TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Accident Avoidance Capabilities of Motorcycles - Lane Change Maneuver Simulation and Full-Scale Tests		5. Report Date July, 1976
		6. Performing Organization Code
7. Author(s) Roy S. Rice and Dennis T. Kunkel		8. Performing Organization Report No. ZN-5899-V-1
9. Performing Organization Name and Address Calspan Corporation 4455 Genesee Street Buffalo, New York 14221 (716) 632-7500		10. Work Unit No.
		11. Contract or Grant No. NHTSA-6-5432
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration Washington, D. C. 29590		13. Type of Report and Period Covered Final Report Feb. 1976 - July 1976
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report describes a brief study of motorcycle handling characteristics employing both analytical (simulation) and experimental (full-scale maneuvering) methods. The objective was to supplement the results of a much broader earlier study on motorcycle accident avoidance capabilities in three areas - - (1) demonstration of the motorcycle/rider dynamic simulation in a transient handling task (a single lane change); (2) acquisition of additional data on motorcycle controllability as evaluated by torque sensitivity parameters; and (3) lane change testing of additional riders to identify differences in riding technique. The report contains results of the simulation studies of six different motorcycles and the effects of changes in the rider model control characteristics on lane change performance, presents time history data for typical full-scale test runs in the lane change, and gives results of lateral-directional response tests for one motorcycle. The results are discussed in terms of design, operational, and rider influences on performance.

17. Key Words		18. Distribution Statement	
Motorcycle Handling Simulation Driver Model			
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	75	

Form DOT F 1700.7 (8-69)

FOREWORD

This report covers the work performed by Calspan Corporation on motorcycle handling under Contract No. NHTSA-6-5432, for the National Highway Traffic Safety Administration. It supplements the information contained in Accident Avoidance Capabilities of Motorcycles, Calspan Report No. ZN-5571-V-1, dated June 1975, which was prepared under Contract No. DOT-HS-4-00976. The Contract Technical Manager for NHTSA was Mr. Donald E. Bischoff and the Project Engineer for Calspan was Mr. Dennis T. Kunkel.

This report has been reviewed and is approved by:

Edwin A. Kidd, Head
Transportation Research Department

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Under Contract No. DOT-HS-4-00976, Calspan Corporation performed a study of motorcycle handling characteristics which is reported in Reference 1. The work involved both analytical (simulation) and experimental methods to define practical test procedures and discriminating performance measures with which to evaluate the accident avoidance capabilities of motorcycles. It included investigations of techniques for measuring motorcycle physical characteristics, the determination of tire cornering performance capabilities, and the development of means for measuring key control input and motion output variables as well as the overall performance evaluations. Since the results of this work are presented in detail in Reference 1 (which includes a volume of appendices containing test data), they will not be discussed here. It was concluded that this initial study produced a foundation on which to base further study of motorcycle handling by defining test procedures for steady-state cornering and transient maneuvering (a lane change) which satisfactorily discriminated among various types of machines.

The purpose of this brief study was to supplement the earlier findings by performing additional simulation and experimental runs to cover rider influences in greater depth and to complete the investigation of several motorcycles in a simulated lane change maneuver. The results of these studies are discussed in Section 2 (Simulation Studies) and Section 3 (Full-Scale Tests). Although it was not possible to analyze these results in sufficient detail to extract all of the subtleties of rider control, several interesting observations on system performance can be made. These are briefly discussed in Section 4 (Conclusions and Recommendations) which also includes suggestions on further approaches to investigations of motorcycle handling. References are listed in Section 5. Copies of plotted output from the simulation work are presented in Appendix A.

2.0 SIMULATION STUDIES

The simulation program used in this phase of work was the same as used for the studies previously reported (which is described in Reference 1). The primary features of the model which deserve recounting here are:

(1) The vehicle simulation consists of a coupled system of eight degrees of freedom (six rigid body motions, steering motion, and rider lean motion) incorporating nonlinear tire performance characteristics.

(2) The rider simulation contains nine motion feedback elements -- three steering torque terms responsive to vehicle roll angle and its derivatives, three rider lean terms responsive to roll angle and its derivatives*, and three path and heading error factors -- in addition to a representation of rider psycho-physical dynamics.

(3) The vehicle and driver models are combined in a man-machine system simulation which permits the study of stability (as in cornering without closure of the guidance loop) and of path-following (as with a lane change maneuver).

(4) The path generation sub-routine was improved for these runs to avoid computational problems that were encountered in the earlier study. This aspect of the simulation is now considered to be in final form.

Simulation runs were made using data sets representative of six different motorcycles. These motorcycles, which were the same six employed in the

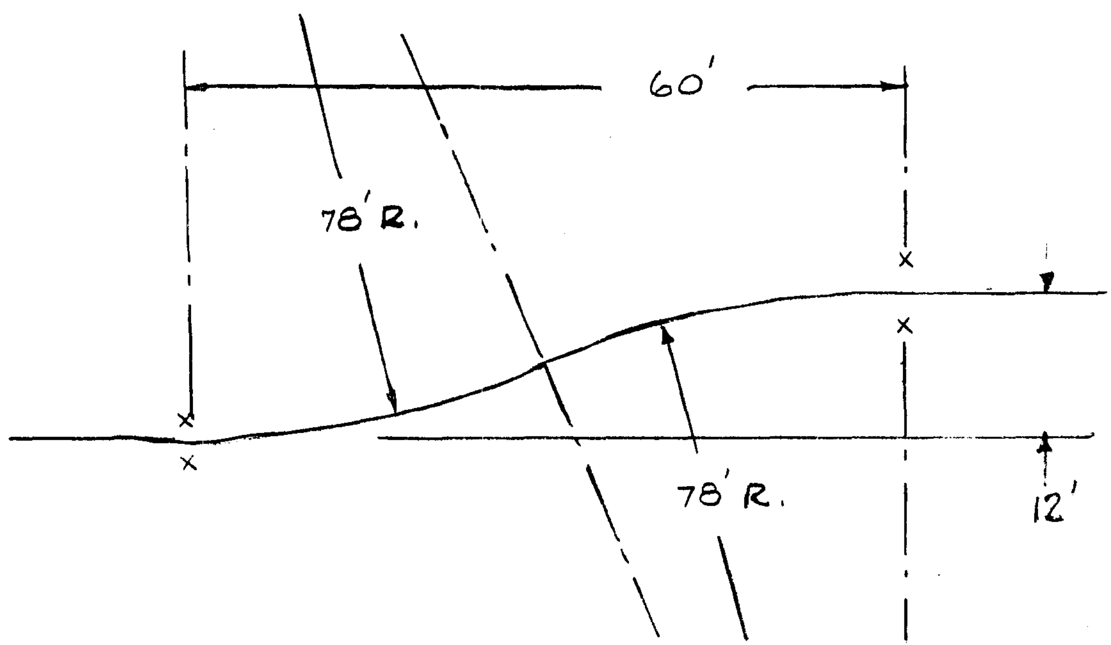
*For these studies, the rider lean control feedbacks were not employed. In effect, this control mode was made passive -- by coupling the rider to the machine by a stiff torsional spring.

Reference 1 study, were the Honda CB-360G, Honda CB125S1, Kawasaki F-11 250, Yamaha XS2 650, Norton 850 Commando, and the Harley-Davidson FLH-1200 Electra Glide. A repeat of the lane change maneuver run from the initial study was made using the Honda 360. The duplication of all results satisfactorily demonstrated the operational status of the simulation so that lane change simulation runs with the other five machines could be undertaken.

2.1 Lane Change Maneuver

All applications of the simulation in this brief study were for investigation of the lane change maneuver by each of the six motorcycles of interest. The important factors for these runs were:

(1) Straight-on approach prior to initiation of a single right-to-left lane change of 12 ft. lateral displacement and 60 ft. longitudinal displacement between entrance and exit gates. The nominal simulation starting point is 60 ft. upstream of the entrance lane gate. The theoretical path in the maneuver consists of two circular arcs of 78 ft. radius tangentially joined at the geometrical midpoint of the maneuver as sketched below:



The three foot wide entrance gate and the six foot wide exit gate, representing the lane delineator cones used in full-scale testing, are included in the sketch for reference purposes and are not part of the simulation path definition.

(2) Rider model control coefficients held constant (i.e., independent of machine). This permits direct comparison of results for a given set of rider characteristics (which were considered to be reasonable).

(3) With the same course geometry and rider model coefficients, runs were made with all six motorcycles at the baseline approach speed of 40 MPH. Runs for the Honda 360 were made at approach speeds of 30 and 50 MPH as well as at 40 MPH.

A typical set of plotted outputs from the simulation (for the Honda 360) is shown in Figure 1. Note the small steering displacement out of the turn initially (which is also illustrated in the torque curve), the basically sinusoidal pattern of roll angle (which reflects the lateral acceleration time-history), and the correction applied to stabilize at the end of the maneuver.

Time histories of the control input variables and output motion from runs for each of the other motorcycles are presented in Appendix A. A more direct comparison among the machines is given in Figure 2 which shows path patterns with respect to the course layout as simulated. The principal observations about these data are:

(1) The paths through the course taken by the different motorcycles are very similar. This is illustrated in Figure 2 where the two extremes are shown. The path of the other vehicles fall within the envelope described by the two which are shown. In effect, the rider model, with the control coefficients held constant for all vehicles, develops steering torque inputs which produce approximately the same path through the course

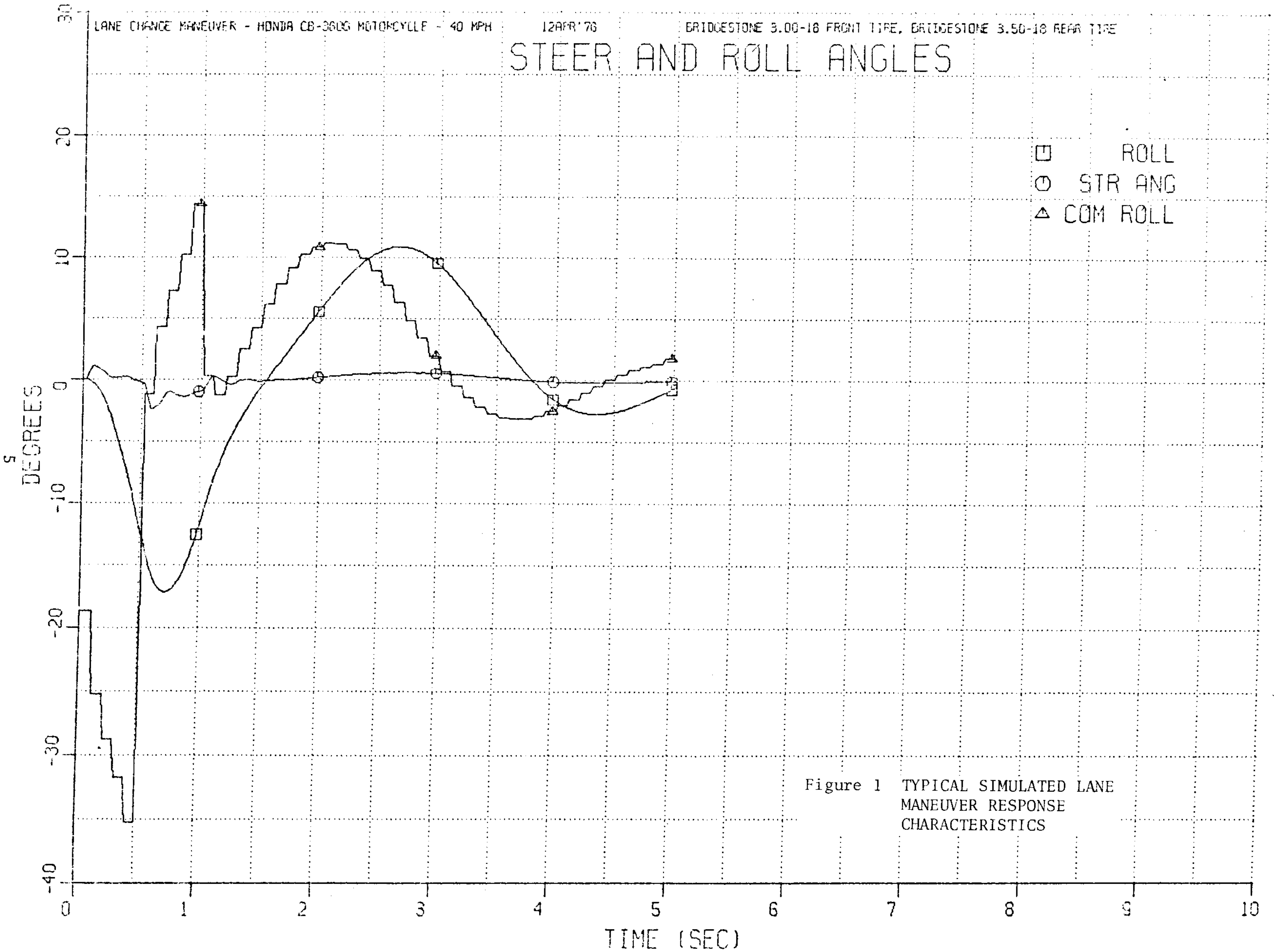


Figure 1 TYPICAL SIMULATED LANE MANEUVER RESPONSE CHARACTERISTICS

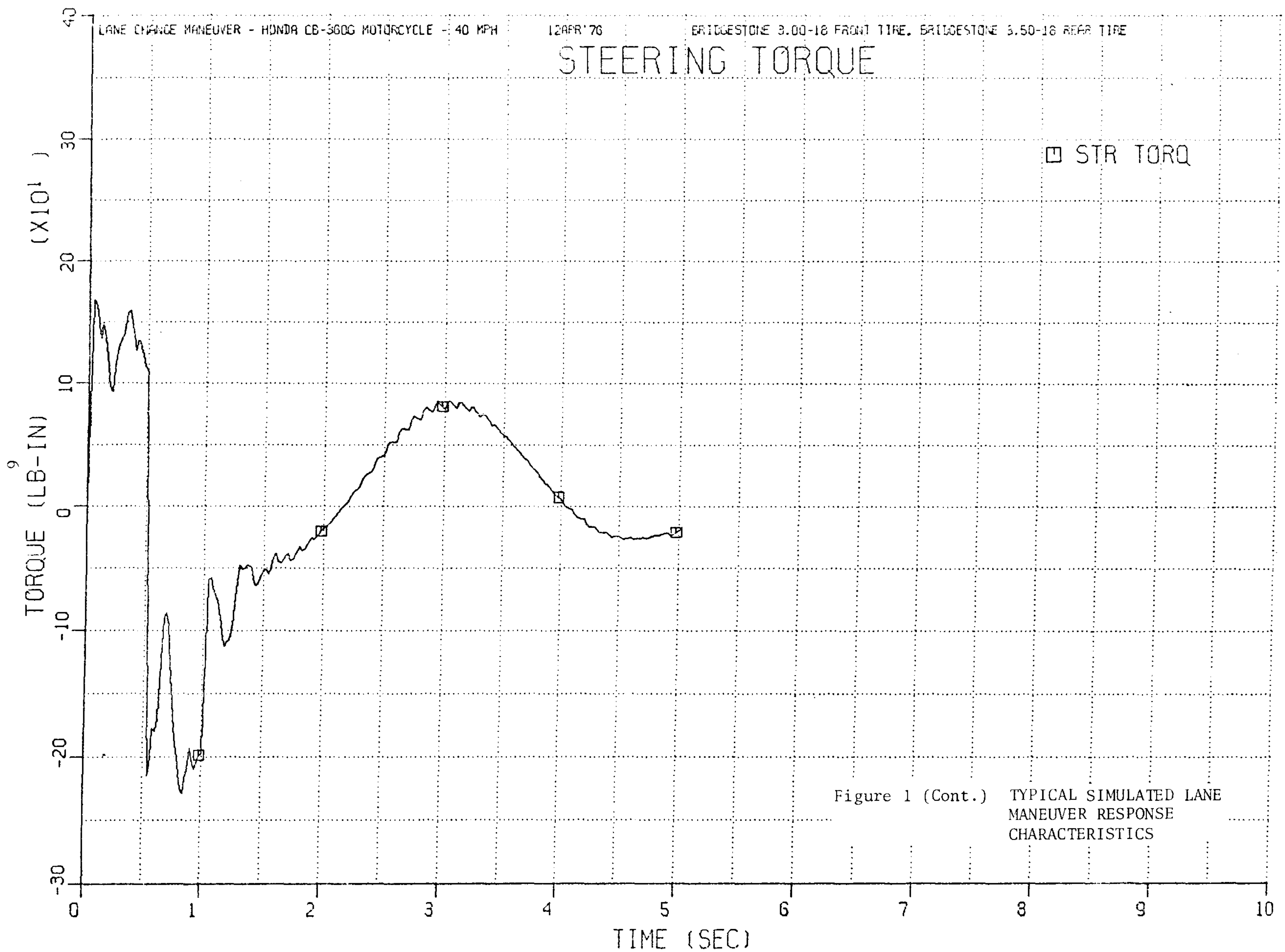


Figure 1 (Cont.) TYPICAL SIMULATED LANE MANEUVER RESPONSE CHARACTERISTICS

and continues well into the exit lane (which is reached in approximately two seconds after start). Maximum lateral displacement is attained about three seconds after start when the machine is some 60 feet beyond the exit lane gate. This path pattern agrees quite well with full-scale results (in which the maneuver at 40 MPH typically requires about four seconds).

Three runs with the simulated Honda 360 were devoted to an evaluation of performance as a function of initial speed. Values of 30, 40, and 50 MPH were investigated. Course geometry was held constant as were all rider model coefficients. The resultant paths are shown in Figure 3. At 30 MPH, the entrance lane gate delineator is just touched and the path is about 5 in. inside the exit lane gate. Only a small path overshoot in the exit lane is experienced. At 40 MPH, the path is outside the entrance lane gate and also just touches the exit lane gate marker. As noted previously, this path is very much like those shown in Figure 2. At 50 MPH, the track is unsuccessful at both ends, falling outside the gates at both entrance and exit. A somewhat larger overshoot of the ideal exit path is also experienced. Thus, the simulated system shows successful performance at 30 MPH (except for the slight longitudinal displacement of the path), just fails at 40 MPH (where approximately 65 ft. of longitudinal distance is required to achieve the necessary lateral displacement), and misses by a substantial amount at 50 MPH (some 76 ft. along the X dimension is needed). This performance corresponds quite well with full-scale results discussed later.

Control inputs for a run in this series are shown in Figure 4. In this case, the initial viewing time of the maneuver was only .8 second rather than 1.0 second as normally used (In effect, this corresponds with a 60 ft. initial viewing distance at 50 MPH.). Under these conditions, the steering control is applied further along the track than for the previously described 50 MPH run and the resultant path undershoots the theoretical path. However, this is compensated for by the use of higher lateral acceleration later in the run. Required gap distance is reduced by about 10%. For comparison, the 50 MPH run with 1.0 second initial view time is shown in Figure 5. This result suggests

