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16. Abstract

Six full-scale tests of an instrumented automobile were conducted on an embankment. The tests were conducted for various combinations of vehicle encroachment speed and encroachment angle. The embankment, which was on Texas State Highway 21, consisted of a 3.5:1 side slope and a relatively flat bottom ditch approximately 20 feet below the paved roadway. Each test was simulated by the Highway-Vehicle-Object-Simulation-Model (HVOSM), a computer program, and the results were then compared with the measured test results. With the exception of the tests in which suspension failures occurred in the test car, the correlation between the measured and predicted data was good.

Volume One describes the study and includes the test results and comparisons. Volume Two contains the HVOSM computer input and sample output related to the study.

17. Key Words	18. Distribution Statement
full-scale tests, embankment, computer simulation, validation study	

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COMPARISONS OF FULL-SCALE EMBANKMENT
TESTS WITH COMPUTER SIMULATIONS

VOLUME I: TEST RESULTS AND COMPARISONS

by

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Research Report 140-7
Volume I

Evaluation of the Roadway Environment by
Dynamic Analysis of the Interaction Between
the Vehicle, Passenger, and Roadway

Research Study No. 2-5-69-140

Sponsored by

The Texas Highway Department
in cooperation with the
U. S. Department of Transportation, Federal Highway Administration

December 1972

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

FOREWORD

The information contained herein was developed on Research Project 2-5-69-140 entitled "Evaluation of the Roadside Environment by Dynamic Analysis of the Interaction Between the Vehicle, Passenger, and Roadway." It is a cooperative research study sponsored jointly by the Texas Highway Department and the U. S. Department of Transportation, Federal Highway Administration.

The basic objectives of the study are to apply mathematical simulation techniques to determine the dynamic behavior of automobiles and their occupants when in collision with various roadside objects or when traversing curves in the road, shoulders, or other situations. It is a continuing study, having been initiated in September 1968.

As part of the first year's work, the computer program HVOSM* (formerly known as CALSVA) was obtained from Cornell Aeronautical Laboratory and made operational on the IBM 360 computer facilities at Texas A&M University. In adapting the program, additions and modifications were made which increased its flexibility and usefulness. These changes and the input requirements of the program are documented in Research Report 140-1.

The primary emphasis of the second year's work was the development of an analytical model which predicts the dynamic response of an automobile's occupant in three-dimensional space. Research Report 140-2 presents the derivation of the occupant model, a validation study, and a description of computer input data for determining the

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*HVOSM: Highway-Vehicle-Object Simulation Model.

occupant's response.

In the 1970-71 year the emphasis was on application of HVOSM to specific roadway design problems. Research Report 140-3 describes an investigation of the *traffic-safe* characteristics of different sloping culvert grate configurations. Criteria are presented for designing a *traffic-safe* sloping grate. Research Report 140-4 describes the development of criteria from which the need and location of guardrail for embankment protection can be determined.

During the 1971-72 years further applications of HVOSM were made. A study was made to determine the dynamic behavior of a vehicle impacting the Texas Concrete Median Barrier. The results of that study are contained in Research Report 140-5. Research Report 140-6 describes a study of vehicle behavior as it traverses selected curbs and a particular median cross-section.

This report presents the results of full-scale embankment tests and a comparison of the tests results with HVOSM predictions.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ABSTRACT

Key Words: Embankment, Full-scale Tests, Computer Simulation, Validation Study.

Six full-scale tests of an instrumented automobile were conducted on an embankment. The tests were conducted for various combinations of vehicle encroachment speed and encroachment angle. The embankment, which was on Texas State Highway 21, consisted of a 3.5:1 side slope and a relatively flat bottom ditch approximately 20 feet below the paved roadway. Each test was simulated by the Highway-Vehicle-Object-Simulation-Model (HVOSM), a computer program, and the results were then compared with the measured test results. With the exception of two tests in which suspension failures occurred in the test car, the correlation between the measured and predicted data was good.

SUMMARY

Criteria were presented in Research Report 140-4 identifying those embankments which needed guardrail protection. A portion of the criteria was based on output from the HVOSM computer program, a program which simulates the dynamic behavior of an automobile. Since the program had not been validated for embankments with relatively steep side slopes and since implementation of the criteria would require changes in current Texas Highway Department design procedures, it was decided that a limited validation study should be conducted.

Six full-scale automobile tests were conducted on an embankment of an in-service roadway on Texas State Highway 21. The embankment had a 3.5:1 side slope and a flat bottom ditch approximately 20 feet below the roadway. A remote controlled automobile was directed off the road at various encroachment angles and speeds. Its subsequent response was recorded on high speed film and electronic instrumentation. Each test was then simulated by the HVOSM program to determine how accurately it could predict what actually happened. With the exception of two tests in which mechanical failures occurred, the correlation between measured and predicted data was considered good. As a consequence, it was concluded that the criteria in Research Report 140-4 were substantiated.

The tests show that an automobile and its occupants can traverse a 3.5:1 side slope with a flat bottom ditch with relative ease and tolerable accelerations for a wide range of encroachment conditions.

IMPLEMENTATION STATEMENT

The guardrail criteria presented in Research Report 140-4 can now be implemented with confidence. Results of the study reported herein show that the HVOSM computer program can accurately predict the dynamic behavior of an automobile as it leaves the roadway and traverses an embankment.

The criteria in Report 140-4 showed that an automobile can traverse 3:1 and flatter side slopes with less chance of injury to its occupants that would exist if the automobile struck a guardrail. The results of the full-scall tests tend to bear this out. Both test and HVOSM results showed that an automobile can negotiate an embankment with a 3.5:1 side slope and a flat bottom ditch without serious injury to the automobile's occupants for a variety of encroachment conditions.

ACKNOWLEDGEMENTS

The writers sincerely appreciate the cooperation and support of Texas Highway Department District 17 personnel during the full-scale tests. Special thanks are extended to Mr. Joe G. Hanover, Mr. Billy G. Bockmon and Mr. Michael L. McClure of District 17. Mr. John Nixon and Mr. Dave Hustace of THD D-8 and Mr. Edward V. Kristaponis of FHWA worked closely with the TTI researchers during the study, and their valuable input is acknowledged.

The cooperation of the TTI support service personnel at the Research Annex is appreciated. Lionel Milberger, with assistance from Dick Zimmer and George Shute, designed and implemented the remote control system used in the test car. Don Cangelose directed the preparation of the test car.

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I. INTRODUCTION

In a previous study at the Texas Transportation Institute (TTI), guardrail need criteria were developed (1). The criteria indicate where guardrail should be used to prevent an automobile from going over a given embankment configuration. To establish the criteria, the severity of an automobile leaving the road and going down an embankment was compared with the severity of striking a guardrail. In this manner, those embankments which were less severe to traverse than to strike a guardrail could be identified. To quantify severity, automobile accelerations were used, from which a *severity index* was computed.

The severity of colliding with a guardrail was determined from full-scale tests results and mathematical simulation techniques. The severity of traversing an embankment was determined by use of HVOSM. Previous validation studies have shown that HVOSM can accurately predict the dynamic motion of an automobile in many types of maneuvers (2,3,4,5,6). However, no reported full-scale tests have been conducted to establish the validity of HVOSM in predicting the behavior of an automobile traversing embankments similiar in geometry to those considered in the aforementioned study (1).

The criteria (1) indicate that guardrail protection is not warranted for side slopes which are 3:1 and flatter with ditch depths less than 50 ft. If adopted, this criteria would require changes in the Texas Highway Department's (THD) current highway design specifications. A limited number of full-scale tests were therefore considered desirable to substantiate the results of HVOSM, and to aid in the decision to make revisions to the specifications.

A series of tests were conducted on an actual field site (S.H.21) to provide data from which the HVOSM predictions could be compared. This report describes the tests and the comparisons.

II. FULL-SCALE TESTS

Test Site

An effort was made to locate an embankment with a side slope of approximately 3:1 (3 lengths laterally to 1 length vertically) and with considerable depth. This slope was desirable since the criteria (1) indicated that embankments flatter than 3:1 do not require guard-rail protection. In other words, it was determined that the severity of transversing 3:1 and flatter slopes was less then striking a guard-rail.

With the assistance and cooperation of THD District 17 personnel, a site was located on S.H. 21. Figure 1 shows the site location and Figure 2 shows photographs of the test site. The slope and depth of the embankment were very close to the desired values.

The test section extended 400 feet along the roadway and approximately 140 feet laterally from the edge of the pavement. A grid layout of the test section is shown in Figure 3. Eleven stations, spaced on 40-foot centers, were established on a control line along the edge of the unpaved 10-foot shoulder. At each station, wooden stakes were set at ground level on 10 feet horizontal centers along a line perpendicular to the control line. Figure 4 shows profiles of Stations 1, 2 and 3. Profiles of all stations and the corresponding elevations are given in Appendix A.

Chalk lines were placed on the embankment grid as shown in Figure 3. These lines provided a reference for determining vehicle path from film analysis and visual observations of tire tracks.

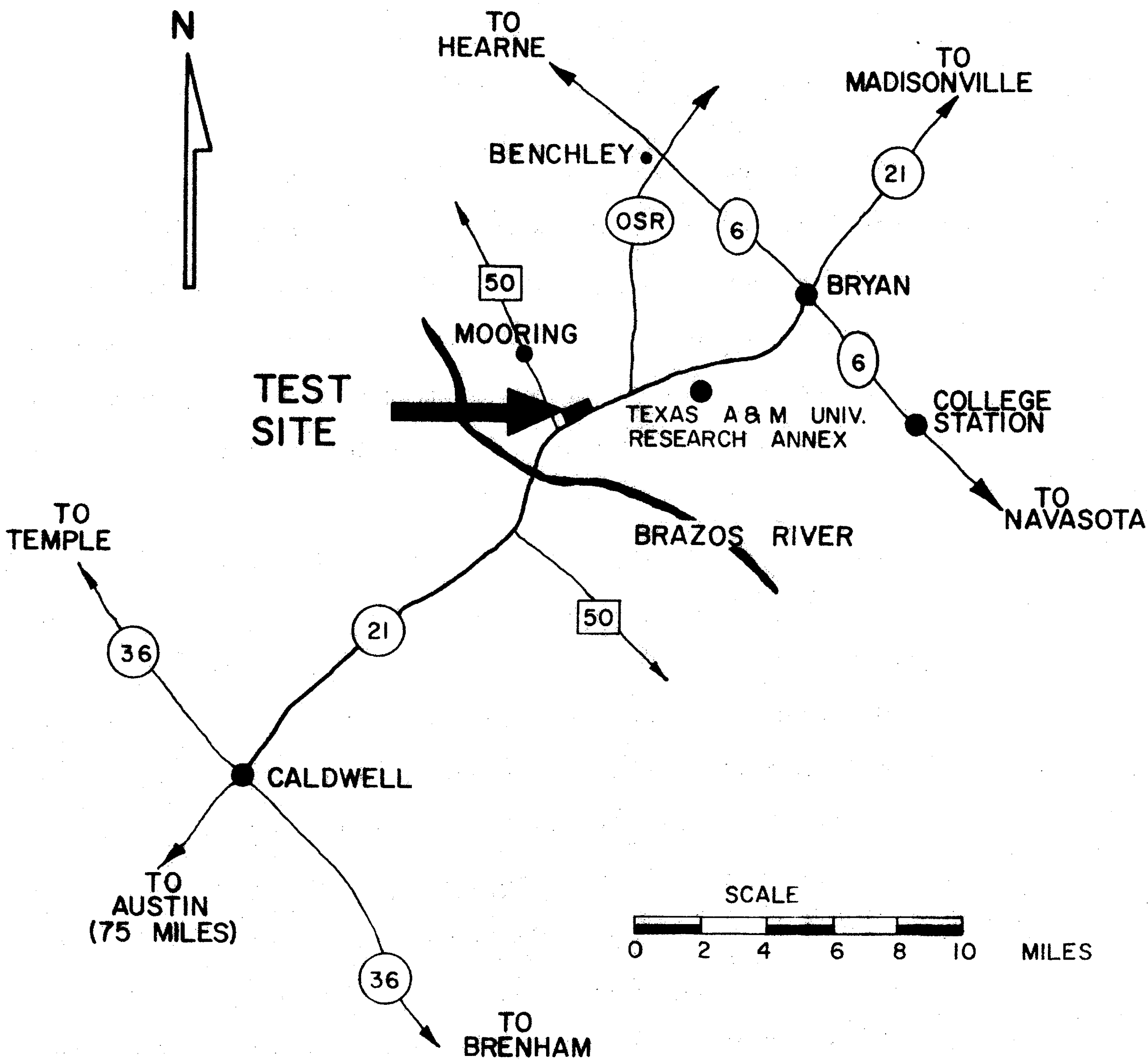
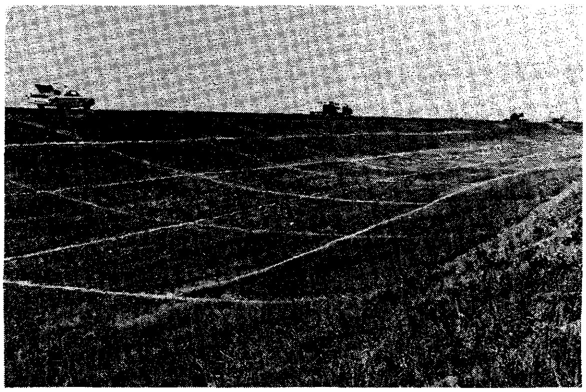
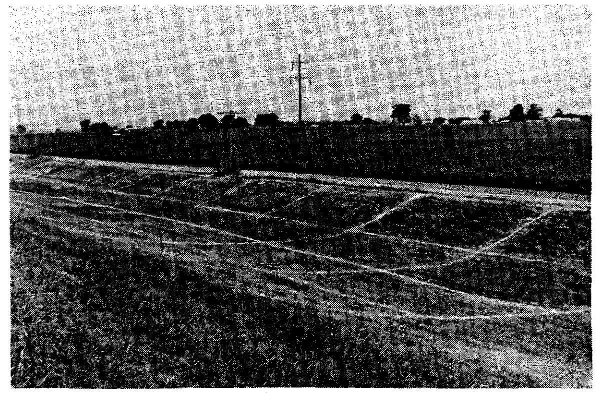


FIGURE 1 EMBANKMENT TEST SITE LOCATION ON TEXAS SH 21



(a) View from top of backslope



(b) View from roadway

(c) View from ditch bottom

FIGURE 2. PHOTOS OF TEST SITE.

