ACCIDENT AVOIDANCE CAPABILITIES OF MOTORCYCLES

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ABSTRACT

This paper describes a study of motorcycle accident avoidance properties involving application of experimental and analytical (simulation) techniques to the determination of performance characteristics.* Emphasis was placed on evaluating motorcycle response and driver-vehicle interaction in two basic maneuvers - steady-state cornering and lane-changing. Results from full-scale tests of one motorcycle and simulation evaluations of six machines are discussed. Several supporting activities - measurement of motorcycle physical characteristics and tire performance capability, definition of equipment and instrumentation requirements, development of procedures and performance parameters, and application of analytical methods to stability and control evaluations - are briefly outlined to give a broad overview of the approach. The paper treats three aspects of motorcycle dynamics of special interest to the safety problem. These are: (1) the sensitivity of a motorcycle's control parameters to the performance characteristics of its tires; (2) rider-vehicle interactions during maneuvering, particularly with respect to rider control inputs; and (3) the application of analytical and simulation methods to motorcycle handling evaluations. Other safety-related problems are identified and recommendations for additional studies are given.

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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 paper is concerned with an investigation of the accident-avoidance capabilities of motorcycles. Particular emphasis was placed on the lateral-directional control properties of these vehicles and the objective evaluation of response characteristics and handling quality.

The overall objectives of the study 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.

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.

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. Even before 1900, various researchers 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).

With the above as a foundation on which to base an approach to accident-avoidance capability evaluations in the face of an almost complete lack of any formalized test procedures for such evaluations, the study was aimed at defining reasonable testing techniques and meaningful performance parameters and then applying these procedures in full-scale tests and simulation to demonstrate applicability. This paper gives a brief summary of the work which was performed. A complete discussion of the study is given in Reference 4.

METHODOLOGY

Since the approach used in this program involved a number of separate activities, each phase will be discussed individually before presenting the collective results of the experimental tests and simulation studies.

Motorcycle Selection

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.

Each of the motorcycles selected for this task is representative of a segment of the motorcycle population with similar design parameters which determine their handling performance.

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 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 absorbers; 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.

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

Heavyweight Street:	Harley Davidson FLH-1200 Electroglide
Superbike:	Norton 850 Commando Roadster Yamaha X52-650
Intermediate Street:	Honda CB 360
Dual Purpose:	F-11 250 Kawasaki
Lightweight Street:	Honda CB 125 K1

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.

Many of the characteristics could be simply measured as linear or angular dimensions or weights. 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 photograph, Figure 1. The primary measurements which were made include total weight and weight distribution, weight of front assembly, roll and yaw moments of inertia of the complete machine, roll and yaw moments of inertia of the front assembly, wheelbase, fork tube angle, fork tube mass offset, and height of center of gravity.

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 principal factors 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; assuming symmetry of performance for ± values of slip angle.
- Inclination angle range - full range of the tire test facility (without modification), assuming symmetry of performance for ± values of inclination angle.

The following measurements were made:

$$\left.\begin{array}{l}\text{three forces}\\ \text{and}\\ \text{three moments}\end{array}\right\}\ \text{vs. slip angle } (\alpha) \text{ and inclination angle } (\gamma)$$

(1) at nominal front tire load and inflation pressure,

(2) nominal rear tire load and inflation pressure,

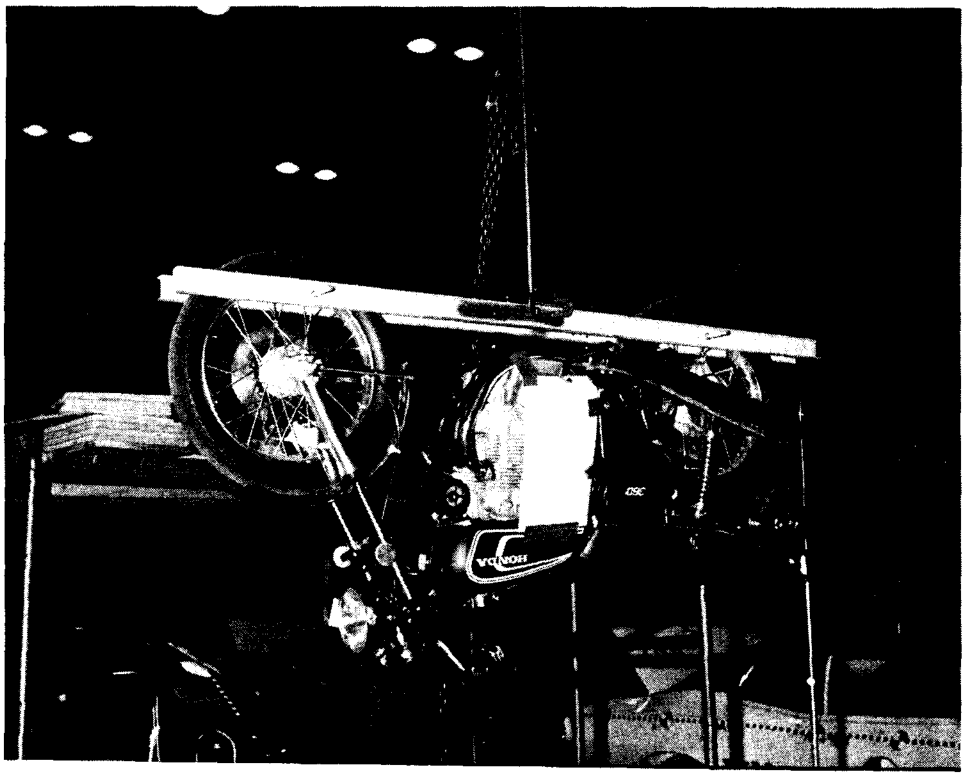

Figure 1a. Measurement of Yaw Moment of Inertia (I_{ZZ})

