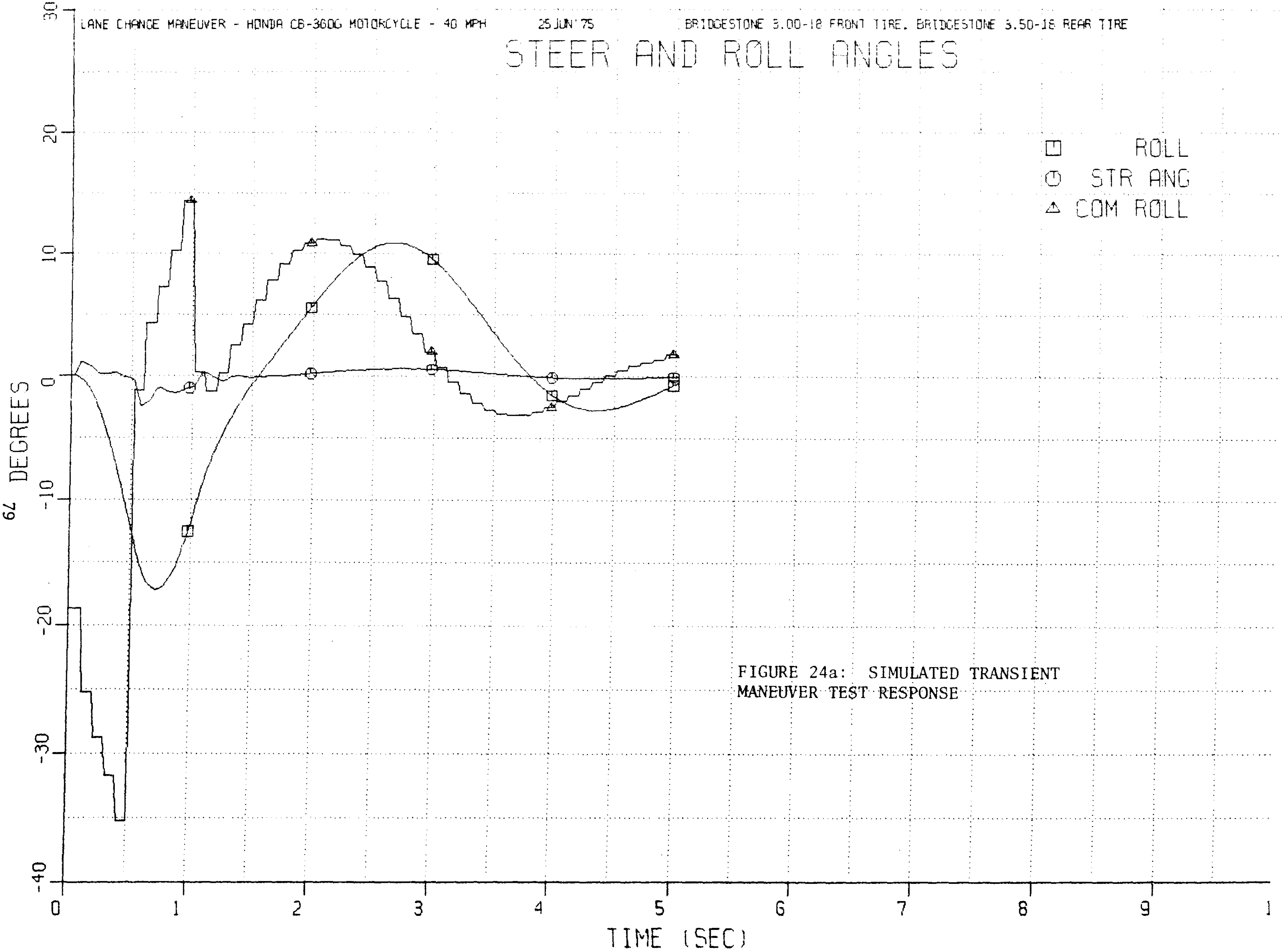


FIGURE 24a: SIMULATED TRANSIENT MANEUVER TEST RESPONSE

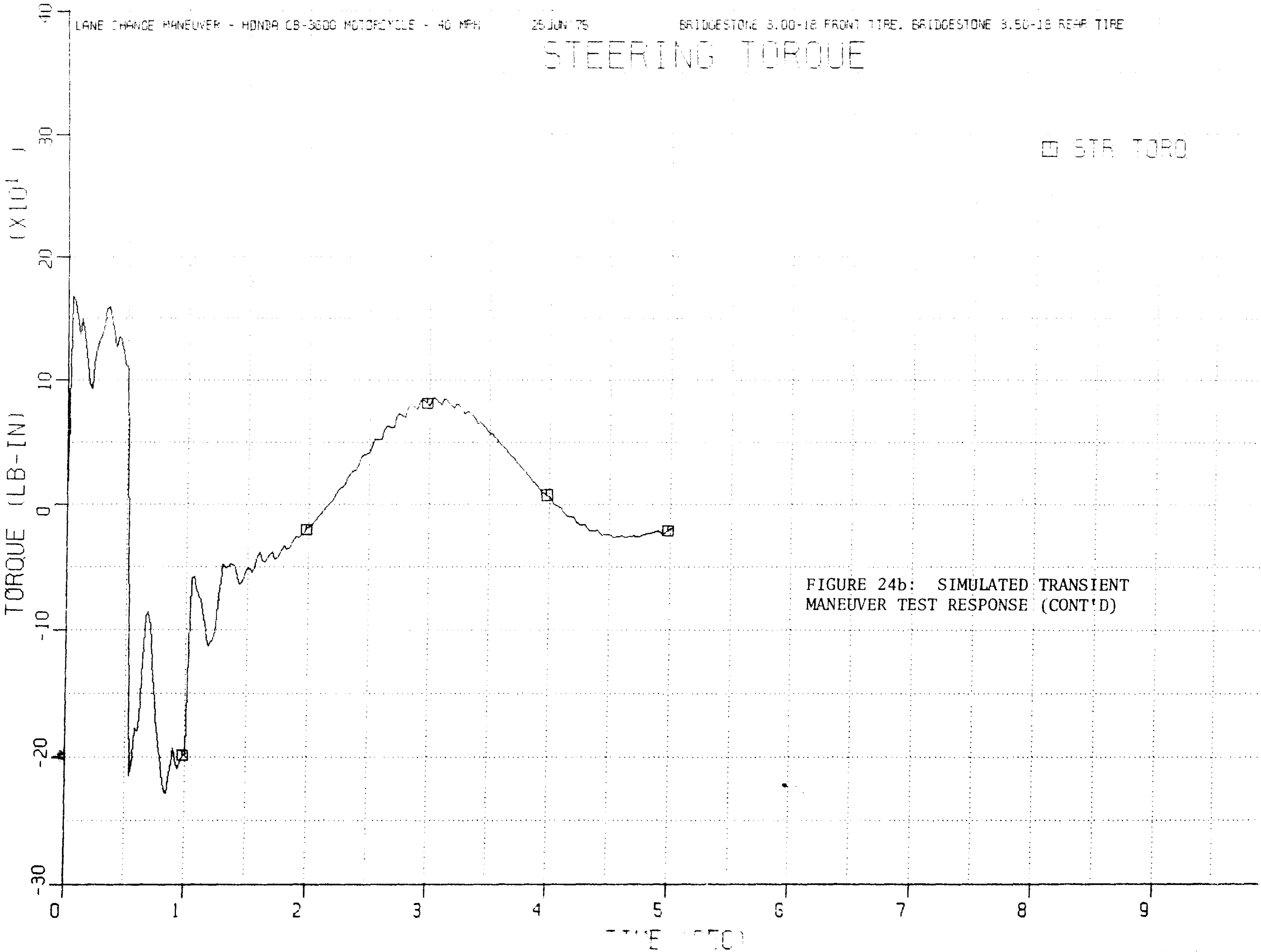


FIGURE 24b: SIMULATED TRANSIENT MANEUVER TEST RESPONSE (CONT'D)

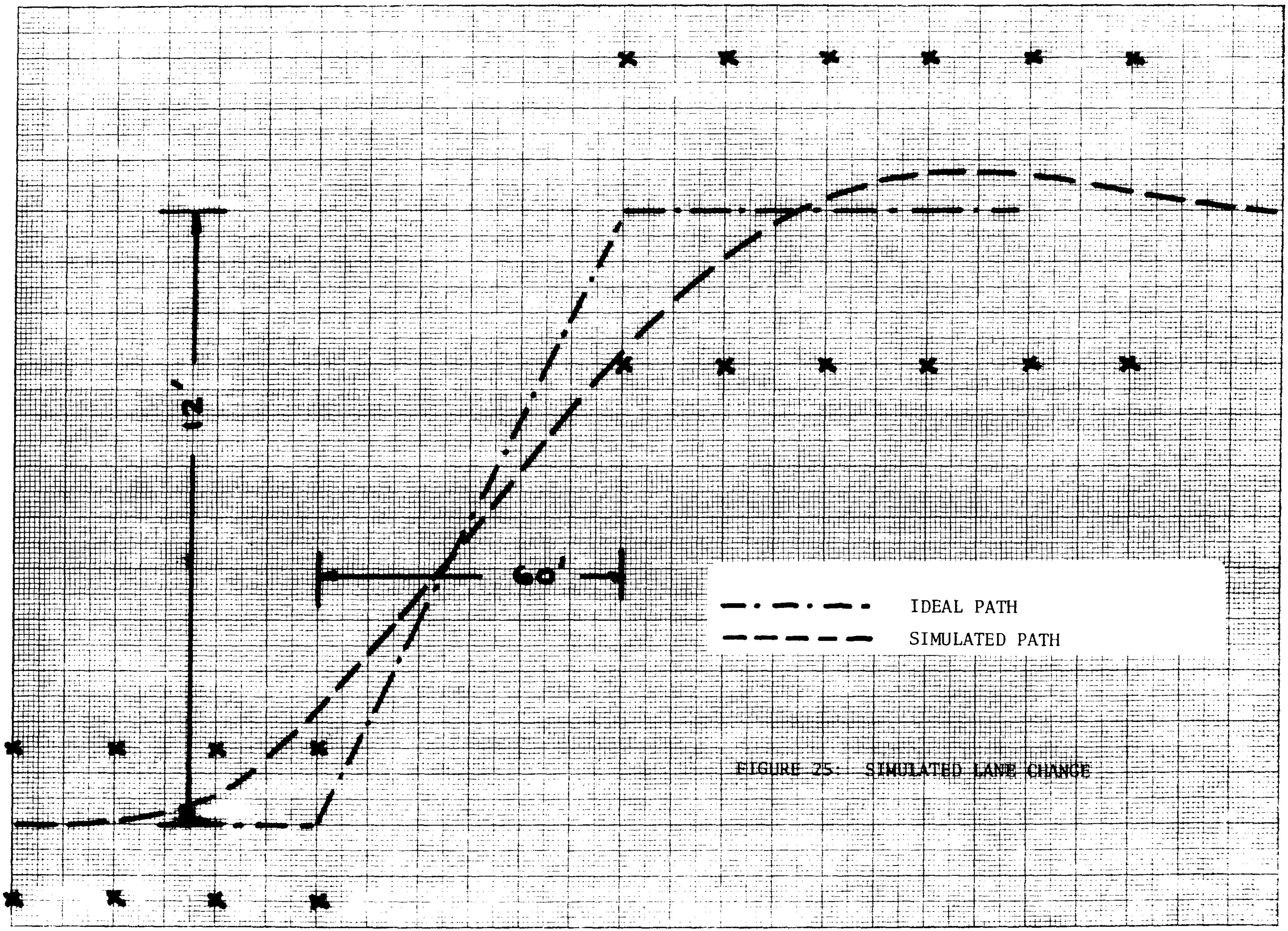


FIGURE 25: SIMULATED LANE CHANGE

2. possible re-evaluation of the current numbers for the guidance coefficients (to decrease the response time by increasing the values of lateral acceleration utilized)

3. re-examination of the values for the rider steer stabilization coefficients for compatability with active rider lean control

4. further study of the preview-predictor model and human controller response model to simplify application.

3.8.2 Full Scale Testing

The full-scale test work in the program involved the measurement of significant control input and output motion variables for one motorcycle in two basic test procedures. A Honda 360G was selected for this work because of its intermediate size and weight and its wide popularity.

A complete instrumentation system utilizing a telemetering link to minimize on-board equipment weight was developed for this program. The experimental work was performed at Calspan's Vehicle Experimental Research Facility (VERF). All tests were performed by a single experienced rider on high skid-number asphalt surfaces under dry conditions. During the course of the test program, much was learned about the special considerations required in motorcycle testing (as contrasted to automobile testing) and these, as well as the output data from the test procedures, are discussed in this section.