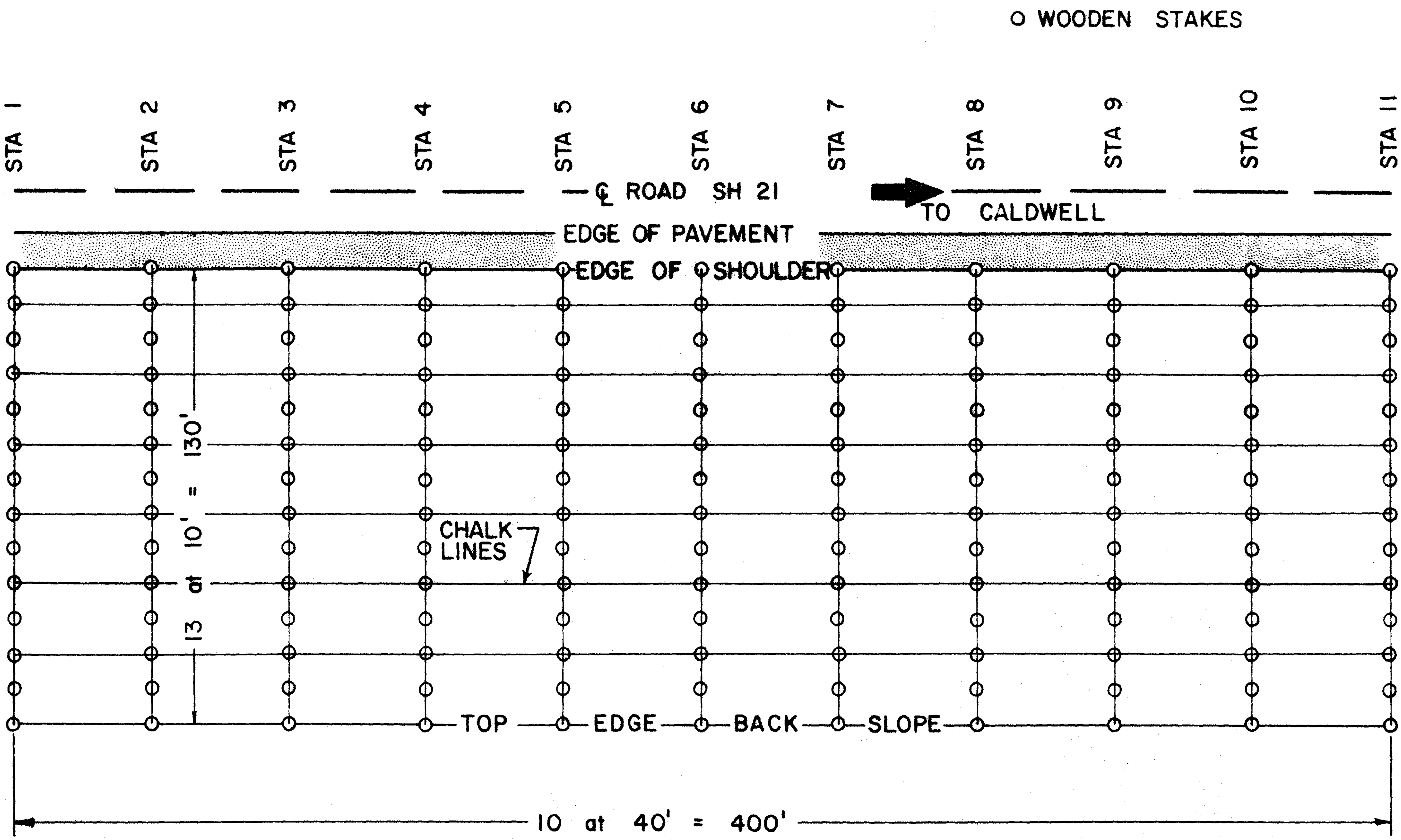


FIGURE 3 EMBANKMENT GRID LAYOUT ON SH 21

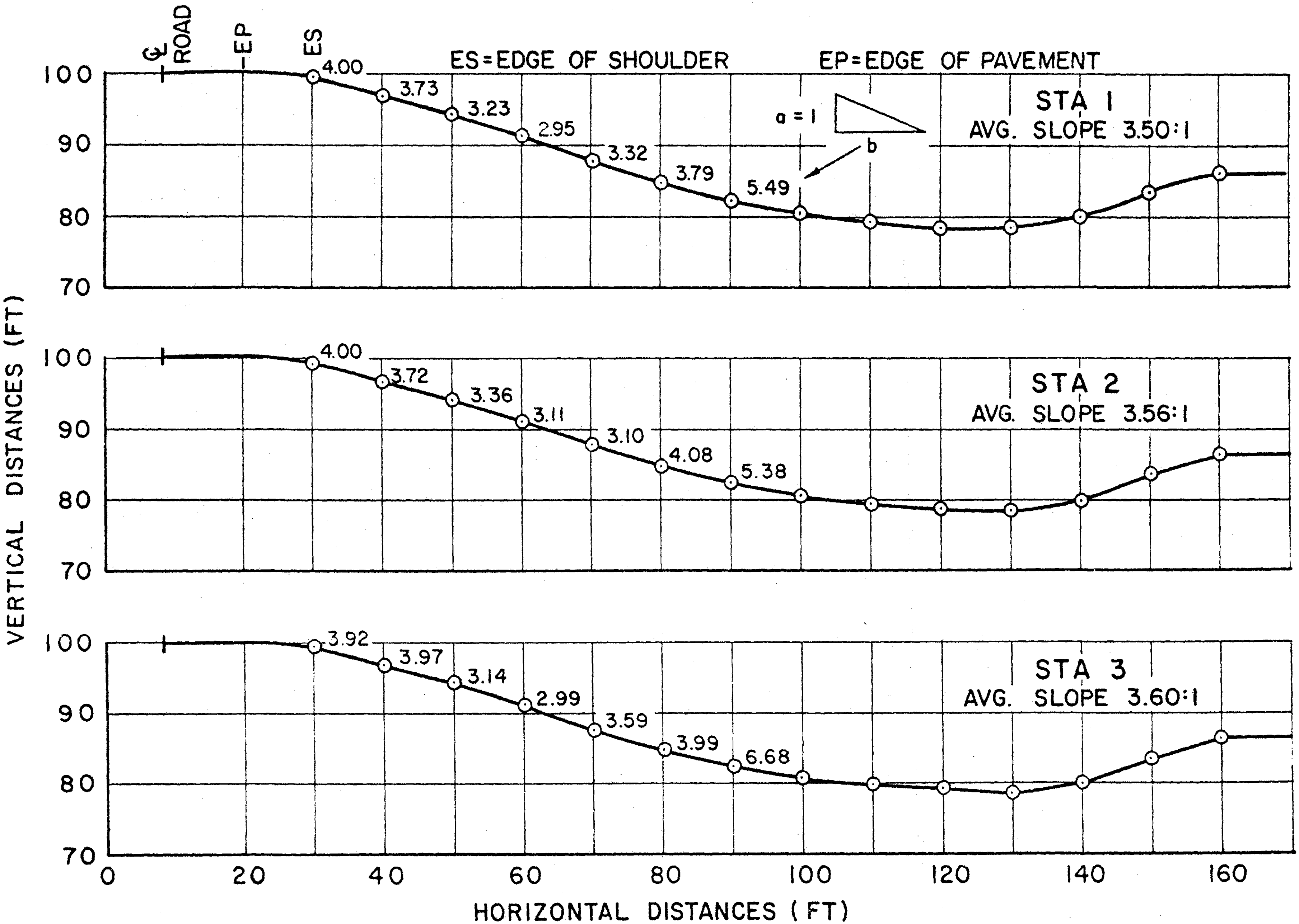


FIGURE 4 - EMBANKMENT PROFILES ON SH 21

Test Vehicle

The 1963 Ford Galaxy used in the test is shown in Figure 5. This particular vehicle was used since TTI has all the parameters needed in its simulation by HVOSM.

The hazardous nature of the planned tests precluded the use of a test driver. Guide cables could not be used to control the vehicle since this would have required blocking traffic on S.H. 21 for an unreasonable time period. The only alternative was to design and build a remote control system for the test vehicle. Details of the remote system are given in Appendix B. Its basic features were closed loop (controlled) proportional steering or open loop (free-wheeling) steering, proportional acceleration, and brake and clutch control. Commands to the test vehicle were transmitted from a trailing vehicle.

Data Measurement

Accelerations, attitude, and path are important parameters which affect the relative severity of a vehicle traversing an embankment. To measure these quantities, accelerometers, high-speed photography, and visual observation of tire tracks were used.

Encroachment speed was determined from the high-speed movie film by observing the time required for the vehicle to traverse a known distance between stadia poles (see Figure 9). The vehicle position and attitude as a function of time could also be determined from the

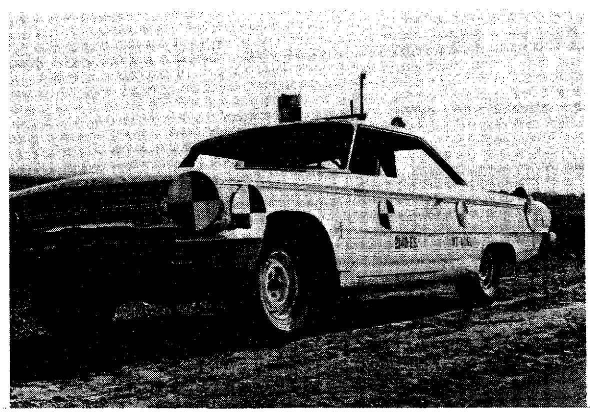


FIGURE 5. PHOTOS OF TEST VEHICLE.

movie film by observing the vehicle's path with respect to the grid lines.

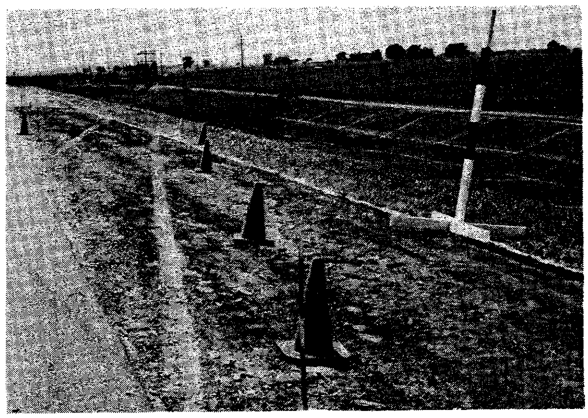
Three accelerometers were mounted in a cluster near the vehicle's center of gravity to measure longitudinal, lateral, and vertical accelerations. The accelerometer cluster was located at the intersection of the longitudinal and lateral center of gravity axes and approximately 7 inches below the vertical position of the center of gravity. Acceleration output was telemetered back to an instrumentation trailer for recording on magnetic tape.

As the vehicle traversed the embankment, distinct tire tracks were made. After each test, the position of the tracks were measured with respect to the grid system and recorded.

Loose dirt was placed along the shoulder where the test vehicle left the roadway. Tire tracks on the dirt provided a simple means of determining the encroachment angle. Figure 6 shows the tire tracks for a test and how the angle was computed.

Test Procedure

Shown in Figure 7 is a plan view of the test setup. Just prior to each test, traffic was halted approximately 1/2 mile from the test site. The test car was then accelerated to the desired speed and guided off the road from the trailing vehicle. The test car and the control vehicle can be seen in Figure 10. Traffic cones were used as guides to aid the remote control operator in steering the car off the road at



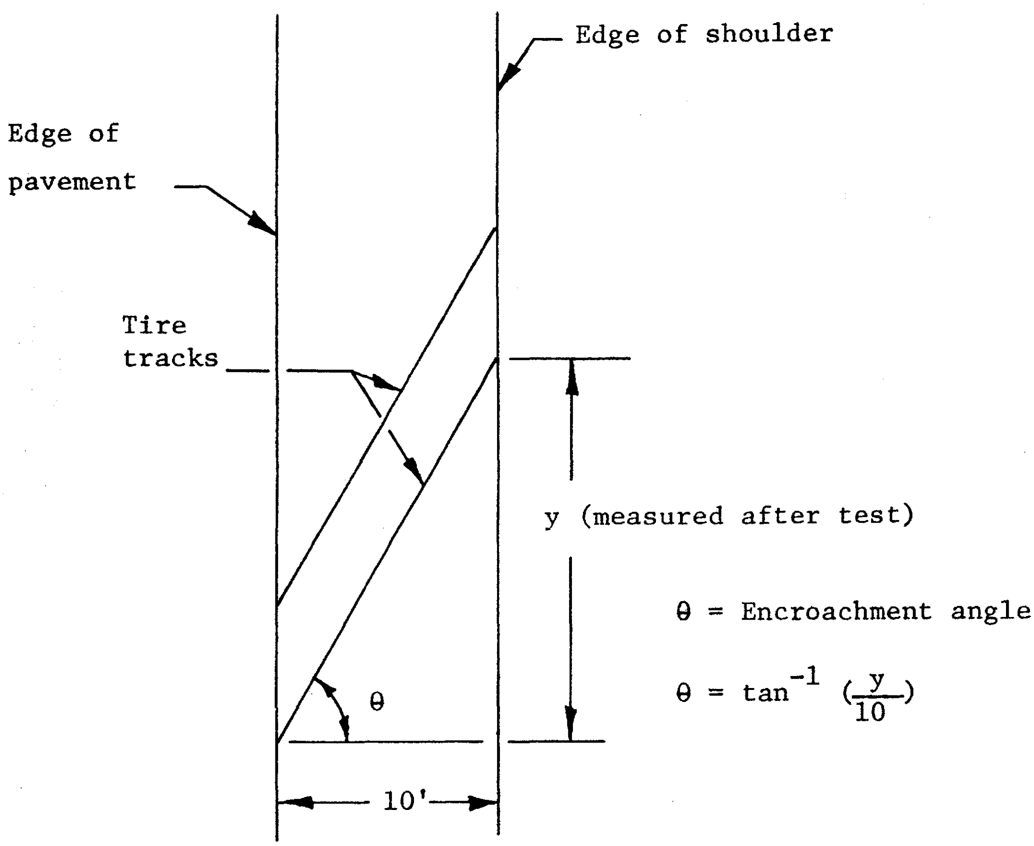


FIGURE 6. MEASUREMENT OF ENCROACHMENT ANGLE.

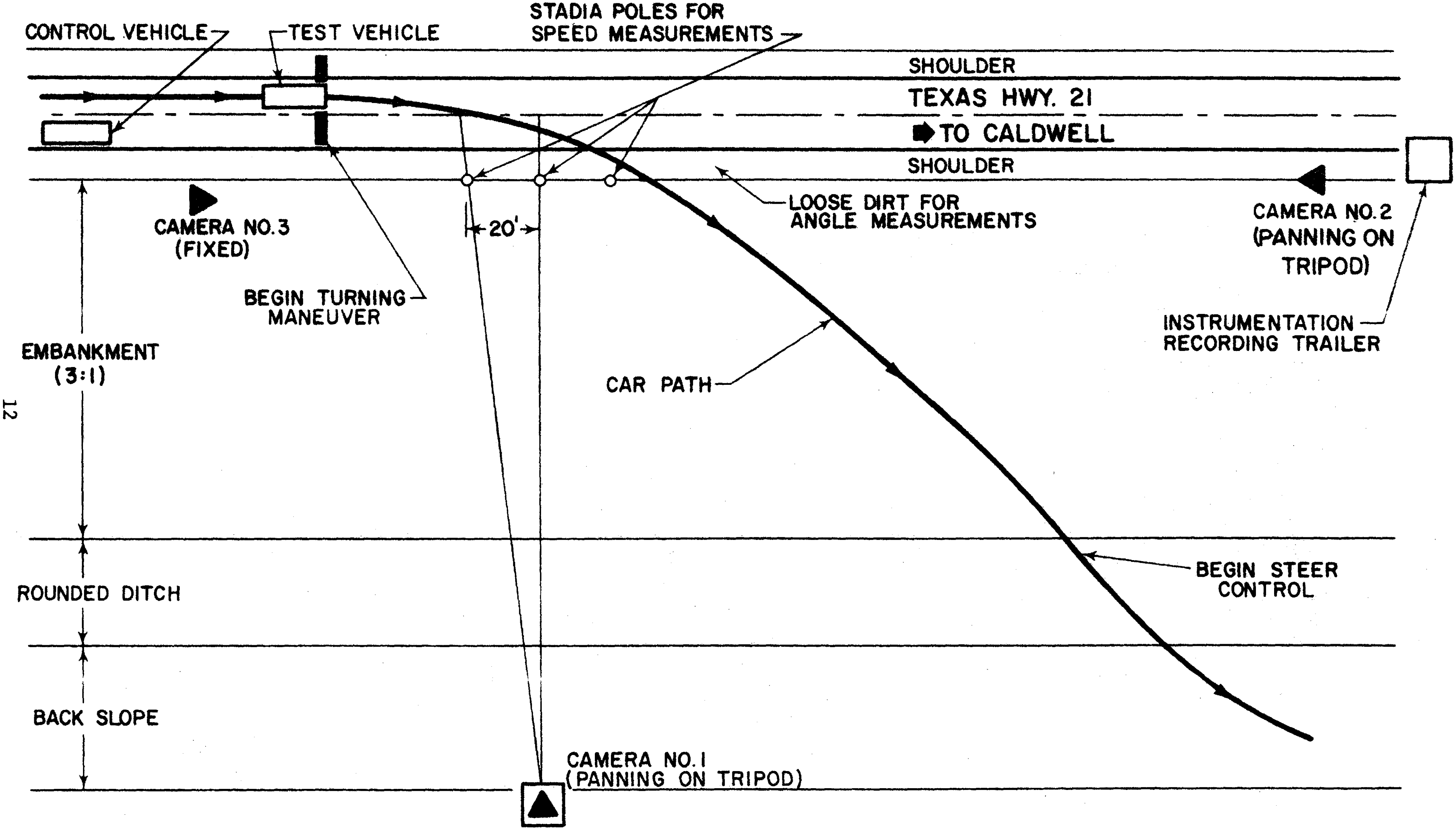


FIGURE 7 - PLAN VIEW OF TEST SETUP

the desired location and encroachment angle.

Upon leaving the roadway, the test car was allowed to traverse the embankment in a no steer control or free-wheeling condition. After reaching the bottom of the slope, steer control was regained and an attempt was made (not always successfully) to prevent the car from going over the back slope.

III. TEST RESULTS AND COMPARISONS WITH HVOSM

A total of six tests were conducted, all in one day, for various encroachment conditions. Table 1 lists the details of each test. The primary reason for the tests was to provide a wide variety of conditions to simulate. Although some mechanical problems were encountered, the tests were considered a success. In addition, the tests provided valuable data on an actual in-service roadway site. Other than tie-rod failures, the test car sustained no significant structural damage and was still in running condition at the conclusion of the tests.

HVOSM Input

Each test was simulated by HVOSM. Input to the program consisted of embankment geometry (Appendix A), vehicle parameters, and test conditions. Volume II of this report contains the entire computer input used in the simulations. Vehicle parameters for the test car were obtained at TTI on another study (4). Sears Supertread tires were used on the test car and their properties were available from the literature (3). A friction coefficient between the tire and the grassy slope was not available. However, skid tests were conducted at the Texas A&M Research Annex on grass and sod similiar to that at the test site. The coefficient was found to be 0.5.

Comparisons

Three types of comparisons were made between test results and HVOSM output. These were plots of the right front tire track, plots of

TABLE 1. TEST CONDITIONS

Test No.	Encroachment Angle (deg)	Encroachment Speed (mph)	Comments
1	9.7	55.7	No problems.
2	13.8	45.1	Tie-rod failure locked right front tire over in full right steer position. Steer control lost and car went over back slope. No other vehicle damage occurred.
3	9.8	45.3	No problems.
4	20.4	47.0	Portable generator powering instrumentation trailer failed, causing loss of accelerometer data. Also, due to the large encroachment angle, sufficient time and space was not available to steer the car back after reaching the ditch bottom and the car went over the back slope. No vehicle damage occurred.
5	8.6	59.9	No problems.
6	13.3	63.6	Tie-rod failure locked right front tire over in right steer position. Steer control was partially lost and car went over back slopes. No other vehicle damage occurred.

vertical acceleration versus time, and computer generated perspective drawings of the simulated vehicle at selected times adjacent to prints of frames from the high speed movie film. Figures 8, 9, 10 and 11 show the comparisons for Test No. 1. The grid lines shown on the tire track plots (see Figure 8) correspond to the chalked grid lines at the test site. All comparisons are given in Appendix C.