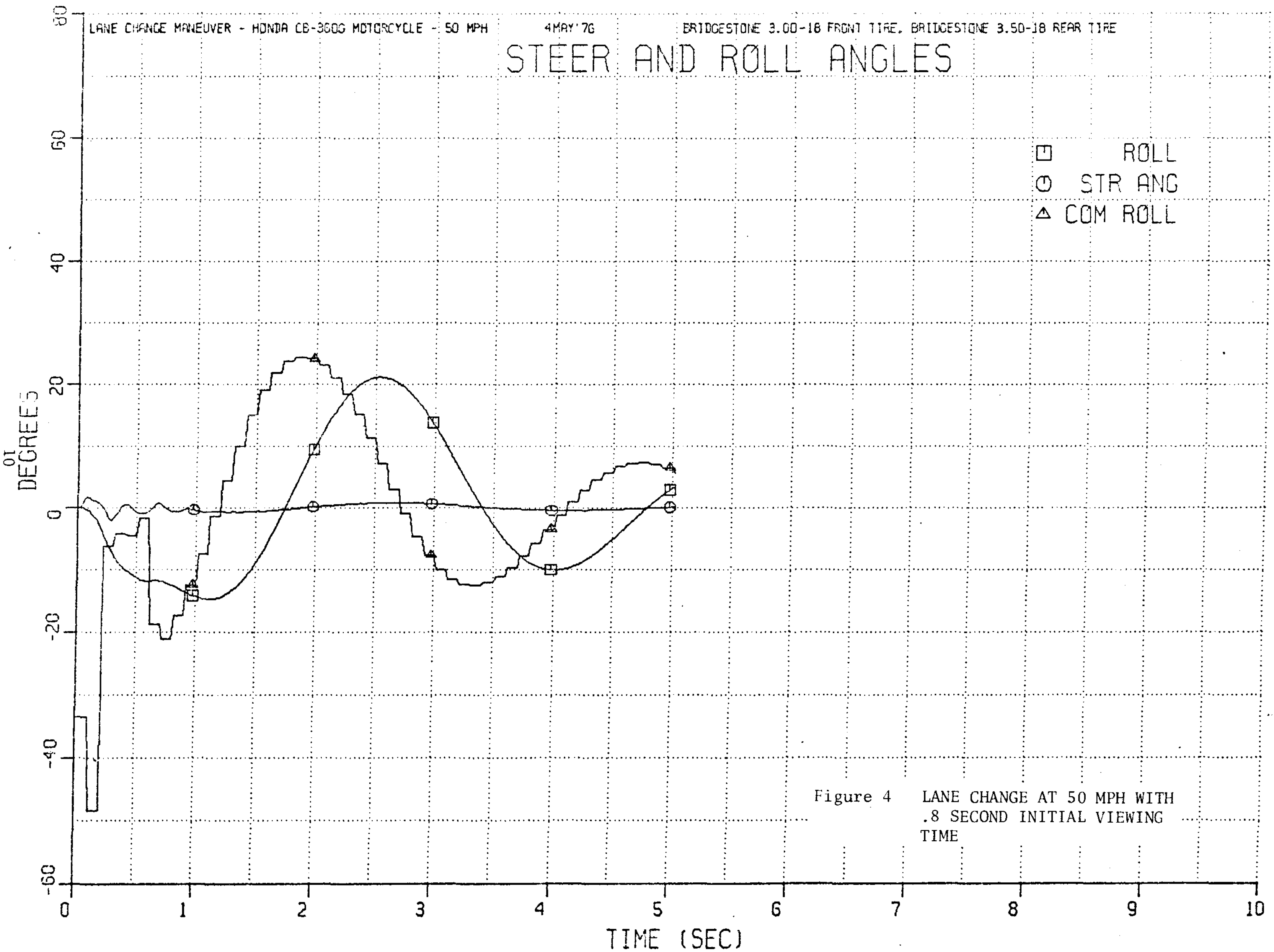


Figure 4 LANE CHANGE AT 50 MPH WITH .8 SECOND INITIAL VIEWING TIME

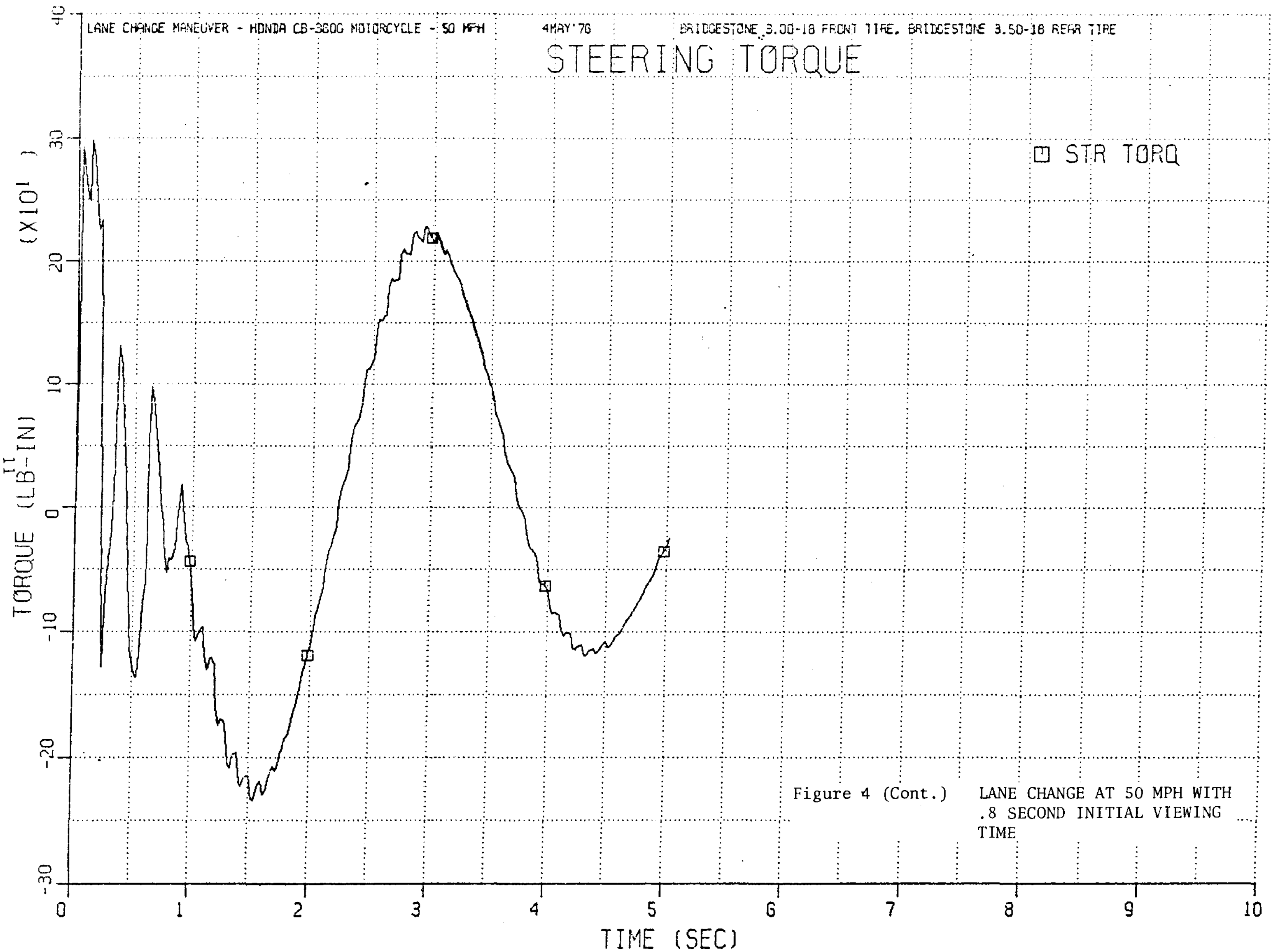


Figure 4 (Cont.) LANE CHANGE AT 50 MPH WITH .8 SECOND INITIAL VIEWING TIME

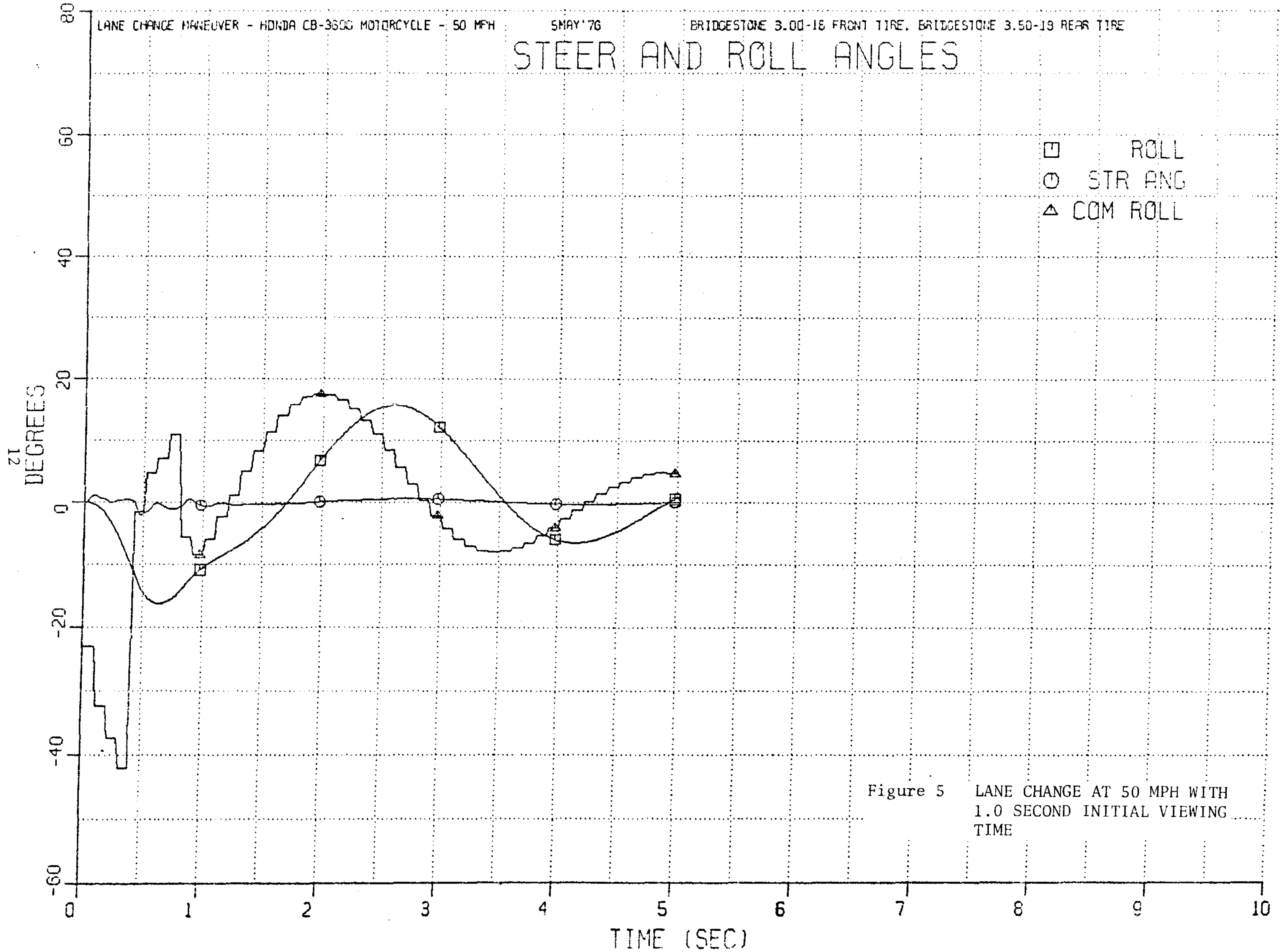


Figure 5 LANE CHANGE AT 50 MPH WITH 1.0 SECOND INITIAL VIEWING TIME

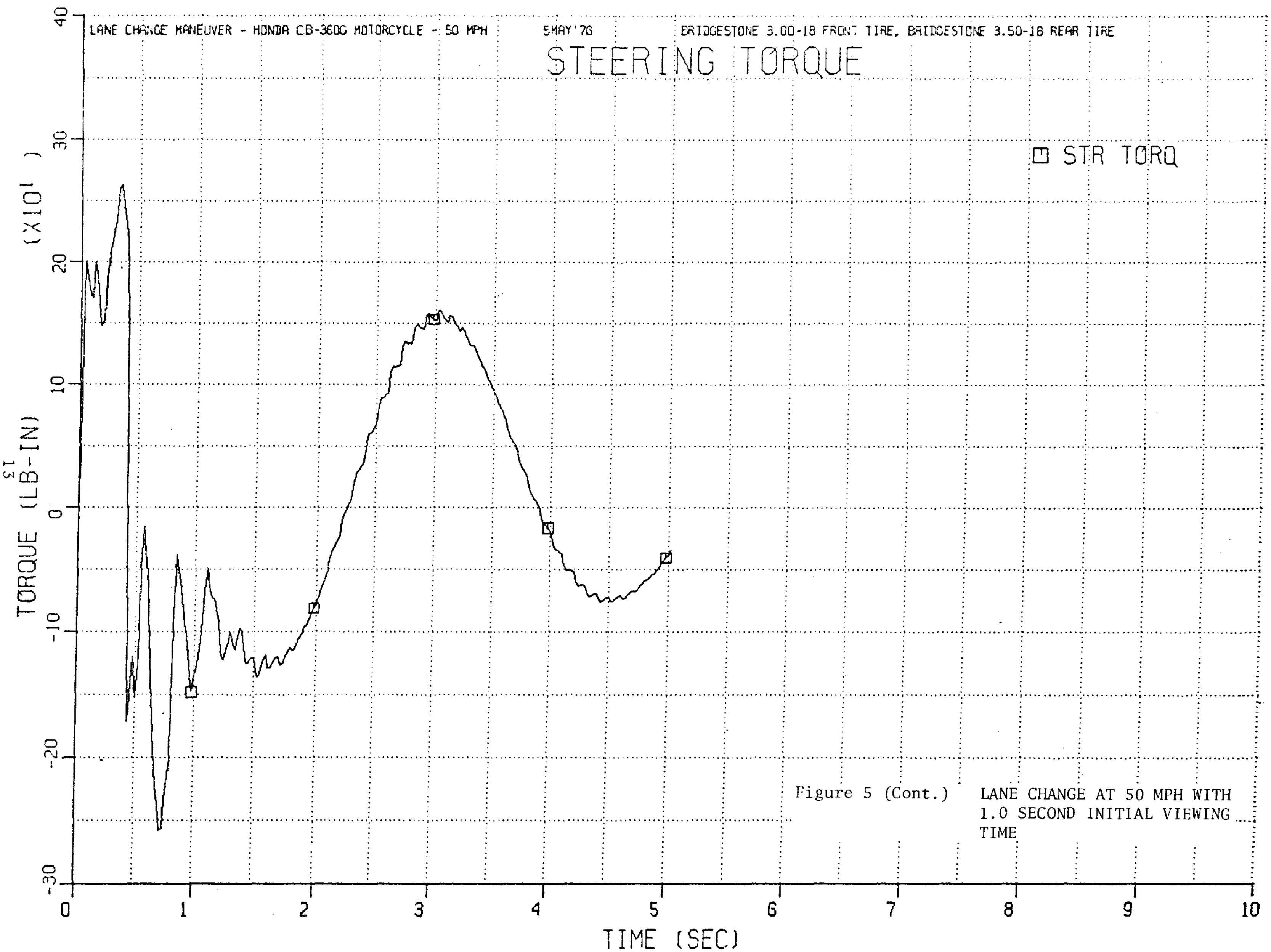


Figure 5 (Cont.) LANE CHANGE AT 50 MPH WITH 1.0 SECOND INITIAL VIEWING TIME

the need to examine the effect of preview time on performance (as well as the feedback control coefficients) -- particularly in rapid transient maneuvers. Additional information on these runs is summarized in Section 2.3.

2.2 Rider Characteristics

In addition to the runs for the six motorcycle configurations, the simulation was employed in a brief study of the sensitivity of performance to values of the rider model coefficients with the Honda 360 parameters in the lane change maneuver. Small improvements in performance were achieved by increasing the guidance loop gain terms for path error and heading angle error but, at least for the conditions which were investigated, the performance was relatively unaffected. Time histories for these runs are given in Appendix A.

A run was also made in which the coefficient of the roll acceleration feedback term in the stabilization loop was reduced to zero (to simulate an unskilled rider). In this case, for which the time histories of several variables are shown in Figure 6, oscillatory instability resulted. The required lateral displacement for the lane change was achieved but a 2 Hz oscillation of all variables is superimposed on the basic response. The guidance loop feedbacks used by the rider are thus seen to be satisfactory (i.e., the basic path is similar to those of the other runs) but the simplified stabilization cues do not produce sufficient damping for successful performance of the maneuver. This result supports the belief that this feedback cue (i.e., roll acceleration) is a significant rider skill parameter that must be included in motorcycle handling studies to assure stability over the entire operating speed range.

The simulation results are summarized in the next section. While this brief look at rider model effects is clearly insufficient to come to any firm conclusions, it did demonstrate how the simulation can be applied to the evaluation of performance sensitivity and identification of critical riding cues.

2.3 Summary of Simulation Study

Table 1 contains listings of several key motion and control variables from selected runs from the simulation study. They demonstrate the applicability of the simulation to the evaluation of performance in the lane change

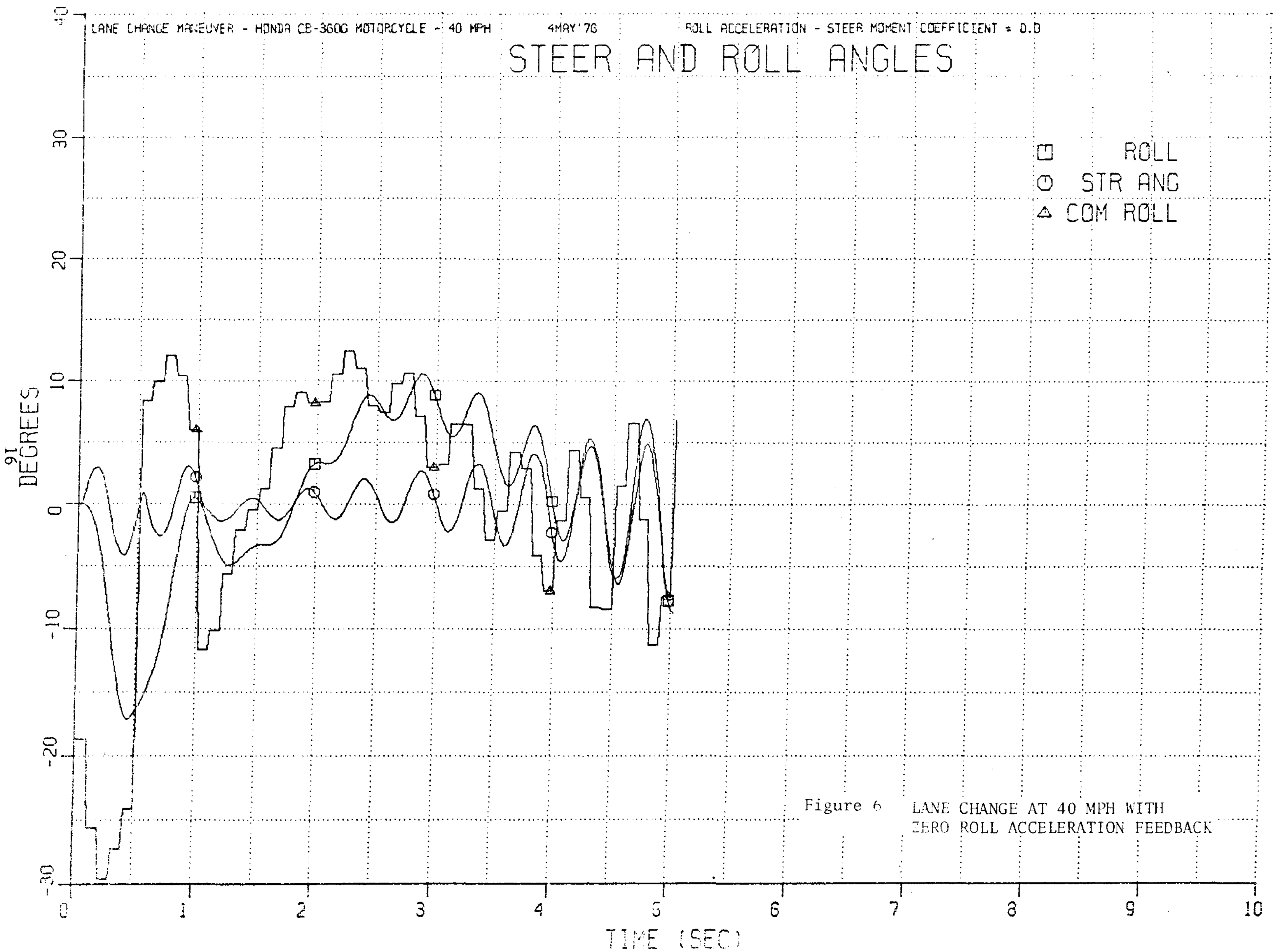


Figure 6 LANE CHANGE AT 40 MPH WITH ZERO ROLL ACCELERATION FEEDBACK

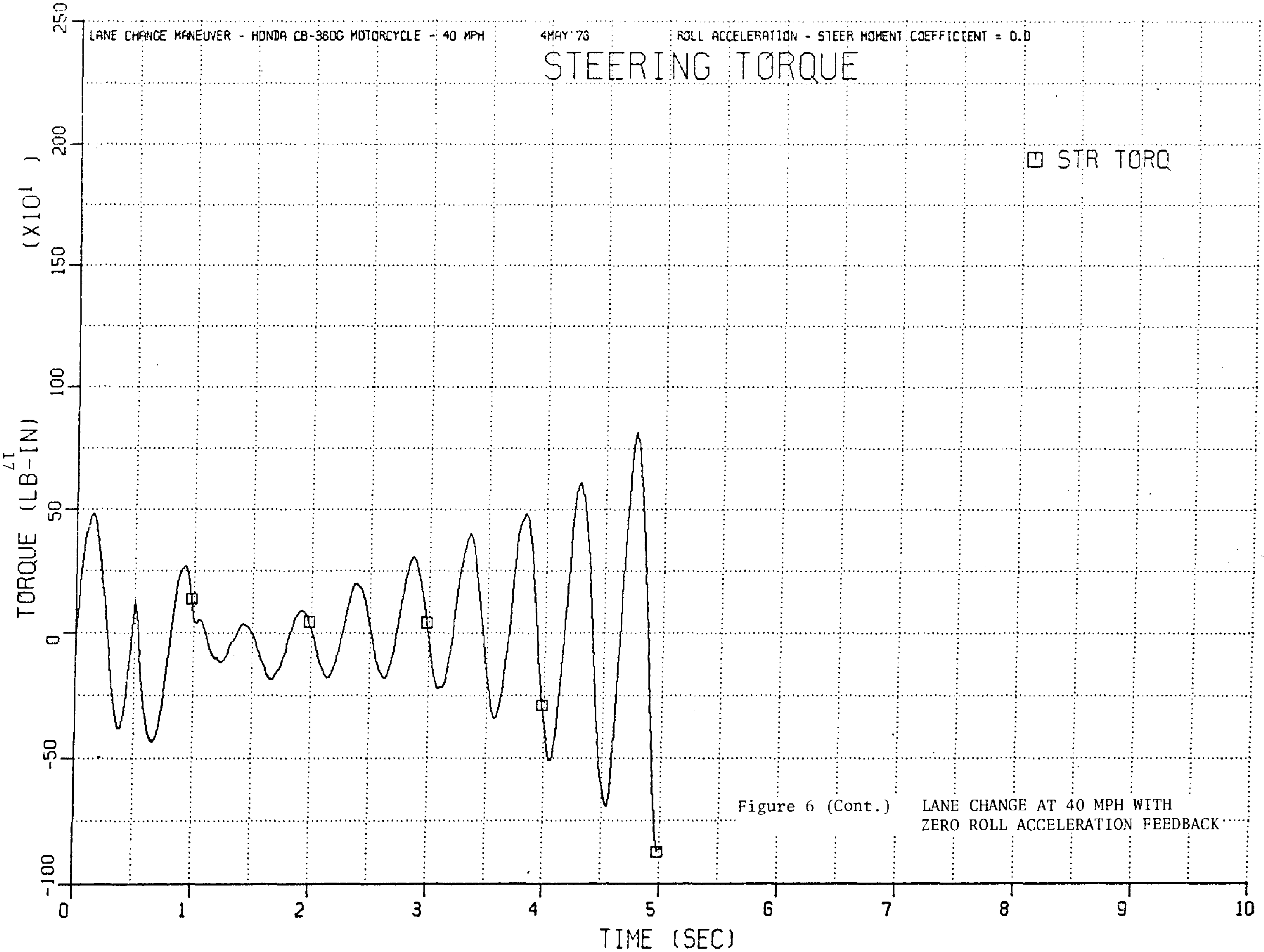


Figure 6 (Cont.) LANE CHANGE AT 40 MPH WITH ZERO ROLL ACCELERATION FEEDBACK

TABLE 1: SUMMARY OF SIMULATED LANE CHANGE PERFORMANCE CHARACTERISTICS

PERFORMANCE VARIABLE \ CONFIGURATION*	Honda 125 at 40 MPH (1)	HD 1200 at 40 MPH (1)	Kawasaki F11 at 40 MPH(1)	Yamaha 650 at 40 MPH(1)	Norton 850 at 40 MPH(1)	Honda 360 at 40 MPH (1)	Honda 360 at 30 MPH (1)	Honda 360 at 50 MPH (1)	Honda 360 at 50 MPH (2)	Honda 360 at 40 MPH (3)	Honda 360 at 40 MPH (4)	Honda 360 at 40 MPH (5)	Theoretical Path.
Lateral Displacement at X = 0 (ft.)	-2.1	-1.95	-2.0	-2.0	-2.0	-2.05	-1.7	-2.25	-1.0	-1.9	-2.0	-2.6	0
Lateral Displacement at X = 60 (ft.)	-8.95	-8.9	-8.8	-8.9	-8.9	-9.0	-9.45	-8.35	-6.75	-9.45	-9.45	-8.5	-12
Maximum Lateral Displacement (ft.)	-12.7	-13.25	-13	-12.95	-13	12.75	-12.65	-13.2	-13.9	-12.65	-12.6	-13.	-12
Maximum Lateral Acceleration-Left (g)	.41	.37	.37	.39	.39	.41	.38	.40	.30	.37	.37	.54	
Maximum Lateral Acceleration-Right (g)	.17	.24	.20	.21	.21	.20	.12	.30	.42	.28	.26	.18	
Maximum Applied Torque-Left (ft.lbs.)	13	25	14.5	19	16.5	19	20	21	19	18	18	(6)	
Maximum Applied Torque-Right (ft.lbs.)	3.5	12	5.5	7.5	6.5	7	5	13	19	10	9	(6)	
Longitudinal Location at y = -1.5 ft. (ft.)	-7	-7	-6	-6	-6	-6	-2	-10	+9	-4	-5	-14	
Longitudinal Location at y = -9 ft. (ft.)	60	61	61	61	61	59	56	66	77	56	56	65	
Longitudinal Distance Used (ft.)	67	68	67	67	67	65	58	76	68	60	61	79	

* See Notes.

NOTES FOR TABLE 1

Note (1): Baseline rider model -- active steer torque control, passive lean control, and reference value of rider coefficients (same as used in Reference 1).

Note (2): Initial viewing time reduced from 1.0 second (75 ft.) to .8 second (60 ft.). Preview time held constant at 1.0 sec.

Note (3): Rider model coefficient for path error gain increased (150% of reference value).

Note (4): Rider model coefficients for path error and heading angle error gain increased (150% of reference values).

Note (5): Rider model coefficient for roll angle acceleration gain reduced to zero.

Note (6): Although the lateral displacement for the lane change was achieved, the system was oscillatorily unstable and did not recover in the exit lane. (See Figure 6) maneuver and facilitate comparisons among configurations. The following explanations of the tabulated performance variables will be helpful in interpreting Table 1.

(1) The lateral displacement values give the lateral location of the machine at the entrance gate (X = 0) and the exit gate (X = 60 ft.) as well as the maximum lateral displacement in the exit lane (where 12 ft. is the ideal value). They may be compared with the theoretical values, shown in the last column, which are based on the reference path through the maneuver.