Two test procedures were devised--one concerned with the measurement of input-output relationships in steady state directional control and the other with rider/motorcycle performance and interaction in a transient control maneuver. These procedures are explained in detail in Appendix A. Briefly, the directional control maneuver consisted of entering and maintaining a constant radius turn from an initial striaght path. Data was acquired starting with the straight path segment (which established a zero reference for all variables except velocity) and continuing through the transition into the curved path and through several seconds of the steady state turn. This maneuver was performed at speeds from 20 to 50 mph and turn radii from 100-700 feet. Various combinations of speed and turn radii were run, giving lateral accelerations between .08g and .55g. The objective of this maneuver was to measure the directional control characteristics of the motorcycle under steady state conditions over a range of speeds and lateral accelerations. Investigations of the maximum performance capabilities of the motorcycle or rider were not undertaken using this procedure.

The transient control maneuver was a single lane change, right to left, with a lateral displacement of 12 feet. This procedure was designed to show the input-output characteristics of the motorcycle during a transient control maneuver at constant speed and also to investigate rider task performance and rider/motorcycle interaction. Tests were run using this procedure with the longitudinal displacement of the entrance and exit lanes (Δx) set at 30', 45', 60', and 80', and test speeds between 20 and 54 mph. Since both rider task performance and motorcycle capabilities were being evaluated, some definition of the limit of performance was sought.

Data records for a typical directional control maneuver and lane change maneuver are presented in Figures 26 and 27. To facilitate interpretation of the data, the sense of each variable has been denoted by "right" or "left" as the rider would view them. Strictly speaking, "right" roll is a positive rotation about an axis parallel to the longitudinal axis of the motorcycle in which positive values are forward. In the case of each variable, "right" is the positive value of that variable in the simulation model.

For each run, the start of the run is indicated by an event mark below the yaw rate trace, which was activated by a tape switch placed at the start of the course layout. For the directional control course, this was the point at which the straight path was tangent to the curve. In the lane change course, it was the last cone pair encountered in the entrance (right) lane.

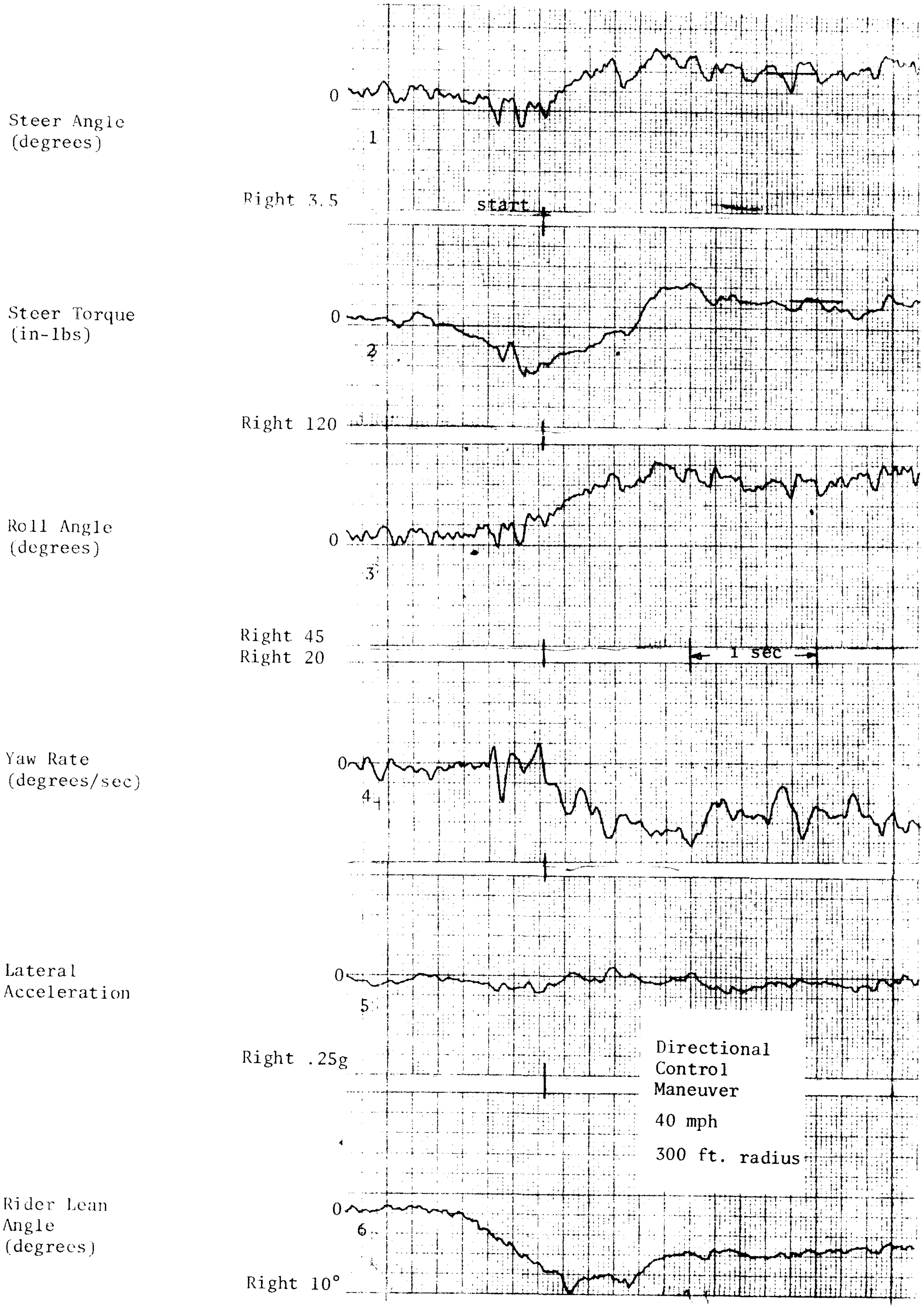


FIGURE 26: FULL SCALE TEST (DIRECTIONAL CONTROL)