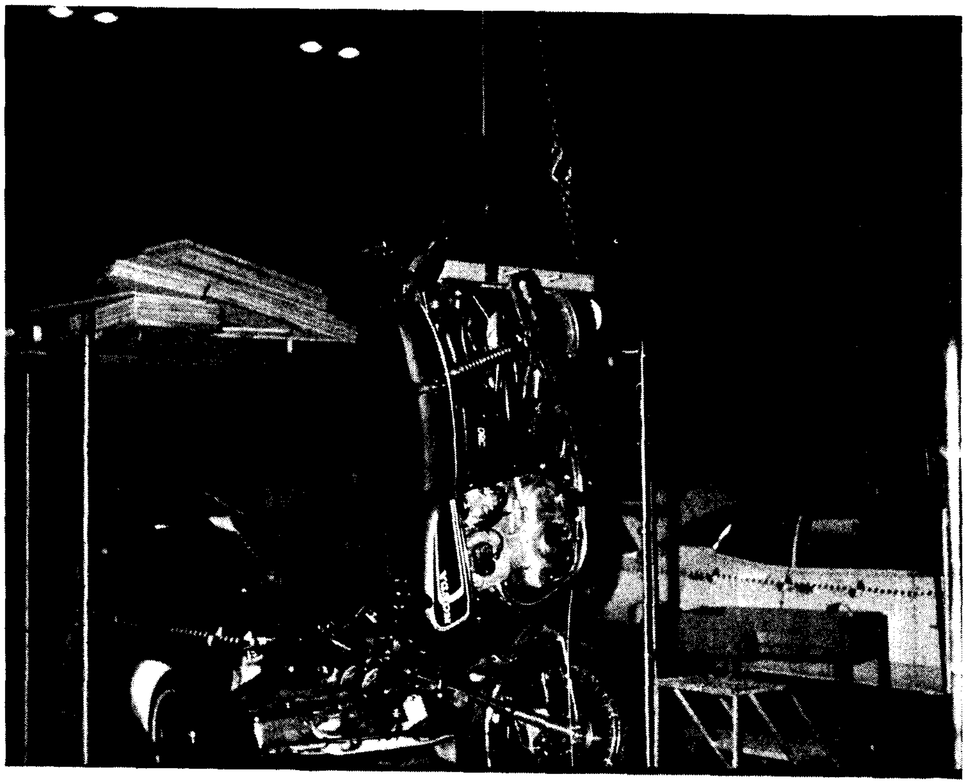

Figure 1b. Measurement of Roll Moment of Inertia (I_{XX})

(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.

A sample data plot as generated by the TIRF system is shown in Figure 2. 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. In addition to side force information which was of primary interest, rolling resistance, aligning torque, and overturning moment data were obtained as well. For use in the simulation, the test data were reduced to simple representations of normalized cornering stiffness, normalized camber thrust stiffness, and effective pneumatic trail for the normal loads at the tires used in the studies. Briefly, the test results showed:

1. Variation in cornering stiffness coefficient (normalized cornering stiffness) from about .33 lbs/deg/lb (at lightly loaded conditions) to about .15 lbs/deg/lb.

2. Values of camber stiffness coefficient (normalized camber thrust stiffness) ranged from .009 lbs/deg/lb to .021 lbs/deg/lb.

3. Values for these coefficients were lower for the trials-type tires than for the other types.

4. For a given tire, the value of the cornering stiffness coefficient decreased with increasing normal load; the value of camber stiffness coefficient was relatively unaffected by normal load.

5. Values of pneumatic trail, based on aligning torque measurements, ranged between 0.5 and 1.0 inches.

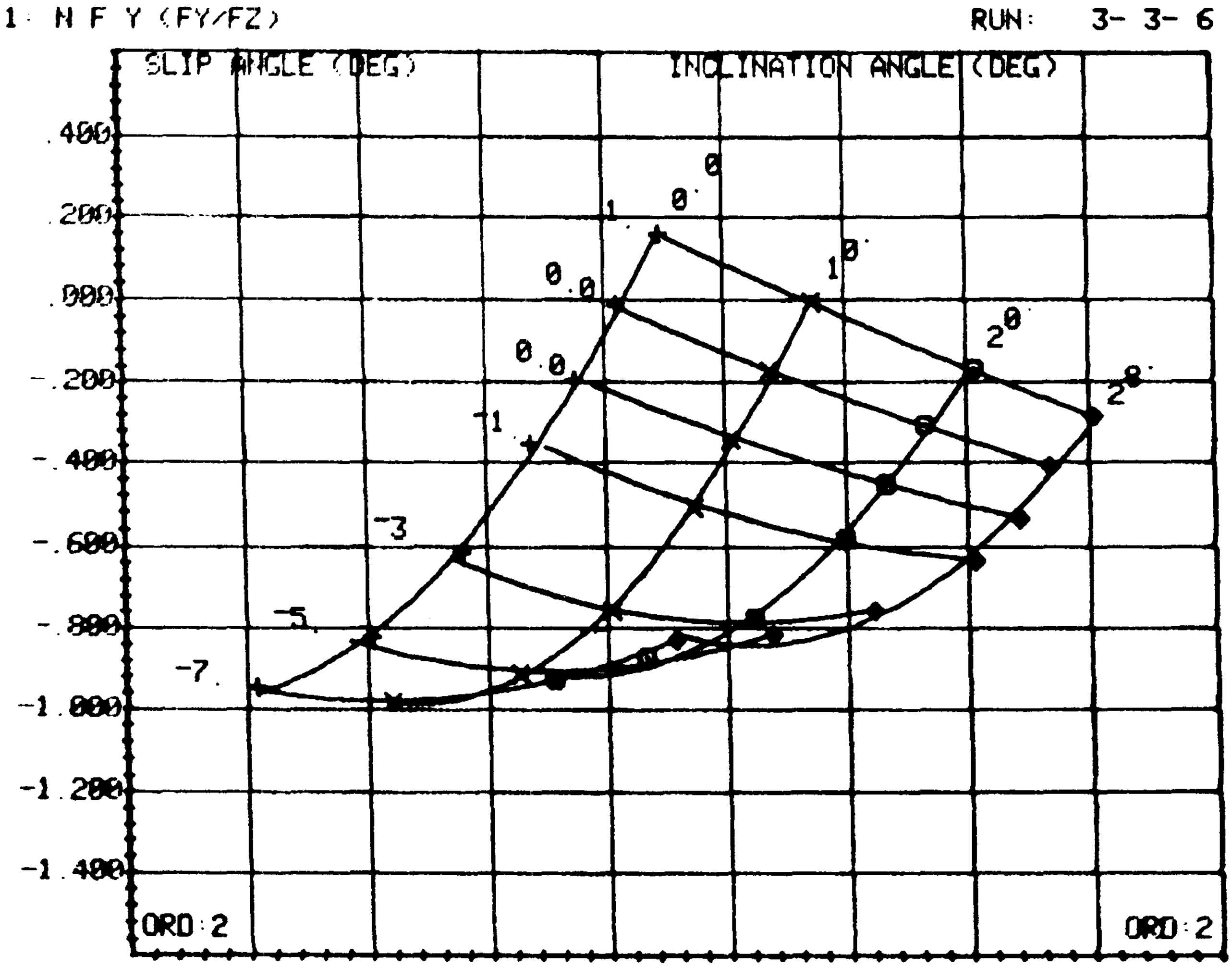

Figure 2. Typical Tire Test Plot

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.

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.

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. 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 - was considered and a constant speed type of test was finally selected.

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

The primary purpose of this test is to measure the steady-state control gains or sensitivities of the vehicle. The parameter of special interest is lateral acceleration 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.

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 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. The rationale for its selection was:

(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.

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 are 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 study, 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.

Simulation Description

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.

The analysis of the model 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 can be 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.