(2) The lateral acceleration values were extracted from the simulation print-out results. All print-out data is available on file at Calspan.

(3) The torque values given in the table are peak instantaneous values. The initial torque application to steer out of the turn is not listed.

(4) The longitudinal location values are provided for comparison with full-scale test results where the lane delineators (cones) of importance are the left-hand cone in the entrance gate (1.5 ft. to the left of the initial path) and the right-hand cone in the exit gate (9 ft. to the left of the initial straight line path). The "longitudinal distance used" value is the difference in the two locations.

The results indicated by the table (and their implications with respect to simulation status) may be summarized as follows:

(1) Precise tracking of the theoretical path requires performance unachievable by real motorcycles. In addition to the implied instantaneous response, lateral acceleration values of almost 1.4 g would be required. The rider-machine simulation (with

the selected rider control coefficients) reduces these requirements by early initiation and late completion of the maneuver (as shown by lines 1 and 2 of the table) utilizing reasonable values of lateral acceleration (lines 4 and 5).

(2) In general, the simulated rider utilizes higher lateral accelerations in the first half of the maneuver than in the recovery phase. This tends to be supported by the full-scale test results (See Section 3.2).

(3) Steering torque values generated by the simulation are higher than were measured in full-scale tests. This is especially true of the first (left-turning) values; the right-turning values agree reasonably well. This anomaly is believed to be due, at least in part, to a non-representative value for pneumatic trail used in the simulation's tire performance model.

Additional refinement of the simulation model should be considered in the following areas:

- incorporation of active ride lean control*
- re-examination of the high frequency content of the applied steering torque
- evaluation of preview time effects on lane change performance
- changes in plotted output format (i.e., inclusion of yaw rate or lateral acceleration)
- addition of a plotting routine to plot the theoretical and actual paths directly.

---

*In an independent study performed after the work reported here was completed, this capability was successfully demonstrated in a path-following cornering maneuver.

3.0 FULL-SCALE TESTS

The experimental phase of effort on the program consisted of two parts --

(1) stability and control evaluations in a series of steady-state directional response tests; and

(2) lane changing tests using the geometry of the earlier program with three riders of varying experience.

The main emphasis in the experimental phase was placed on measuring steering torque sensitivities in the directional control tests and on detecting differences in riding technique in the maneuvering task.

The Honda 360 motorcycle used in the earlier studies was again utilized in this program. The basic instrumentation equipment remained the same -- analog measurement of six primary control input and motion variable output telemetered to a ground station from the test unit and recorded on a six-channel strip chart recorder. A new yaw rate gyro was installed and the steering torque transducer was removed to repair a connection link and re-installed after recalibration. Some difficulties were encountered with noise and synchronization in the data-transmission link but these were solved prior to data-taking. The recording speedometer developed slippage at elevated speeds midway in the program and was discarded. All other equipment performed satisfactorily throughout the test program. The need for precision and accuracy in the data channels for steer angle, steer torque, and rider lean angle is emphasized because of the very small values of these variables measured in experiments of this type.

3.1 Lateral-directional Control Tests

To improve understanding of the steady state force control directional stability of the motorcycle, a series of tests aimed at isolating the effects of operating factors on cornering requirements was performed. This series consisted of the following three parts:

(1) Constant speed runs. These runs were made to obtain comparisons with similar runs from the earlier program with a different rider. They provided information on the value of the lateral acceleration sensitivity at constant wheel angular momentum.

(2) Constant radius runs. This is the method which was used by JAMA in its Experimental Safety Motorcycle (ESM) study (Reference 2). This method provides low speed - low lateral acceleration data where the steering system geometrical design effects on torque requirements are most significant. It is an effective method for determining the speed region at which torque crossover occurs.

(3) Constant acceleration runs. This method was employed in order to evaluate speed effects on control torque requirements with minimal contamination from lateral acceleration-sensitive terms. That is, the moments due to front assembly mass offset and to gyroscopic effects are held nominally constant for all test points.

Results of the constant speed runs (at nominally 40 MPH) showed reasonable agreement with the results for similar conditions reported in Reference 1 within the limits imposed by data scatter and rider lean angle contaminations. Similar problems were encountered in the constant acceleration series (performed at approximately .25 g) but the general trends in steer angle and steering torque data indicated nearly neutral steer position control and very small torque variations across the speed range.

Test results from the constant radius series of runs are shown in Figures 7 and 8. Figure 7 provides plots of several primary control and motion variables as a function of steady state lateral acceleration developed in the

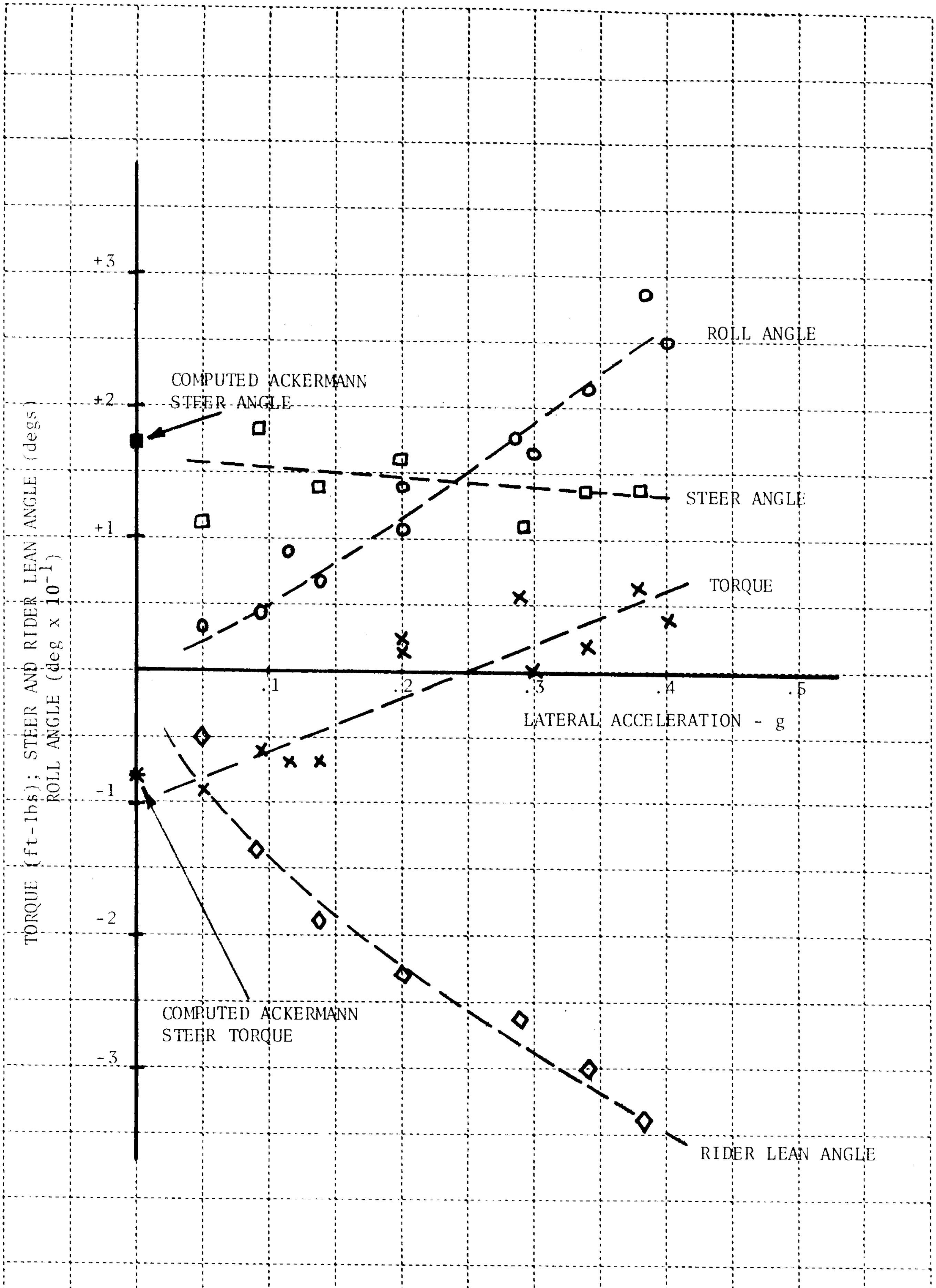


Figure 7 CONSTANT RADIUS DIRECTIONAL CONTROL TEST RESULTS - 150 FT.

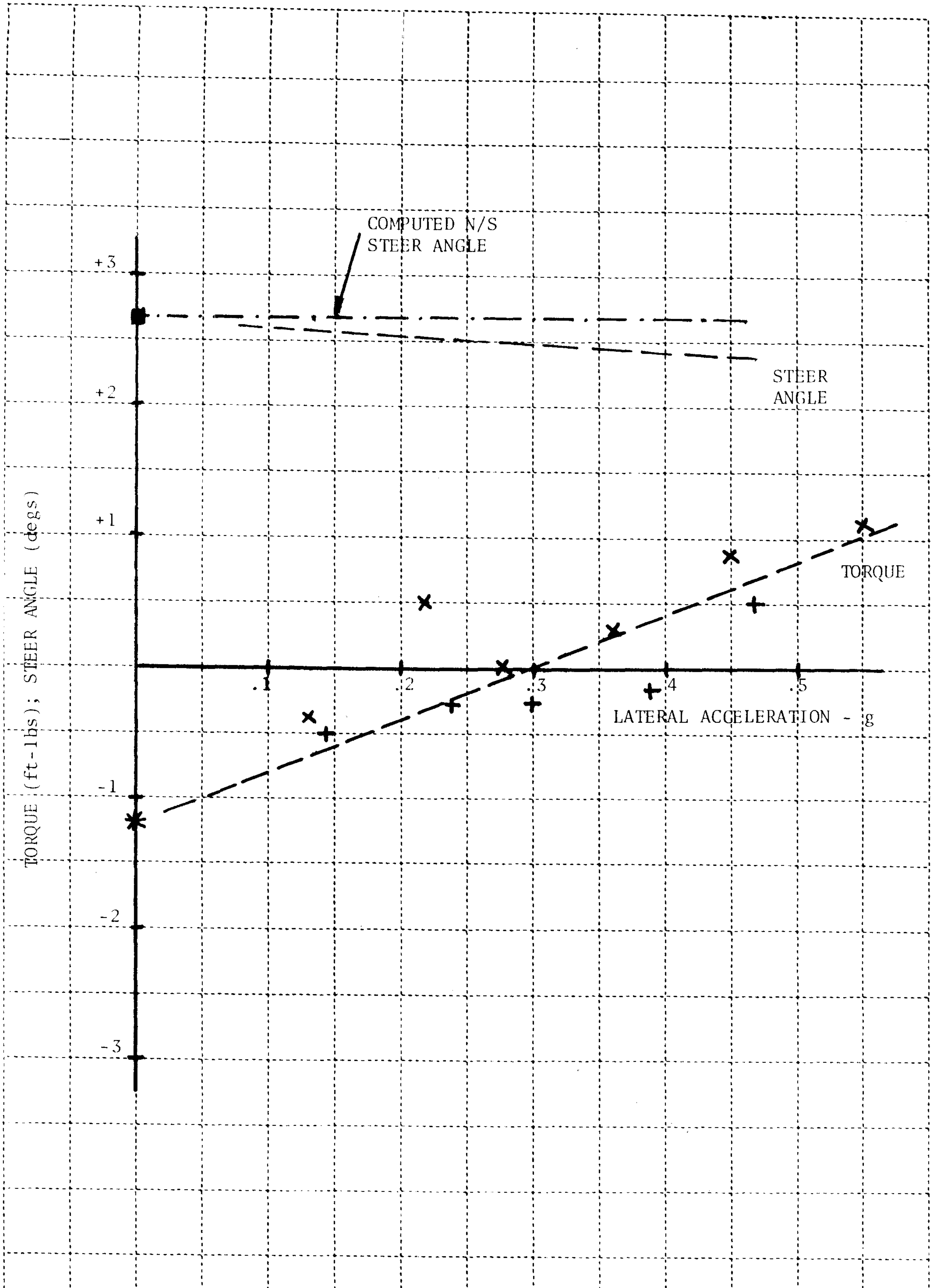


Figure 8 CONSTANT RADIUS DIRECTIONAL CONTROL TORQUE REQUIREMENTS - 100 FT

150 ft. constant radius test. Steer data only are shown at 100 ft. radius in Figure 8. For convenience, two reference curves are also shown -- one representing the theoretical steer angle for neutral steering at this condition and the other, the general trend of the measured steer angle data over the range of the test.

Figure 7 contains points showing the computed values for the effective Ackermann steer angle (i.e., the steering angle required at low speed and zero roll angle) and the associated torque requirement at this condition, referred to below as "Ackermann torque". The Ackermann steer angle is simply ℓ/R, the wheelbase divided by the path radius. The Ackermann steer torque is based on a constant coefficient model of motorcycle dynamics that was described in Reference 1. At zero speed, the steer torque equation reduces to:

$$T = \delta\ (A \sin \sigma)$$

where T is the applied torque which is required to maintain the steering angle δ at the Ackermann value. This Ackermann torque is necessary because of the moments about the steer axis (inclined at an angle of σ) created by front wheel normal force and steering assembly mass.

The term A is evaluated as:

$$A = -W_F t - W_S f$$

where W_F = total load on front wheel
t = trail distance
W_S = steering assembly weight
f = perpendicular distance from steering assembly c.g. to steer axis (mass offset).

For the Honda 360, the value of A is approximately -.46 ft.lbs./deg.

3.2 Lane Change Tests

In the earlier study reported in Reference 1, a series of lane change maneuvers was performed by one rider on the Honda 360 motorcycle at several variations of course geometry and initial speed. In this program, a single course layout as shown in Figure 9 was used and approach speed was varied at the discretion of the riders. This course geometry is similar to that of the previous study which was determined to be suitable for testing at about 40 MPH by an experienced motorcycle rider.

Some 43 runs were performed by three different riders in this maneuver. The run log for this group of tests is given in Table 2. The riding backgrounds of the three may be briefly described as:

Rider A: Moderate experience with intermediate street machines.

Rider B: Extensive experience with many different motorcycles up to 750 cc. size. Off-road experience. Rides about 4,000 miles per year.

Rider C: Novice rider (less than 2 hours on intermediate street motorcycle).

Program scope limitations did not permit in-depth analysis of all results of this experiment. Nevertheless, several observations are clearly supported by the basic data obtained in these runs. Table 2 shows initial speeds, success/failure information, and the cones struck in unsuccessful runs. The numbers of the struck cones in Table 2 correspond to the cone numbering in Figure 9. Figures 10, 11, and 12 are selected run time histories which are representative of the control inputs used by the three riders in successful attempts to perform the maneuver. These figures also show the resultant vehicle motions of roll angles and yaw rates achieved. Attention is called to the following:

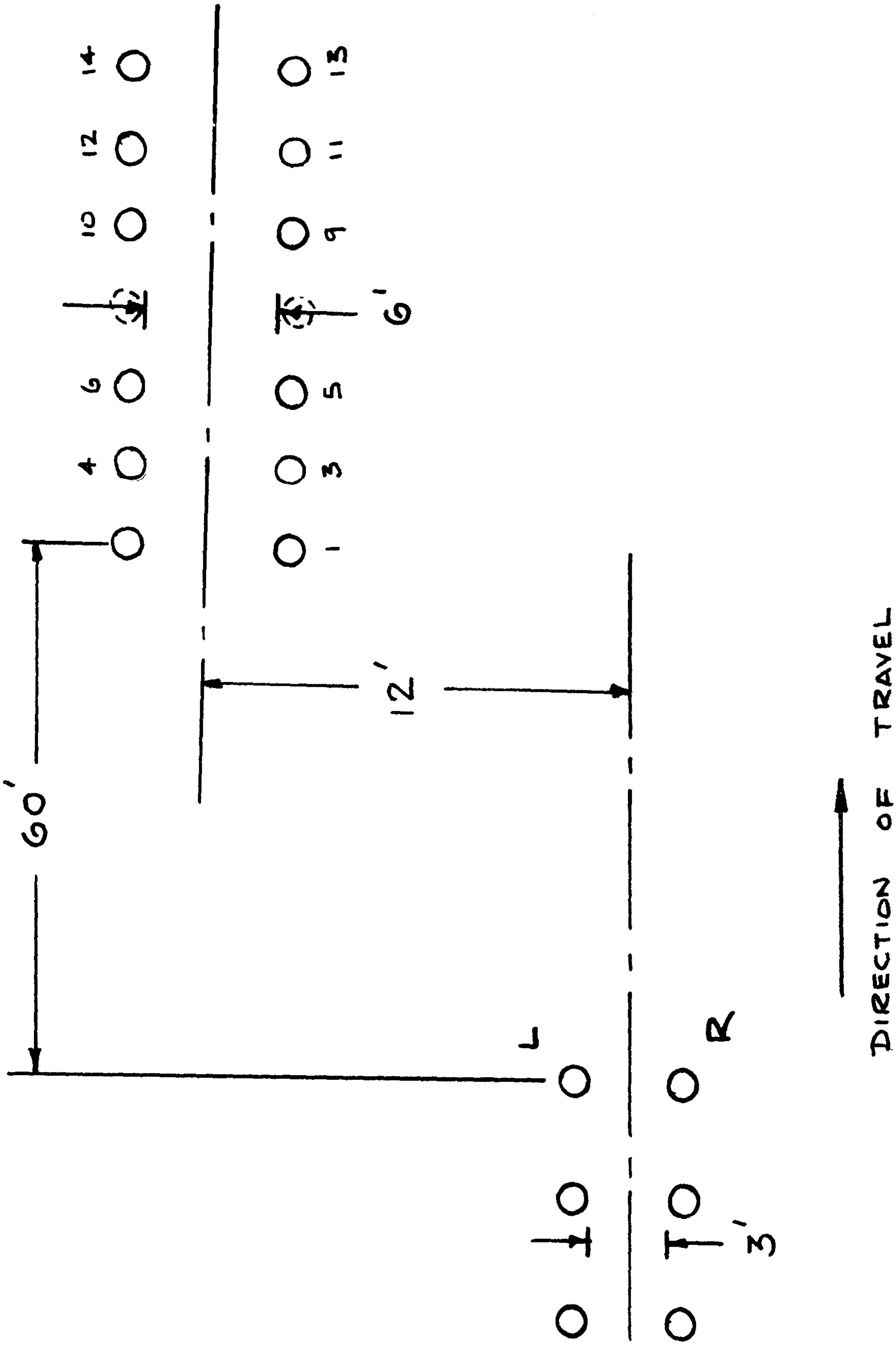


Figure 9 LANE CHANGE TEST MANEUVER GEOMETRY

TABLE 2: FULL-SCALE LANE CHANGE TESTS - RUN LOG AND PERFORMANCE RECORD

DRIVER	RUN NUMBER	APPROACH SPEED (MPH)	SUCCESS-FAILURE	STRUCK CONES	REMARKS
A	1	33	S		
	2	34	S		Figure 10
	3	35	F	1	
	4	35	S		
	5	36	F	L	
	6	35	F	L,1,3,14	
	7	36	S		
	8	36	F	1	
	9	38	S		
	10	38	S		
	11	39	F	L,1,14	
	12	39	F	1	Figure 14
	13	39	S		Figure 13
	14	40	S		Best successful run
	15	40	F	L	
	16	40	F	L,1,12,14	
B	1	23	S		Familiarization run
	2	30	S		
	3	34	S		Figure 11
	4	35	S		
	5	38	F	L	
	6	40	F	1	
	7	40	F	1	
	8	43	S		Best successful run
	9	43	F	1	
	10	43	F	14	Barely tipped cone
C	1	25	S		
	2	29	F	1,12,14	
	3	28	F	14	
	4	29	S		
	5	30	F	1,12,14	
	6	30	F	--	ABORTED
	7	30	S		
	8	30	F	--	ABORTED
	9	29	S		
	10	30	F	1,10,12,14	
	11	29	S		
	12	31	F	1,12,14	
	13	30	S		Figure 12
	14	32	F	1,12,14	
	15	33	F	--	ABORTED
	16	30	S		Best Successful run (See # 13 also)
	17	32	F	14	