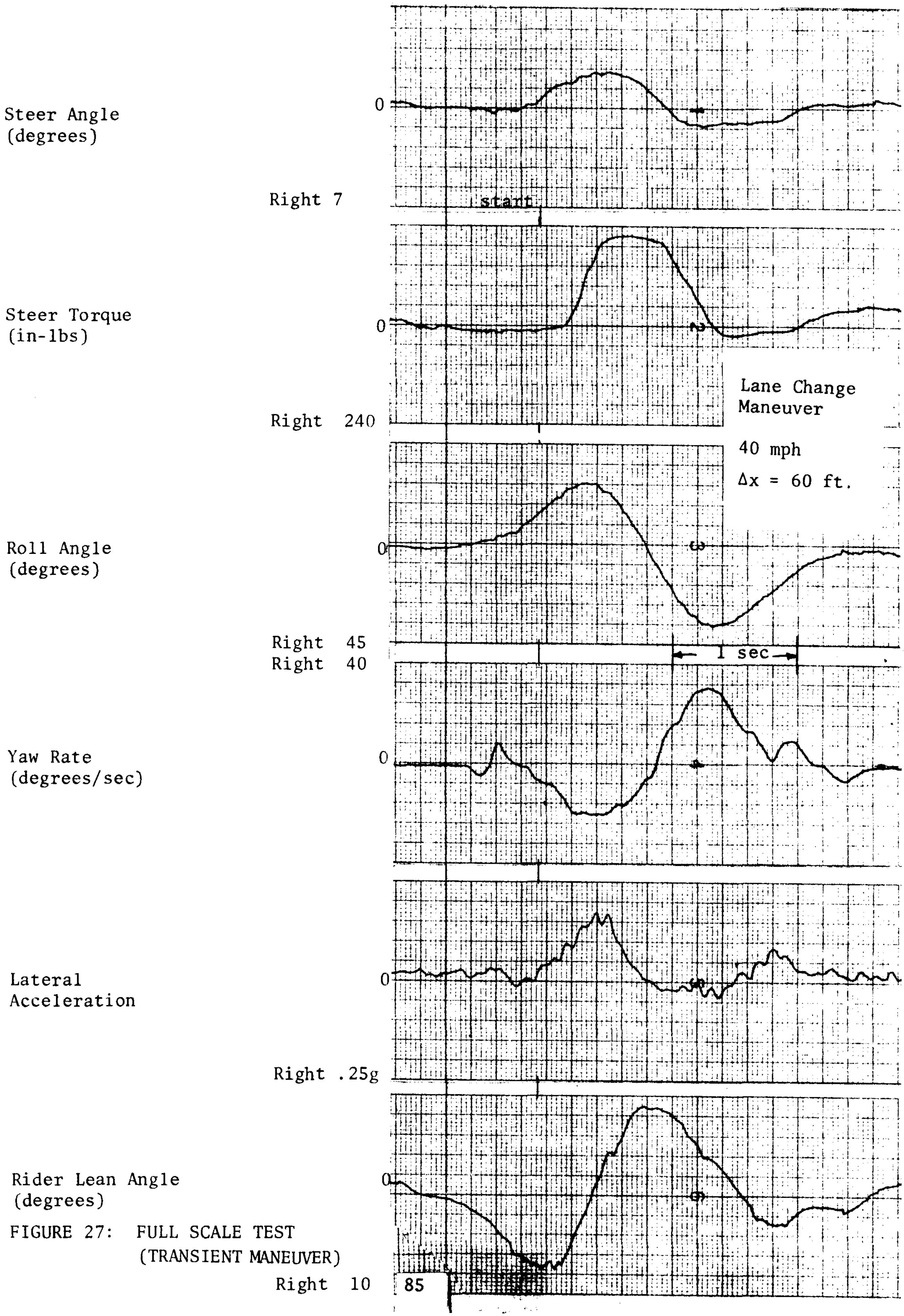


FIGURE 27: FULL SCALE TEST
(TRANSIENT MANEUVER)

Fifteen additional data records from the full scale work that are of particular interest are included in Appendix D. A total of 117 test runs were recorded, with an approximately even distribution between the two procedures.

Directional Control

The primary result of the directional control maneuver was the data acquired after the control and motion variables had achieved steady state following the decay of the transients arising from the initiation of the turn. In general, the transient lasted about one second, followed by five to ten seconds of steady state cornering.

These data have been used to calculate response parameters in steady state lateral acceleration. Figure 28 shows steer angle and applied steer torque as a function of lateral acceleration during 40 mph turns of 300-700 ft. radii (runs 13-17) and during 20 mph turns of 100-300 ft. radii (runs 55, 59, 61). The position control sensitivities (δ/a_y) and torque control sensitivities (T/a_y) shown in the figure are:

δ/a_y:	20 mph =	11 degrees/g
	40 mph =	3.5 degrees/g
T/a_y:	20 mph =	30 in-lb/g
	40 mph =	75 in-lb/g

At 20 mph the dominant control input is steer angle, as steer torque has dropped nearly to zero. The influence of steer torque is more pronounced at 40 mph, and the effect of steer angle is diminished.

In all but one of the eight runs shown here the rider lean angle is equal to zero (i.e., the rider is in the vertical plane of the motorcycle) throughout the steady state portion of the run, and thus is exerting no lean control. The data from the runs made on the 400 ft. radius and smaller turns shows that lean control is apparently used during the transient condition of entering the turn, but dies out when the turn is stabilized.