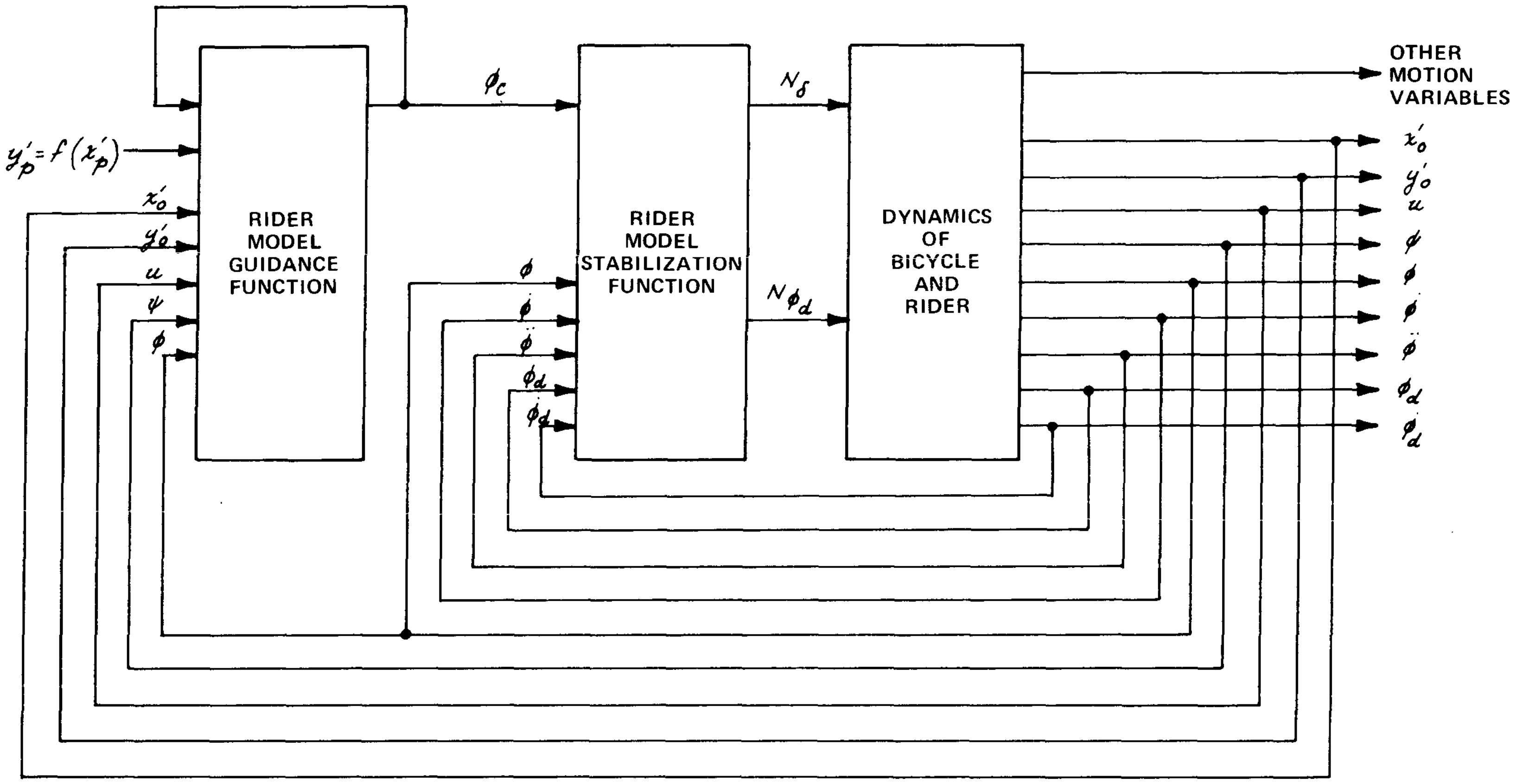
(4) Tire lateral forces as functions of slip angle, inclination (camber) angle, and vertical load are modeled independently for front and rear tires.

(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 can be included between the front assembly and the rear frame.

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 general form of the rider control model is shown in Figure 3. 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.



x_o', y_o' – BICYCLE COORDINATES
u – FORWARD VELOCITY
ψ – YAW ANGLE
ϕ – ROLL ANGLE
$\dot\phi$ – ROLL VELOCITY
$\ddot\phi$ – ROLL ACCELERATION

ϕ_d – RIDER LEAN ANGLE
$\dot\phi_d$ – RIDER LEAN ANGULAR VELOCITY
ϕ_c – COMMAND ROLL ANGLE
N_δ – STEER TORQUE
N_{ϕ_d} – RIDER LEAN TORQUE
$y_p' = f(x_p')$ – DESIRED PATH

Figure 3. Block Diagram of Bicycle Rider Control Model

RESULTS

A few typical results of motorcycle performance are shown here to demonstrate the type of information obtained in the study.

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.

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 4. 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 .5g. The rider remained approximately in-plane with the motorcycle throughout the 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.

Results for a series of runs over a range of lateral accelerations for all machines with this test procedure are shown in Figure 5. They give values for steer angle sensitivity at a reference operating condition -- 40 mph speed, 200 pound rider, and recommended tires. The range of data for the Honda 360 shown in the figure 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.