Figure 10 LANE CHANGE MANEUVER AT 34 MPH - RIDER A

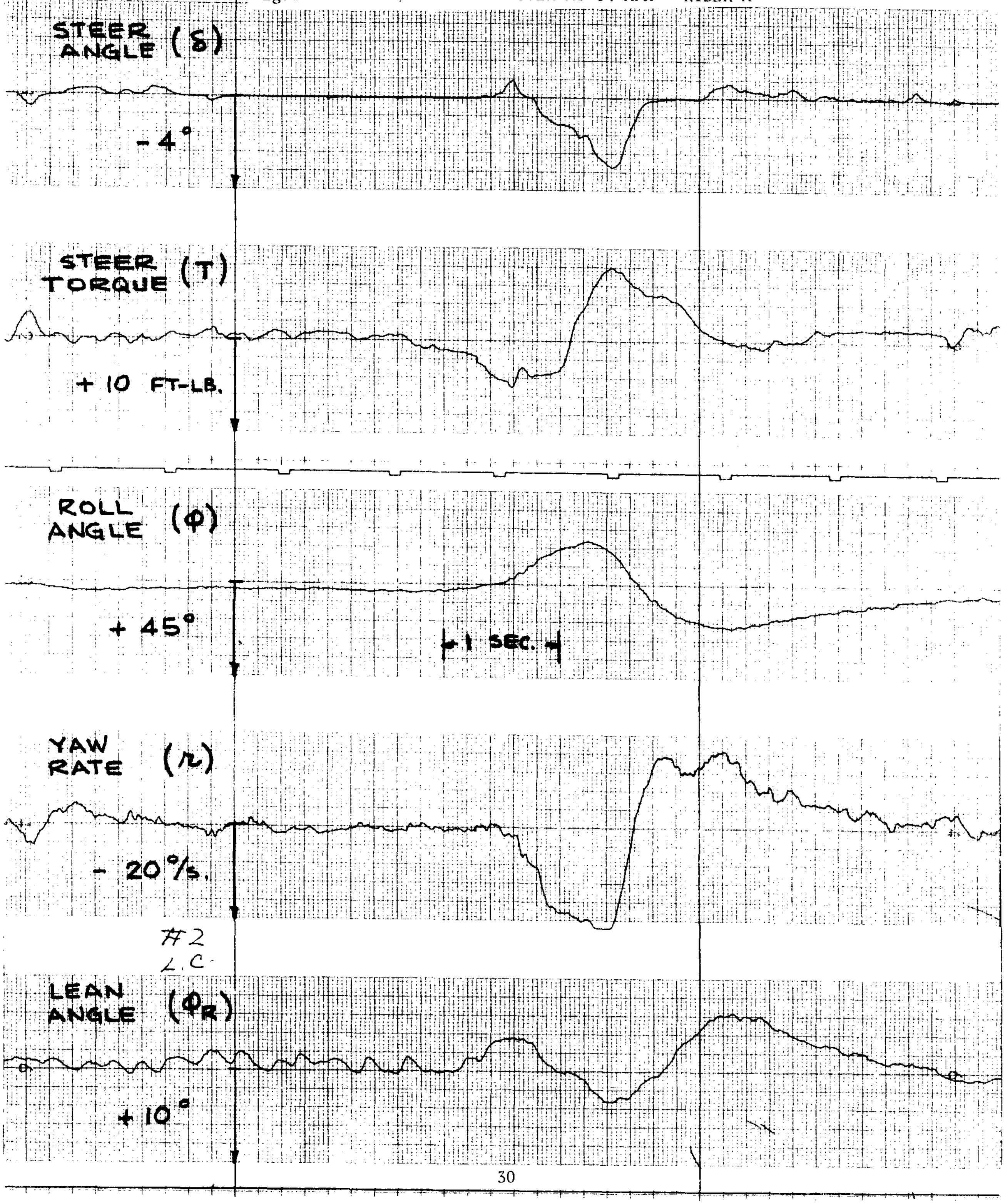


Figure 11 LANE CHANGE MANEUVER AT 34 MPH - RIDER B

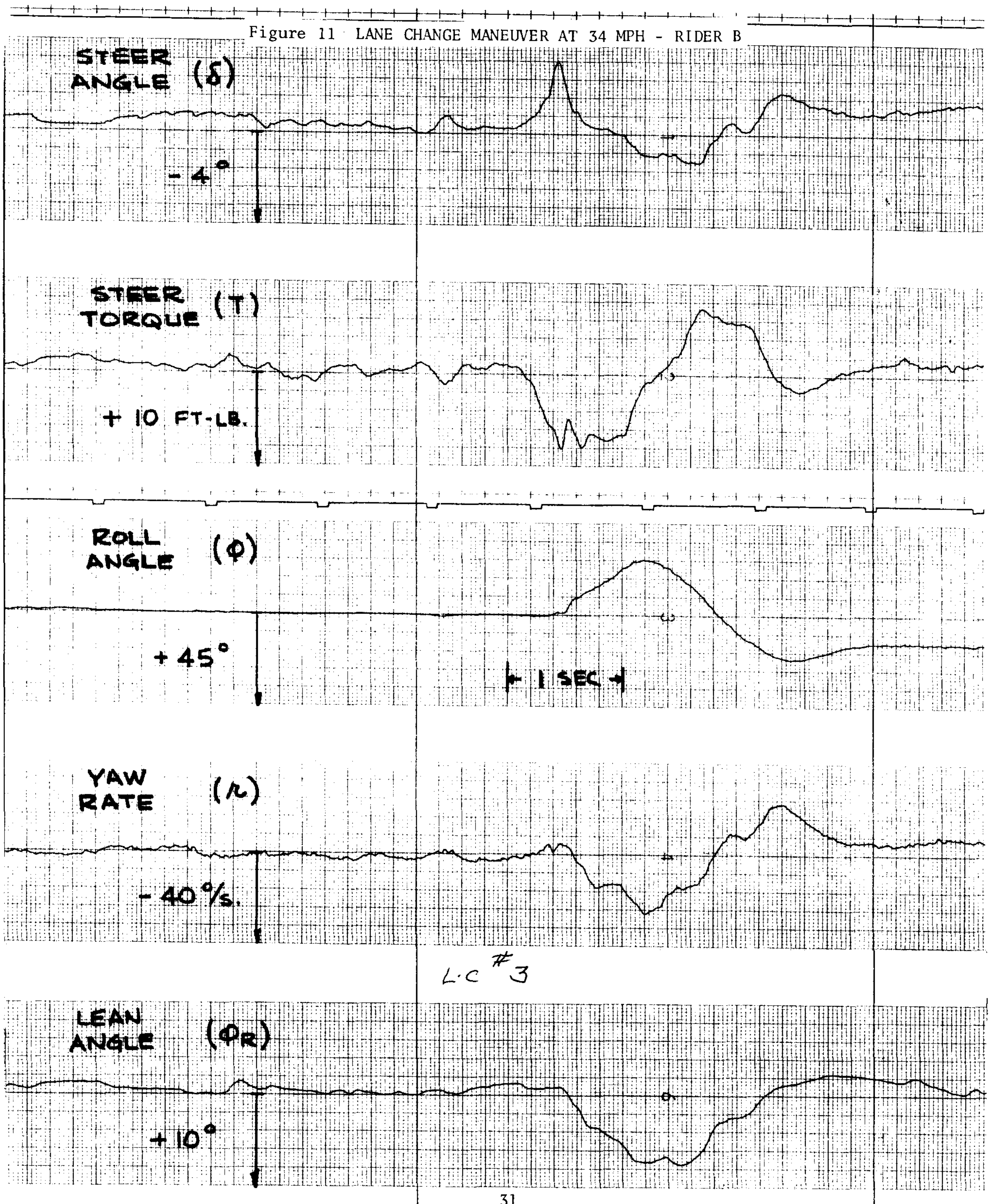
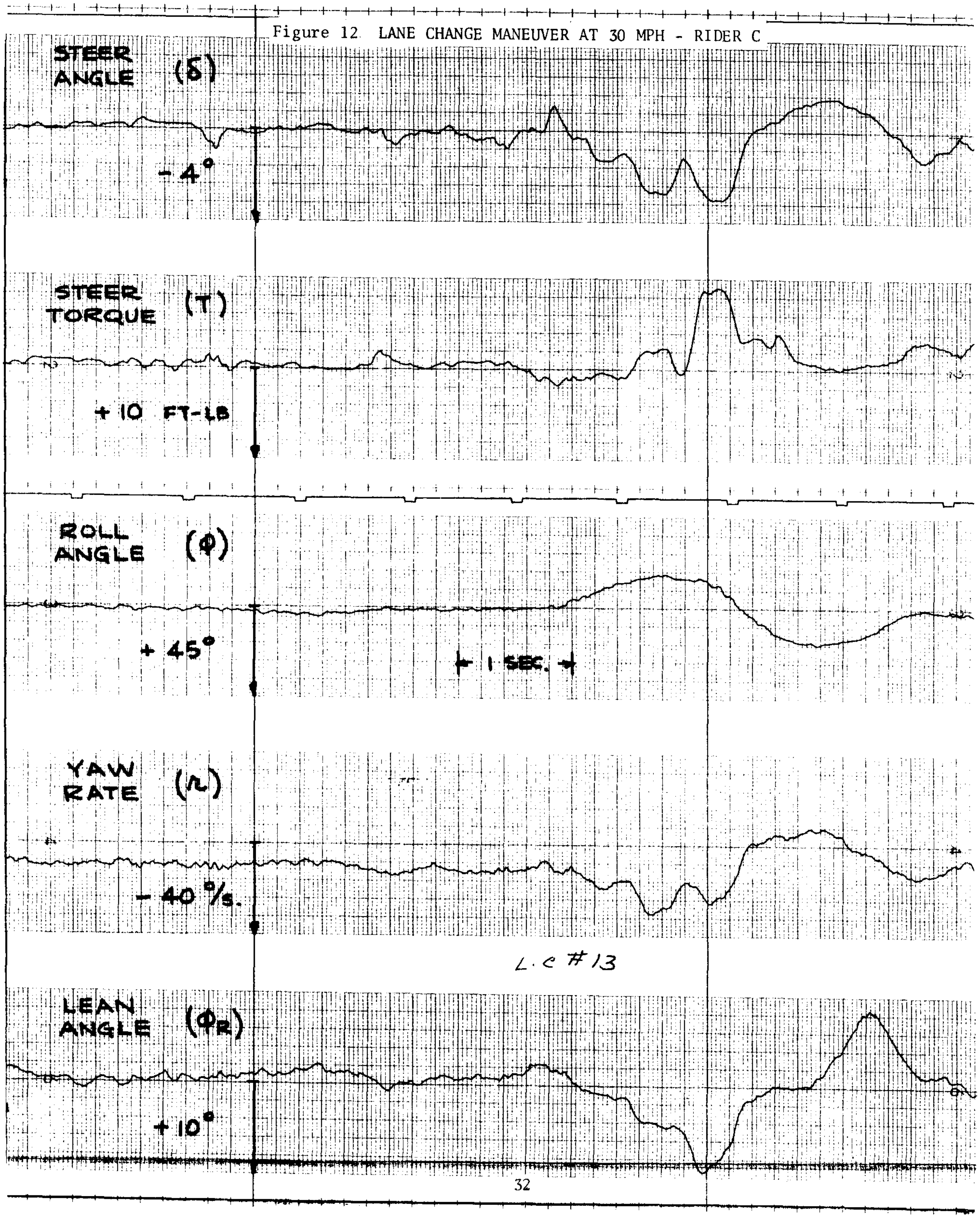


Figure 12 LANE CHANGE MANEUVER AT 30 MPH - RIDER C



(1) All riders clearly attempted to "straighten the path" by initiating the maneuver while still in the entrance lane (note the violation of the cone identified as L on the course geometry figure) and by narrowly missing the right hand cones of the exit lanes (cones 1 and 3 in the figure). This path straightening trend in full-scale is similar to the path straightening which occurs in the simulation runs (see Section 2.2).

(2) All of these riders initiated the maneuver with steering torque input.* However, the most experienced rider (B) employed lean control only in the latter part of the maneuver by leaning out of the initial turn whereas the rider with moderate experience (A) first leaned with the machine before leaning out of the turn. The lean motions of the novice rider (C) appears to be more reactive than deliberate control.

(3) The novice rider employed many more steering torque reversals than did the more experienced riders. In one run (not shown), the frequency of this oscillatory input was about 3 Hz., which is generally acknowledged to be outside the sensible bandwidth of human controllers.

(4) In these runs, at speeds in the range of 35 - 40 MPH, the total time in the maneuver was approximately 4 seconds. This translates into a maneuvering distance of 230 feet, compared with the actual longitudinal gate distance of 60 feet. This pattern repeats that from the earlier full-scale tests and from the simulation (See Figure 2 for example). The riders are still cornering at reasonable levels ($\sim$.3 g.) at the start of the exit lane.

*In the earlier study, Reference 1, the rider first leaned into the turn to start the motorcycle rolling in the desired direction.

(5) The most experienced rider was able to perform the maneuver successfully at an initial speed of 43 MPH (although it will be noted that he also had some runs at lower speeds which were not successful). In this run, he employed more body lean control than he used in the lower speed runs, apparently to get the vehicle rolling in the proper direction more quickly than he could with steering torque control only.

(6) The phasing between the control inputs and motion outputs is of interest. Note, in Figure 10 for example, that ϕ, r, and δ are approximately in-phase*. T and ϕ_R are almost completely out of phase and T leads the motion variables by up to 90 degrees.

(7) It was difficult to choose a "typical" run for the novice rider. Although Runs C11, C13, and C16 were all successful attempts at about 30 MPH, the control patterns differed markedly among them. One of the interesting features of these runs, however (as shown in Figure 12), is the phasing between applied steer torque and rider lean angle -- each torque application is accompanied by an opposing lean motion. This phasing apparently brings the steering deflection more closely in phase with steer torque than is indicated in the data traces of the more experienced riders.

(8) Failures to perform the maneuver are not directly identifiable from the data traces. That is, unsuccessful runs are not marked by readily discernable variations in control input patterns (See Figures 13 and 14). In general, incorrect timing of the chosen action is seen as the principal cause of failure in this maneuver (none of which resulted in loss of control). Thus, it is hypothesized that the experienced riders applied some type of preprogrammed control pattern with which they were either

* The senses of the individual traces are indicated by the signs at the left side.

Figure 13 SUCCESSFUL LANE CHANGE AT 39 MPH - RIDER A

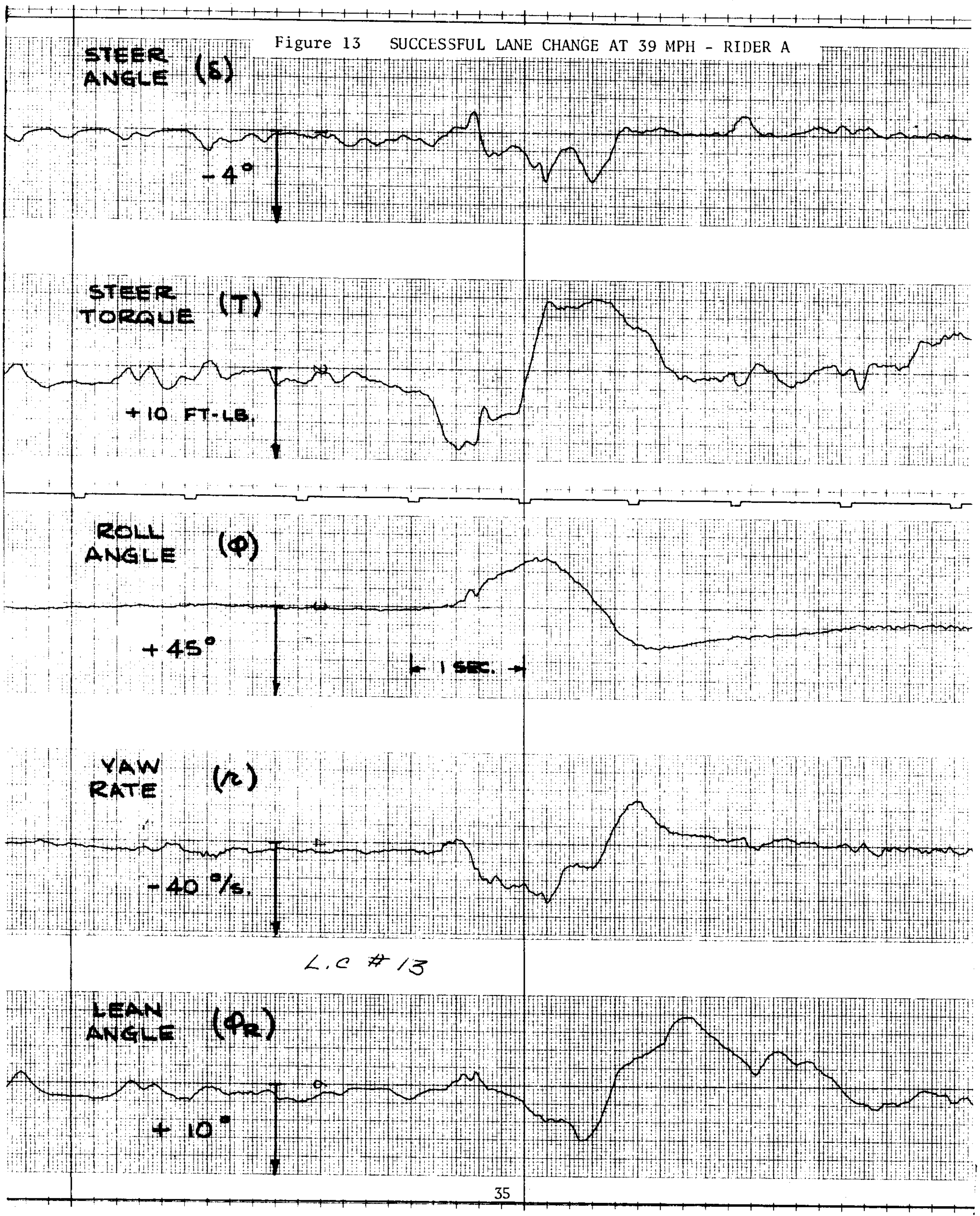
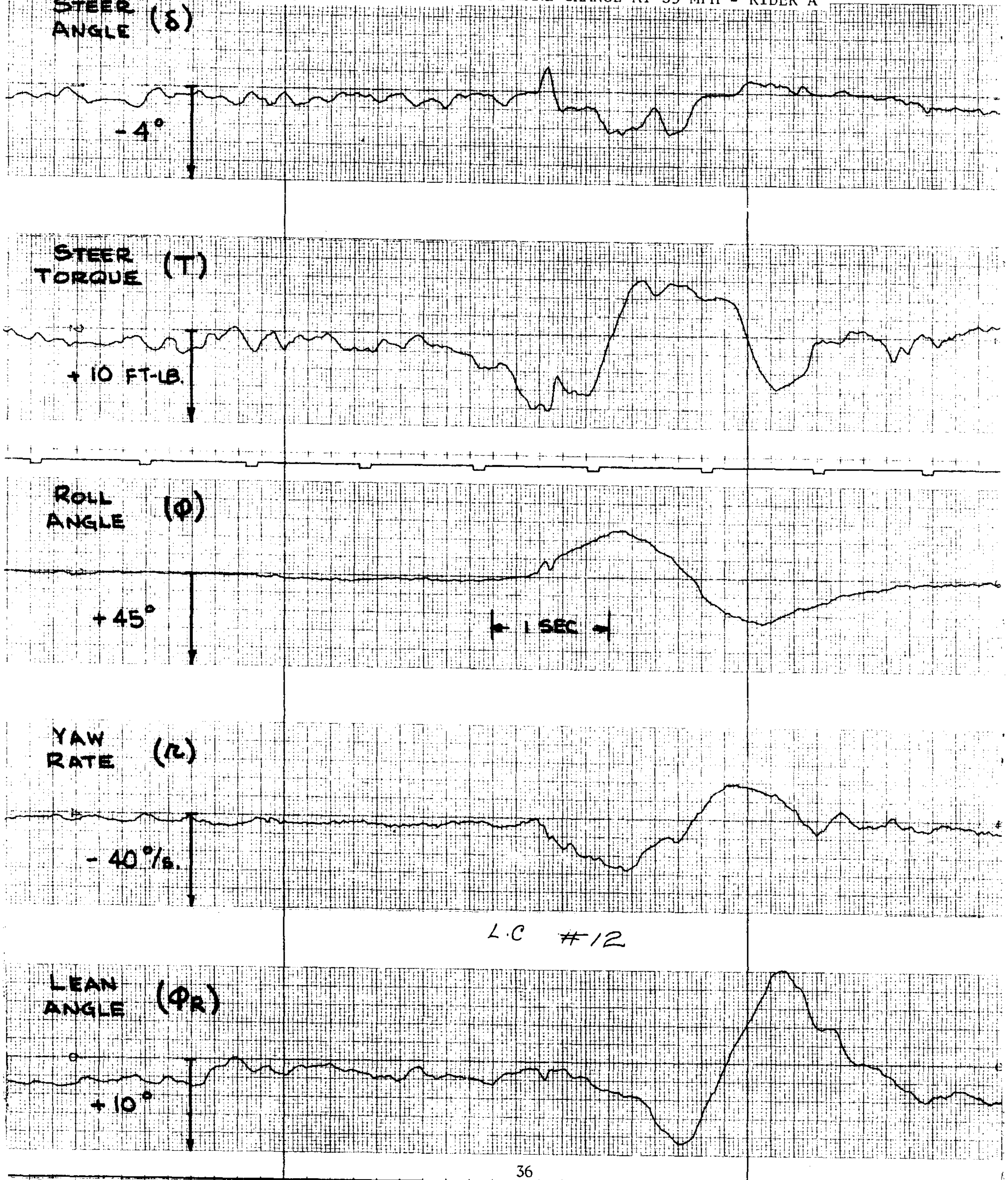


Figure 14 UNSUCCESSFUL LANE CHANGE AT 39 MPH - RIDER A



successful or not but which (because of the nature of the task) was not substantially varied after initiation of the maneuver.

3.3 Summary of Full-Scale Tests

In brief, the full-scale test phase of this study produced results which not only re-emphasized the need for great care in all aspects of instrumentation and performance measurement for motorcycles, but which also provided new insights into how different riders exercise control in a transient maneuvering task and how test speed affects the response parameters in directional control tests. Specific results were treated in the previous sub-sections but program limitations precluded in-depth analysis of many features of the experimental data. All results are on file at Calspan and can be made available to NHTSA if desired. Several points regarding the test data should be emphasized.

(1) Results from the directional control response tests and the transient maneuver clearly demonstrate the interaction of the control methods available to the rider (steer torque and lean angle) and point up a need for a well-ordered test program specifically directed to separation of their effects. In this limited study, observations suggest that the more experienced rider utilizes lean control more effectively than the novice.

(2) The constant radius directional response test method indicated a steady state steering torque control gain parameter ($^{a}y/_{T}$) value of about 4 ft-lbs/g for the Honda 360 motorcycle over a speed range of 0 - 30 MPH. This value compares favorably with values from the earlier study (based on the constant speed test method) of 30 in-lb/g (2.5 ft-lb/g) at 20 MPH and 75 in-lb/g (6.25 ft-lb/g) at 40 MPH (page 86 of Reference 1).

(3) The condition for steer torque inversion (i.e., the condition for which the rider applied steering torque is zero) is a function of lateral acceleration but these tests on the Honda 360 indicate that it occurs in the steady state at approximately 25 MPH for lateral accelerations in the 0.2 - 0.3 g range.

(4) The variations in rider control technique as measured in these tests (and the resultant differences in ability to perform the lane change successfully) identify some of the problems in defining a rider model for simulation evaluation purposes. On the other hand, the similarities between the full-scale test and simulation results in terms of path (the same cones come into play in unsuccessful runs), steer angles used, and average yaw rates achieved suggest good fidelity in the model.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this brief study demonstrate an improvement in the motorcycle dynamics simulation that verifies its applicability to the steering torque-controlled transient maneuver (such as the lane change) and give an indication of the range of variability in rider behavior in the performance of such maneuvers as measured in full-scale tests. Although it was not possible to analyze all results in great depth, this extension to the earlier work on motorcycle handling as reported in Reference 1, has provided additional insight into methods for evaluating performance characteristics of motorcycles. In particular, the following conclusions (which are based on the results discussed in the previous section) are pertinent.

(1) The Calspan motorcycle dynamics simulation (including the rider model) can be used in studies of transient handling situations to give quantitative information on differences in applied control and motion output for different machines.

(2) Current values for the rider model control coefficients define a rider skill level and produce simulated performance results which are consistent in most respects with full-scale test results achieved by experienced riders.

(3) The rider model is a highly adaptable representation that offers a means for studying rider behavior in a variety of situations to identify essential driving cues for successful stabilization and control.

(4) Rider variability can be measured in full-scale task performance maneuvers to identify differences in riding technique which affect total system response.

There are still a great many aspects of motorcycle stability and control to be explored before a thorough understanding of safe handling requirements can be achieved. It is not appropriate to outline an overall plan based on the results of this limited study but it is recommended that the following efforts be considered --

(1) Extend the analysis and evaluation of the lane-change test results. This would involve comparison of rider control strategies, analyses of the sequence of actions in the maneuver, and path computations.

(2) Perform additional simulation runs of the lane-change maneuver incorporating active rider lean control. Extend the study to include a cornering maneuver with active lean control.

(3) Perform full-scale experiments in selected maneuvers with sufficient replications to obtain statistical measures of repeatability and variability of results.

(4) Improvements in the simulation and in testing techniques are needed in the following areas:

- Better data resolution in measurements of applied steering torque and rider lean angle.
- Addition of path information to testing operations. Direct plotting of path information with the simulation.
- Incorporation of active rider lean control in simulation studies. This capability exists at present, but suitable control coefficients must be determined.

5.0 REFERENCES

1. Rice, R. S., Davis, J. A., Kunkel, D. T., Accident Avoidance Capabilities of Motorcycles. Calspan Report No. ZN-5571-V (two volumes). July 1975.

2. Taguchi, M., A Preliminary Test Report on the Controllability and Stability of Experimental Safety Motorcycle. December 1975.