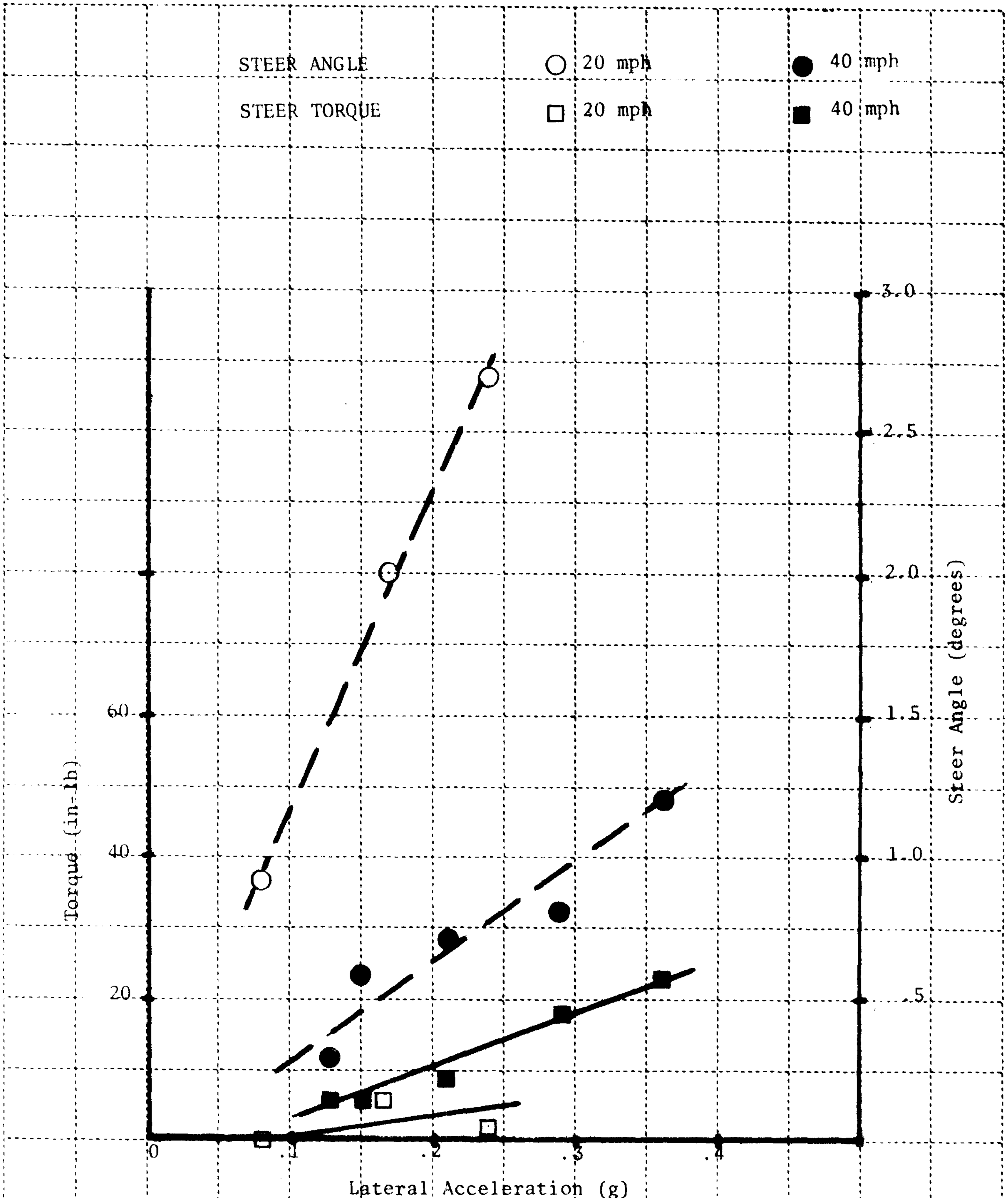


FIGURE 28: DIRECTIONAL CONTROL - STEER ANGLE AND TORQUE CONTROL SENSITIVITIES

Runs 33-35 (included in Appendix A) were performed to demonstrate the influence of lean on steady state control. Run 33 was performed normally at 40 mph on the 300 ft. turn, but in runs 34 and 35 the rider leaned abnormally far inward and outward, respectively. Steady state values of the observed variables are as follows:

Run No.	33	34	35
Lean Control	Normal	Inward	Outward
Steer Angle (degrees)	-1.4	-1.6	-1.4
Steer Torque (in-lb)	-22	0	-58
Roll Angle (degrees)	-27	-34	-34
Yaw Rate (degrees/sec)	-12.3	-14.5	-13.3
Rider Lean Angle (degrees)	+5	-13	+21

The 34° difference in lean between runs 34 and 35 appears to be countered prinicpally by an increase in the opposing steer torque.

Lane Change Maneuver

These tests provided an opportunity to evaluate both motorcycle capabilities and rider task performance under transient control conditions. The lane change course was run with Δx equal to 30, 45, 60 and 80 feet so that a range of speeds could be investigated at the same degree of difficulty. Tests were also run at Δx=60 ft. and speeds of 20, 30 and 40 mph.

Tests using this maneuver were performed to both demonstrate the input/output characteristics of the motorcycle and rider and to define the limits of performance at the various values of Δx. The first tests were all performed at a speed at which the rider could consistently follow the course layout successfully, that is, without upsetting any of the lane marking cones. In the second type of tests the run speed was increased until the rider could not negotiate the course without upsetting one or more cones. During these tests, the goal was not ultimate refinement of rider technique, but rather the achievement of a consistent level of performance. After 5-10 practice runs at a given Δx, the rider attempted to negotiate the course at a given maximum speed. If there were no successful runs in five tries, a lower speed was attempted. Figure 29 shows the success/failure pattern for various values of Δx.