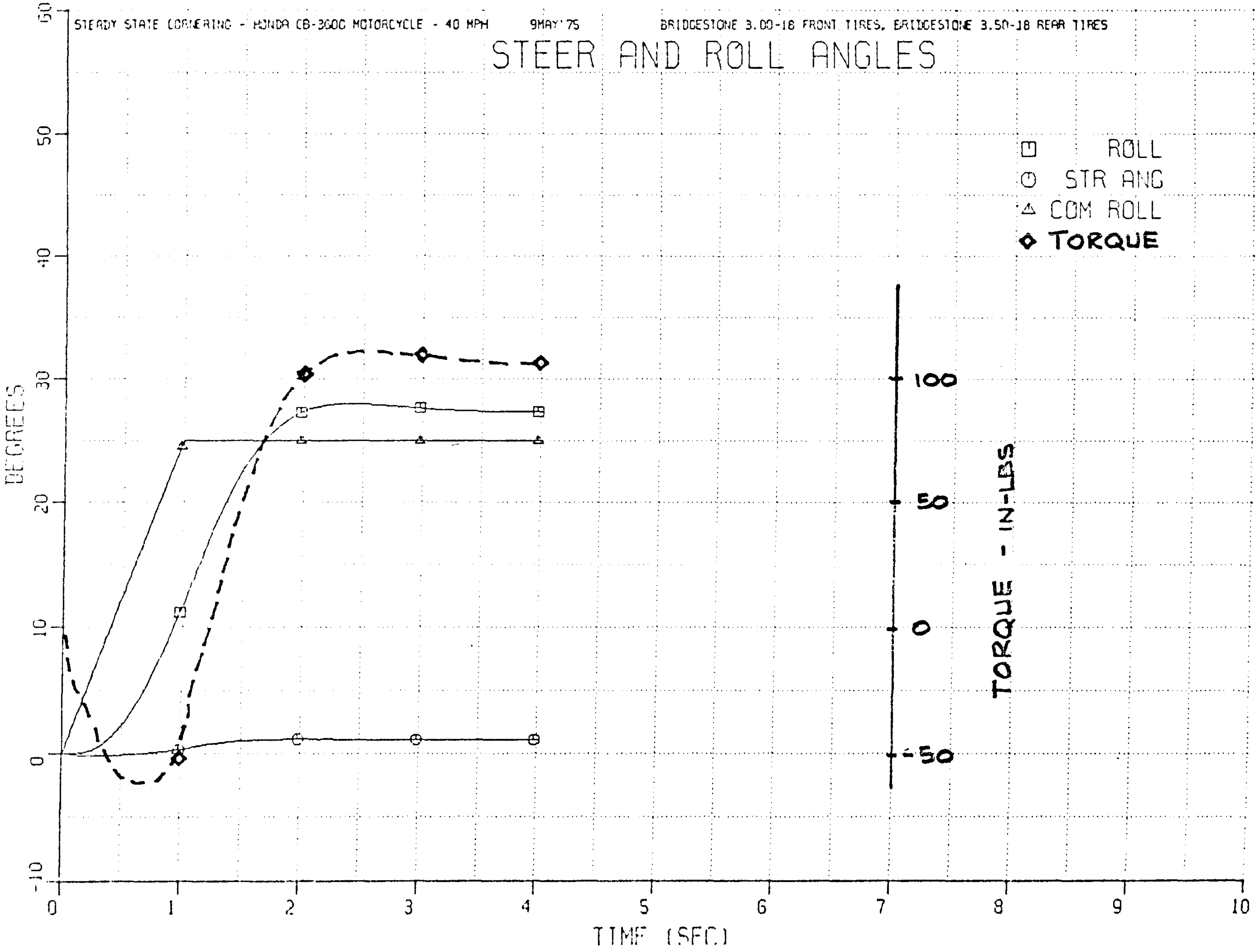


Figure 4. Simulated Directional Control Test Response

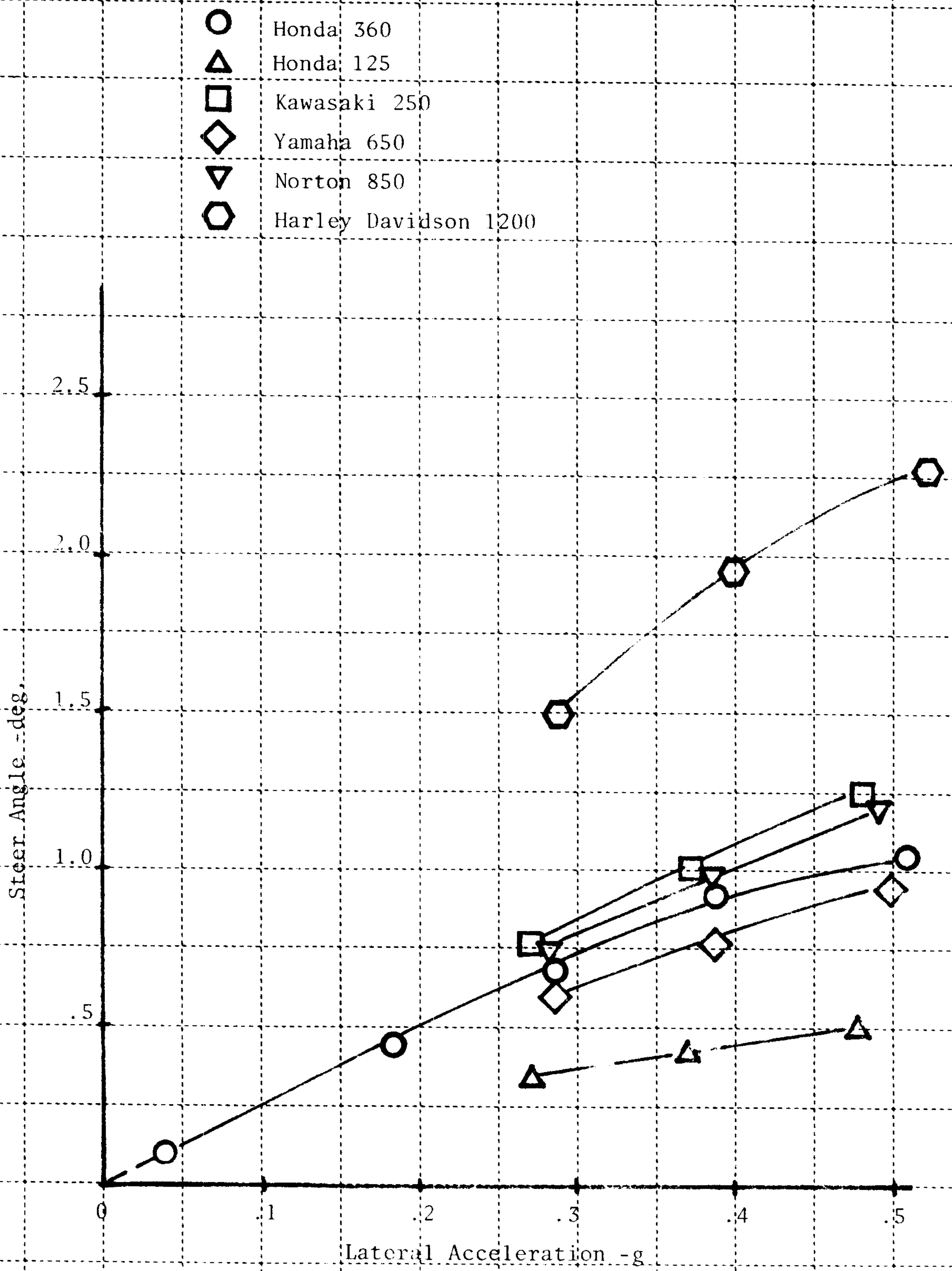


Figure 5. Simulated Directional Control Response Characteristics - Steer Angle

Transient Handling Maneuver

The transient handling maneuver used for this study was the single lane change. This simulated maneuver requires operation of the complete rider-motorcycle mechanization. For the rider model used in the simulation 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 was demonstrated.

Figures 6a and 6b show plotted time histories of the primary control and motion variables in the maneuver. Figure 7 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 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.

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 the two basic test procedures. A Honda 360G was selected for this work.

A complete instrumentation system utilizing a telemetering link to minimize on-board equipment weight was used. Figure 8 contains photographs of the sensors. All tests were performed by a single experienced rider on high skid-number asphalt surfaces under dry conditions. Two test procedures were used -- 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. Briefly, the directional control maneuver consisted of entering and maintaining a constant radius turn from an initial straight path. Data were 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. Investigations of the maximum performance capabilities of the motorcycle or rider were not undertaken using this procedure.