APPENDIX A

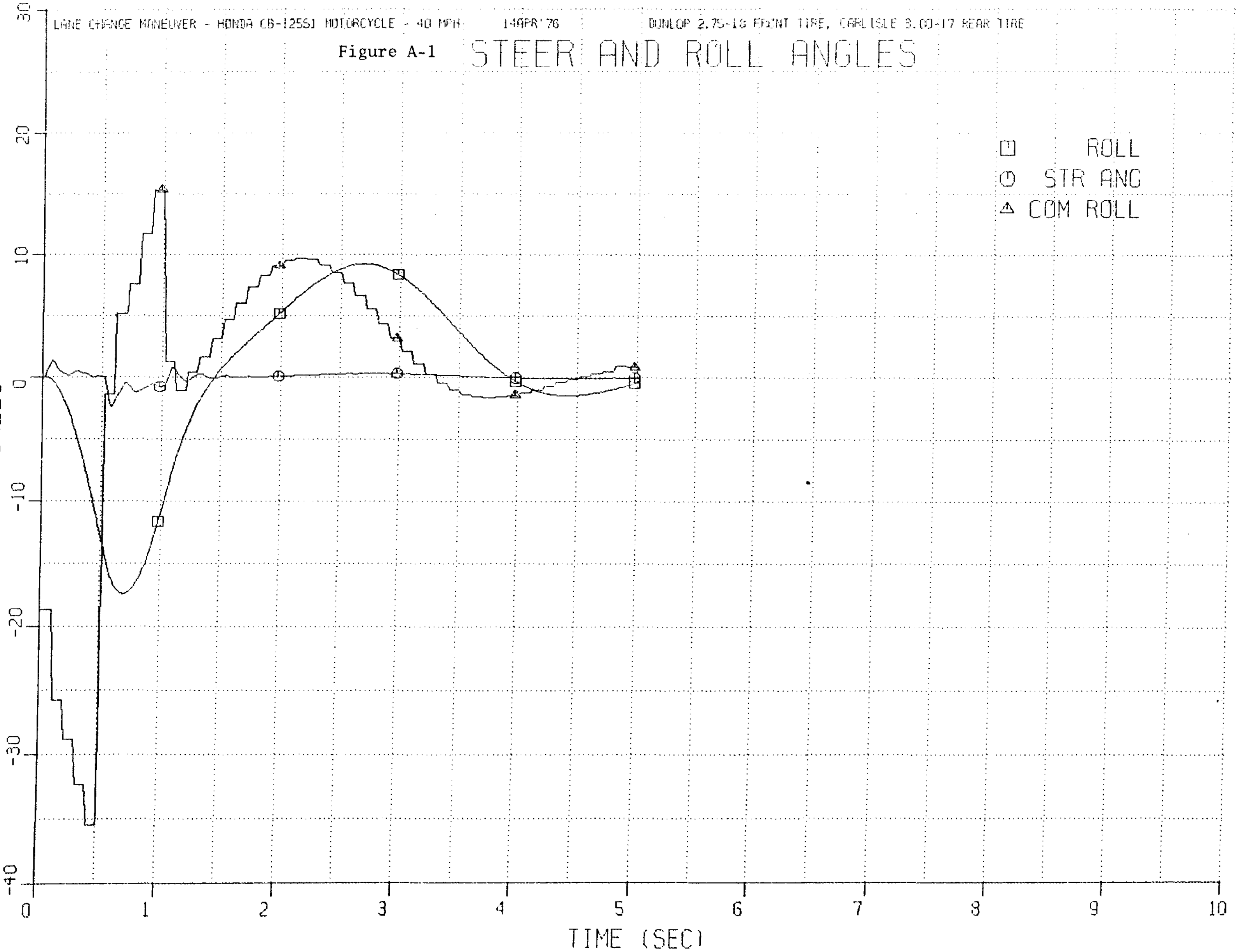
SIMULATION RUNS

This appendix contains copies of the plotted outputs for all simulation runs performed during this study including those which are in Section 2.0. Figures A-1 through A-6 show the results of the lane-change maneuver for each of the motorcycles at 40 MPH, utilizing the same rider model control coefficients for all machines. Figures A-7 and A-8 show the lane-change maneuver for the Honda 360 at 30 and 50 MPH. Figure A-9 shows the results of a 0.8 sec. preview time on the Honda 360 response at 50 MPH as compared with 1.0 sec. in Figure A-8. Figures A-10 through A-12 show the results of a series of runs for the Honda 360 in which the rider coefficients and operating conditions were varied from those used for Figure A-6, to evaluate their effects on performance. Table A-1 identifies the conditions for each figure. In all cases, the maneuvering geometry was a right-to-left single lane-change for 12 ft. lateral displacement within a longitudinal distance of 60 ft.

TABLE A-1 SIMULATION STUDY RUN CONFIGURATIONS AND FIGURE NUMBERS

FIGURE NO.	CONFIGURATION	SPEED (MPH)
A-1	HONDA CB-125S1 MOTORCYCLE	40
A-2	HARLEY-DAVIDSON FLH-1200 MOTORCYCLE	40
A-3	KAWASAKI F-11 250 MOTORCYCLE	40
A-4	YAMAHA XS-2 650 MOTORCYCLE	40
A-5	NORTON 850 COMMANDO MOTORCYCLE	40
A-6	HONDA CB-360G MOTORCYCLE	40
A-7	HONDA CB-360G MOTORCYCLE	30
A-8	HONDA CB-360G MOTORCYCLE	50
A-9	HONDA 360 - 0.8 SECOND PATH PREVIEW TIME	50
A-10	HONDA 360 - PATH ERROR COEFFICIENT INCREASED BY 50%	40
A-11	HONDA 360 - PATH & HDG ANGLE ERROR COEFFS INCREASED BY 50%	40
A-12	HONDA 360 - ROLL ACCELERATION-STEER MOMENT COEFFICIENT = 0	40

Figure A-1 STEER AND ROLL ANGLES



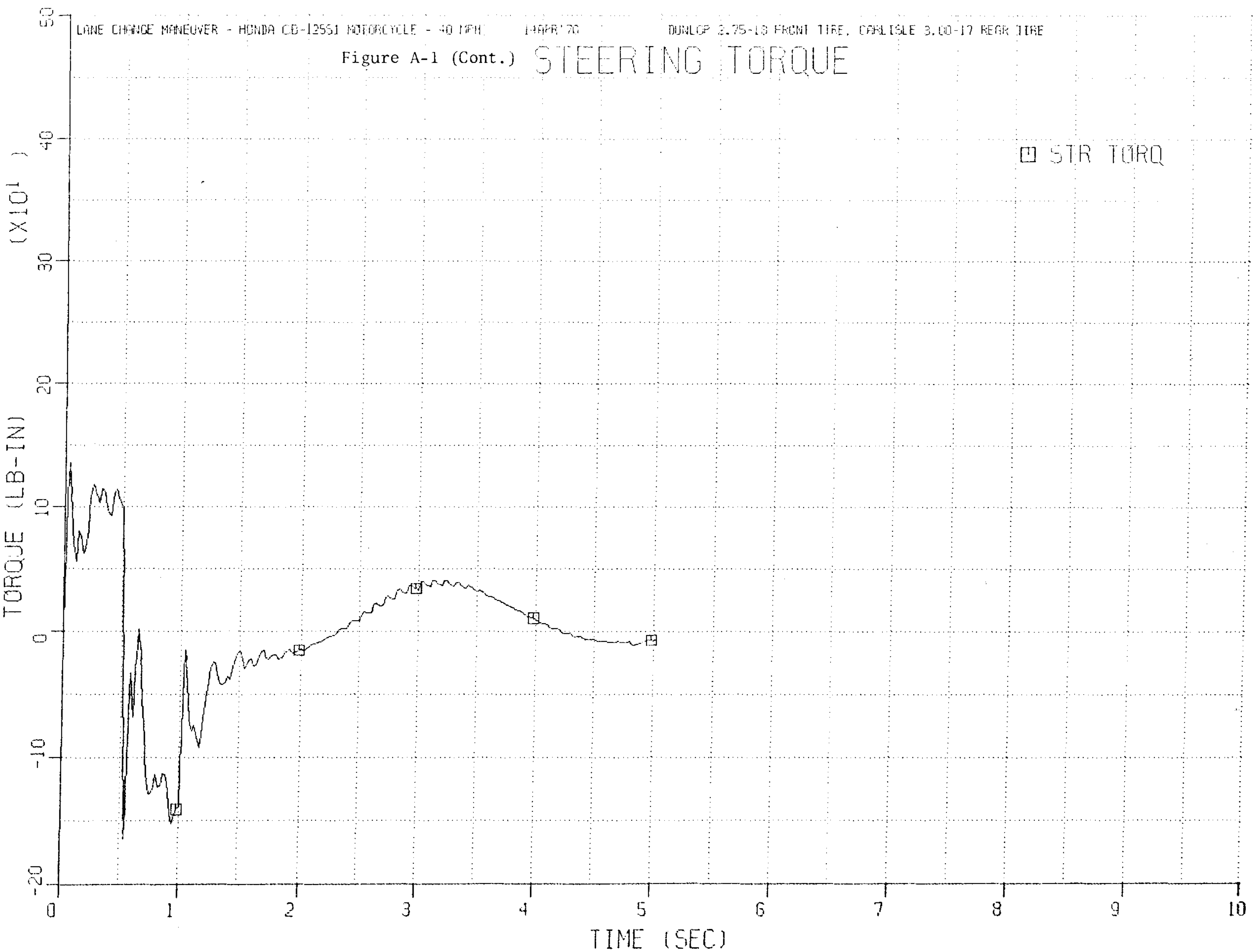


Figure A-1 (Cont.)

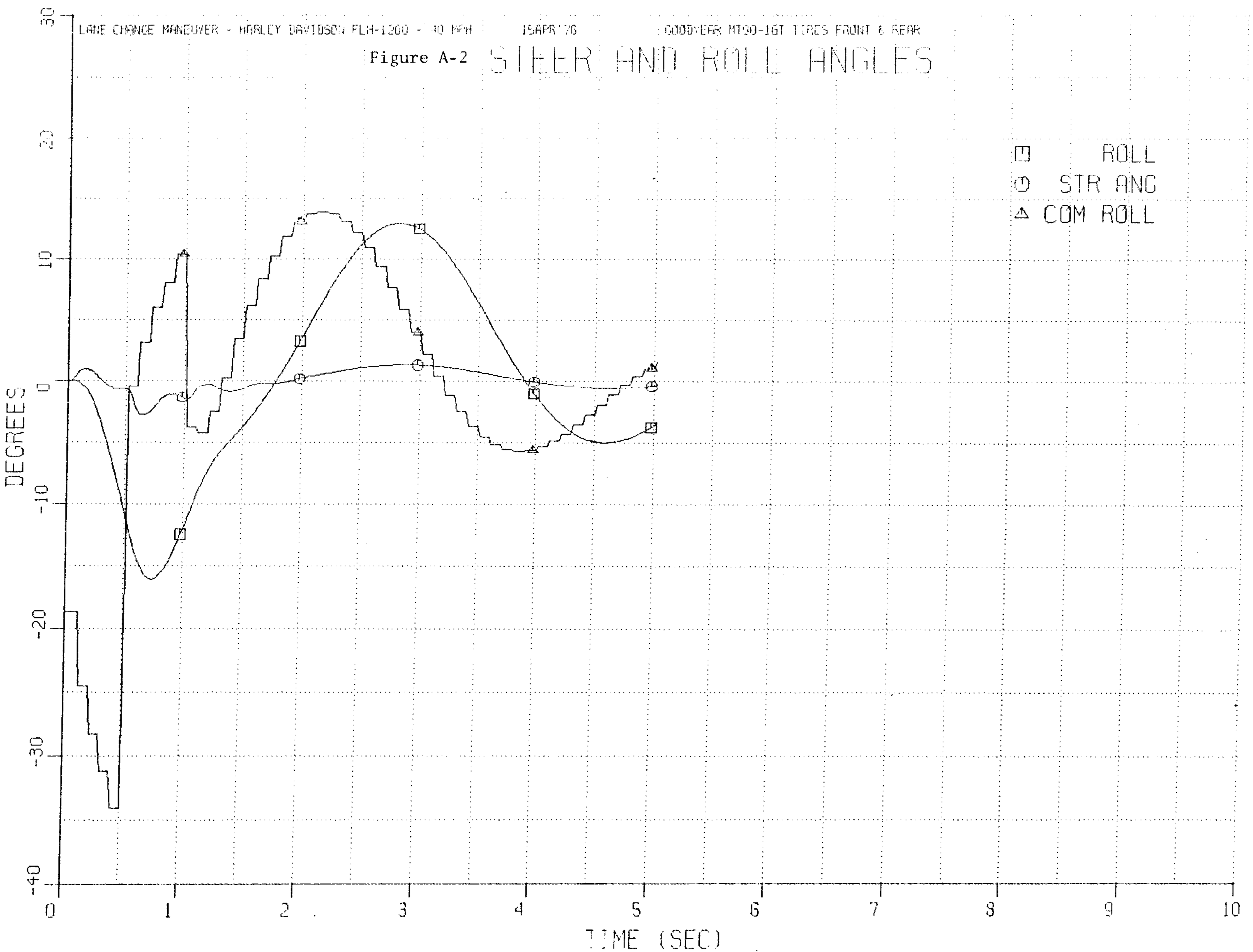

LANE CHANGE MANEUVER - HARLEY DAVIDSON FLH-1200 - 40 MPH
15APR'76
GOODYEAR MT90-16T TIRES FRONT & REAR
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10
TIME (SEC)

Figure A-2

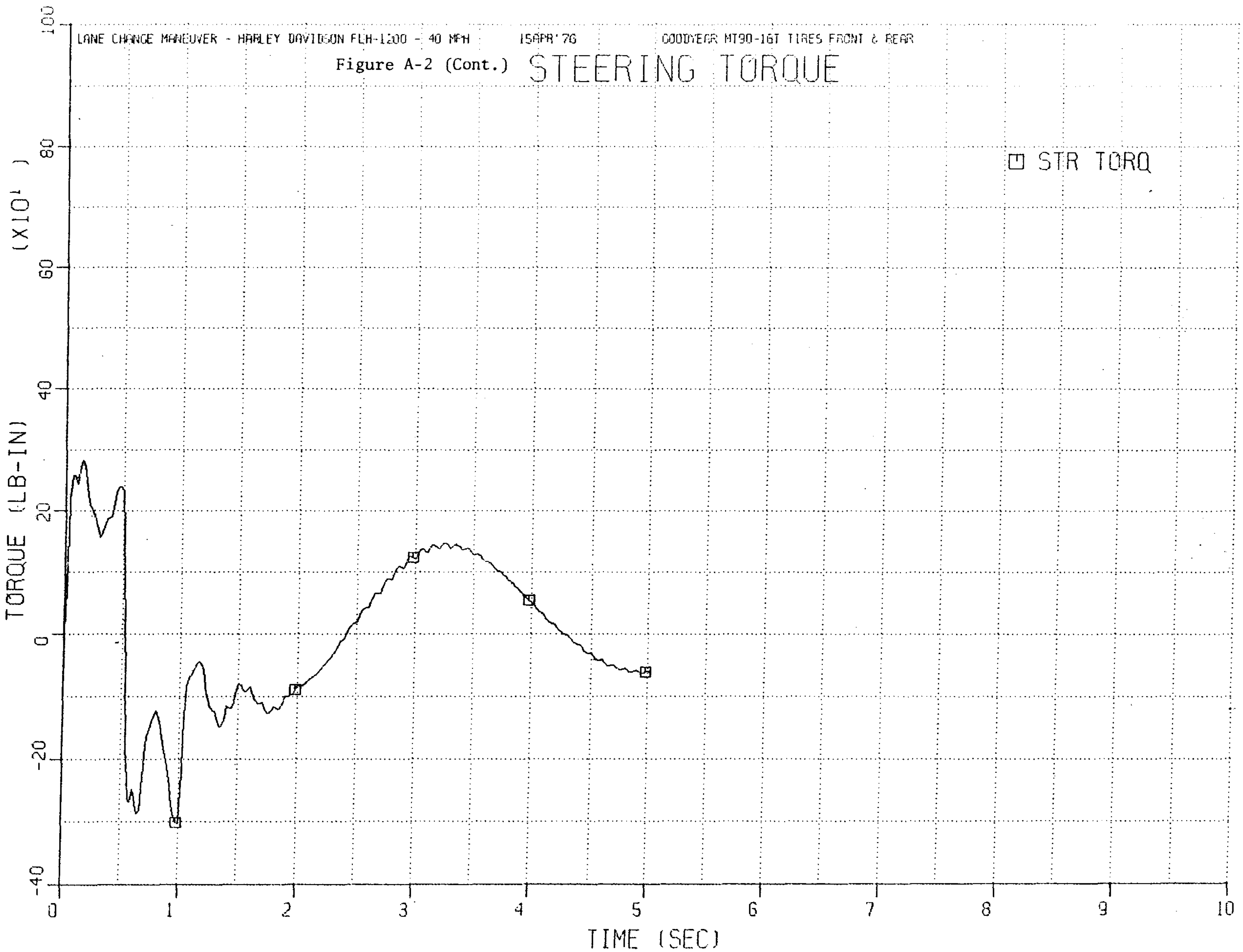
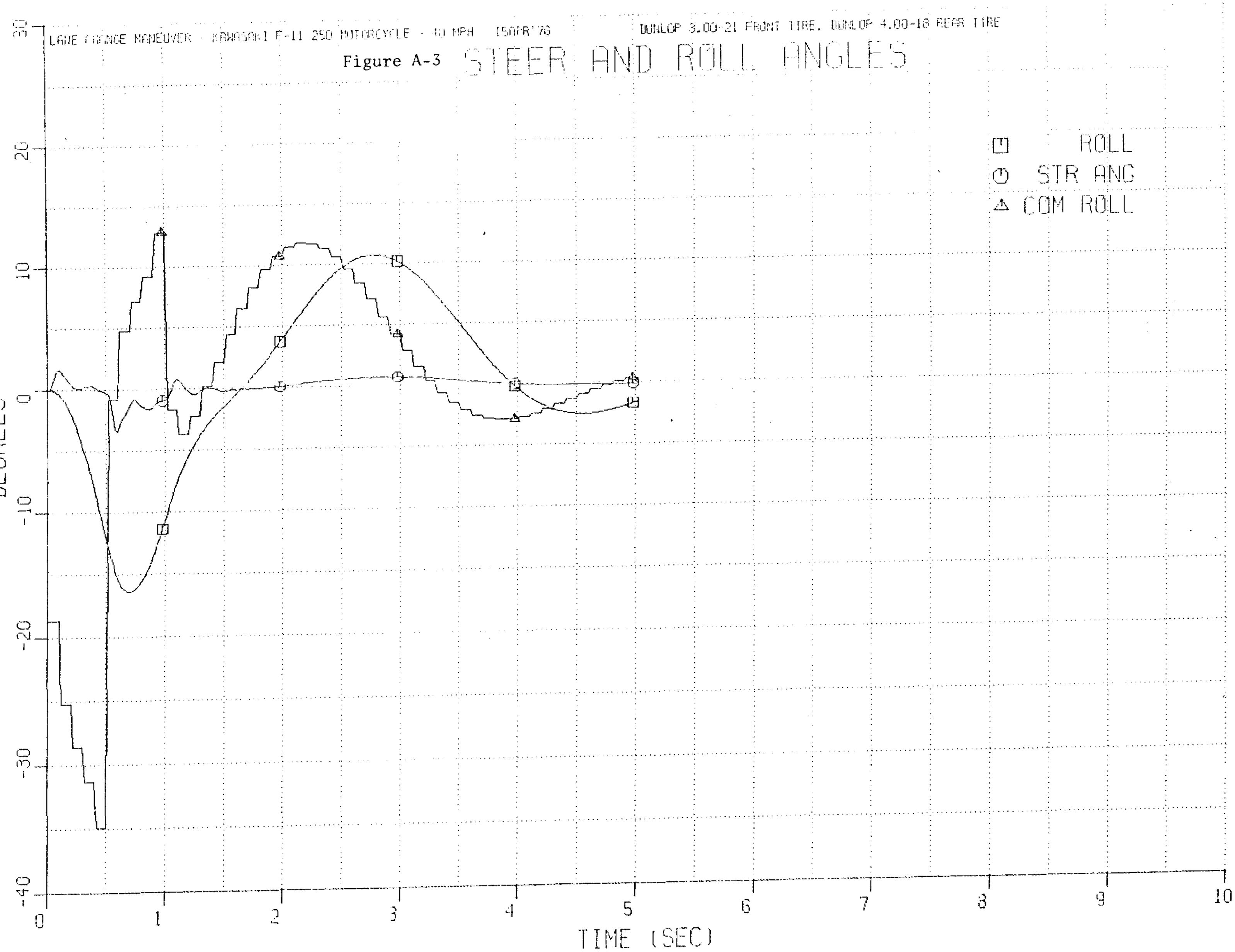


Figure A-2 (Cont.)

Figure A-3


STEER AND ROLL ANGLES
DUNLOP 3.00-21 FRONT TIRE, DUNLOP 4.00-18 REAR TIRE
ROLL
STR ANG
COM ROLL
DEGREES
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10
TIME (SEC)

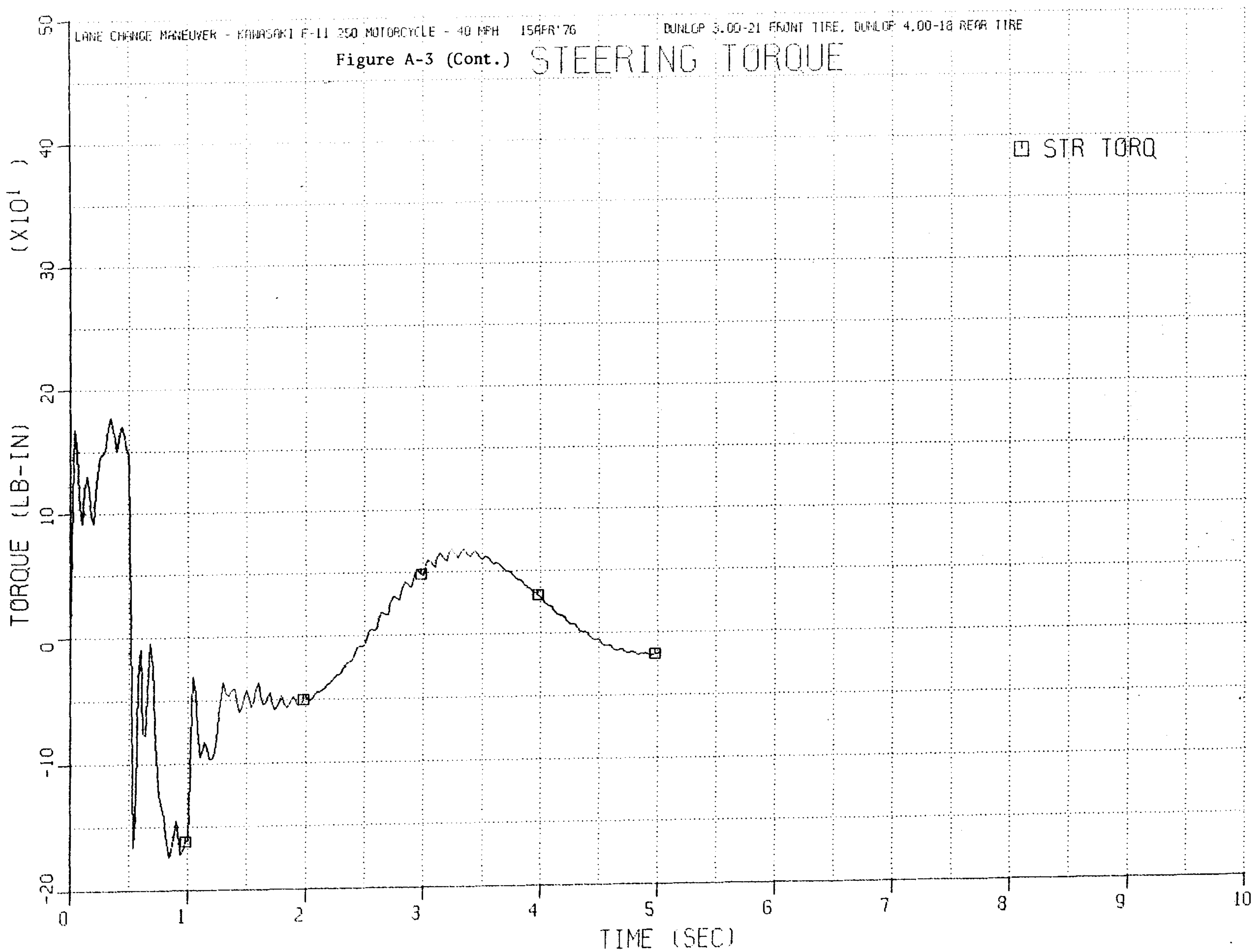


Figure A-3 (Cont.)