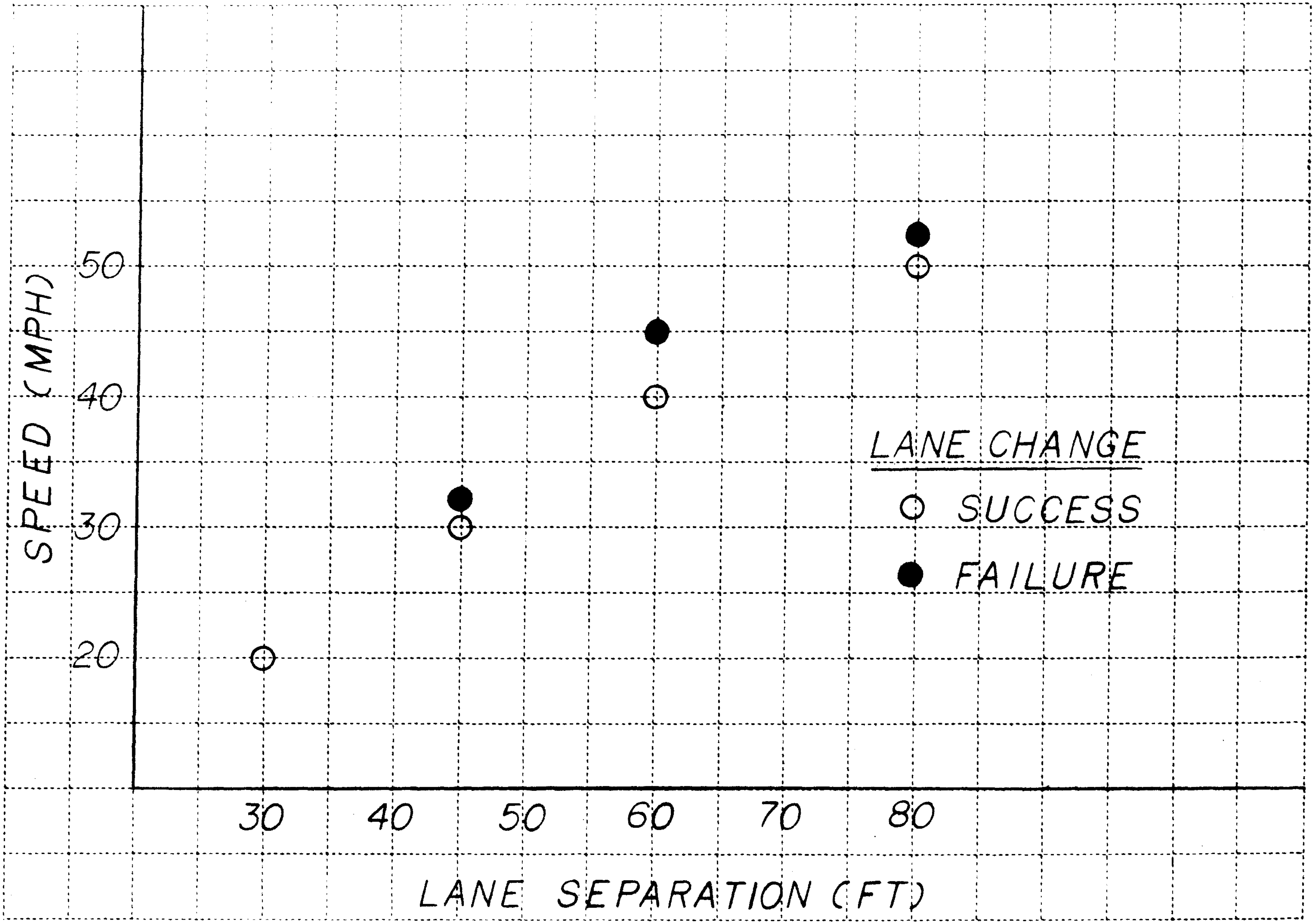


FIGURE 29: LANE CHANGE TEST RESULTS

A successful run was one in which no cones were upset. Use of this criterion in the maximum speed runs demonstrated one of the problems with this procedure. To achieve maximum speed through the course, the rider initiated the maneuver before the end of the entrance lane and completed it past the start of the exit lane. This is demonstrated in Figure 30, where significant lean and roll angles can be seen at these two points. The maneuver shown is opposite in sense to the recorded test runs when this characteristic was first noticed in the early phases of procedure development, but the entrance and exit lanes were narrowed from four and eight feet, respectively, to three and six feet. Further constriction of these lanes would impose unrealistic path following demands on the rider.

The "success" speeds of Figure 29 were the speeds used for most of the recorded test runs. A sample of data records for these runs are given in Appendix D, Figures D-10 to D-15. The typical lane change data shown in this section in Figure 27 was run under the same conditions (Δx=60', 40 mph) as Figure D-10.

The rider's anticipation of the start of the maneuver is apparent in each of the data records. The rider begins to lean as much as a full second before reaching the end of the entrance lane, and a significant roll angle is already established by that point. It can also be seen that the rider is well into the exit lane before he is stabilized in a straight path. At 40 mph, the distance between the lanes should be covered in about one second. At a point one second after the start of the run shown in Figure 27, steer torque, rider lean angle, and roll rate are all at their maximum values.

The methods used for the analysis of data from a lane change maneuver would be directed by the objectives of the individual tests, especially as to whether the subject of the study is rider performance, motorcycle capabilities, or a combination of the two. In some cases a basic measure such as success/failure vs. speed might be adequate. However, a more detailed analysis of the recorded data would more likely be necessary.

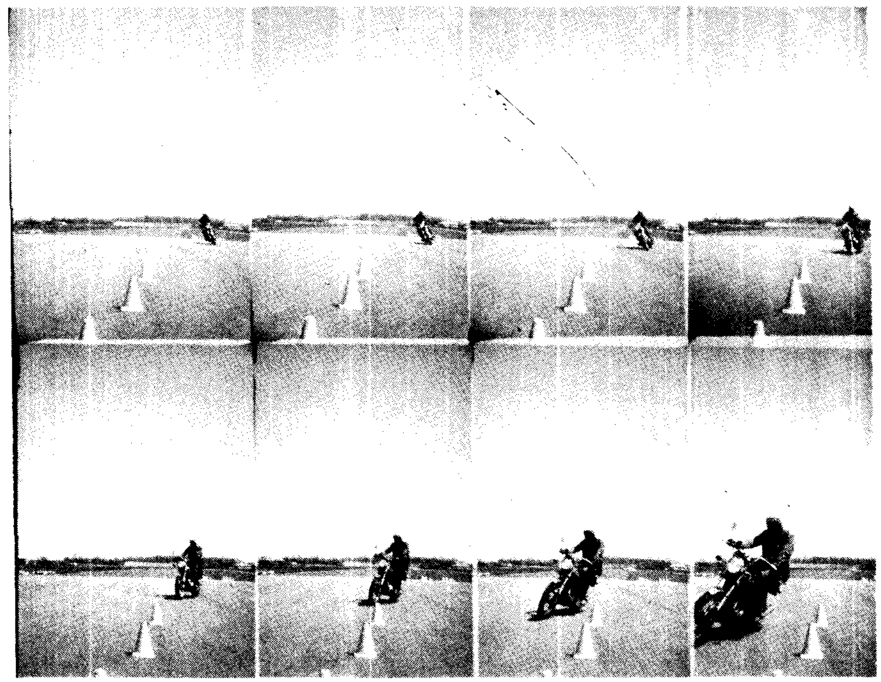


FIGURE 2 - TRANSIENT MANEUVER
(Lane Change)

Table 14 gives the results from a limited analysis of the data in Figures D-10 through D-15, which include lane change maneuvers for the range of speeds and Δx values tested. The first block of data includes the maximum values of the variables measured in the maneuver. For each variable in this first set two values are given. The upper number is the peak value of the first control input or motion respone, which occurs upon entering the lane change maneuver. The lower number is the peak value of the input or response associated with the transition to the exit of the maneuver. The second block of data is a listing of the rate of change of each variable during the initiation of the maneuver.

A first review of this data reveals certain significant trends. The data for the runs where Δx=60 ft. and speed was varied show that as speed was increased, the dominant rider control input changed from steer angle to rider lean angle. As speed was increased, though, more torque was required to limit the steer angle.

Comparison of the data at various values of Δx is not as straightforward. For runs 108, 100, 114, and 94 both Δx and speed were varied. Judged on a success/failure criteria, however, their degree of difficulty was about the same. Apparently some of the measured variables are more closely related to motorcycle characteristics and others more dependent on rider performance. Steer angle, for instance, decreased consistently with increasing speed. Rider lean angle, on the other hand, remained essentially constant for all four runs. Clearly, further study is needed to define significant metrics for the evaluation of motorcycle and rider performance.

3.8.3 Full Scale Test--Simulation Comparison

Representative results affording an opportunity to compare simulation output with experimental data were obtained for the Honda 360 in both the directional control and transient handling tests. These comparisons are shown in Figure 31 (directional control) and Table 15 (transient handling). In general, the steering angle values show reasonable agreement between the two approaches; differences are of the order of a few tenths of a degree. A substantial difference in applied steering torque, however, is shown in the directional control test results.