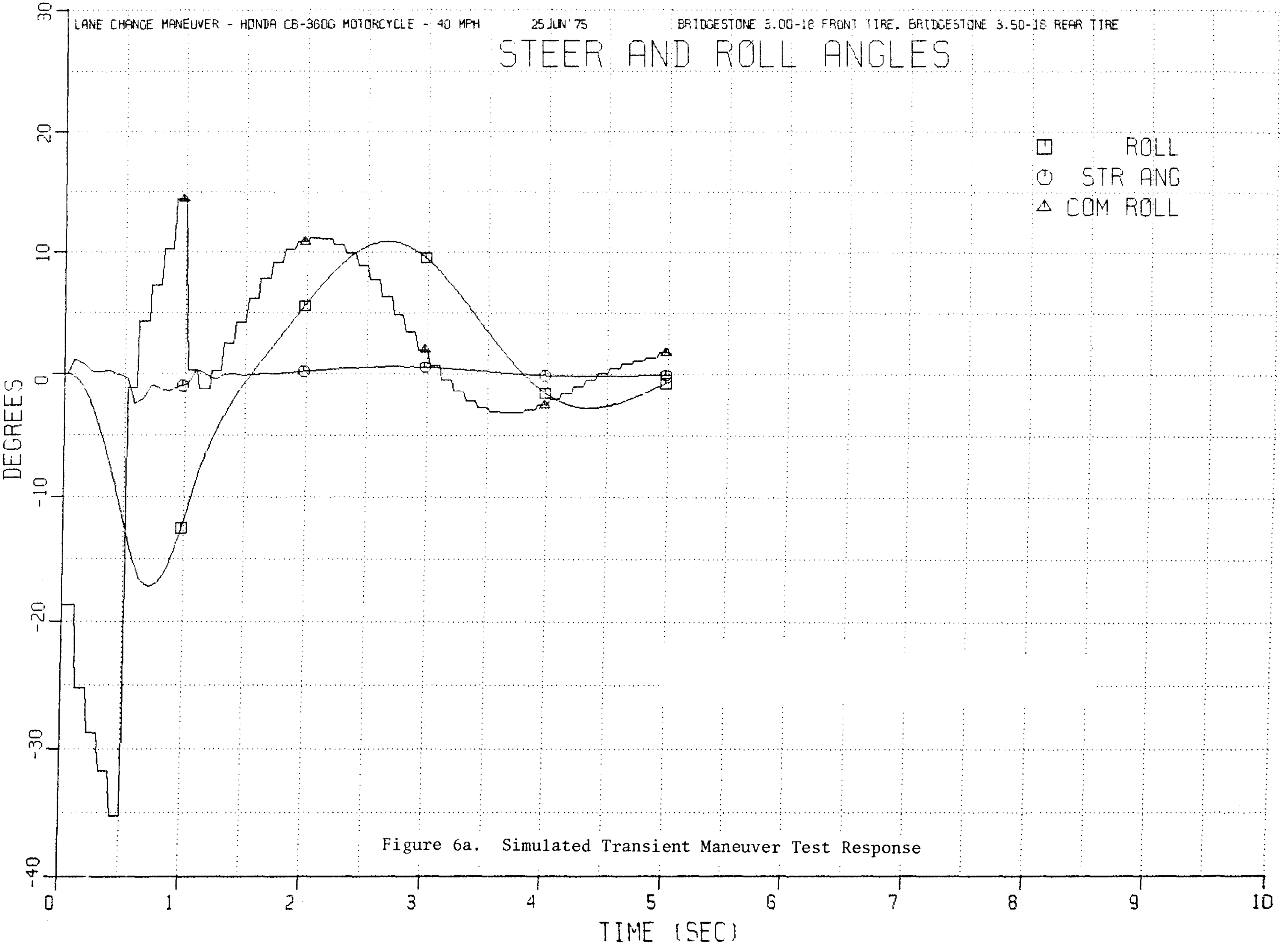


Figure 6a. Simulated Transient Maneuver Test Response

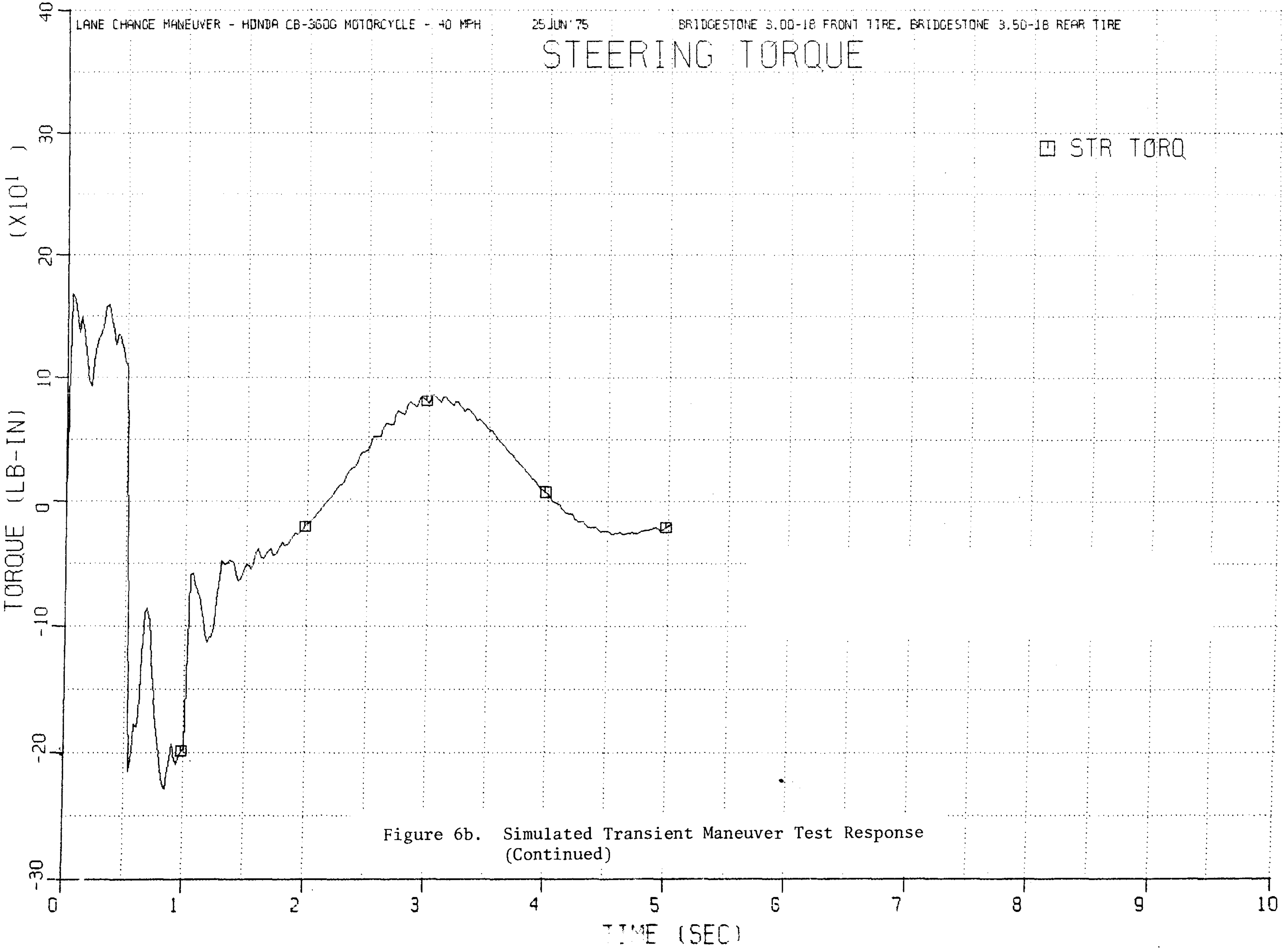


Figure 6b. Simulated Transient Maneuver Test Response (Continued)