Figure A-4

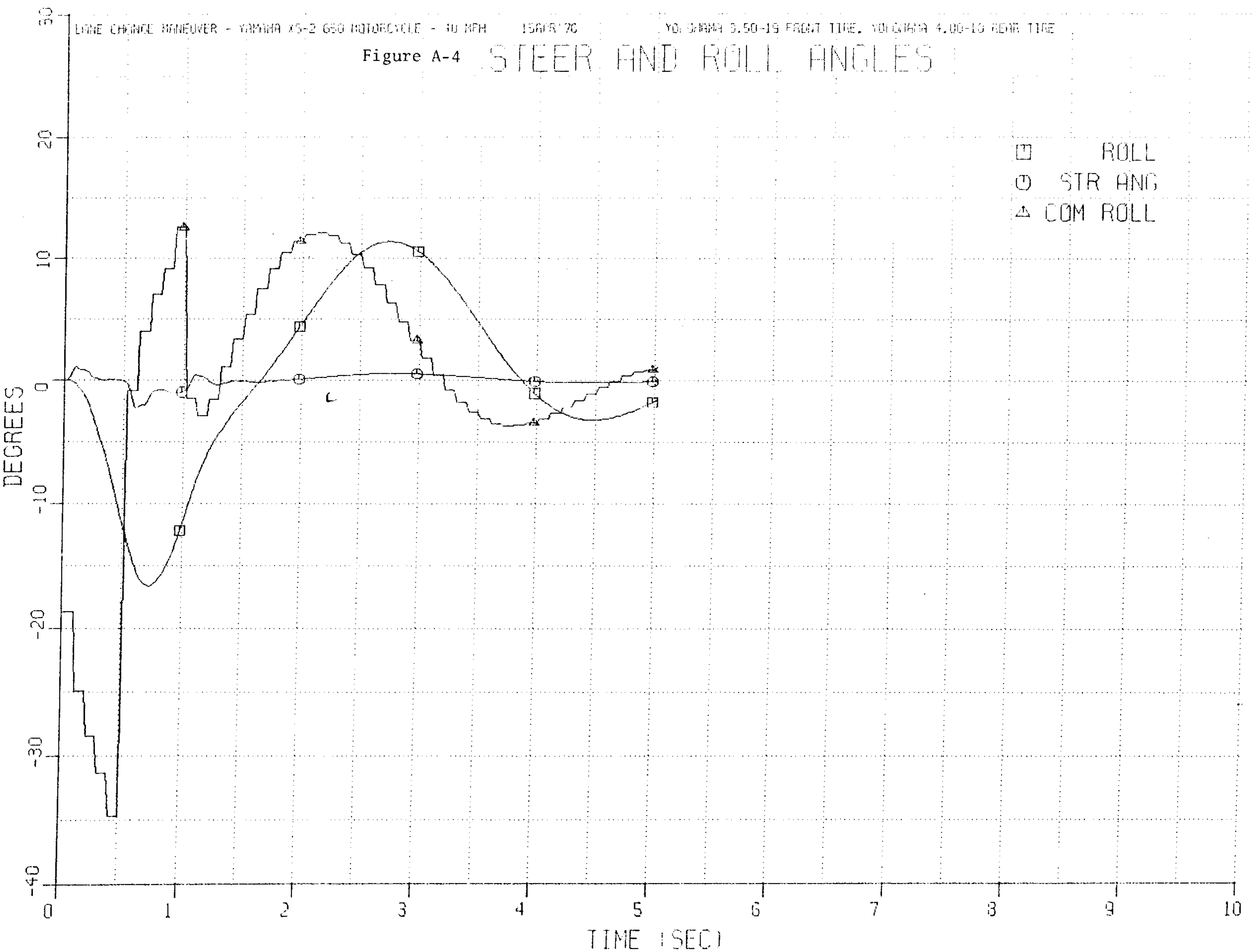
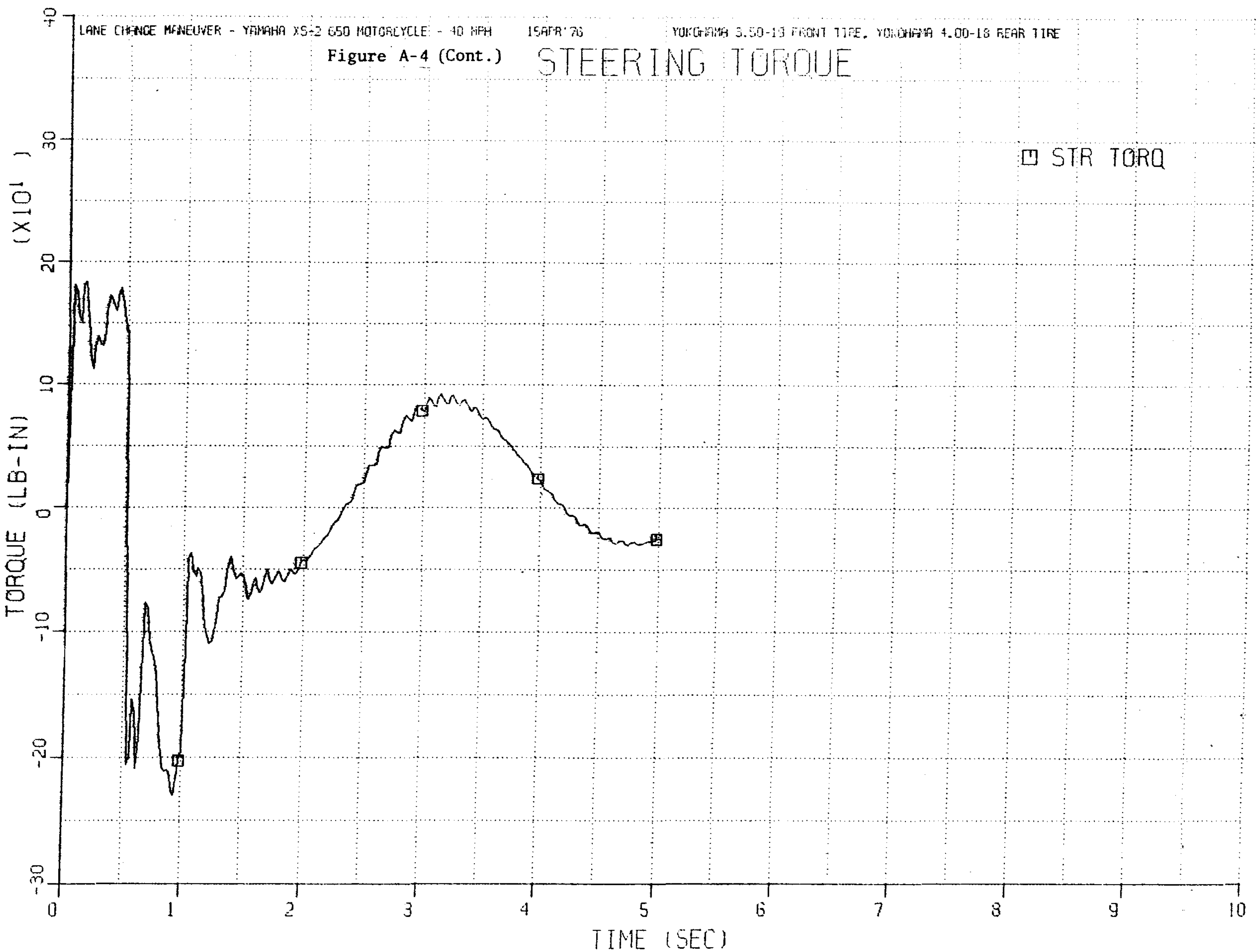

LANE CHANGE MANEUVER - YAMAHA XS-2 650 MOTORCYCLE - 40 MPH 15APR'76
YOKOHAMA 3.50-19 FRONT TIRE, YOKOHAMA 4.00-18 REAR TIRE
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
30
20
10
0
-10
-20
-30
-40
TIME (SEC)
0
1
2
3
4
5
6
7
8
9
10

Figure A-4 (Cont.)



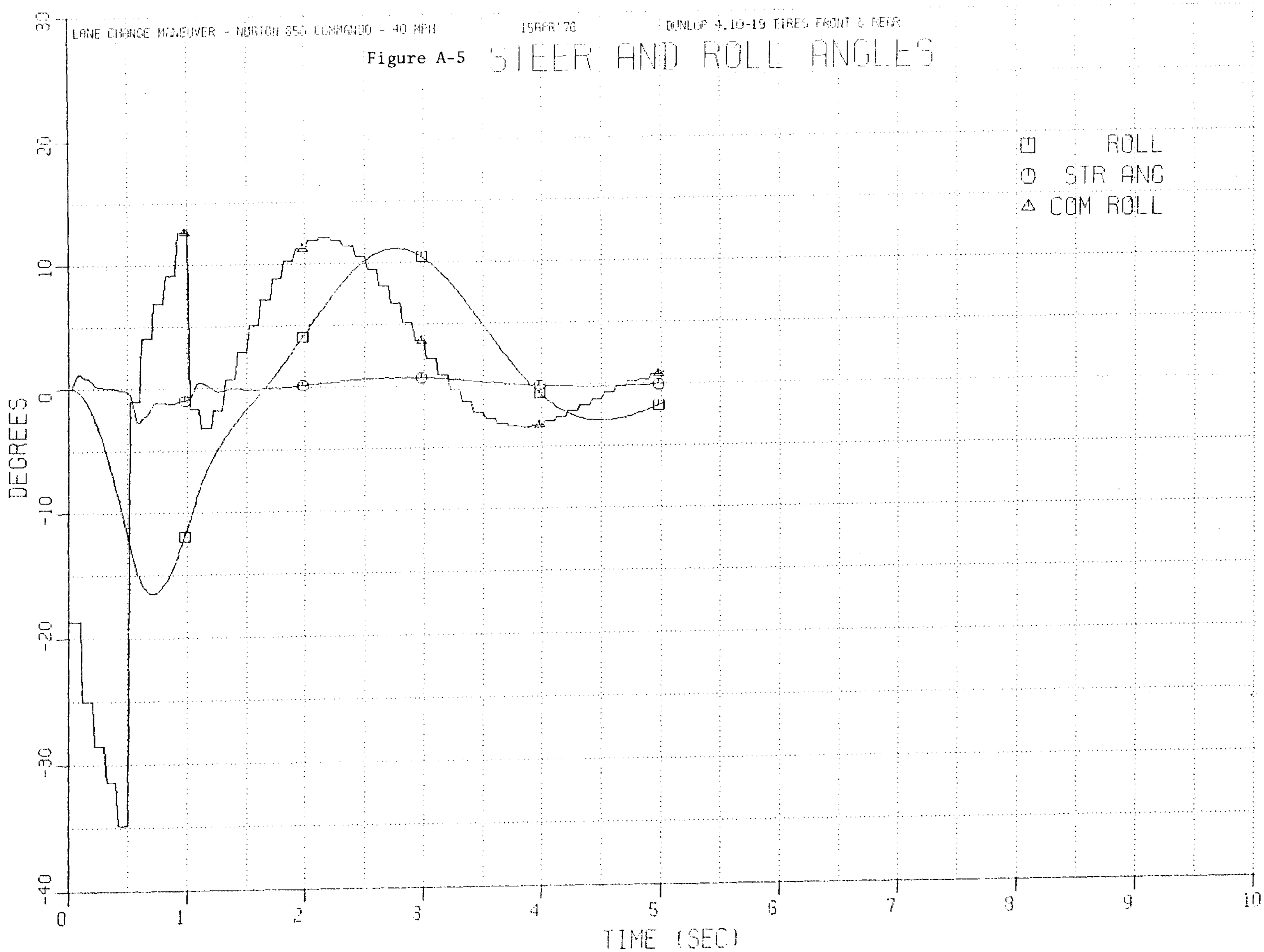

LANE CHANGE MANEUVER - NORTON 850 COMMANDO - 40 MPH
15APR'78
DUNLOP 4.10-19 TIRES FRONT & REAR
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
TIME (SEC)
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10
Figure A-5

Figure A-5 (Cont.)

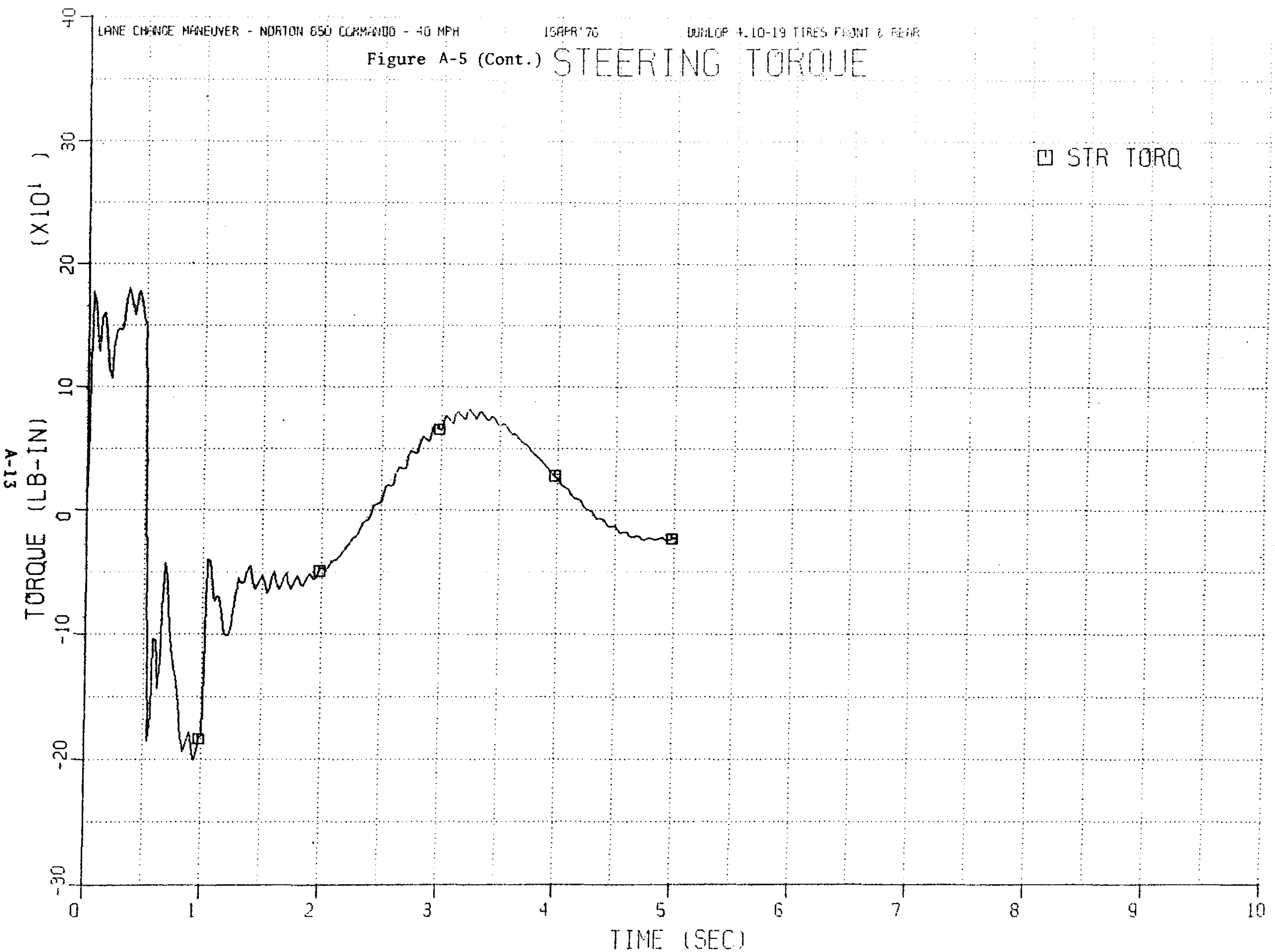
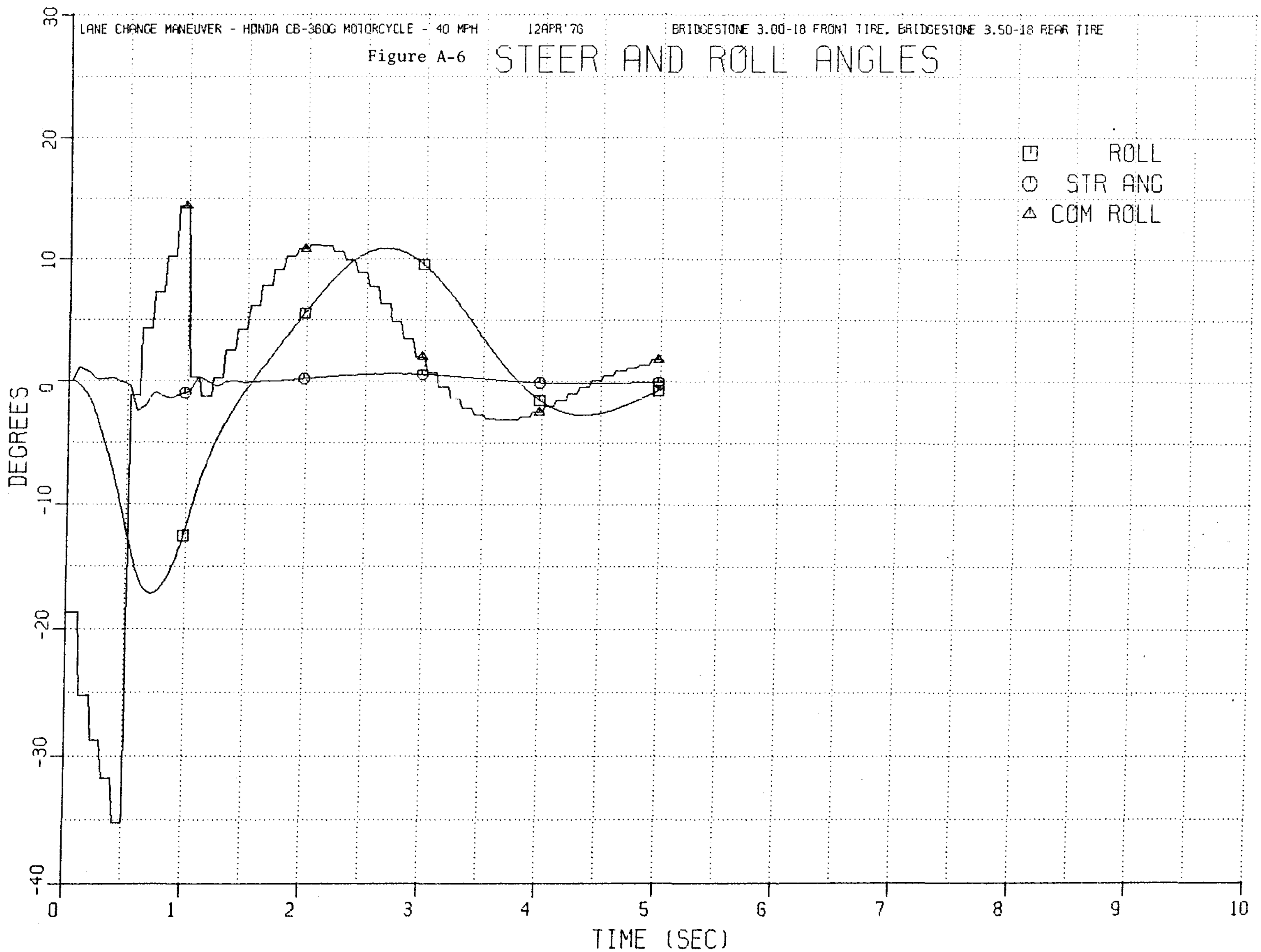


Figure A-6



LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 40 MPH
12APR'76
BRIDGESTONE 3.00-18 FRONT TIRE, BRIDGESTONE 3.50-18 REAR TIRE
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
TIME (SEC)
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10

Figure A-6 (Cont.)