TABLE 14

LANE CHANGE MANEUVER DATA

Lane Separation - Δx (ft)		30	45	60			80
Speed (mph)		20	30	20	30	40	50
Run Number		108	100	84	83	114	94
Steer Angle (Degrees)	(Left)	11.2	4.2	3.9	3.1	2.1	1.7
	(Right)	9.1	4.6	2.9	2.7	1.5	1.4
Steer Torque (In-Lbs)	(L)	150	120	48	72	140	210
	(R)	96	48	38	43	20	29
Roll Angle (Degrees)	(L)	36	32	18	27	27	29
	(R)	32	32	14	27	36	34
Yaw Rate (Degrees/Sec)	(L)	32	29	22	24	24	19
	(R)	35	34	22	28	32	28
Lean Angle (Degrees)	(R)	12	10	2.0	4.4	10	10
	(L)	2.0	7.0	2.6	1.8	7.0	10
Steer Rate (Degrees/Sec)	(L)	29	11	6.4	5.6	7.0	2.4
Steer Torque Rate (In-Lbs/Sec)	(L)	530	440	88	170	850	920
Roll Rate (Degrees/Sec)	(L)	67	59	28	37	47	26
Yaw Acceleration (Degrees/Sec^2)	(L)	160	98	33	39	48	80
Lean Rate (Degrees/Sec)	(R)	24	23	8.3	11	12	8.8

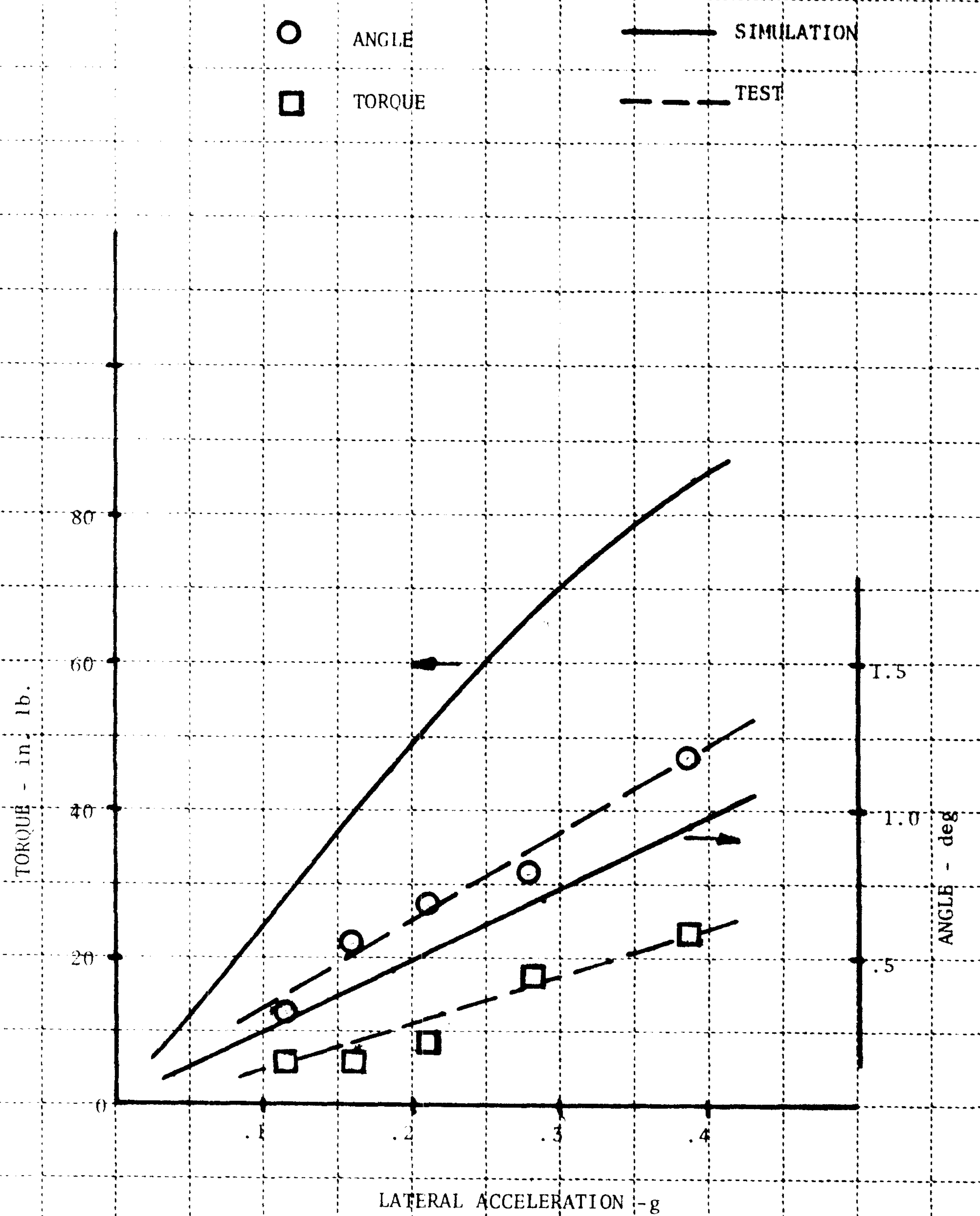


FIGURE 31: DIRECTIONAL CONTROL TEST COMPARISON

TABLE 15: LANE CHANGE COMPARISON

VARIABLE	EXPERIMENT	SIMULATION
Steer Angle (deg)		
Peak Positive	2.5	2.4
Peak Negative	1.1	.6
Steer Torque (in-lbs)		
Peak Positive	0	230
Peak Negative	220	85
Roll Angle (deg)		
Peak Positive	27	17
Peak Negative	36	11
Yaw Rate (deg/sec)		
Peak Positive	20	27
Peak Negative	30	7
Peak Recorded Lateral Accelerometer Output (g)	.16	.15
Rider Lean Angle (deg)		
Peak Positive	7	1.2
Peak Negative	9	.2

The failure to obtain good agreement between the simulation and full-scale tests results in the values of torque controlled lateral acceleration gain is attributable to the sensitivity of this parameter to the value of pneumatic trail. As noted previously, the simulation utilized a tire model which treated this factor as a single-valued constant; the results suggest that a more sophisticated representation is required (at least for some tires) to improve agreement over a large part of the operating range of the machine.

In the lane change maneuver, results from the simulation and full-scale tests can be compared for the 40 mph - 60 ft. gap test course geometry. The separate results were previously shown in Figures 24 & 25 (simulation) and Figure 27 (full-scale).