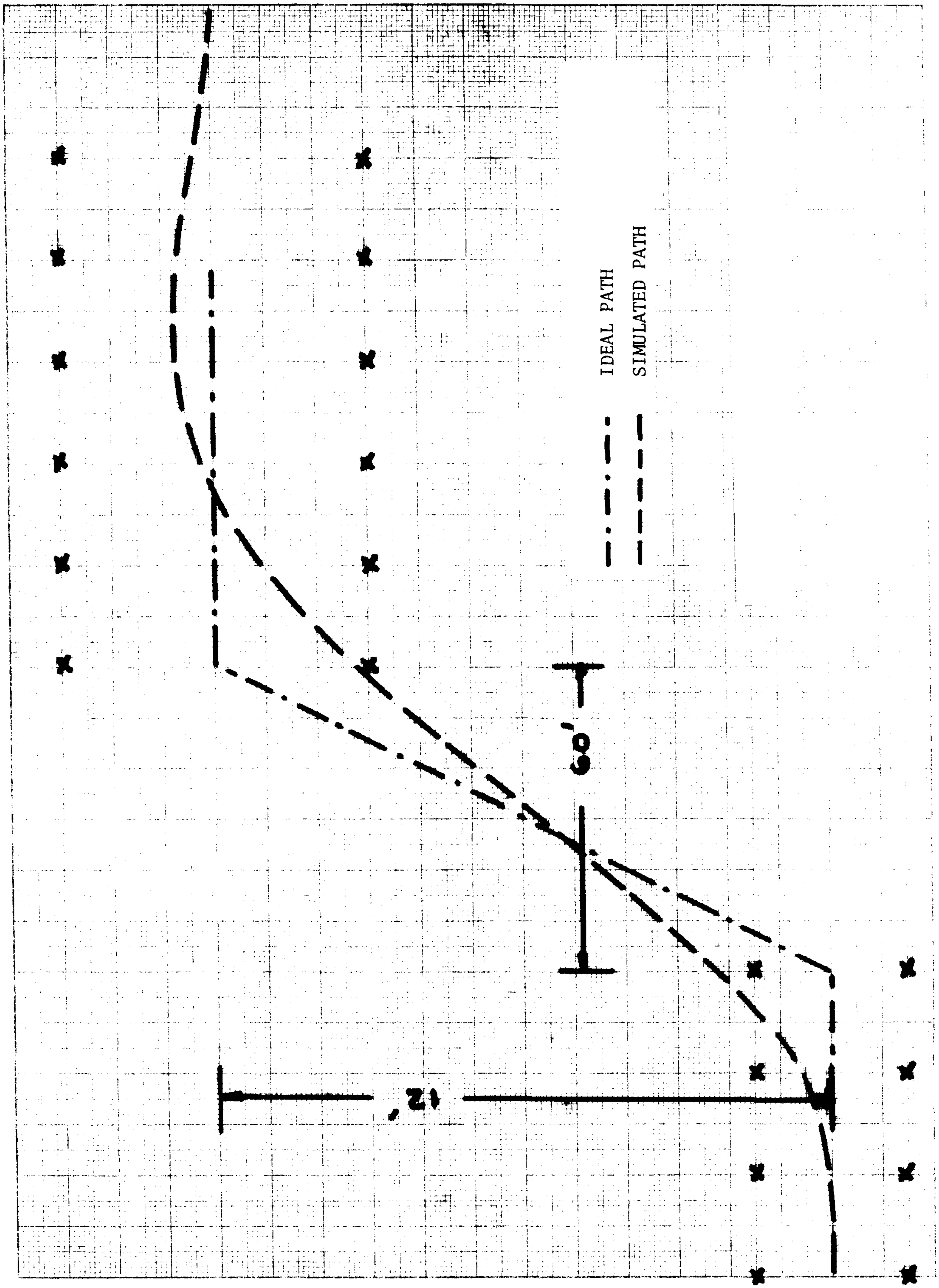


Figure 7. Simulated Lane Change

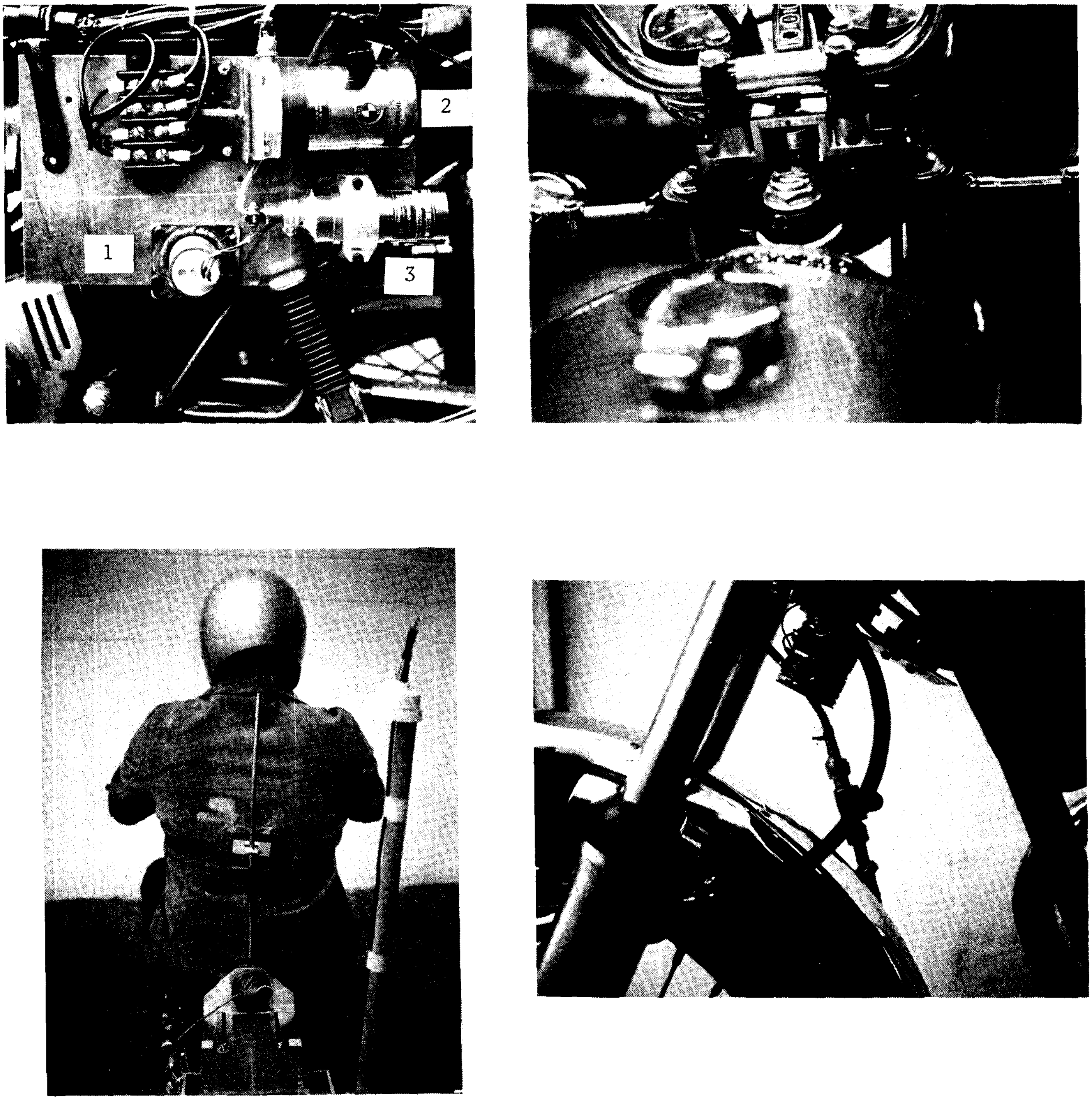


Figure 8. Input and Motion Sensors

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 a longitudinal gap between the entrance and exit lanes set at 30', 45', 60', and 80', and test speeds between 20 and 54 mph. Both rider task performance and motorcycle capabilities were evaluated.

Data records for a typical directional control maneuver and lane change maneuver are presented in Figures 9 and 10. To facilitate interpretation of the data, the sense of each variable has been denoted by "right" or "left" as the rider would view them. For each run, the start 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.