Comparisons of the type shown in Figures 9 and 10 were made for Tests 1, 4 and 6 only due to the expense of their production. Prints of selected movie film frames were made for Tests 2, 3 and 5 and are also included in Appendix C.

The vertical acceleration was found to be the predominate component of the resultant acceleration, in both measured and simulated values. As a consequence, only the vertical acceleration component was plotted and compared. In the acceleration plots, as well as the other comparisons, time equal to 0.0 represents the time when the right front tire crossed the pavement's edge. A discussion of the comparisons for each test follows.

Test No. 1--In comparison with the others, this test was the most successful in terms of correlation between test data and HVOSM predictions. This could be expected since with each succeeding test the vehicle's suspension system was subject to progressive degradation. No mechanical failures occurred during Test No. 1, and as seen in Figures 8, 9, 10 and 11, the correlations of path, attitude and accelerations was excellent.

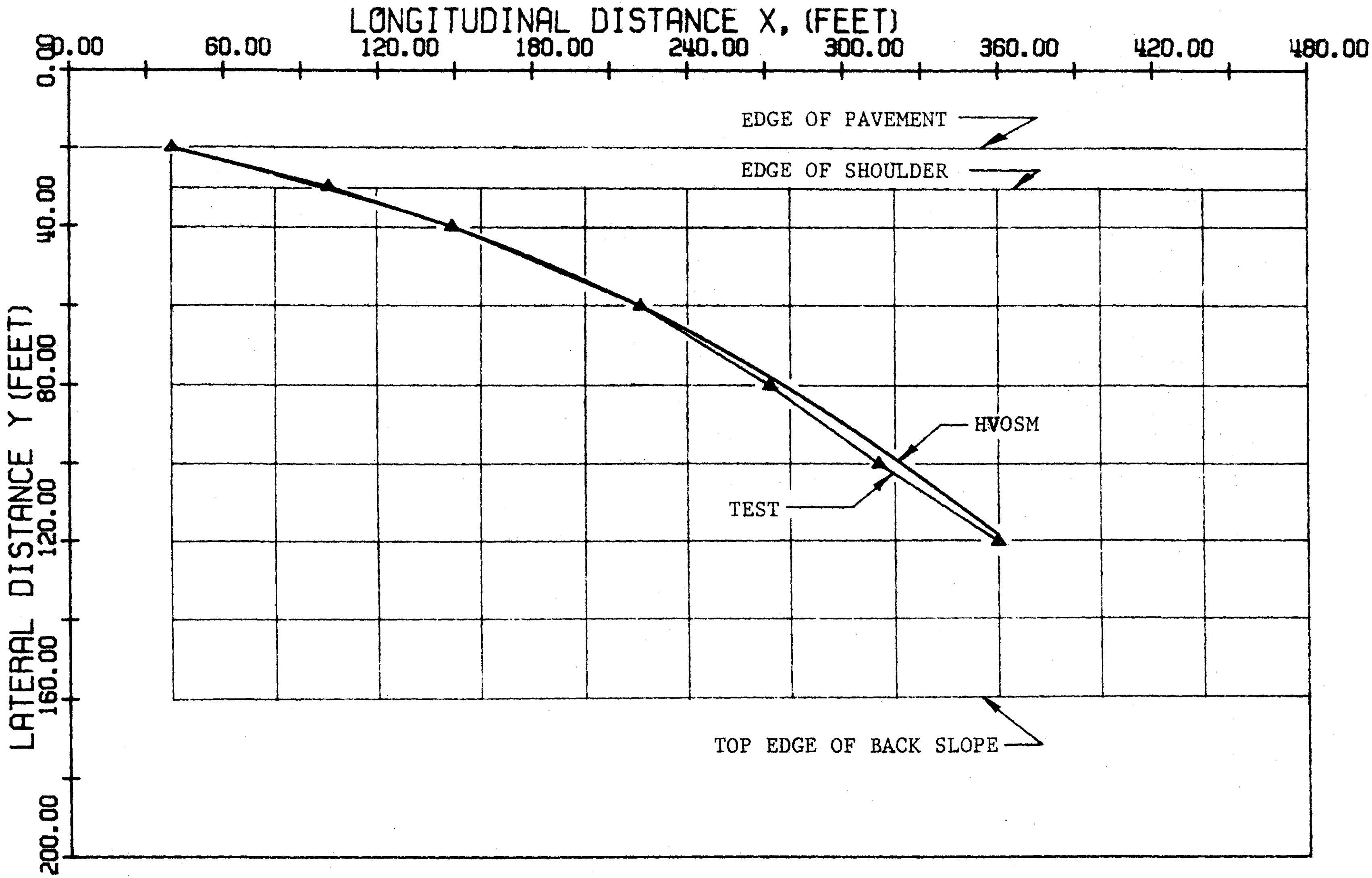


FIGURE 8. RIGHT FRONT TIRE TRACK, TEST NO. 1.

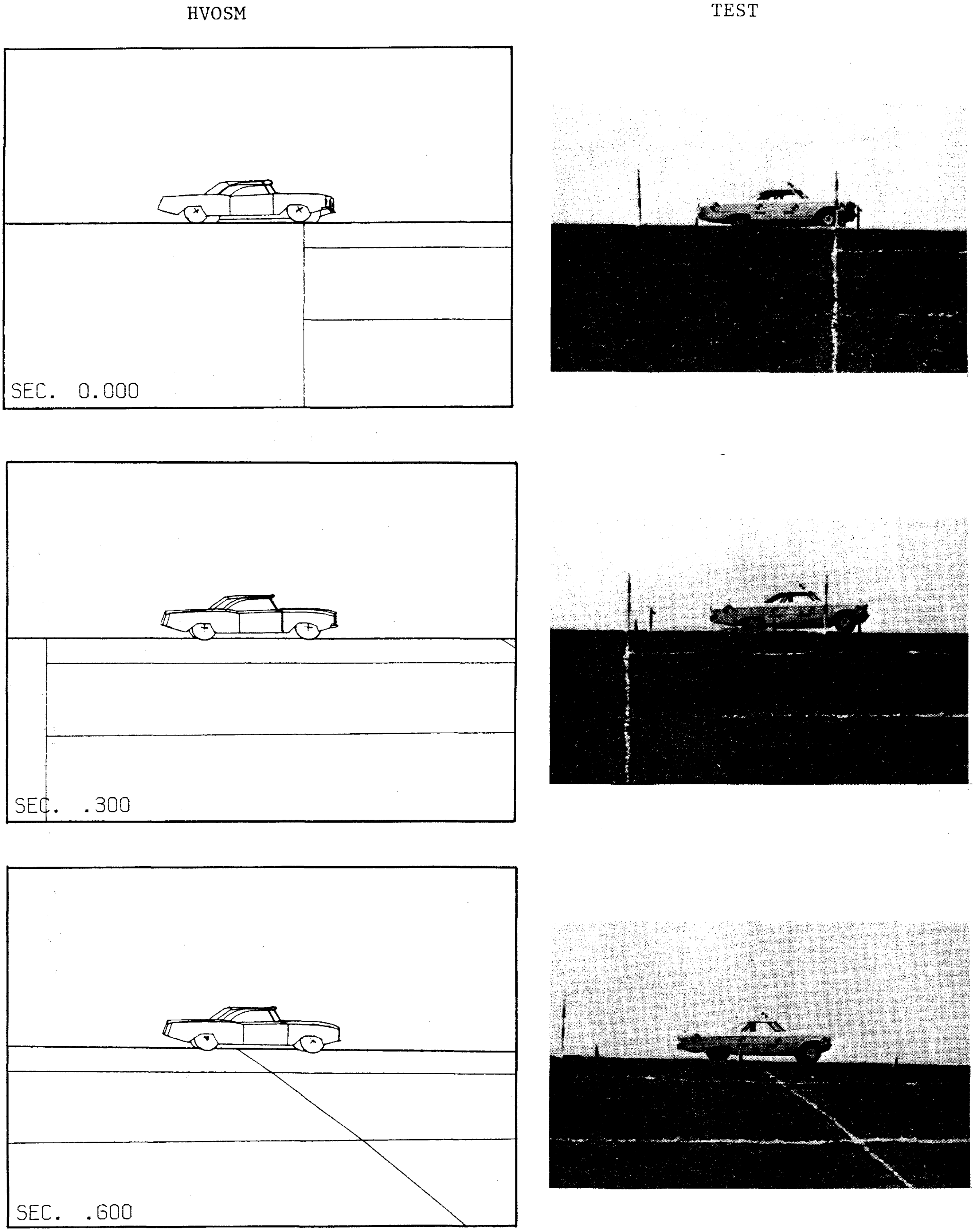


FIGURE 9. HVOSM VERSUS TEST RESULTS, TEST NO. 1, CAMERA NO. 1.

HVOSM TEST

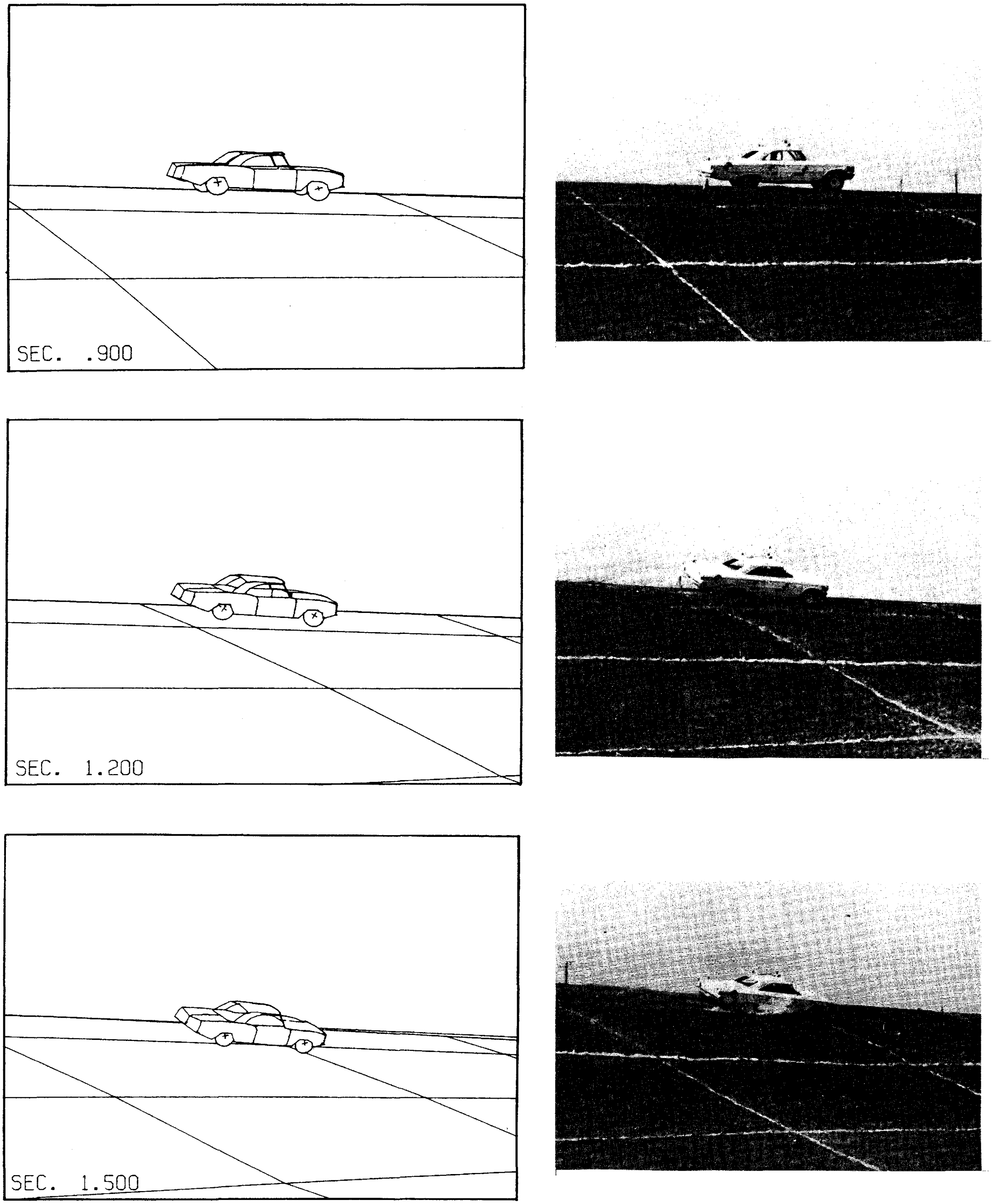


FIGURE 9. CONTINUED.

HVOSM TEST

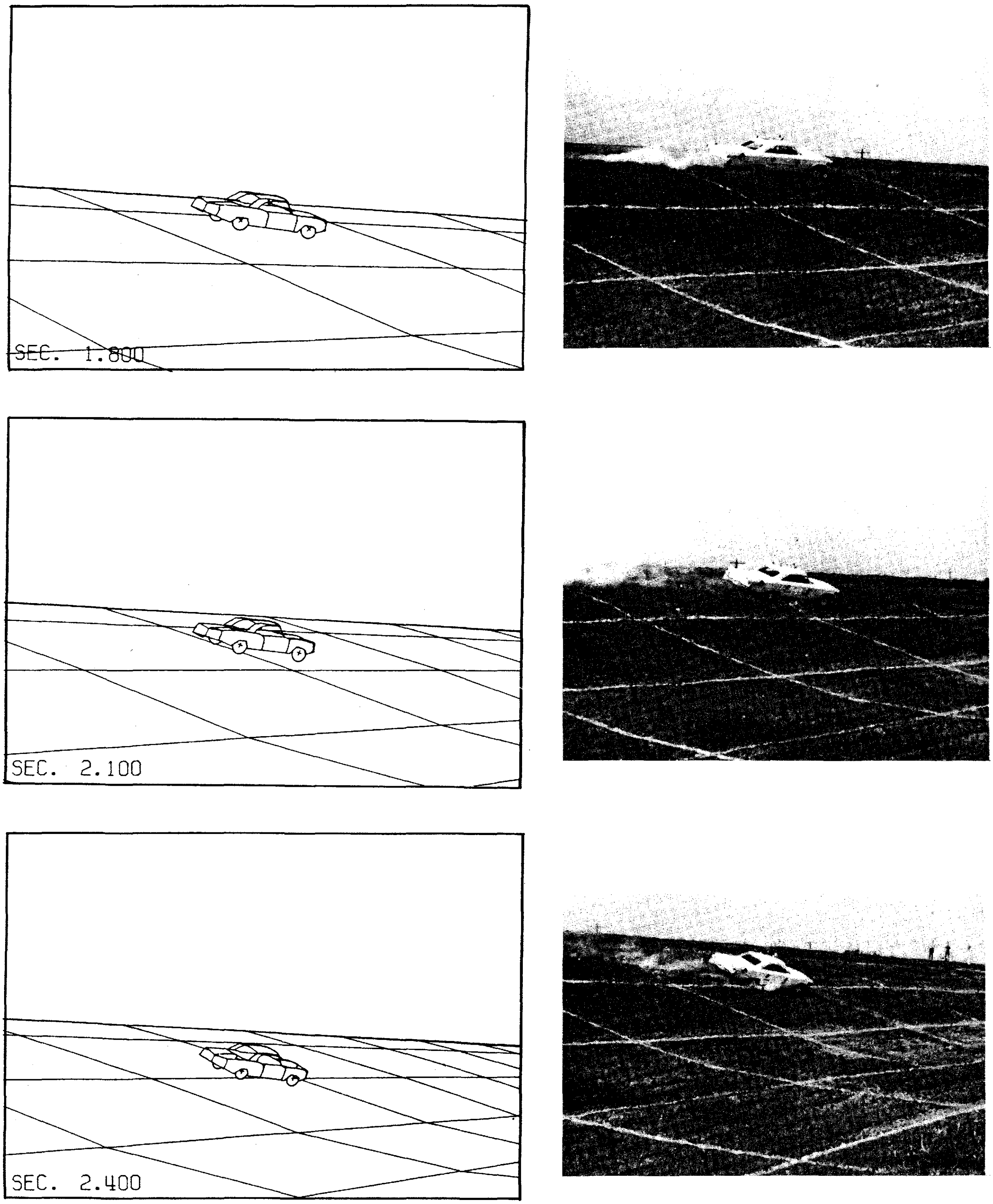


FIGURE 9. CONTINUED.