The absence of active rider lean control in the simulation prevents direct correlation of the time histories for the two runs but it is of interest to compare values for some of the variables to demonstrate the reasonableness of the simulation results. Table 15 shows these comparisons. The principal differences are in rider lean angle (which the rider in the full scale tests employed to initiate the maneuver), motorcycle roll angle (where, in the full-scale tests, the larger values imply higher lateral acceleration and harder cornering, and thereby achieving the desired lateral displacement more quickly--and in a shorter distance--than in the simulation), and yaw rate (also a measure of lateral acceleration.) Peak values of steer torque, steer angles, transient lateral acceleration (as measured by the hard-mounted accelerometer) agree quite well between experiment and simulation.

In effect, the simulated rider in this run was less aggressive than the actual rider (in part because of the use of steering only), thus requiring more time and distance to execute the lane change, but tracked a similar, although elongated, path.

To summarize these comparisons, good agreement exists for many of the parameters for which direct matching is possible. The simulation produces reasonable response patterns for both maneuvers and is judged to be valid within the limits of accuracy of the input data applied to it. In view of the riding techniques used in transient handling situations, the lean control mode of the rider model needs improvement for general application to such tasks, but the representations of both rider and motorcycle used in the simulation appears to be acceptable.

4.0 CONCLUSIONS AND RECOMMENDATIONS

In the previous section, the approach and methodology used in the program were described in some detail and typical results from both the experimental and analytical phases were given to illustrate the capabilities and effectiveness of the chosen approaches to meet the program objectives. In this section, an attempt is made to gather together these results in order to emphasize the accomplishments and to define a point of departure for future activity. With respect to the overall objectives of the study, test procedures that provide discriminating measures of motorcycle lateral-directional response for both steady-state and transient operating conditions have been devised and successfully demonstrated in simulation and full-scale experimental studies. The applicability of these measurements, and the associated performance parameters, to the definition of accident avoidance capability has still to be established; in this regard, however, the motorcycle state-of-the-art is no worse off than that of passenger vehicles. But, on the positive side, the program has identified some interesting characterizations and special considerations of motorcycle stability and control and handling quality which deserve further examination. These include:

1. Development of a steady state directional control test procedure with which to evaluate the principal performance response parameters. This procedure has been demonstrated in full-scale tests to be suitable for motorcycles; to produce repeatable data, to discriminate among effects of different control inputs, and to be highly flexible for studying performance in any operating regime. Simulation results with this procedure indicate good discriminatory capability to differentiate among machines.

2. Demonstration of the capability of the currently available simulation of two-wheel vehicle dynamics to produce useful results on motorcycle performance characteristics. Although it is clear that certain improvements in the model are essential for broad application to studies of motorcycle accident avoidance capability (e.g., addition of suspension effects, addition of braking and acceleration capability, rider model improvements), the simu-

lation has been shown to yield reasonable representations of motorcycle-rider behavior in selected applications.

3. Compilation of baseline information on motorcycle physical characteristics and tire performance that has not previously been available. These baseline data (especially the dynamic inertial properties and tire performance) encompass a wide range of machines and can be used for other studies (perhaps using simplified analytical methods) of additional performance characteristics.

4. Identification of the very significant role of tire characteristics in motorcycle response. In particular, the sensitivity of the response parameters to camber thrust coefficient (with respect to absolute value and to any differences between front and rear tires), the importance of pneumatic trail to steer torque requirements, and the initial categorizations of steer requirements at trim may be cited.

The simulation results show that motorcycle performance may be reasonably predicted with respectable accuracy for certain types of operation. They showed good agreement in the steering position performance parameters in steady state operation compared with full scale tests, high sensitivity of the steering torque performance parameters under the same conditions to tire model characterization, and a clear need for improvement in the rider model to permit successful prediction of transient maneuver performance.

As indicated above, the major effort on this program has been devoted toward outlining two constant speed test procedures and associated performance measurements which can be applied to discrimination of motorcycle response characteristics. This was an essential first step in evaluating accident-avoidance capabilities. Much remains to be accomplished, but care should be exercised so that the development is rationally expanded along all approaches. In the long term, it will be necessary to investigate the following in detail:

1. Rider-machine interaction - skill levels, riding techniques, utilization of lean control in both transient and steady-state operation, other rider control modes in which system c.g. is laterally shifted.

2. Operating conditions - surface characteristics (wet, gravel, etc.), load (double-riding, load location), tire characteristics (in-use effects, replacement tires) speed variability influences.

3. Additional maneuvers - combined cornering and braking, acceleration influences, on-center control instabilities, new performance parameters, new evaluation methods.

4. Correlation of performance parameters with accident involvement - identification of problem machines, accident statistics, critical maneuvers and conditions, expansion of performance data base.

5. Upgrading of simulation - incorporation of suspension model, structural compliance terms, braking capability, tire model improvement, rider model improvement.

For the short term, however, it is recommended that effort be applied toward extending the data base initiated in this program with special attention being given to certain operational variables.

The suggested program may be outlined as follows:

1. Perform full-scale tests according to the procedures given in this report on several motorcycles.

2. Investigate performance as a function of the following operational variables -

- Speed (up to 90 mph)
- Rider experience (or skill level)
- Tire in-use factors (wear, pressure, front-rear mismatch)
- Loading and/or distribution

3. Review and improve the simulation to achieve validity over a wider range of operation.

4. Analyze results in terms of vehicle performance comparisons (values of the performance parameters, sensitivity of parameters to operating conditions, possible correlation with accident involvement, identification of critical parameters, etc.).

The recommended next step is therefore seen to be one of building on current results so that performance/accident-avoidance relationships can begin to be identified.

The results of this program represent a first step in characterizing motorcycle performance in quantifiable terms. This foundation now needs to be extended, utilizing the methods and procedures demonstrated in the study, to cover a broader range of operating conditions and to examine certain handling aspects in greater depth. It is recommended that the following be considered for further study:

1. Evaluation of the suggested performance parameters at reduced skid number conditions. Both full-scale test and simulation methods should be employed in an effort to identify and define lower limits of conditions for reasonable performance or to evaluate changes in the response characteristics to be expected at such operating conditions. This effort would simply involve expansion of the current work to cover more of the total operating envelope, emphasizing conditions at which two wheel vehicles are notoriously difficult to handle.

2. Additional study of the effect of tire performance characteristics on overall lateral-directional behavior. Initial indications from the currently available results point toward the existence of significant changes in response parameter sensitivity with tire characteristics. Both full-scale tests and simulation techniques could be used in coverage of several tires (front, rear, and in combination) on one machine (e.g. the Honda CB 360). An effort would be

made to correlate directional control performance parameters and transient handling success with subjective evaluations. This latter aspect is considered an important step in establishing the meaningfulness of the parameter values in the accident-avoidance sense.

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