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 11 (directional control) and Table 1 (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.

CONCLUSIONS AND RECOMMENDATIONS

The approach and methodology used in the program have been described, and typical results from both the experimental and analytical phases have been given to illustrate the capabilities and effectiveness of the chosen approaches to meet the program objectives. With respect to these objectives, 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:

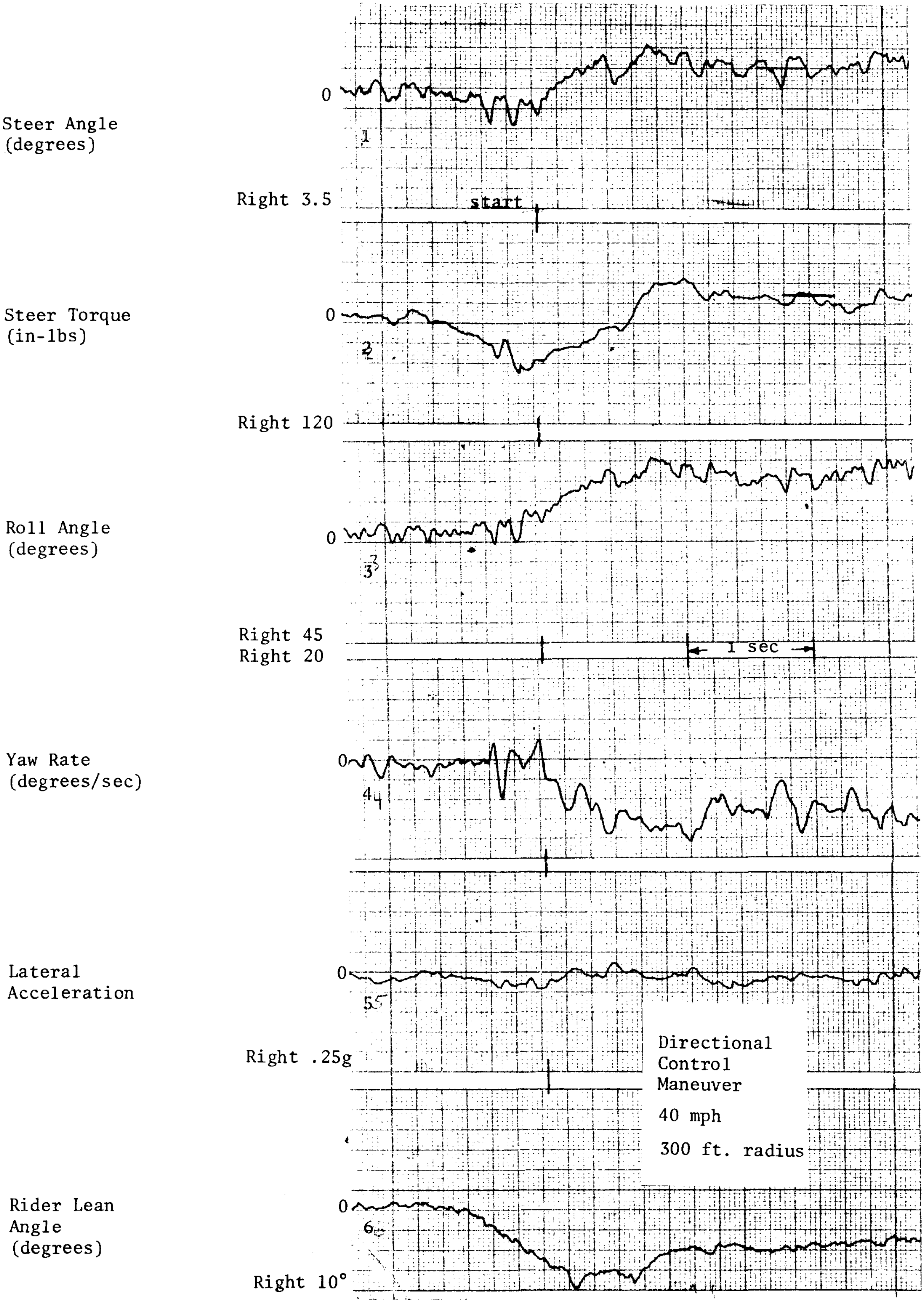


Figure 9. Full Scale Test (Directional Control)