HVOSM TEST

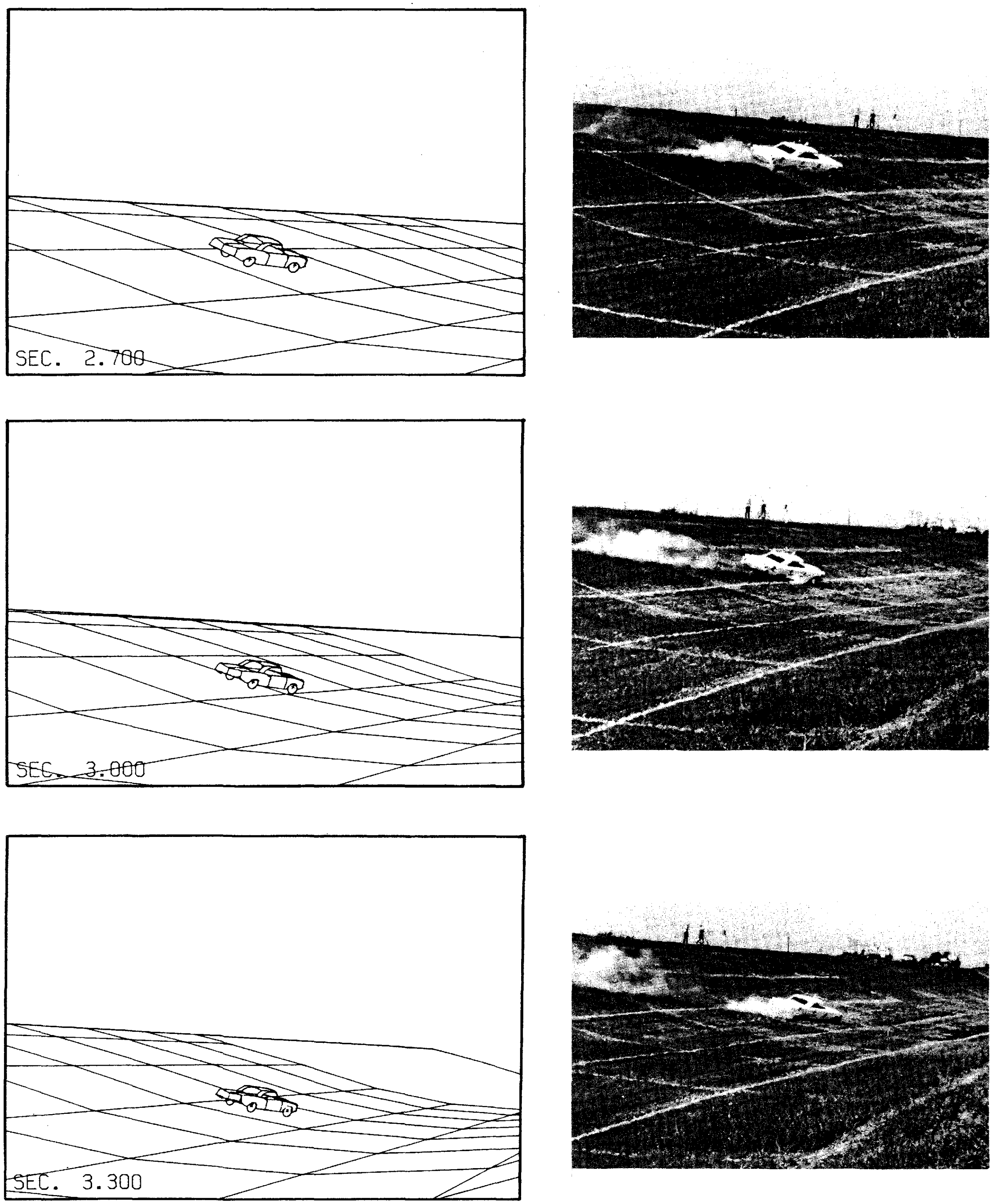
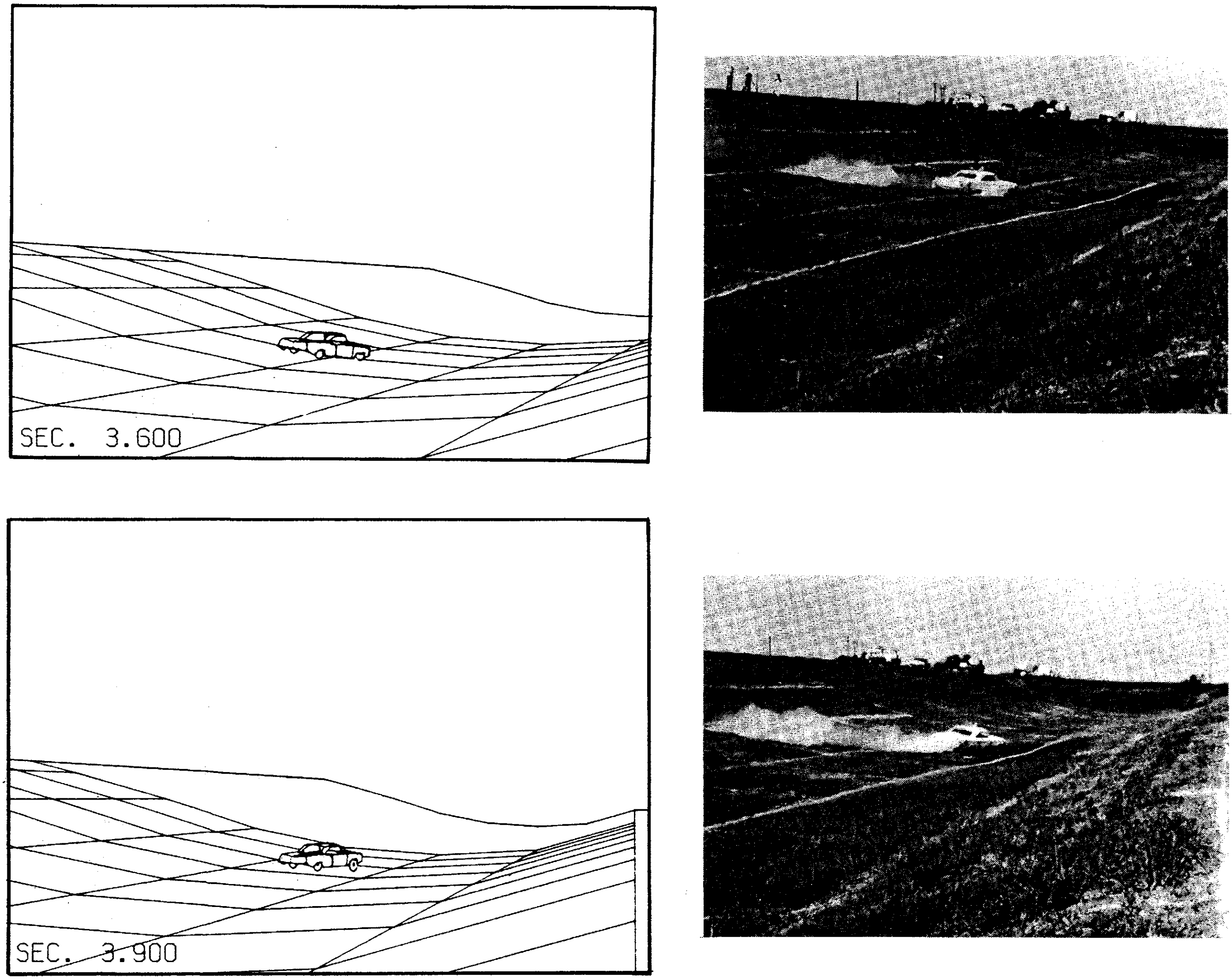


FIGURE 9. CONTINUED.

HVOSM TEST



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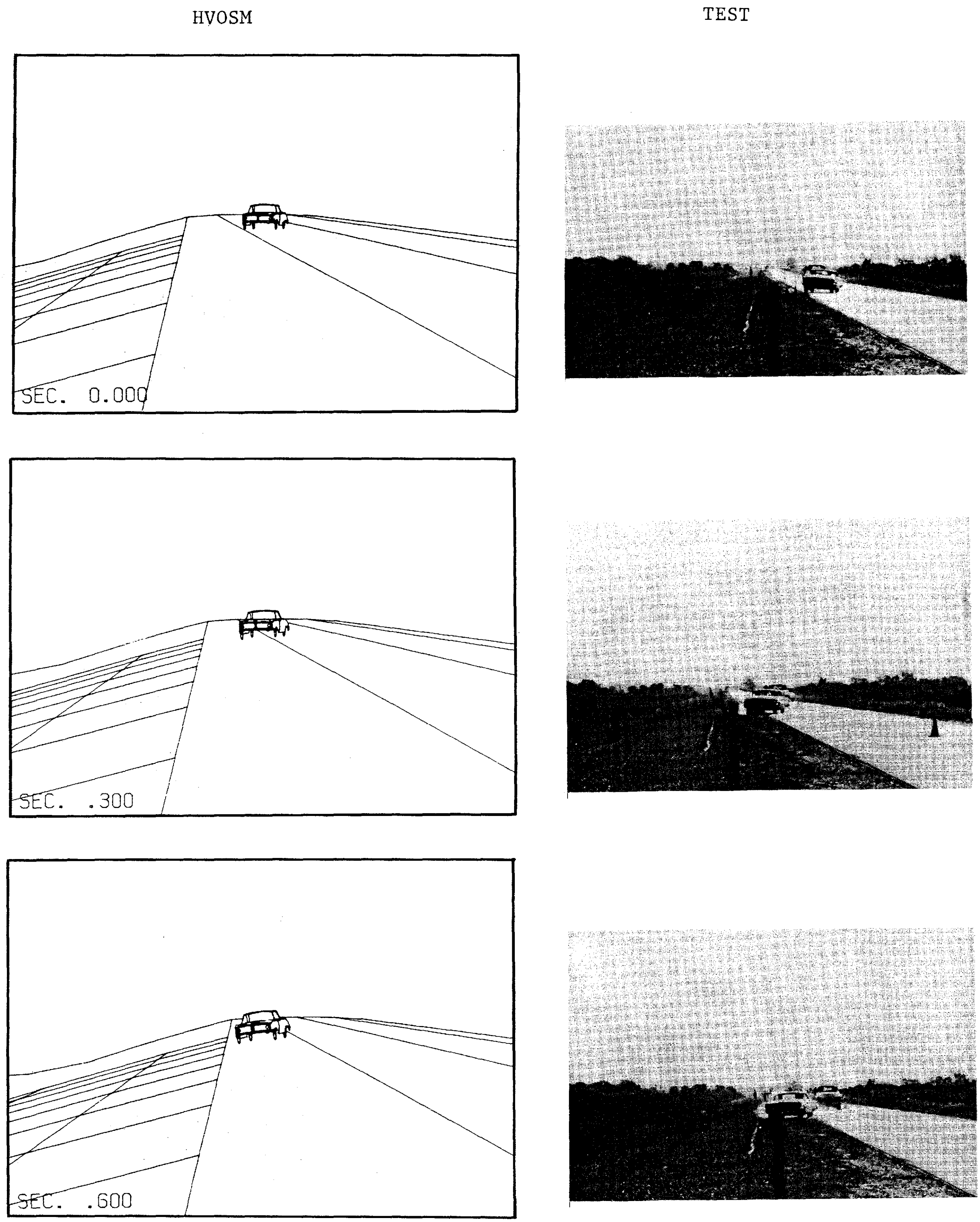

FIGURE 10. HVOSM VERSUS TEST RESULTS, TEST NO. 1, CAMERA NO. 2.

HVOSM TEST

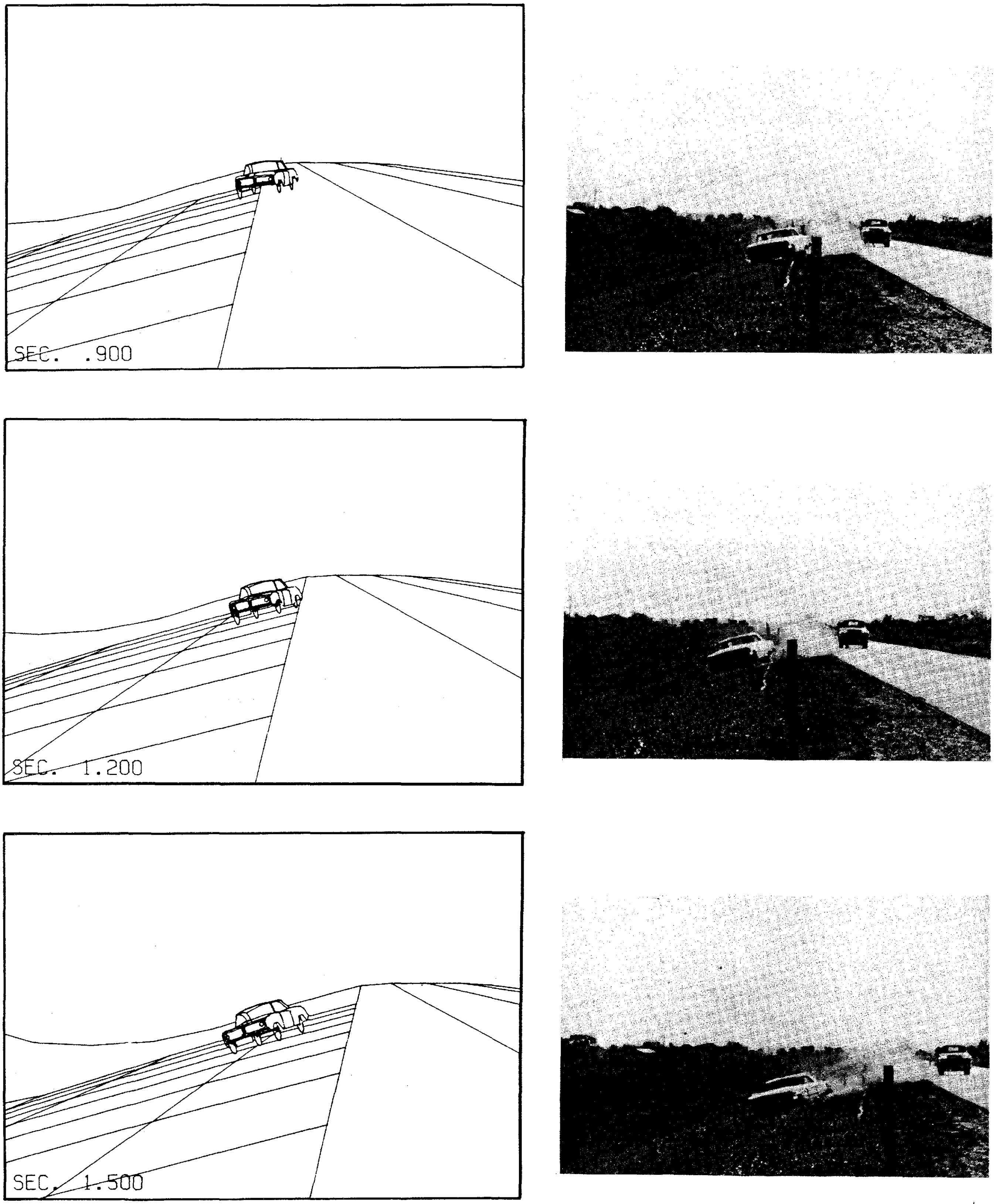

FIGURE 10. CONTINUED.

HVOSM TEST

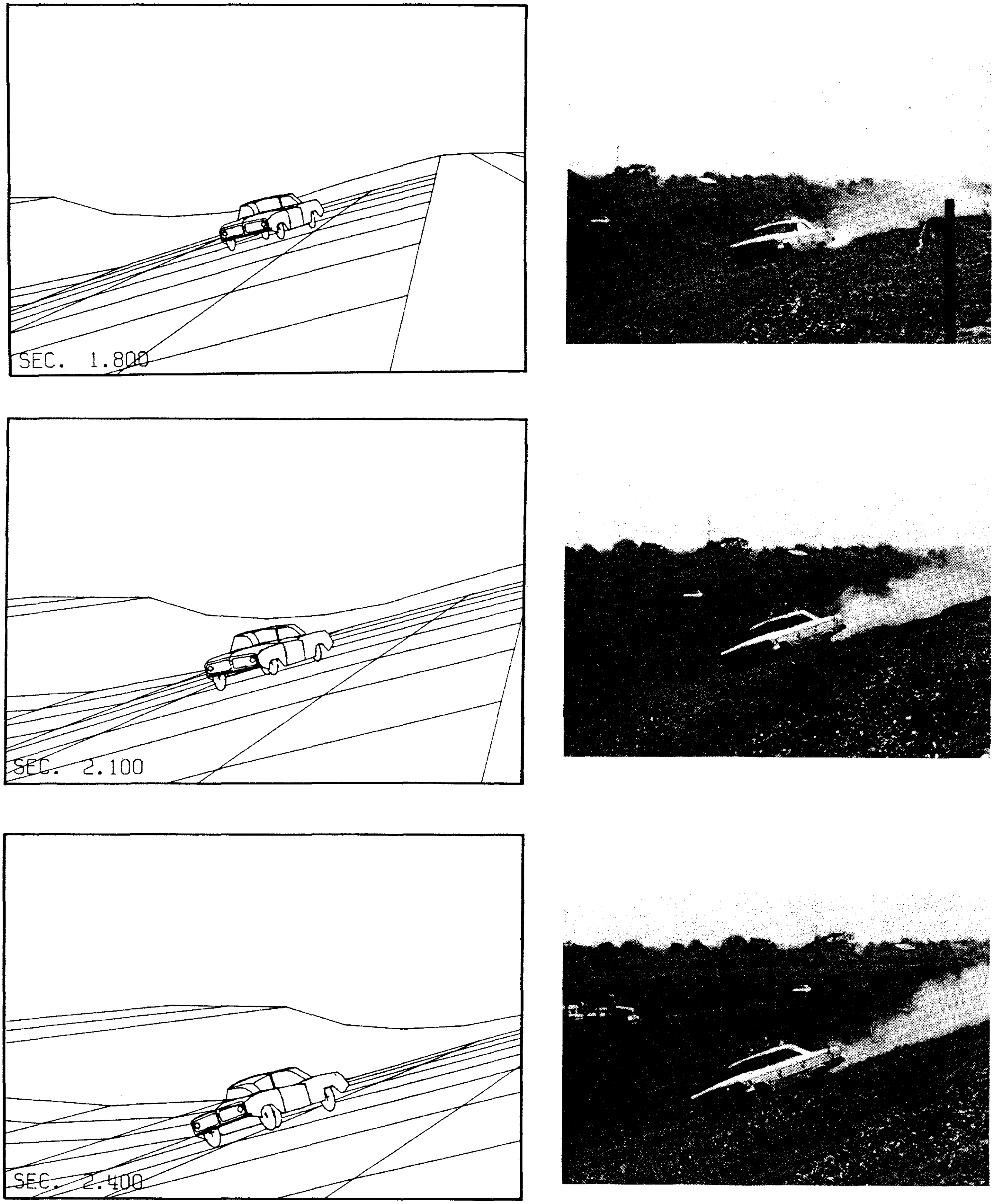

FIGURE 10. CONTINUED.