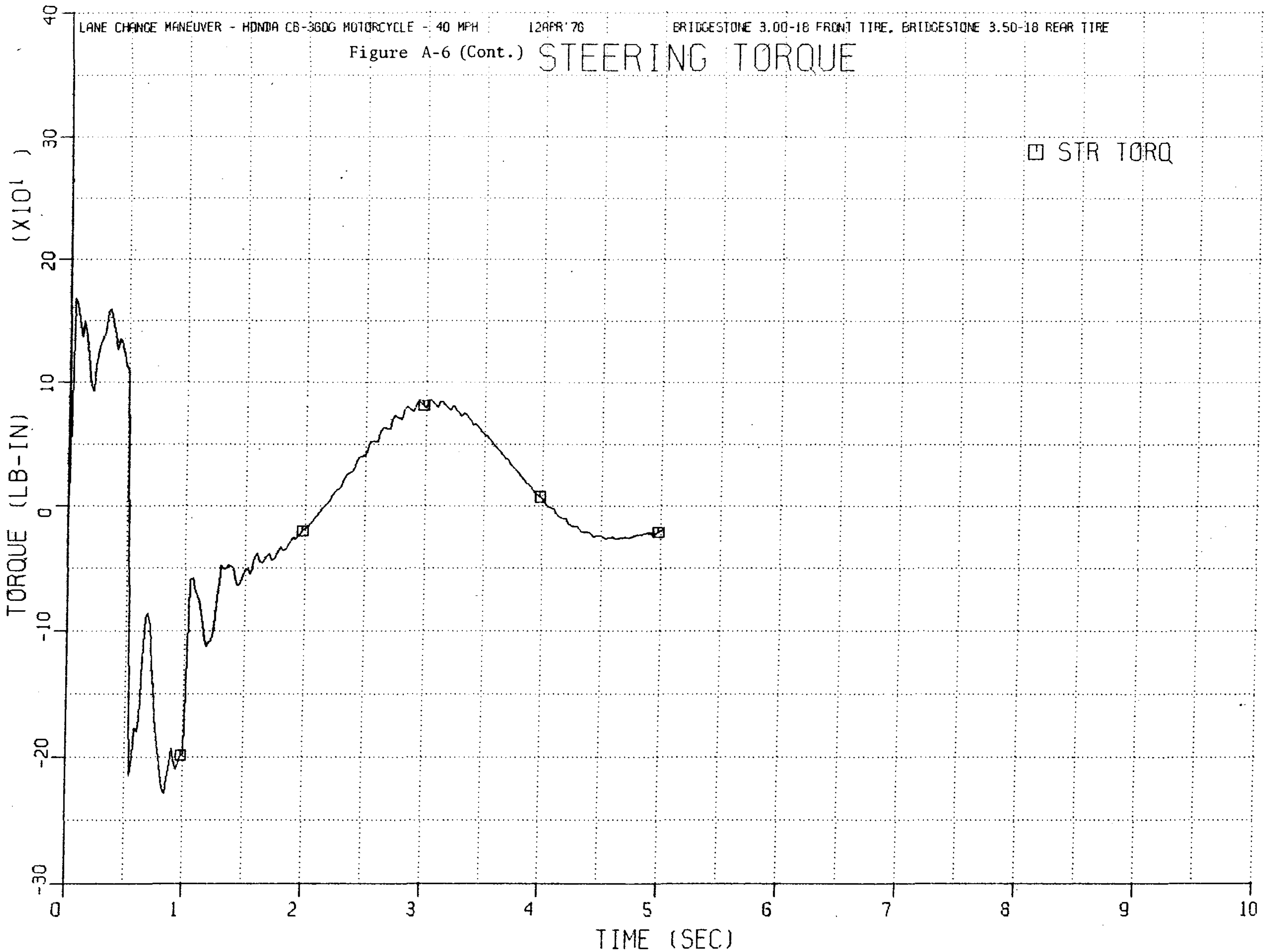


Figure A-7

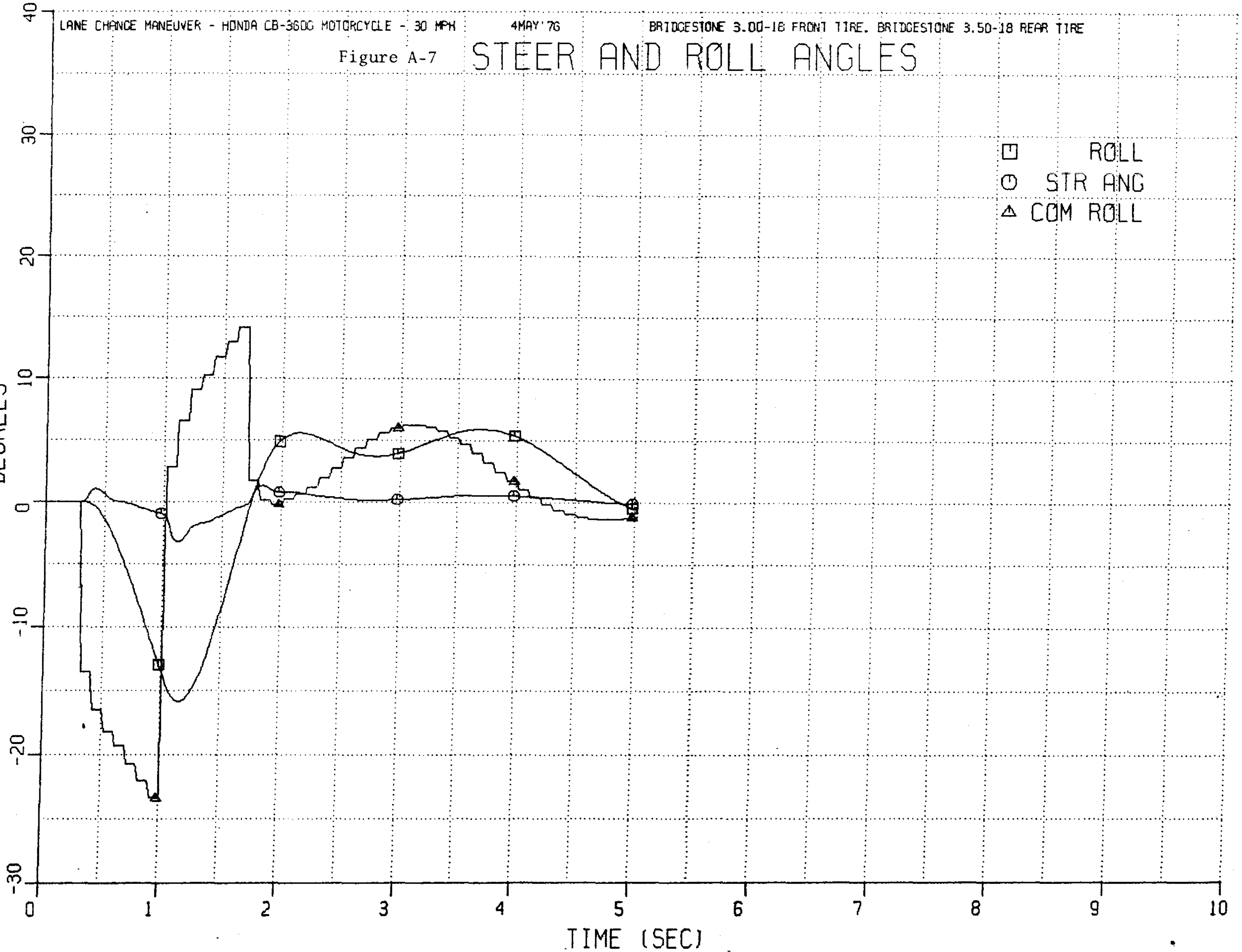

LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 30 MPH
4MAY'76
BRIDGESTONE 3.00-18 FRONT TIRE, BRIDGESTONE 3.50-18 REAR TIRE
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
40
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
9
10
TIME (SEC)

Figure A-7 (Cont.)

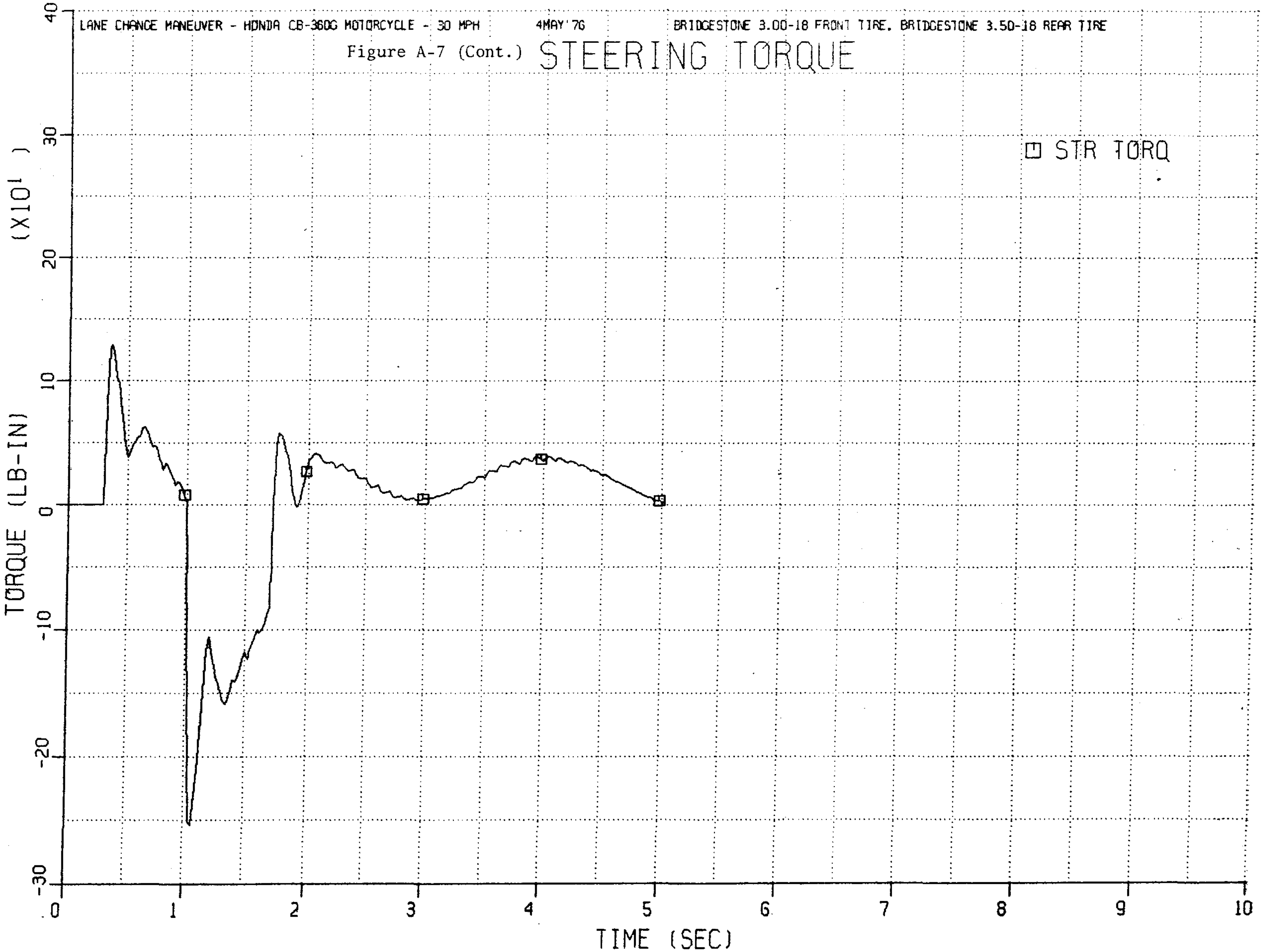
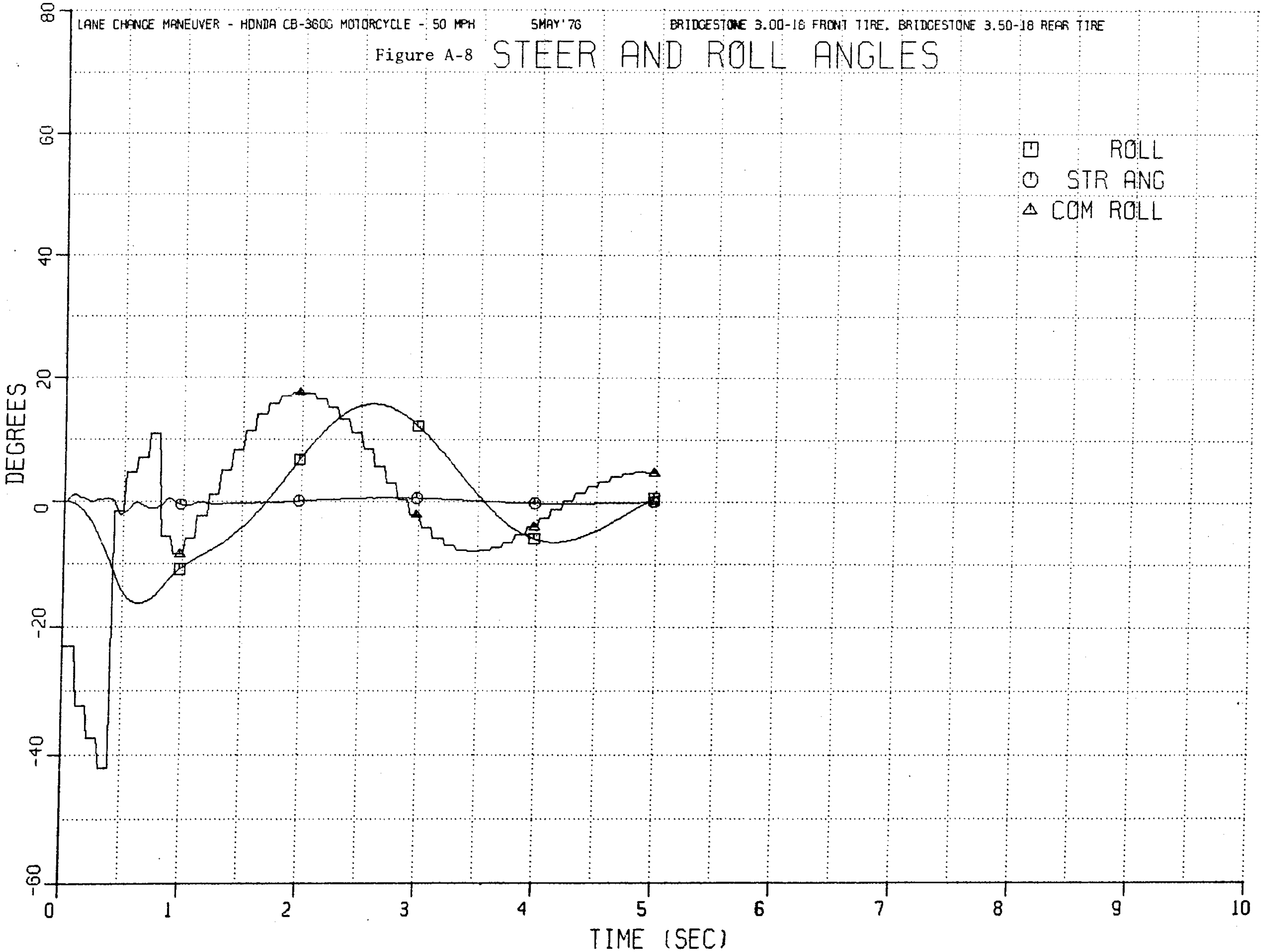
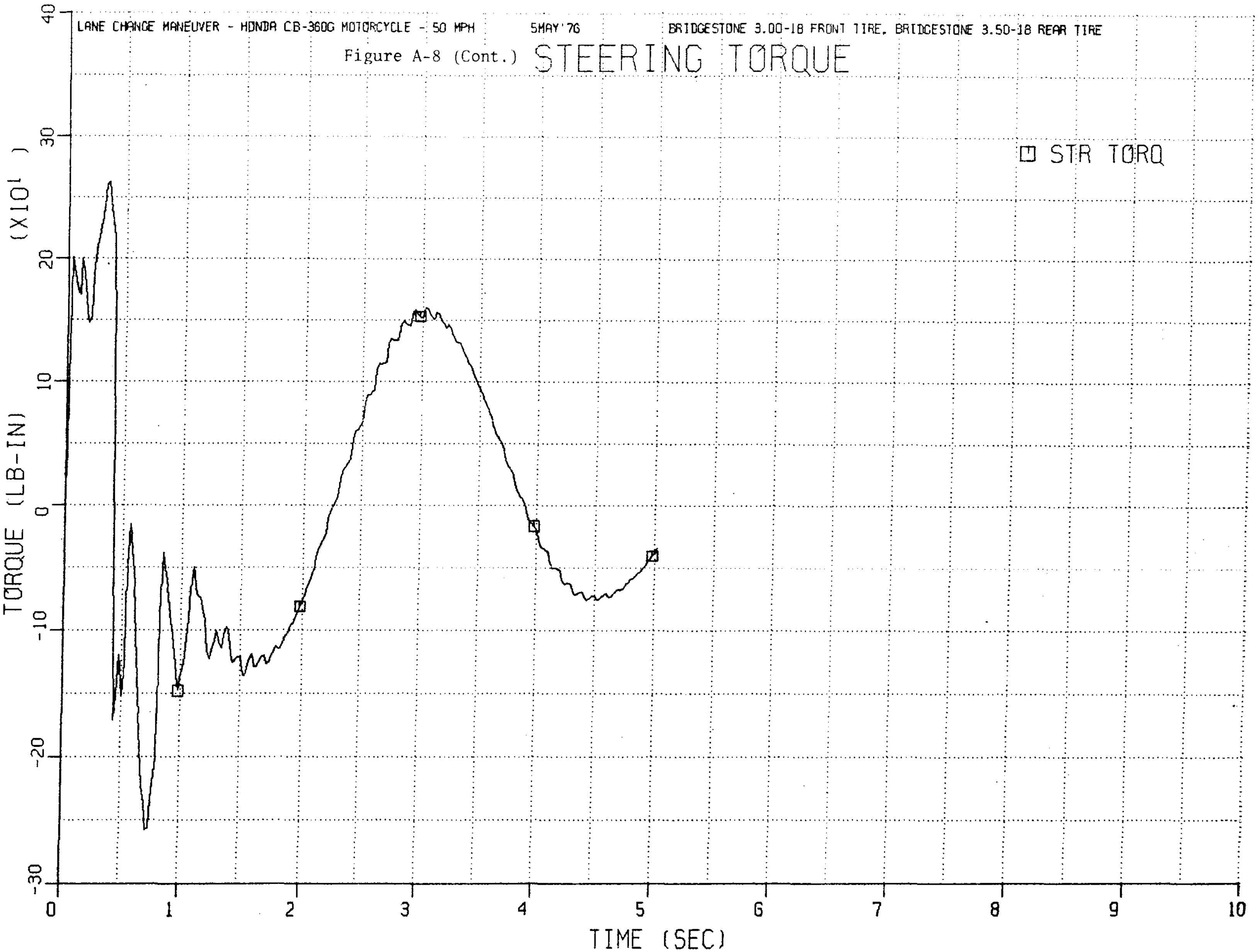


Figure A-8


LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 50 MPH
5MAY'76
BRIDGESTONE 3.00-18 FRONT TIRE. BRIDGESTONE 3.50-18 REAR TIRE
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
TIME (SEC)
80
60
40
20
0
-20
-40
-60
0
1
2
3
4
5
6
7
8
9
10


LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 50 MPH
5MAY'76
BRIDGESTONE 3.00-18 FRONT TIRE, BRIDGESTONE 3.50-18 REAR TIRE
Figure A-8 (Cont.)
STEERING TØRQUE
STR TØRQ
TØRQUE (LB-IN)
(X10¹)
40
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
9
10
TIME (SEC)