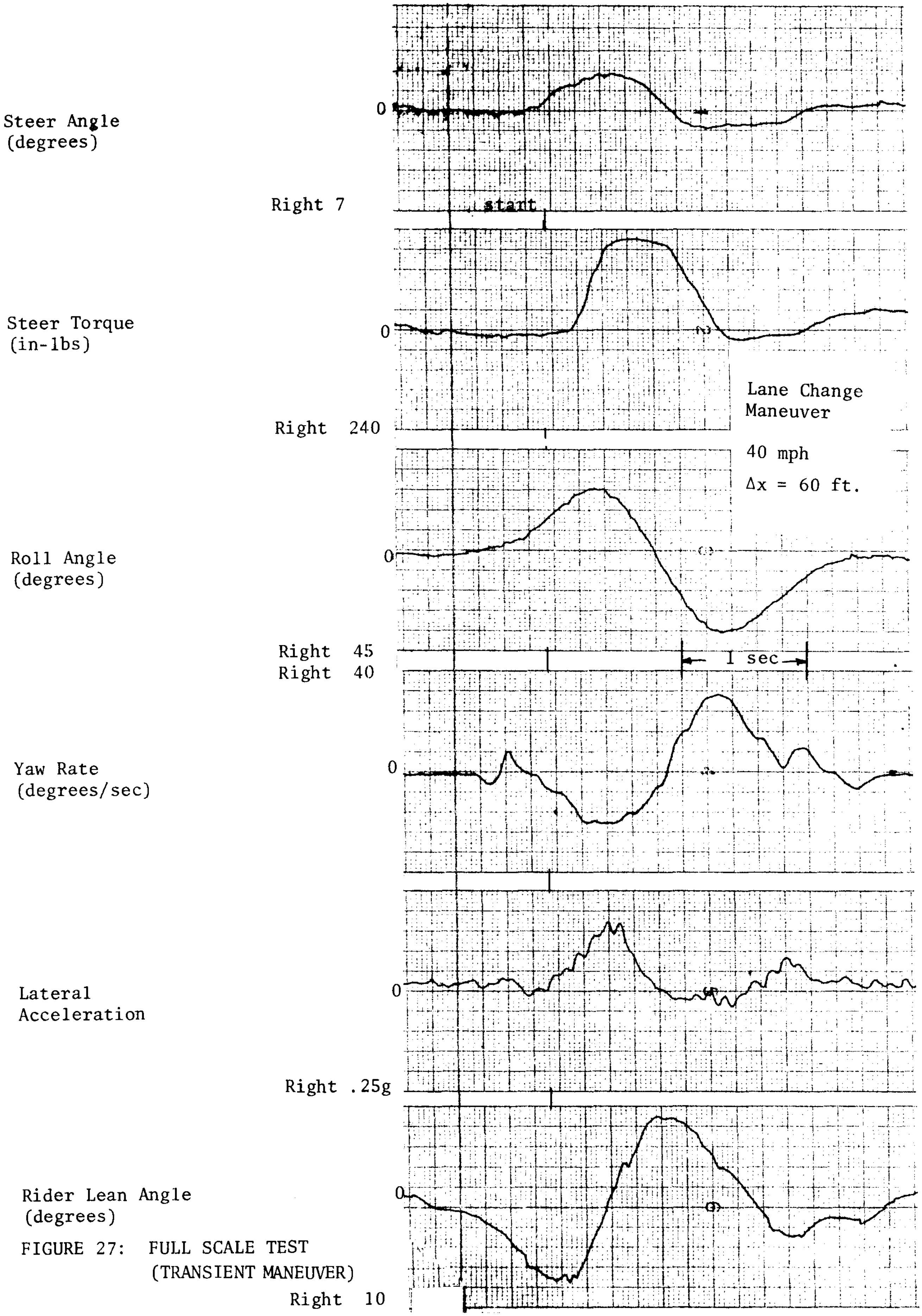


Figure 10. Full Scale Test (Transient Maneuver)

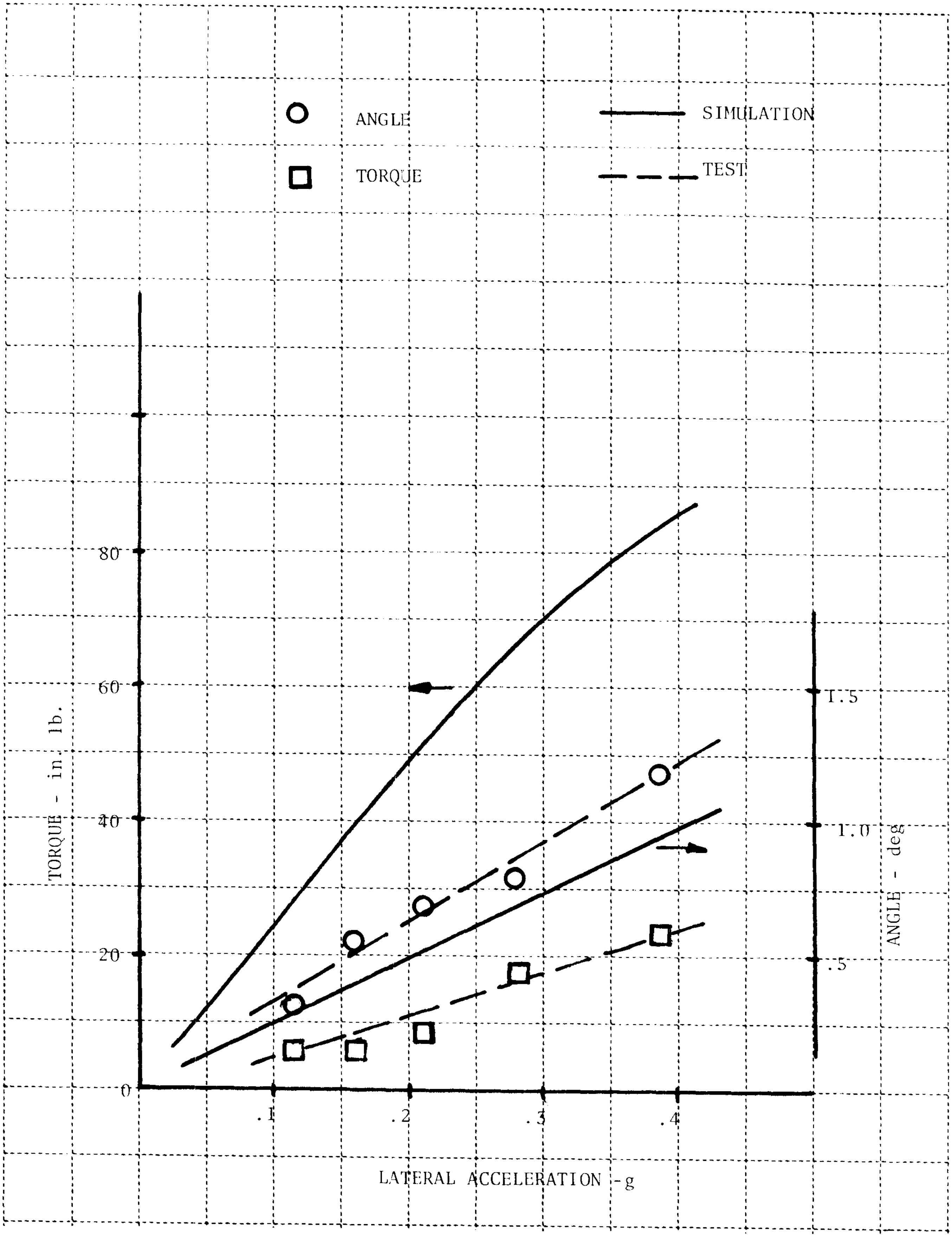


Figure 11. Directional Control Test Comparison

Table 1
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

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.

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, the simulation 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 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 major effort on the 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. In the long term, it will be necessary to investigate the following:

1. Rider-machine interaction.

2. Operating conditions.

3. Additional maneuvers.

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.

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