HVOSM TEST

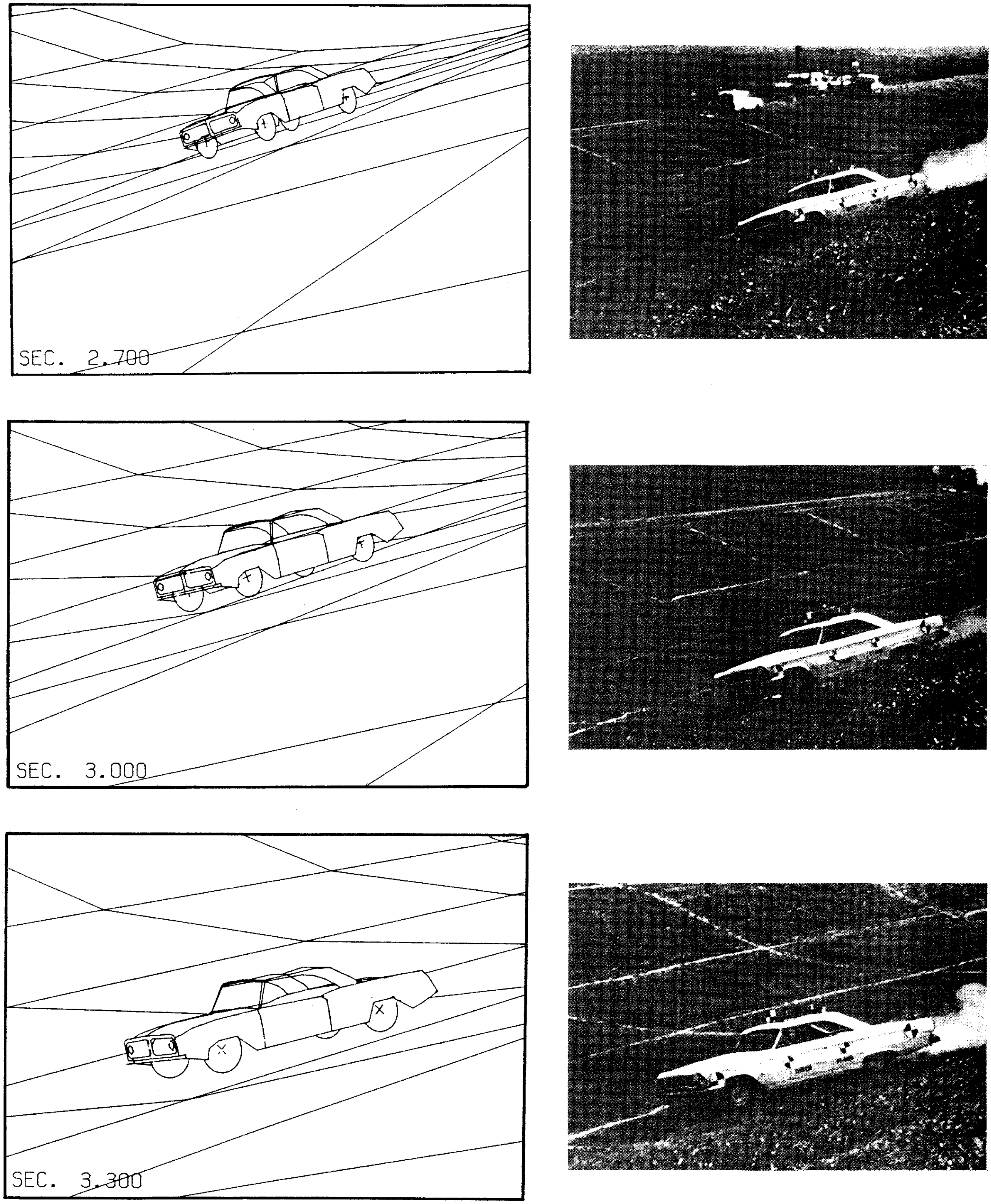

FIGURE 10. CONTINUED.

HVOSM TEST

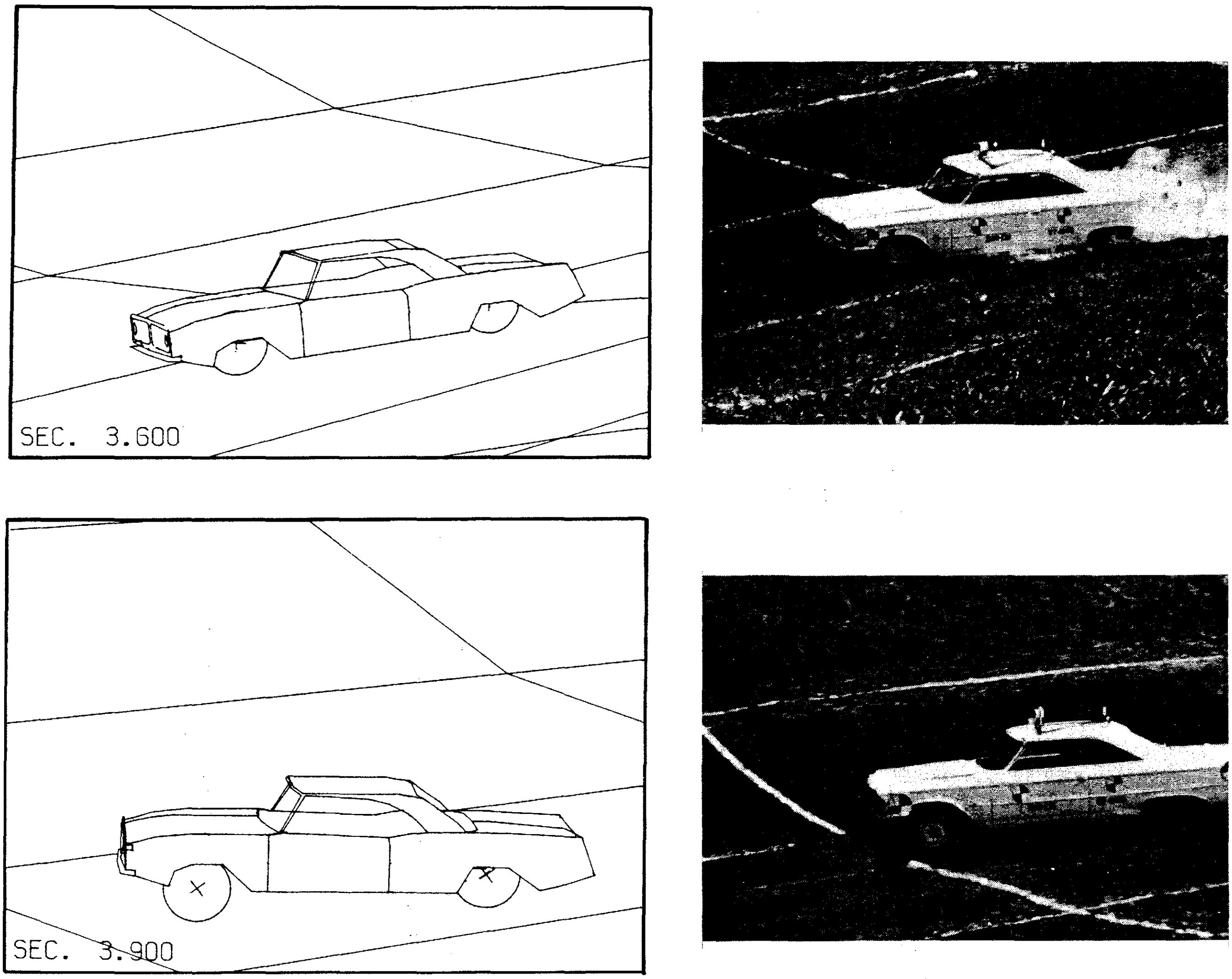

FIGURE 10. CONTINUED.

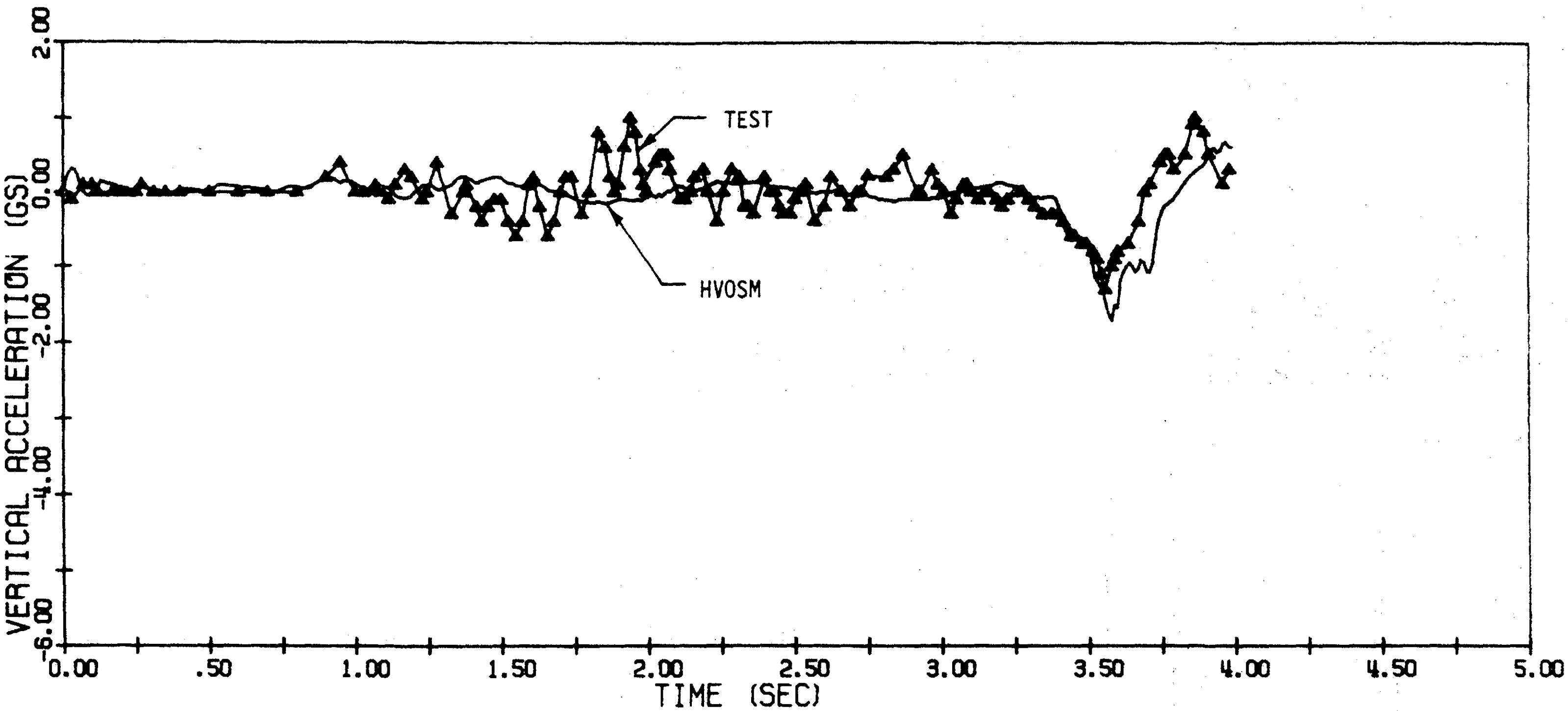

FIGURE 11. VERTICAL ACCELERATION VERSUS TIME, TEST NO. 1.

Test No. 2--By closely studying the movie film, it was determined that the front suspension system was subjected to relativelly high vertical loads approximately 1.6 seconds after the car left the roadway. At that time the right front tire was approximately 27 feet laterally from the edge of the pavement (Y = 47 feet). This loading resulted in a tie-rod failure which locked the right front wheel over in a full right turn position (a steer angle of approximately 22 degrees). Figure 12 shows a photograph of the test vehicle after Test No. 2 with the right front wheel in its locked position. Prediction of such a failure is not within the capabilities of HVOSM. It was therefore decided that an attempt would be made to simulate the effect of the failure. This was done by programming in a locked over steer angle of 22.5 degrees at T = 1.6 seconds after the simulated vehicle left the roadway.

The plot of tire tracts (Figure C-5) shows an increasing difference between test results and HVOSM predictions for Test No. 2. This disparity is attributed primarily to slight rutting that occurred in the test, an occurrence which could not be simulated by the version of HVOSM used by TTI at the time of this study. Although the grassy slope was hard and well compacted, the extreme steer angle that resulted when the wheel locked caused the tire to dig in slightly as shown in Figure 13. As a consequence larger than predicted side forces occurred, causing the test car to turn more sharply than the simulated car.

The mechanical failures and subsequent path differences undoubtedly contributed to the differences that occurrred between the measured and predicted vertical accelerations in Test No 2 (see Figure C-8). A summary of the factors which probably caused differences between predicted and measured

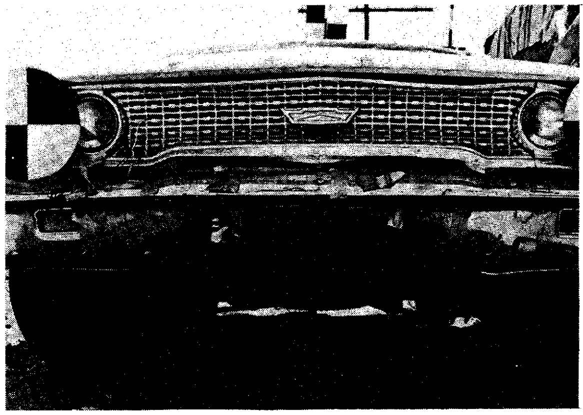

FIGURE 12. TEST CAR AFTER TEST NO. 2.

FIGURE 13. TIRE RUTTING.

acceleration in Test No. 2 as well as the other tests, follows:

(1) *Terrain Irregularieties*-- Limitations on the number of grid points that could be measured and that could be accepted by HVOSM precluded an exact simulation of the terrain. Local irregularities such as bumps and indentations could not be simulated. They undoubtedly caused unpredictable accelerations. In most cases, accelerations caused by irregularities would not be of major significance with regard to accident severity. The irregularities may, however, cause mechanical failures in the suspension system which could lead to a more hazardous condition later.

(2) *Type and Location of Accelerometer Support*-- The vibratory motion of both the acclerometer support and the vehicle's structural framework caused accelerations in the test car which, due to the limitations of the structural idealization, could not be computed by HVOSM. The degree to which structural vibration contributed to the measured values is unknown. It is probable, however, that the effect was small and would be characterized by relatively high frequencies of vibration.

(3) *Path Variations*--When the predicted and actual path did not closely compare, there was a twofold effect on the acceleration comparisons. First, the test car and the simulated car traversed different terrain which obviously caused some differences in accelerations. Secondly, the lateral position (in the Y direction) of the test car at any given time differed from the simulated vehicle. For example, in Test No. 2, the test car began traversing the back slope at approximately T = 4.0 seconds, while the simulated car entered it at approximately T = 4.6 seconds. Note that if the HVOSM curve in Figure C-8 were shifted to the left the comparison would

improve.

(4) *Tire Rutting*-- As discussed in a previous paragraph, some tire rutting occurred, especially for large steer angles. By studying the movie film it was observed that the front portion of the vehicle would undergo a bouncing or skipping type of motion during these large steer angles. The instability apparently caused some fluctuations in the measured accelerations that were not simulated by HVOSM.

Prior to conducting Test 3, the test car was returned to the Research Annex and new tie rod assemblies were installed. The steering system was then realigned.

Test No. 3--Comparisons of the tire track for this test (Figure C-9) show good agreement up to the point where steer control was regained in the test car (at Y + 90 feet approximately). The simulated car remained in a no-steer control mode throughout the run.

A comparison of vertical accelerations for Test 3 (Figure C-12) shows that the HVOSM trace approximated a mean of the test trace. Fluctuations in the test values are attributed to terrian irregularaties and the effects of structural vibrations in the vehicle, as previously discussed. The relatively large accelerations of HVOSM between 4.5 seconds and 5.0 seconds were caused by the simulated vehicle entering the back slope.

Test No. 4--From the movie film it was observed that the front wheels of the test car went from a zero degree steer angle at T = 0.50 seconds to a full right turn at T = 1.0 seconds. They remained in a full right position until approximately T = 2.0 seconds, at which time they returned to a zero degree steer angle and remained at approximately zero for the remainder of the test. No suspension damage occured during the test. The remote control operator reported that attempts to steer back to the left after the car reached the ditch bottom (at about T = 2.4 seconds) were unsuccessful. There was apparently some malfunction in the control system. Nevertheless, it is probable that the car could not have been redirected prior to going over the top of the back slope due to the large encroachment angle the car had upon entering the ditch bottom.