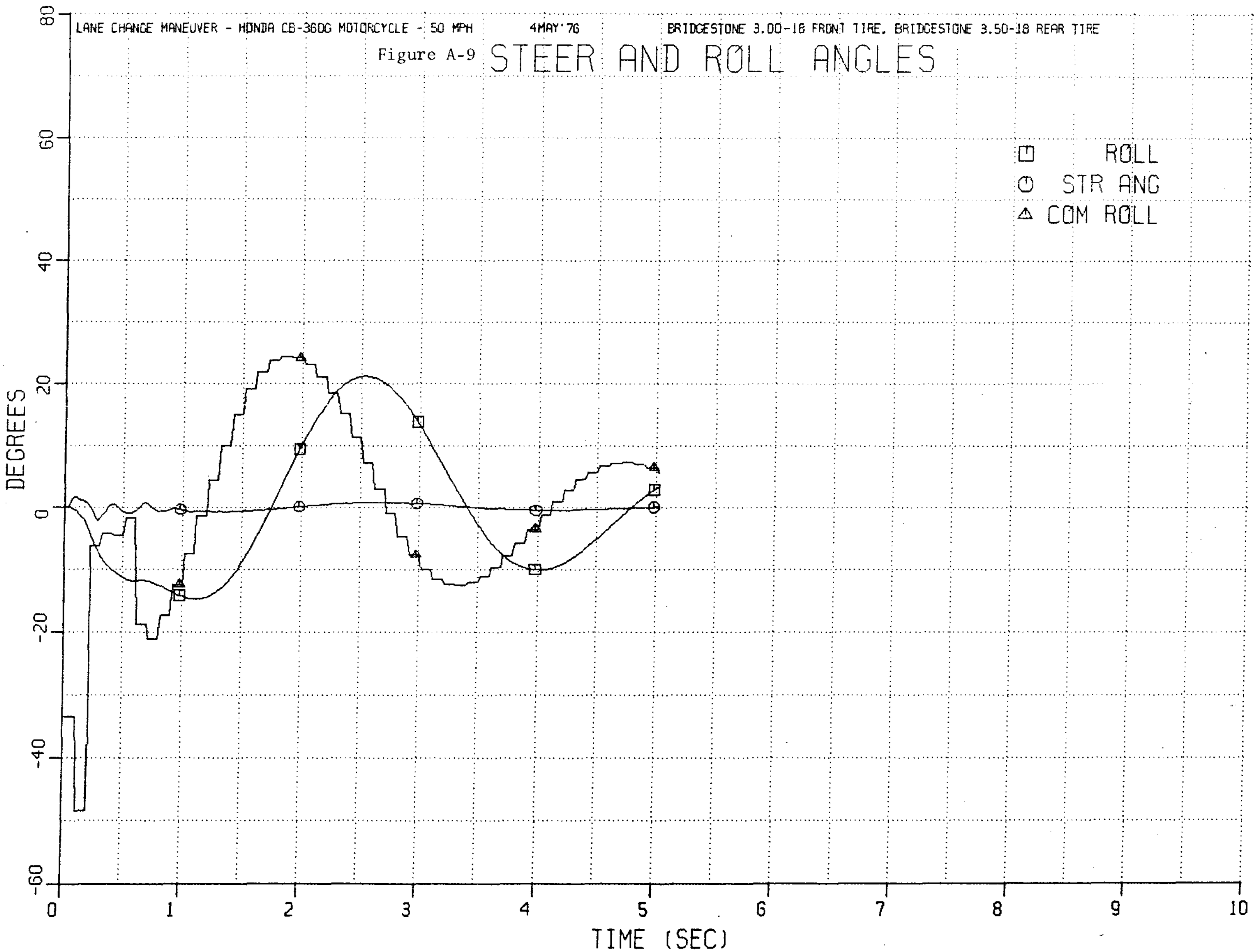


Figure A-9 STEER AND ROLL ANGLES

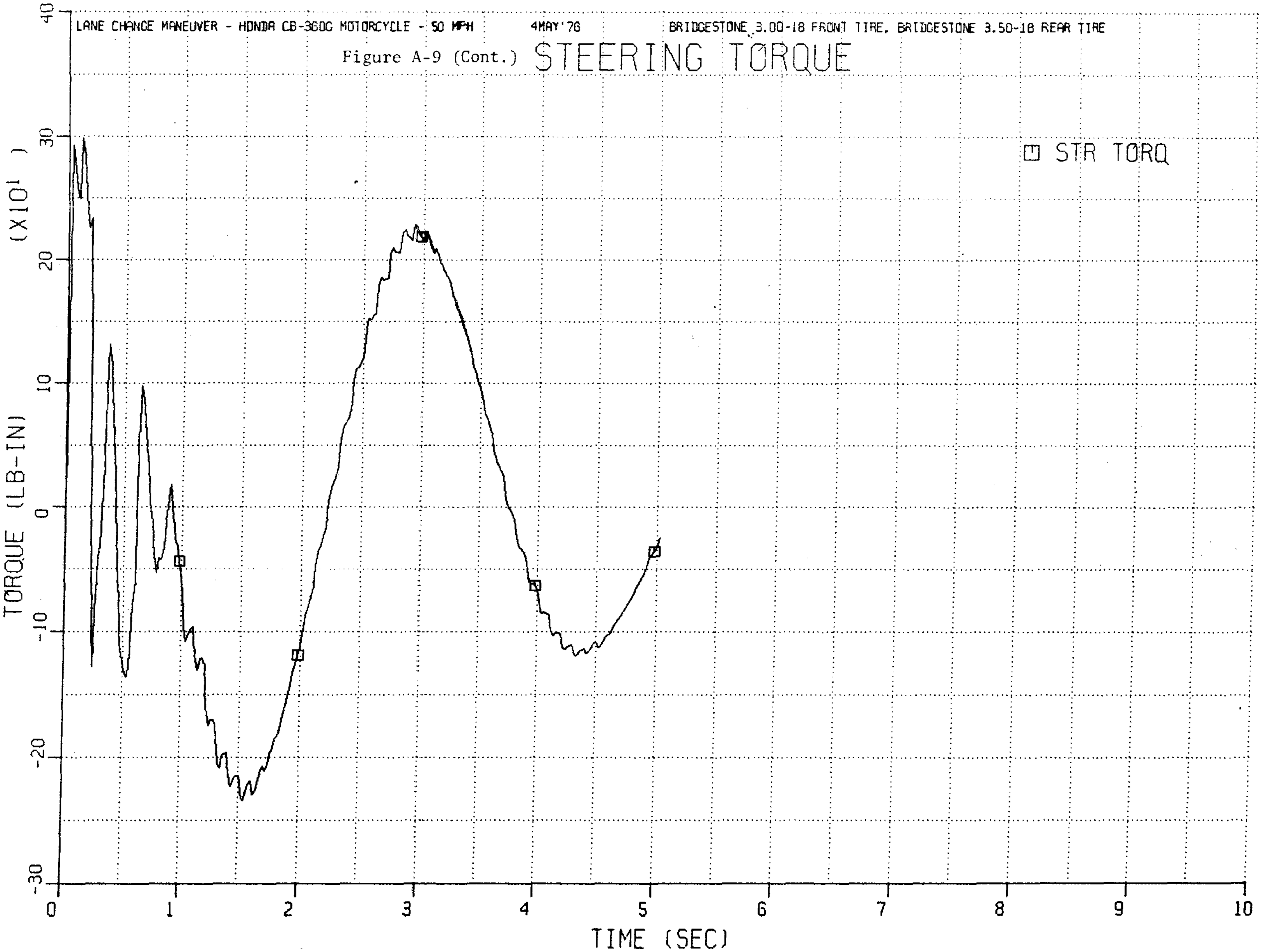
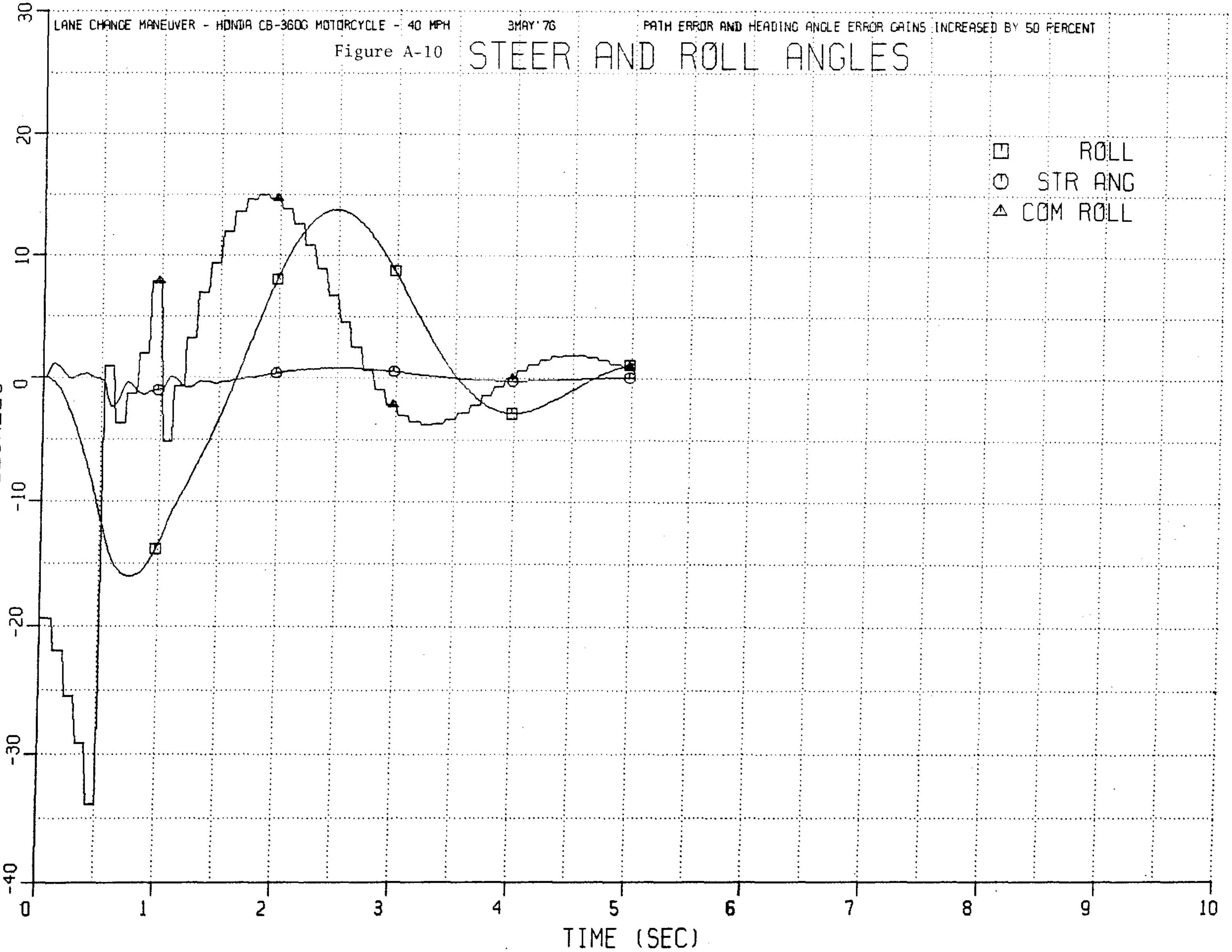


Figure A-9 (Cont.)



LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 40 MPH
3MAY'76
PATH ERROR AND HEADING ANGLE ERROR GAINS INCREASED BY 50 PERCENT
STEER AND RØLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
TIME (SEC)
30
20
10
0
-10
-20
-30
-40
0
1
2
3
4
5
6
7
8
9
10

Figure A-10

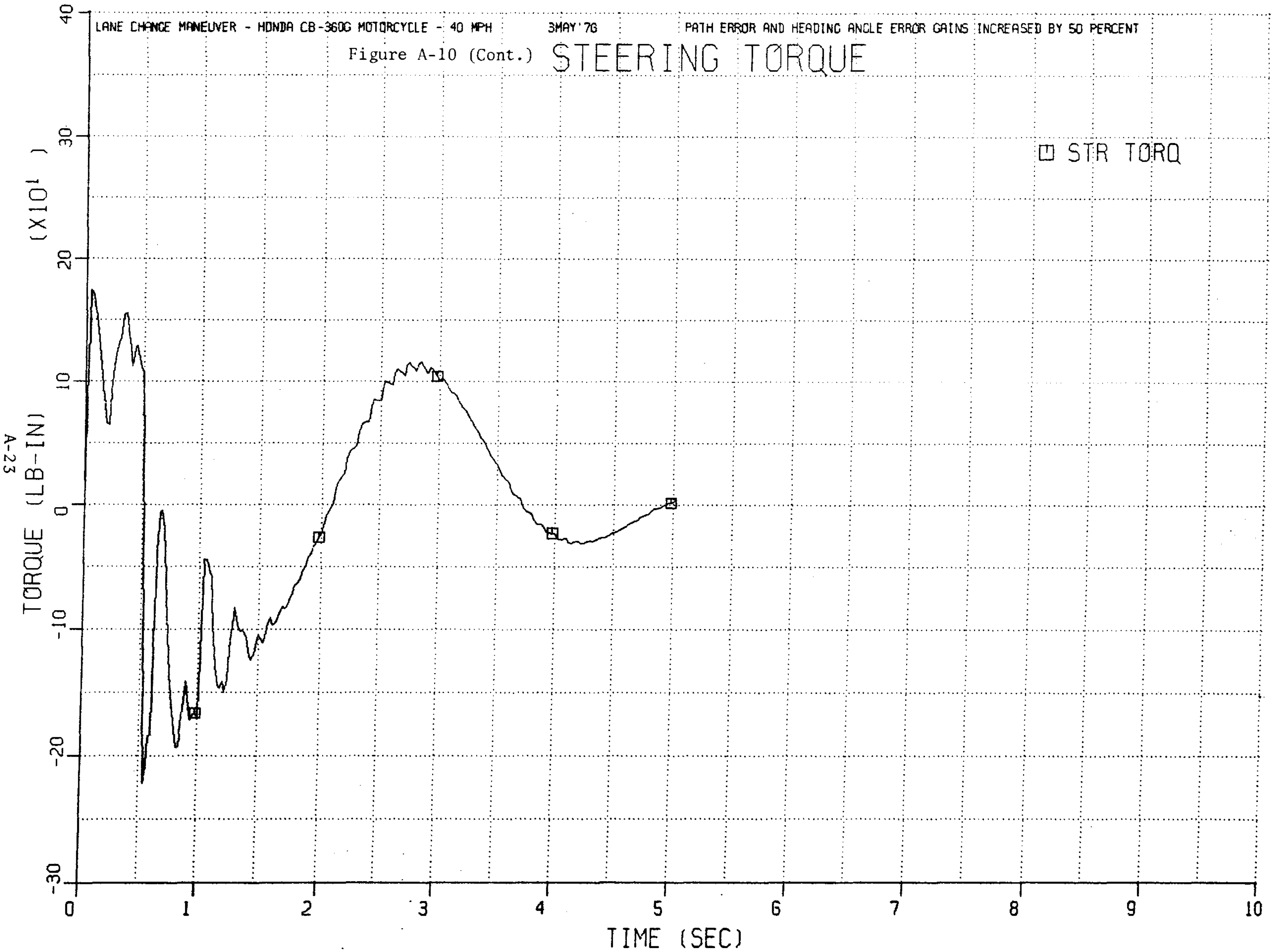
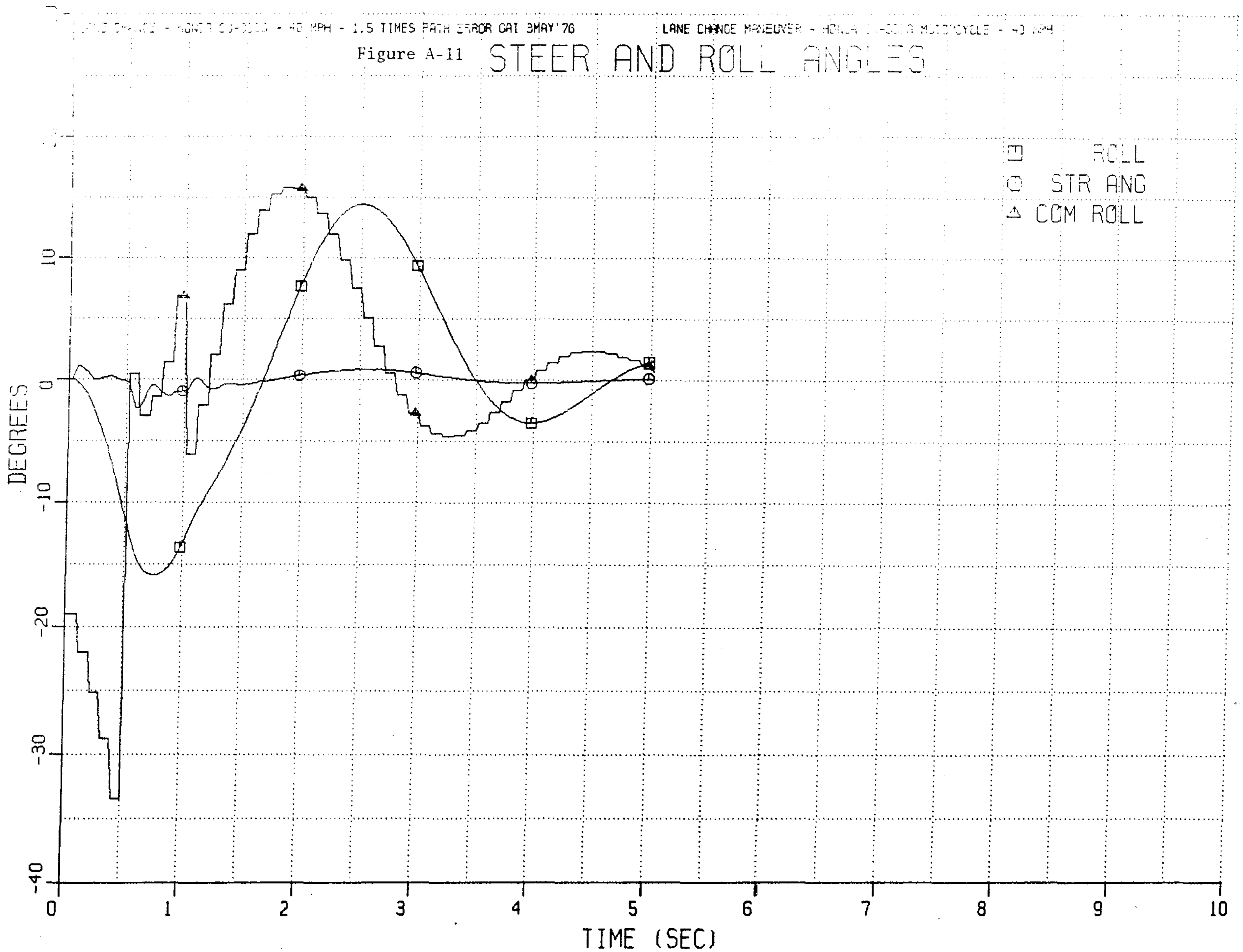


Figure A-10 (Cont.)

Figure A-11


1.5 TIMES PATH ERROR GAI 3MAY'76
LANE CHANGE MANEUVER
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
10
0
-10
-20
-30
-40
TIME (SEC)
0
1
2
3
4
5
6
7
8
9
10

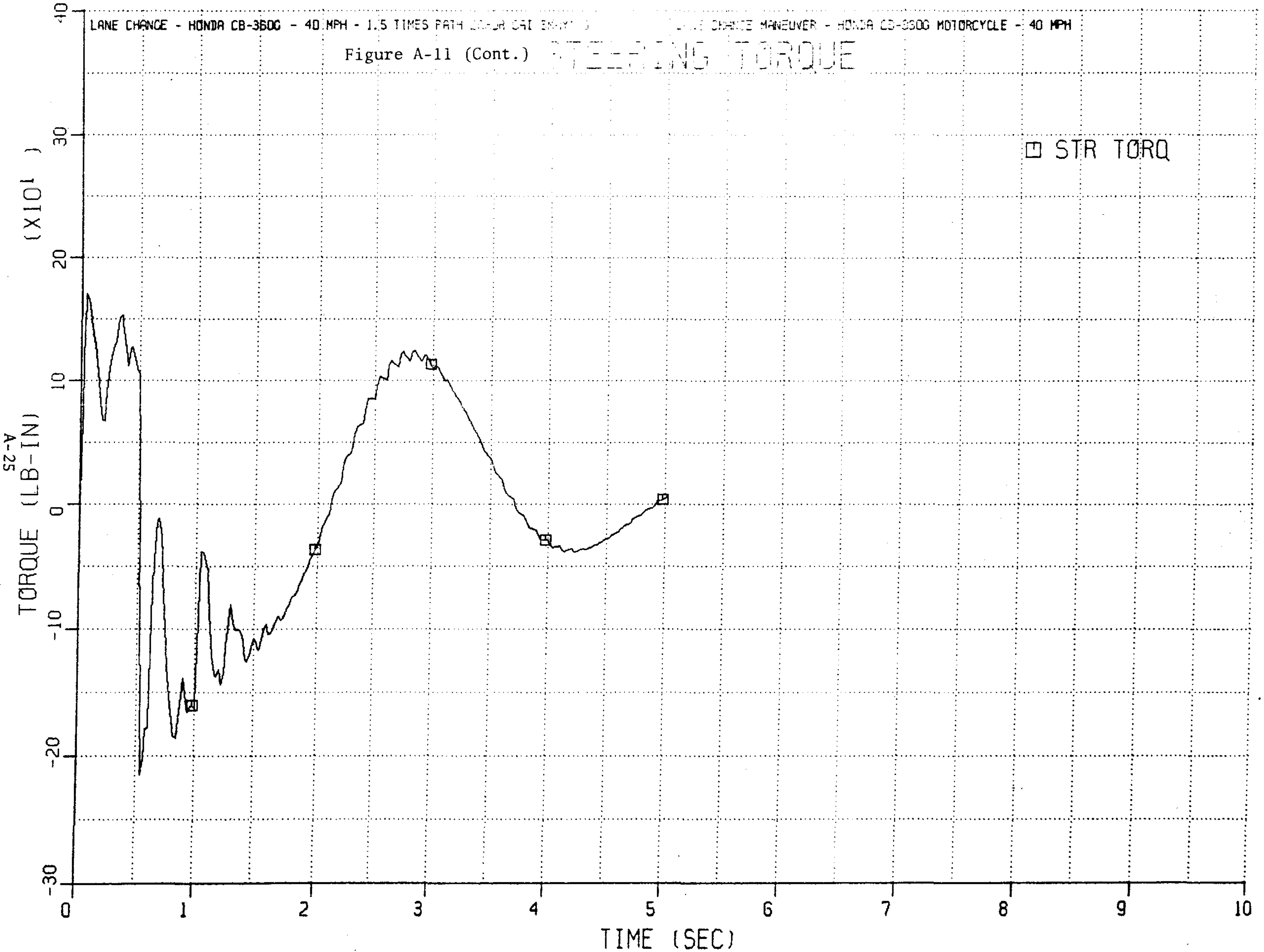
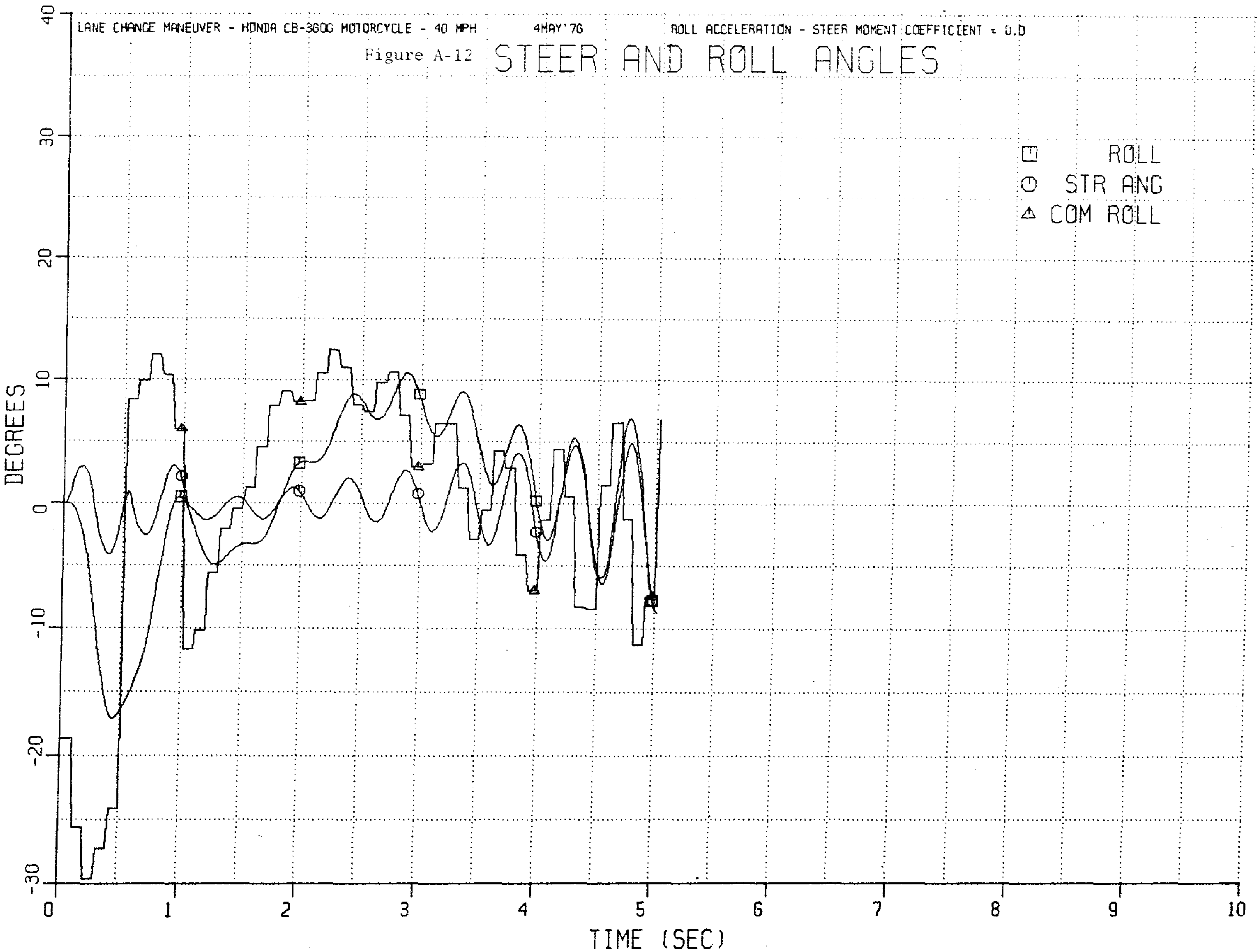


Figure A-11 (Cont.)


LANE CHANGE MANEUVER - HONDA CB-360G MOTORCYCLE - 40 MPH
4MAY'76
ROLL ACCELERATION - STEER MOMENT COEFFICIENT = 0.0
STEER AND ROLL ANGLES
ROLL
STR ANG
COM ROLL
DEGREES
TIME (SEC)
40
30
20
10
0
-10
-20
-30
0
1
2
3
4
5
6
7
8
9
10
Figure A-12

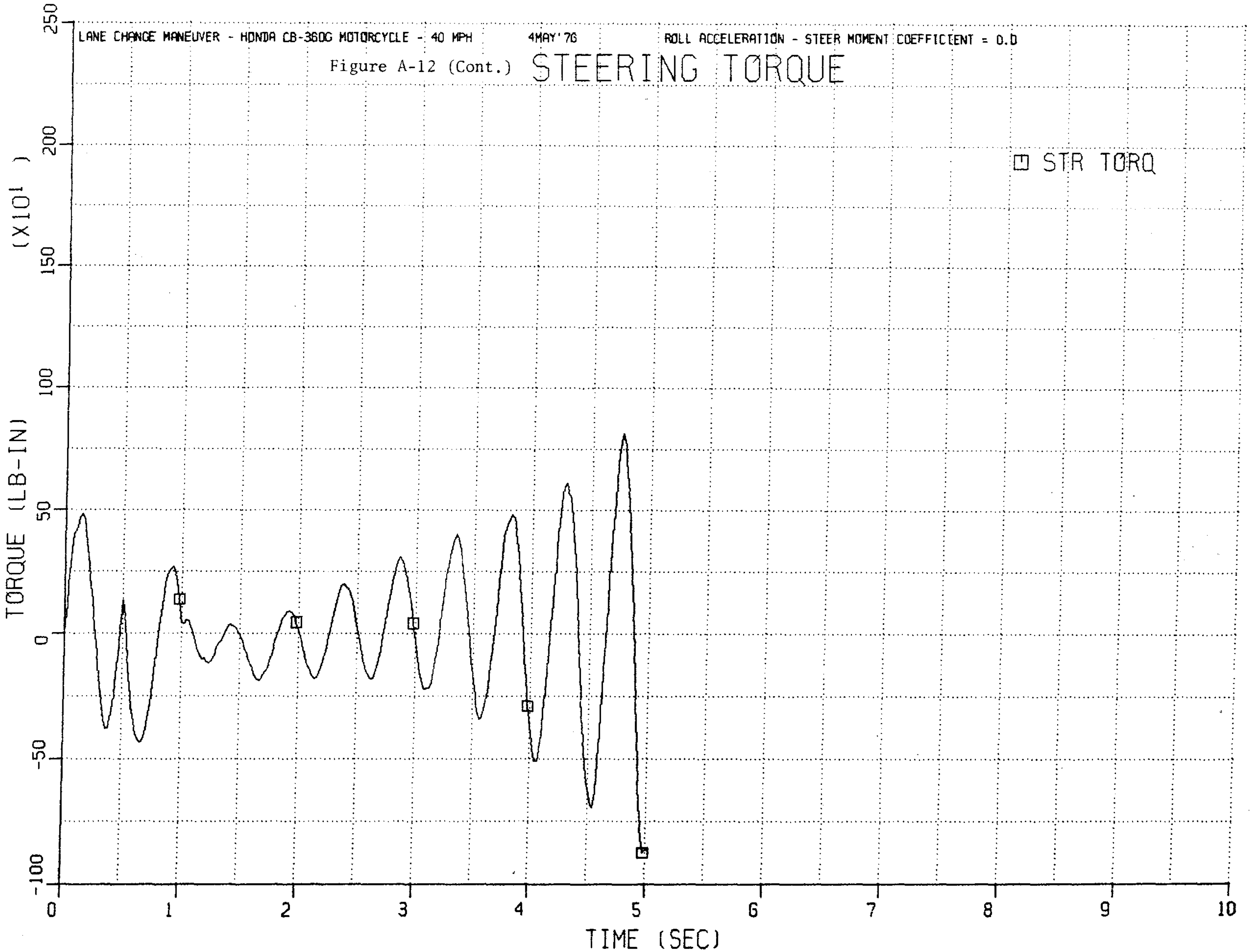


Figure A-12 (Cont.)