It is not certain what caused the front wheels in Tests 2 and 4 to turn sharply to the right after entering the side slope. However, it is interesting to note that the paths of Test 2 and 4 were almost identical after the car reached a lateral distance of 20 feet off the edge of the pavement. In both tests the wheels turned sharply to the right at a lateral distance of approximately 27 feet off the edge of the pavement. An inspection of the side slope in that particular area showed no major irregularities, although there were local indentations and bumps which could have caused the problems.

In HVOSM the steer angle of the simulated car was programmed to be similar to that of the test car for Test 4. Upon leaving the roadway, the steer angle was zero up to T = 0.5 seconds. The steer angle was then increased linearly up to 22 degrees at T = 1.0 seconds. It was held at 22 degrees up to T = 2.0 seconds and was then decreased linearly back to zero at T = 2.5 seconds, where it remained for the duration of the simulation.

The tire track comparisons between test and simulation (Figure C-13) showed reasonable agreement. The smaller turning radius of the test path is attributed to the added side forces created by the slight rutting that occurred during the test.

Position and attitude comparisons from the perspective drawings and photos (Figures C-14 and C-15) show good agreement, especially during the side slope and ditch traversal phase of the test. Divergence in positions in the latter phase is due to braking of the test vehicle. No braking was applied to the simulated vehicle.

The generator supplying power to the instrumentation trailer failed during Test 4 and all accelerometer data were lost. A plot of the HVOSM accelerations for Test 4 is given in Figure C-16.

Test No. 5-- No technical problems occurred during Test 5. The car left the road at a relatively shallow angle (8.6 degrees) and remained on the side slope during most of the test.

Good agreement between test and HVOSM tire tracks was obtained through most of Test 5. It can be seen in Figures C-17, C-18 and C-19 that steer control of the test car was regained and the car was steered back up the slope before it reached the ditch bottom. Note in Figure C-17 the change in path curvature at an X distance of about 280 feet and a Y distance of about 66 feet. The ditch bottom begins at a Y distance of approximately 100 feet. The remote control operator related that he was "determined not to allow the car to hit the cotton patch again."

Although not planned, it is significant that steer back on the side slope was attempted. It had been speculated that if such a maneuver occurred, the car would likely roll over. Analysis of the film for this test showed that the car never appeared to be in danger of rolling over. It would be premature to conclude, however, that there are no conditions which would cause this car or any other car to roll over on a 3.5:1 side slope. As a matter of fact, tests at TTI on other studies have shown that when subjected to a particular sequence of severe steering and braking maneuvers, certain automobiles will roll over on a flat concrete pavement.

Reasonably good comparisons of accelerations were obtained in Test 5 (Figure C-20), especially during the first half of the test. For the remainder of the test, the amplitude of the accelerations was comparable, but their variation with time differed. Differences in the latter phases of the test are attributed to path differences and differences in speed between tests and HVOSM.

Test No. 6--This test began with a moderate encroachment angle (13.3 degrees) and a relatively high encroachment speed (63.6 mph). Large steer angles again occurred during this test. Note in the pictures of Figures C-22 and C-23 that the front wheels turned sharply to the right at approximately T = 1.2 seconds (or Y = 50 feet, approximately). They remained in this position for about one second and then returned to approximately a zero steer angle. Examination of the suspension system after Test 6 showed that a tie-rod failure had again occurred, causing the right front tire to be locked in a partial right turn position (about 10 degrees). Repeated testing of the car had obviously caused degradation in the suspension systen (loose ball joints, out of alignment, etc.).

It was decided to simulate Test 6 in HVOSM by assuming a free-wheeling condition (no steer control) throughout the test. In so doing the extent to which steer irregularities in the test affected the vehicle's path and attitude could be determined. As shown in Figure C-21, the test and HVOSM paths agreed up to a Y = 70 feet, approximately. From that point the two paths began to diverge with the test vehicle turning more to the right. The attitude of the test and simulated vehicles remained relatively stable.

Differences in predicted and measured accelerations are attributed to the factors presented in the discussion of Test No. 1. The test car can be seen bouncing considerably in the pictures of Figures C-22 and C-23, causing relatively large vetical accelerations (at T = 1.8 seconds and at T = 2.5 seconds). The test car enters the back slope at about T = 3.3 seconds while the HVOSM car enters it at T = 3.5 seconds. The large acceleration in the HVOSM car at T = 3.5 seconds was caused by the back slope. The test accelerations were not larger during the back slope traversal because the test car brakes were applied just prior to entering the back slope. The remote control operator sensed that the car could not be redirected and was therefore attempting to stop it.

Summary

From an overall assessment of the comparisons, HVOSM was generally in reasonable agreement with the test results. The differences that did occur are attributed primarily to the mechanical failures in the test car's suspension system and their subsequent effects on the dynamic behavior of the car. It is known that the condition of the suspension system continued to deteriorate with each test. It is not known, however, just how much the suspension system deterioration contributed to causing each failure.

A wide variety of encroachment conditions were encountered in the study. Encroachment speeds ranged from 45.1 mph to 63.6 mph, and encroachment angles ranged from 8.6 degrees to 20.4 degrees. In addition, suspension failures (Tests 2 and 6) and the steer back on the side slope (Test 5) created special test conditions. This range of test conditions is believed to encompass many of the conditions that occur in run-off-the-road accidents. It is significant that for these conditions both test and simulation results showed that a car could traverse the embankment with no tendency to roll over.

Reasonably good correlations were obtained between test and predicted accelerations for Tests 1, 3 and 5, where no mechanical or electrical failures occurred. It is significant that in all six tests both measured and predicted accelerations were below tolerable limits as established in previous studies for unconstrained occupants (1).

IV. CONCLUSIONS

1. The Highway-Vehicle-Object-Simulation-Model can accurately predict the dynamic behavior of an automobile traversing an embankment, with the exception of those instances when mechanical failures occur in the vehicle (see conclusion 4).

2. As a consequence of conclusion 1, the criteria on guardrail need, presented in Research Report 140-4(1), has been substantiated.

3. An automobile and its occupants can traverse a 3.5:1 side slope with a flat bottom ditch 20 feet below the roadway with relative ease and tolerable accelerations for a wide variety of encroachment conditions.

4. HVOSM is incapable of predicting mechanical failures which may occur in an automobile and the subsequent effects of such failures. The suspension failures that occurred in two of the six tests were attributed in part to the condition of the test car's suspension system. The condition of the suspension system degenerated with each test.

5. Although vehicle control was lost due to mechanical failures in two of the six tests, the vehicle remained in a stable attitude and traversed the embankment without any serious problems.

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2. McHenry, R. R., and Segal, D. J., "Determination of Physical Criteria for Roadside Energy Conversion Systems," Cornell Aeronautical Laboratory Report No. VJ-2251-V-1, July, 1967.

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4. Weaver, G. D., Marquis, E. L., and Luedecke, A. R., Jr., "Vehicle Dynamics on Roadway Slopes," Report No. 626A-1, Texas Transportation Institute, Texas A&M University, October, 1971.

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6. Weaver, G. D., Ross, H. E., Post, E. R., and Olson, R. M., "Effect of Curb Geometry and Location of Vehicle Behavior," Final Report on Task Order No. 5, NCHRP Project 20-7, Texas Transportation Institute, Texas A&M University, October 1972.

APPENDIX A

PROFILES AND ELEVATIONS OF TEST SITE

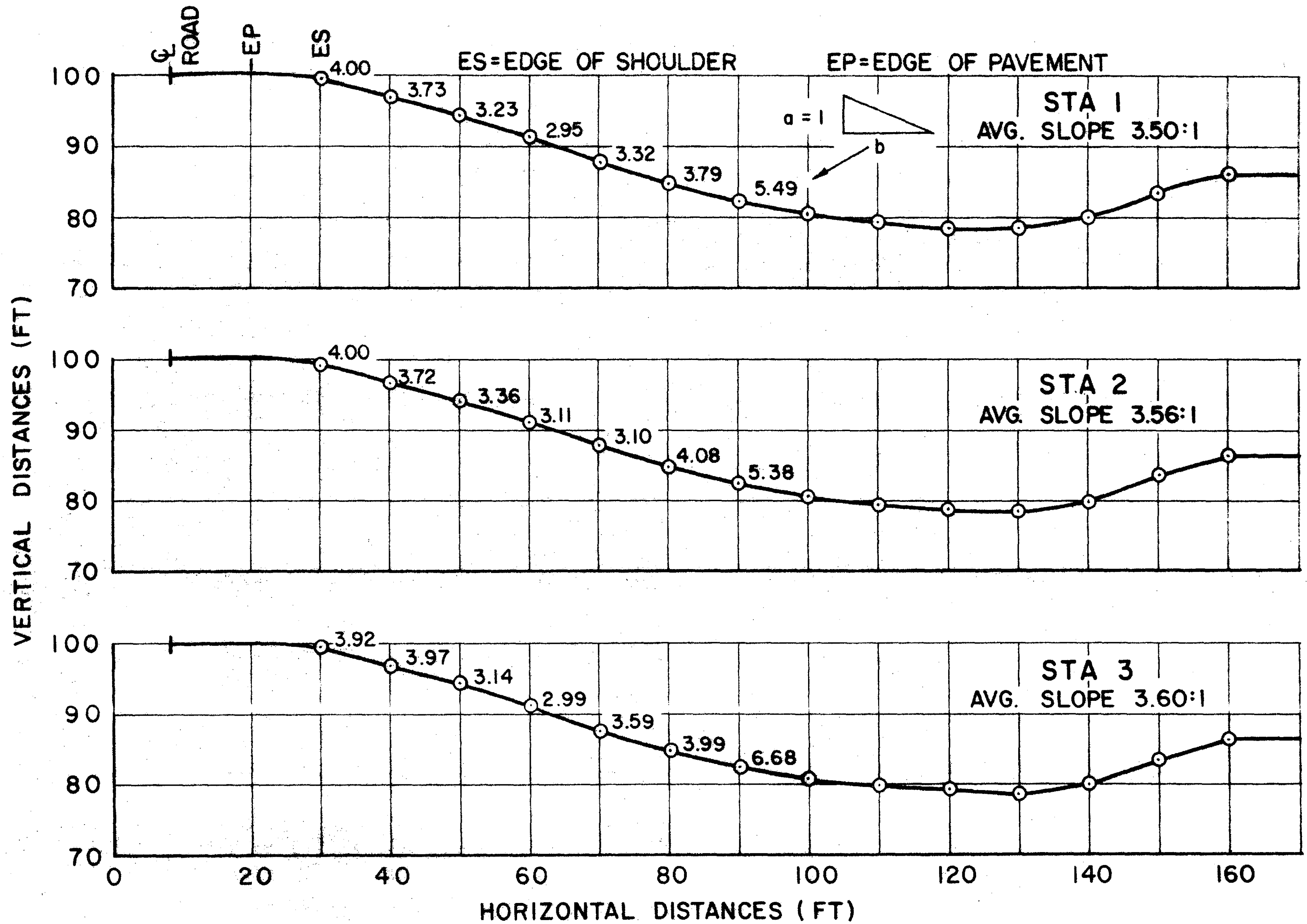


FIGURE A-1 - EMBANKMENT PROFILES ON SH 21

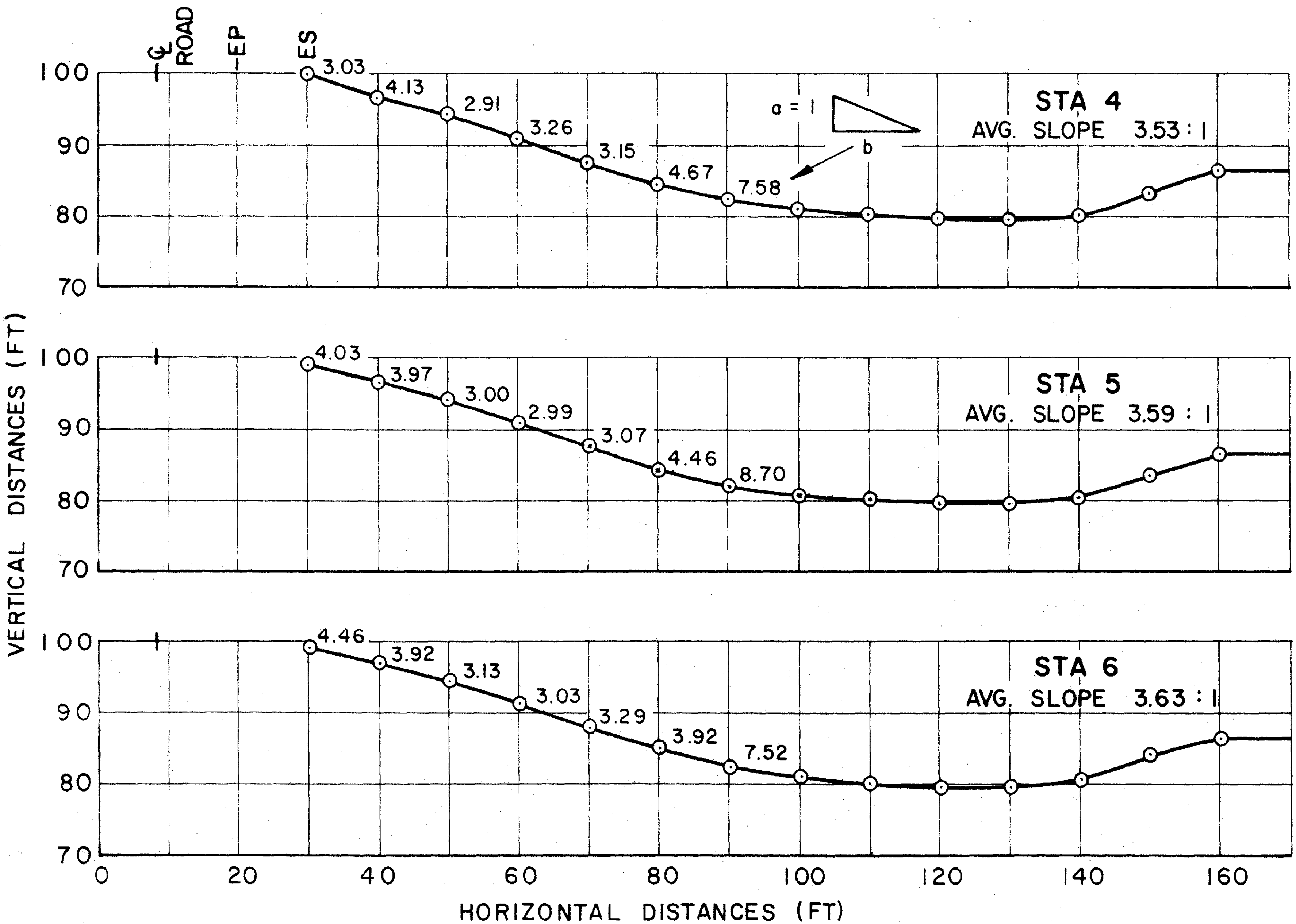


FIGURE A-1 - CONTINUED

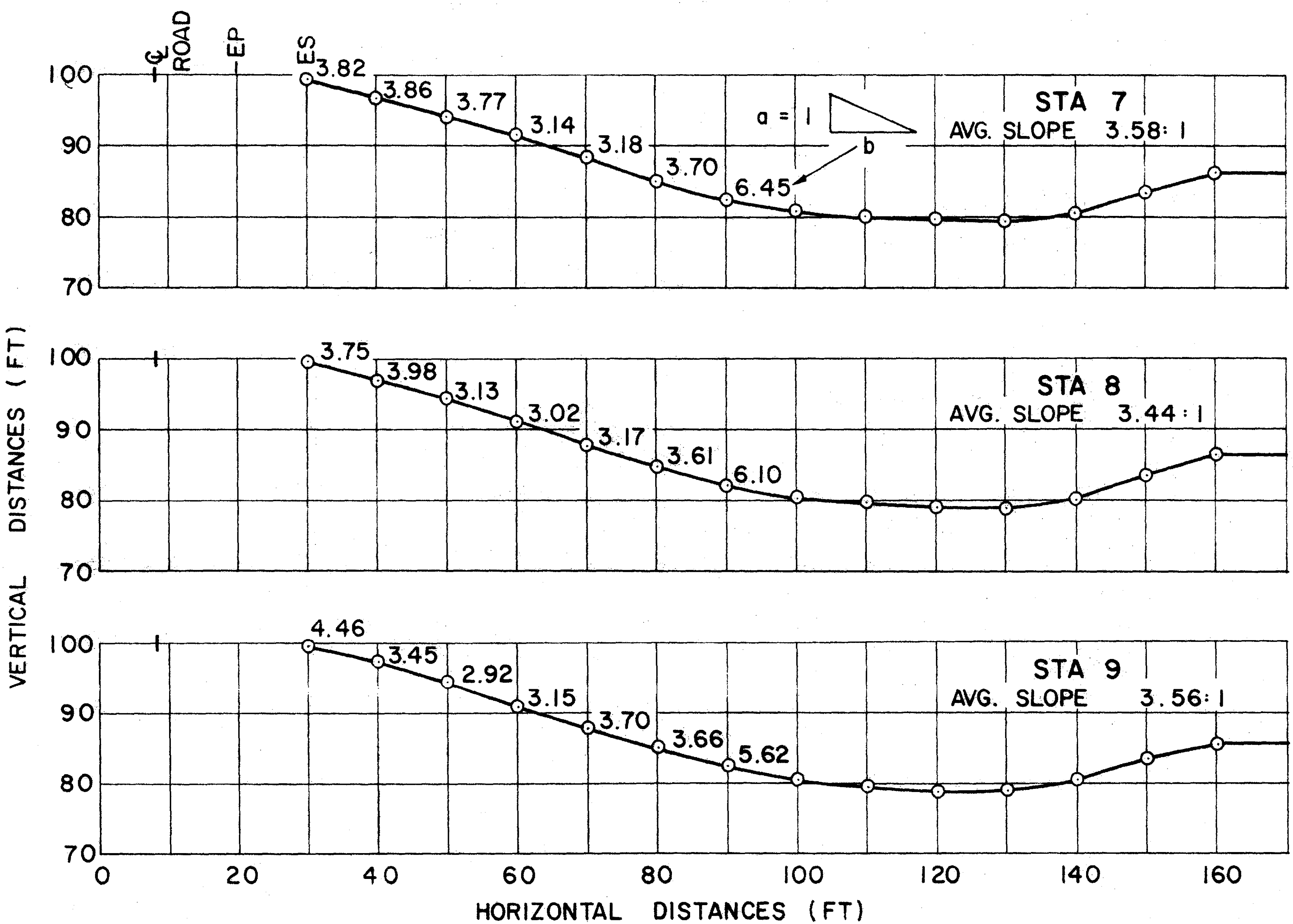


FIGURE A-1 – CONTINUED

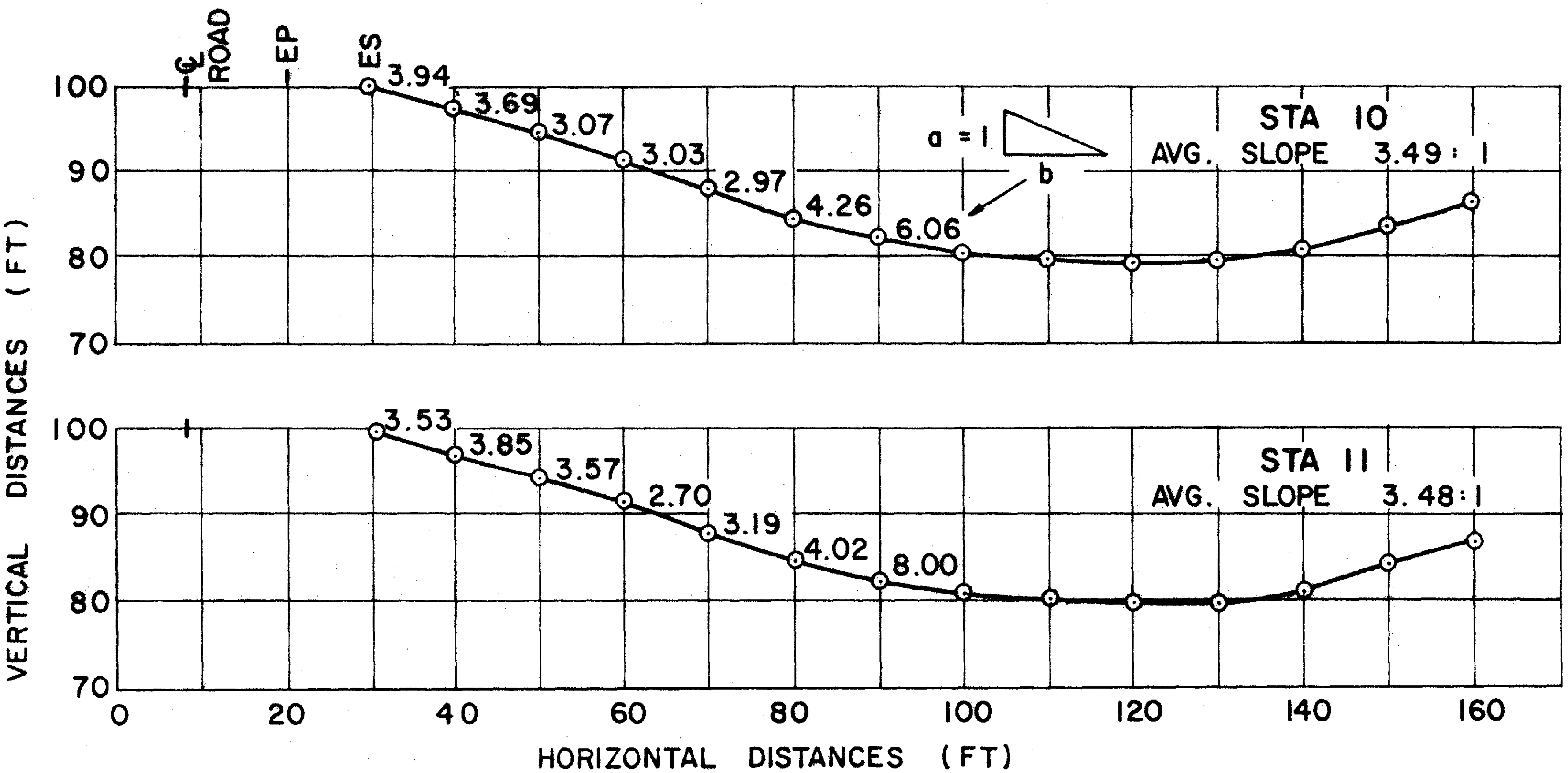


FIGURE A-1 — CONTINUED

TABLE A-1

EMBANKMENT ELEVATIONS ON SH 21

HORIZONTAL DISTANCE (FT)	ELEVATIONS (FT)										
	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6	STA 7	STA 8	STA 9	STA 10	STA 11
CENTERLINE OF ROAD	100.24	100.24	100.16	100.06	100.00	100.09	100.24	100.24	100.37	100.71	100.79
EDGE OF PAVEMENT	100.23	100.20	100.04	99.90	99.85	99.98	100.10	100.22	100.24	100.56	100.65
EDGE OF SHOULDER	99.50	99.30	99.23	100.01	99.12	99.20	99.30	99.52	99.42	99.90	99.97
40	97.00	96.80	96.68	96.71	96.64	96.96	96.68	96.85	97.18	97.36	97.08
50	94.32	94.11	94.16	94.29	94.12	94.41	94.09	94.34	94.28	94.65	94.48
60	91.22	91.13	90.98	90.85	90.79	91.22	91.44	91.15	90.86	91.39	91.68
70	87.83	87.91	87.63	87.78	87.45	87.92	88.26	87.84	87.69	88.09	87.97
80	84.82	84.68	84.84	84.61	84.19	84.88	85.12	84.69	84.99	84.72	84.84
90	82.18	82.25	82.33	82.47	81.95	82.33	82.42	81.92	82.26	82.37	82.35
100	80.36	80.39	80.82	81.15	80.80	81.00	80.88	80.28	80.48	80.72	81.10
110	79.33	79.34	79.81	80.32	80.18	80.09	80.04	79.73	79.42	80.01	80.45
120	78.62	78.67	79.15	79.78	79.76	79.53	79.81	78.97	78.69	79.47	80.02
130	78.45	78.39	78.63	79.48	79.46	79.53	79.39	78.84	79.03	79.70	79.91
140	80.04	79.89	80.08	80.08	80.18	80.52	80.54	80.07	80.58	81.15	81.27
150	83.42	83.65	83.37	83.25	83.53	83.92	83.30	83.56	83.64	83.83	84.40
BACK SLOPE EDGE	86.12	86.21	86.33	86.38	86.49	86.20	86.23	86.38	85.35	86.48	87.03

APPENDIX B

REMOTE VEHICLE CONTROL SYSTEM

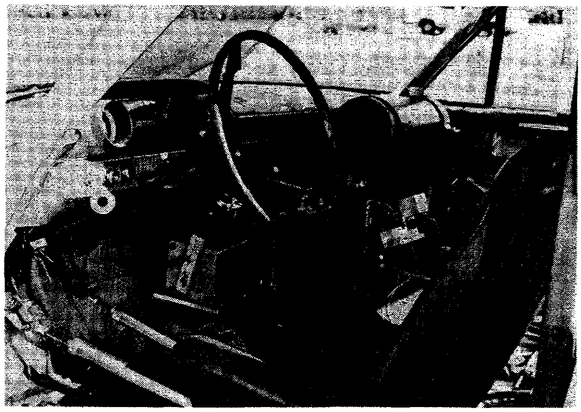
REMOTE VEHICLE CONTROL SYSTEM

The TTI Remote Vehicle Controller (RVC) was designed to perform 5 functions normally accomplished by an automobile driver. The controller is used in research tasks which are too dangerous or which cannot be proper'y accomplished by a live driver. Photos of the major components of the RVC are shown in Figure B-1.

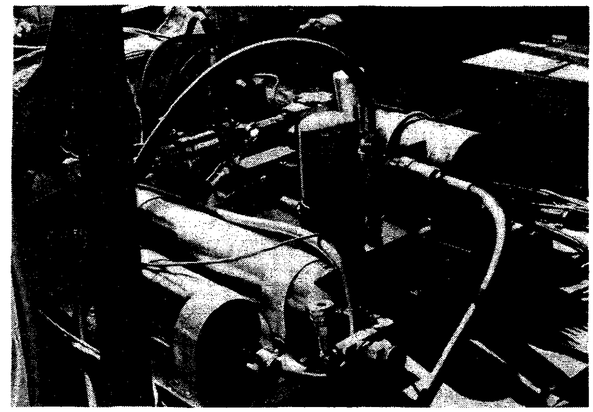
The Test System consists of the remotely controlled vehicle, and a chase vehicle. The chase vehicle contains a driver, a transmitter operator and a five channel digital-proportional transmitter. The controlled vehicle contains a five channel digital-proportional receiver, a hydraulic servo system, an electrical servo system and a pneumatic system. Hydraulic power is achieved by a hydraulic pump driven by the controlled vehicle engine. Pneumatic power is stored in a 1 gallon tank precharged to 1500 psi. Electrical power is provided by an on-board battery power pack and by the controlled vehicle's battery.

By manipulating the appropriate controls on the transmitter, the operator can control the following functions:

1. Steering is proportionally controlled with a slew rate capability of 1100 degrees per second and adjustable level control for full-scale. Fifty foot-lbs of steering torque is available.
2. Accelerator depress is proportionally controlled with capability of six inches stroke at 8 lbs. of force. Other stroke-force combinations are readily available.
3. Upon command the steering servo can be decoupled from the



(a) Steer, accelerometer, brake, and clutch servomechanisms



(b) Pneumatic and hydraulic hardware

(c) Telemetry, signal conditioner and radio control packages

FIGURE B-1. PHOTOS OF TEST CAR INSTRUMENTATION.

steering clutch. This is a binary command which allows the vehicle to be "free wheeling" upon command and to regain controlled steering upon command.

4. Brake application is a binary function operated from the pneumatic supply.

5. Automobile clutch depress and release is available as a binary function for use on vehicles having standard transmissions.

An abort function in the system applies the vehicle brake and removes ignition power if either of the following signals are lost:

(a) radio transmitter carrier signal

(b) hydraulic pressure

(c) pneumatic pressure

(d) vehicle electrical power source or on-board battery pack

The block diagram in Figure B-2 depicts the relationships among the various components of the system.

The following data signals generated within the controller are available for recording.

1. steering angle input (analog)
2. acceleratory input (analog)
3. automobile brake application (binary)
4. automobile clutch application (binary)
5. steering clutch decouple/couple command (binary)

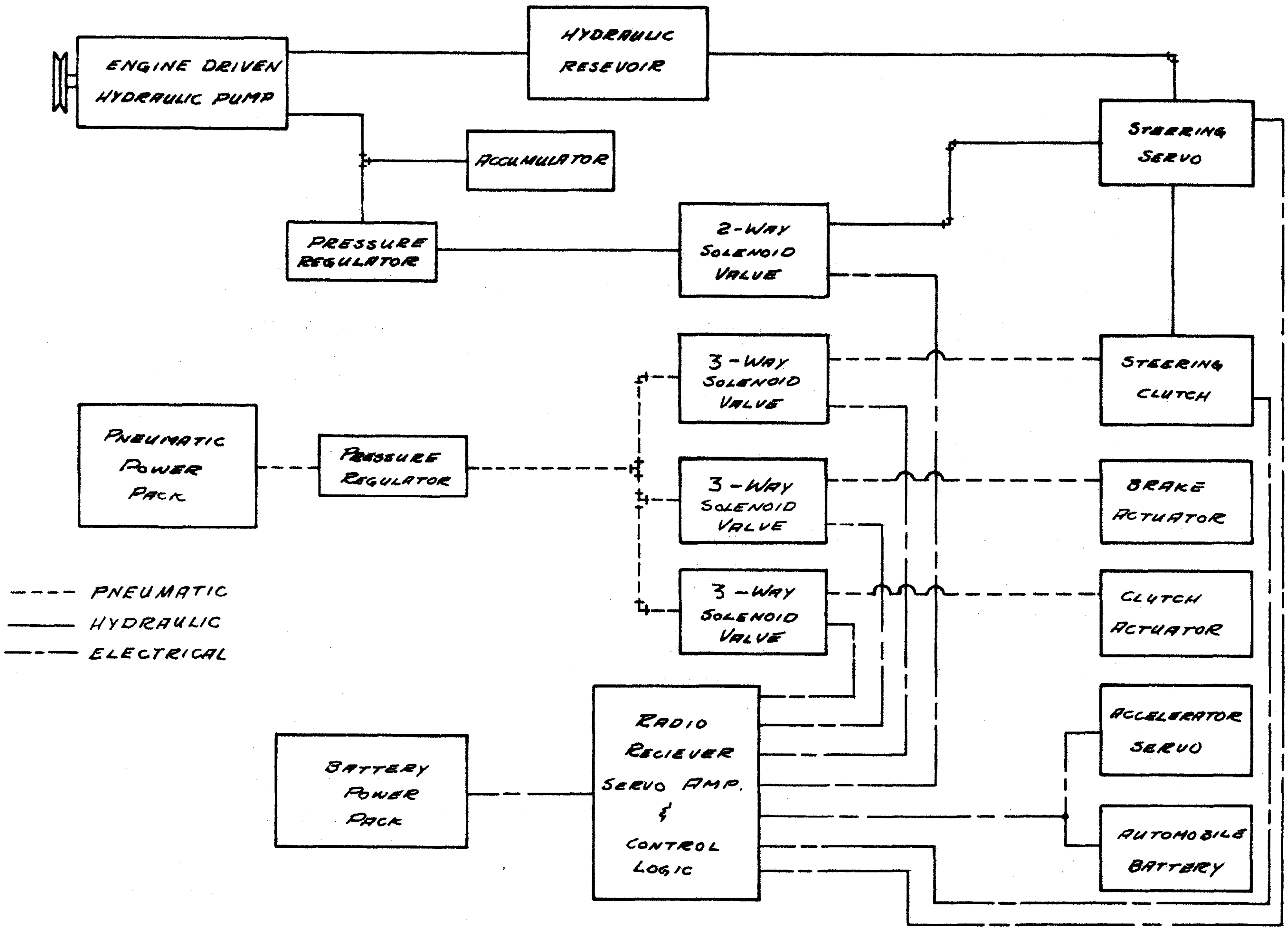


FIGURE B-2. REMOTE VEHICLE CONTROLLER BLOCK DIAGRAM.

APPENDIX C

TEST RESULTS AND COMPARISONS WITH HVOSM OUTPUT

TEST NO. 1

ENCROACHMENT ANGLE = 9.7 DEGREES

ENCROACHMENT SPEED = 55.7 MPH

Note: Test No. 1 results and comparisons with HVOSM are given in the body of the report (see Figures 8 through 11) and will not be repeated here.

TEST NO. 2

ENCROACHMENT ANGLE = 13.8 DEGREES

ENCROACHMENT SPEED = 45.1 MPH

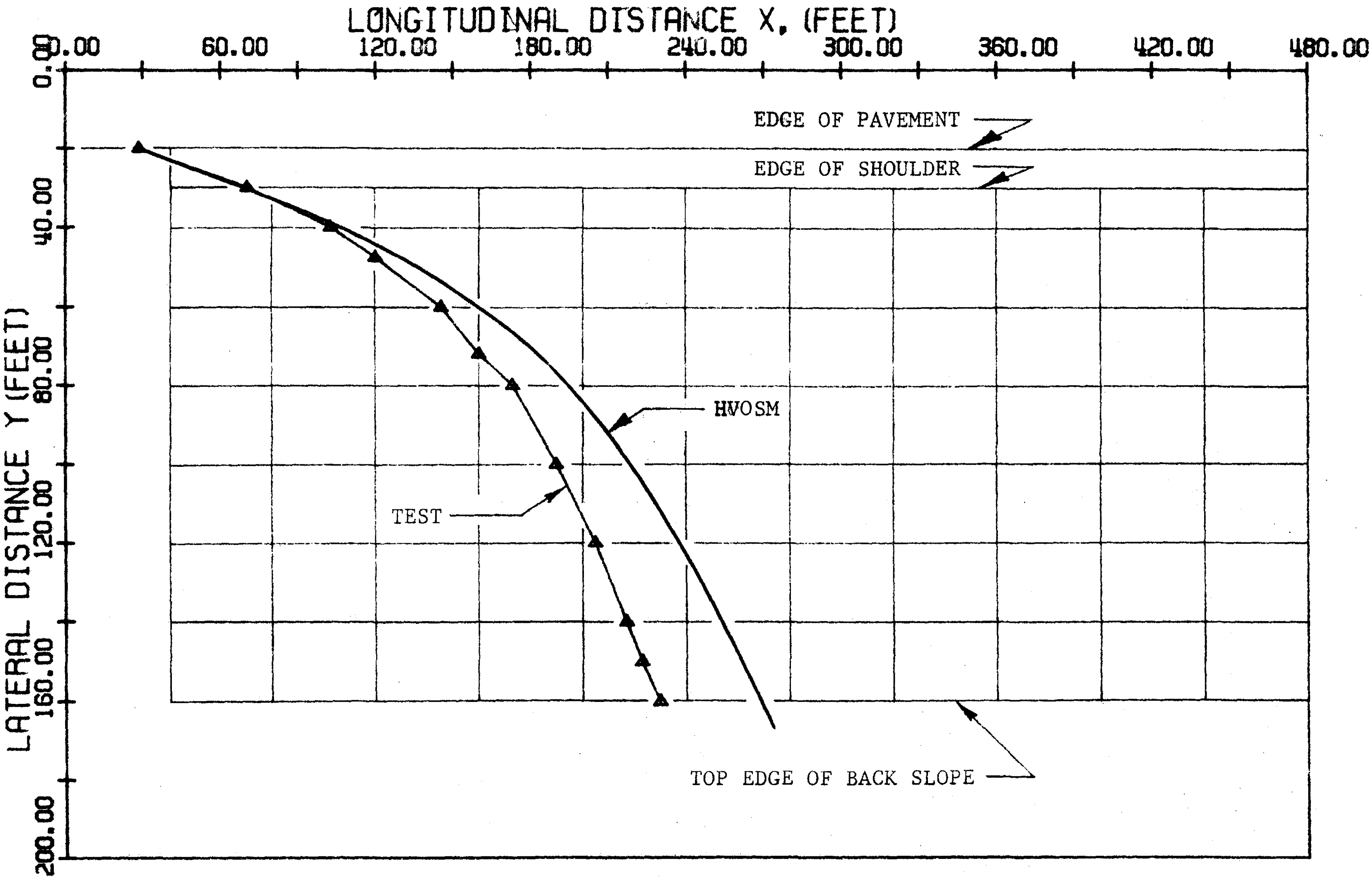
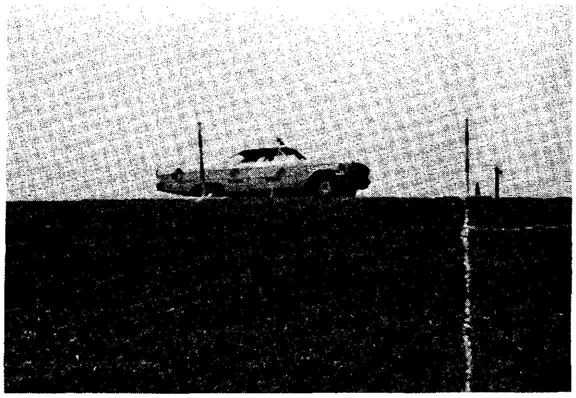


FIGURE C-1. RIGHT FRONT TIRE TRACK, TEST NO. 2 .



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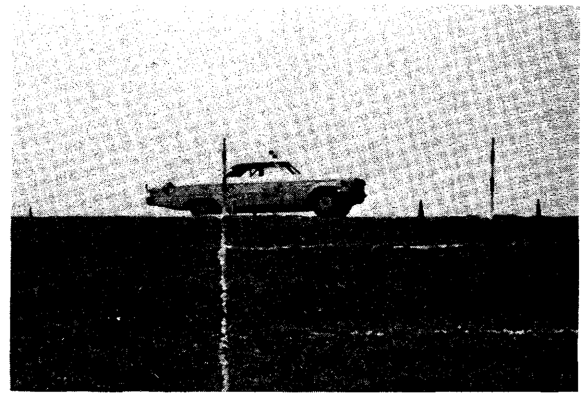

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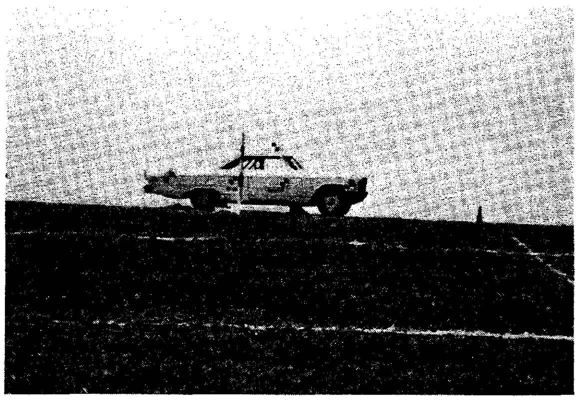

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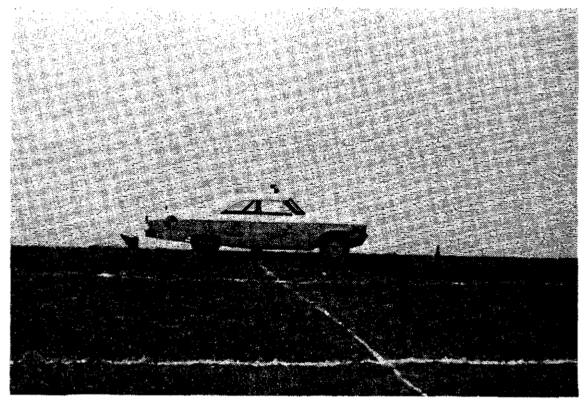

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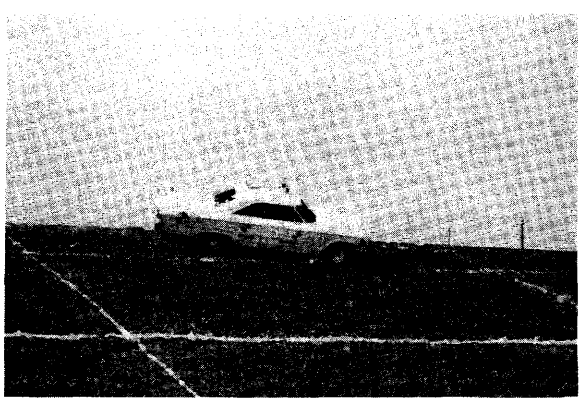

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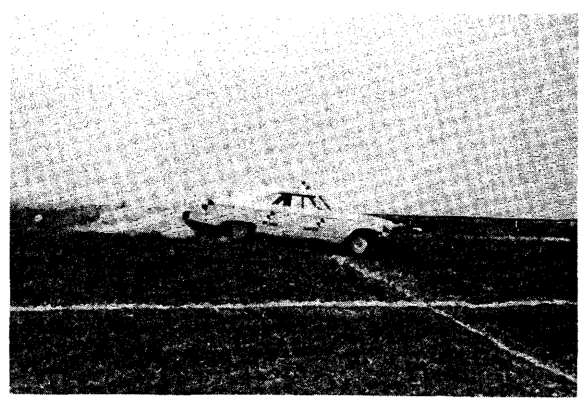

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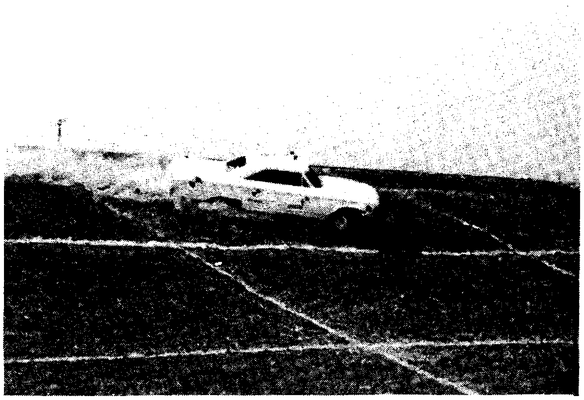
FIGURE C-2. TEST NO. 2 RESULTS, CAMERA NO. 1.



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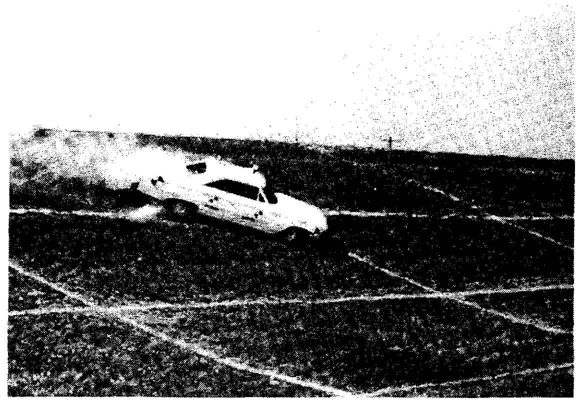

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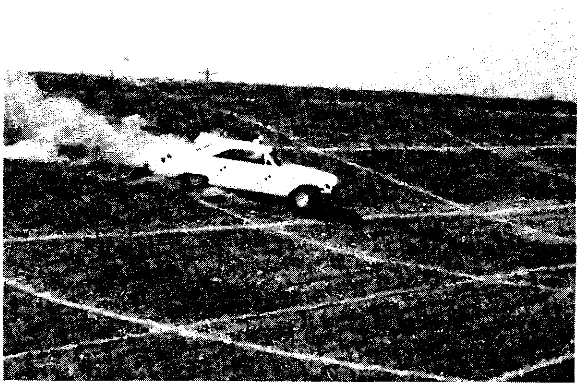

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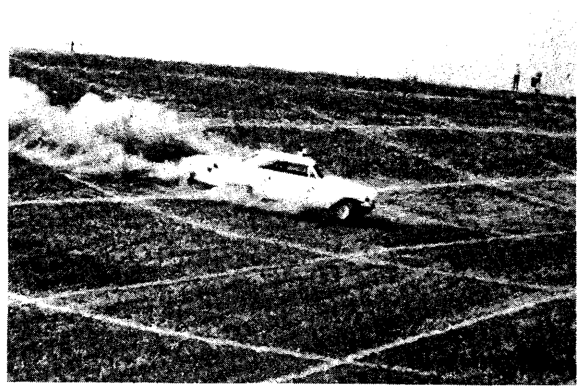

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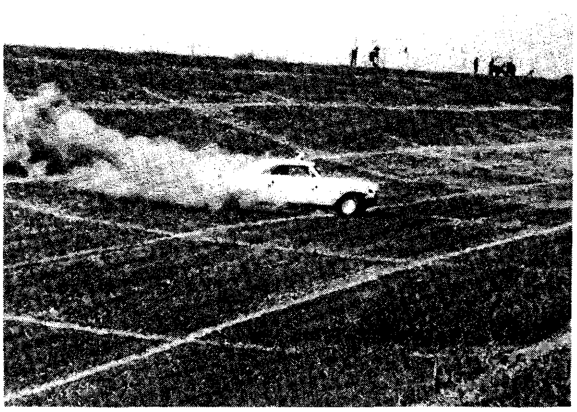

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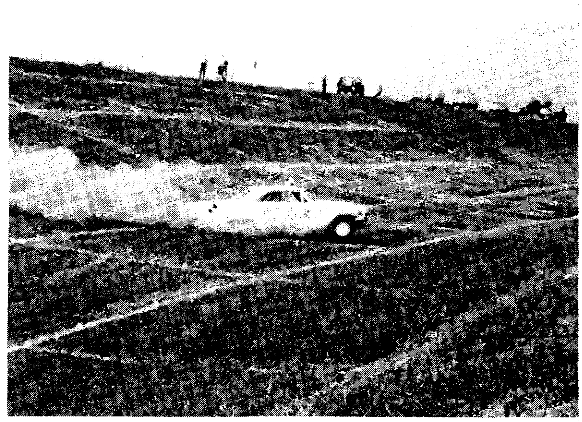

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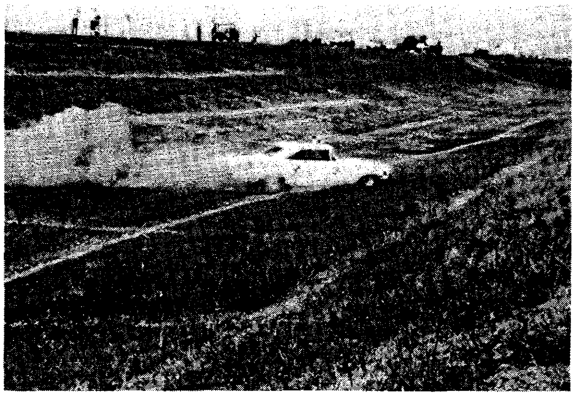
FIGURE C-2. CONTINUED.



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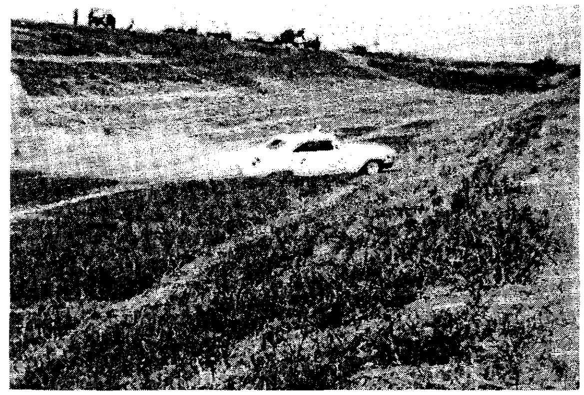

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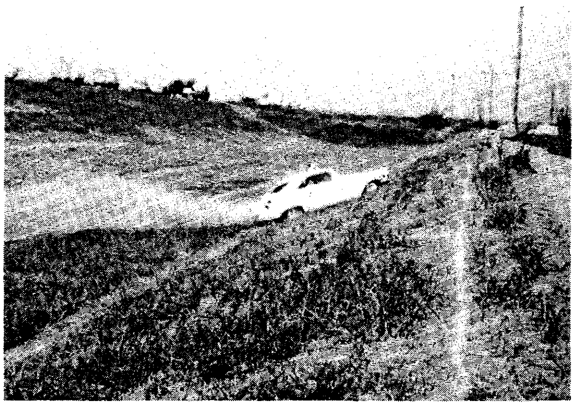

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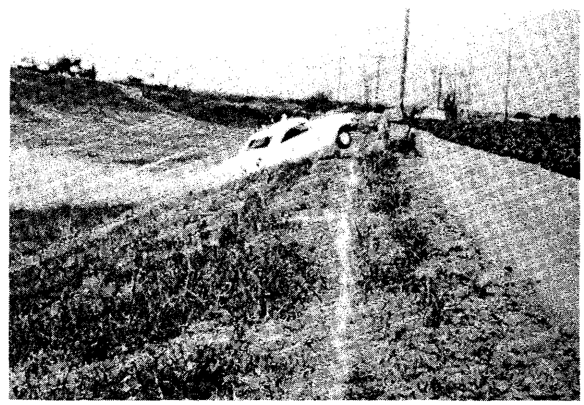

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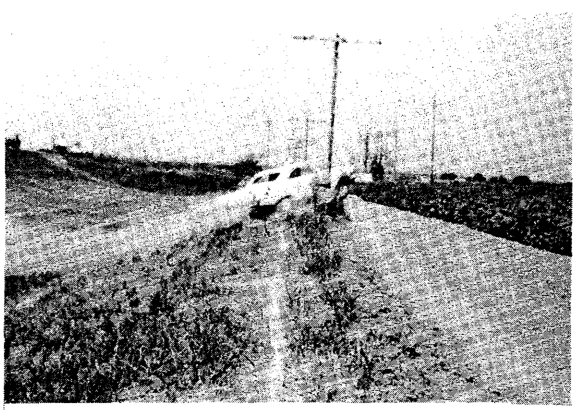

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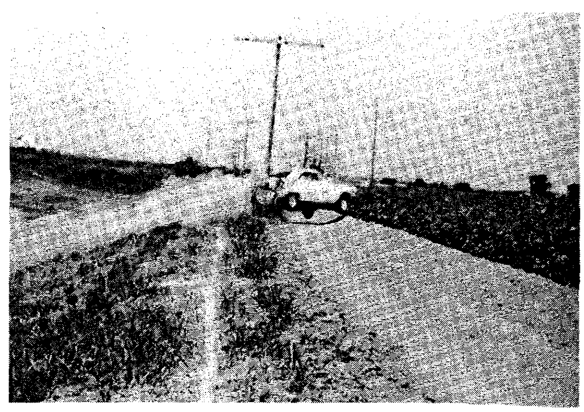

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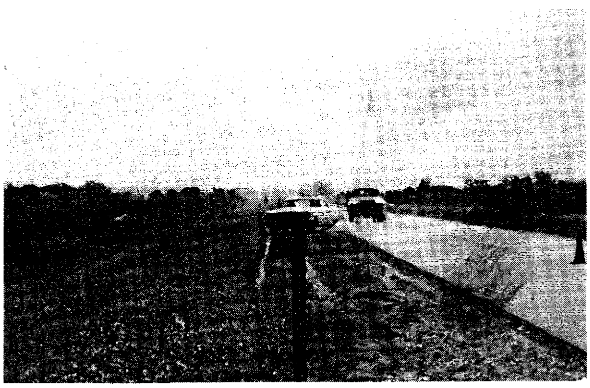

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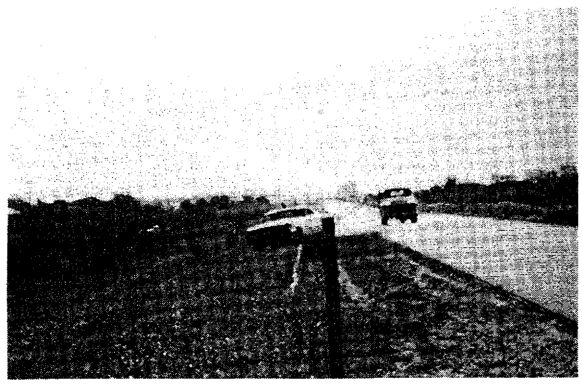

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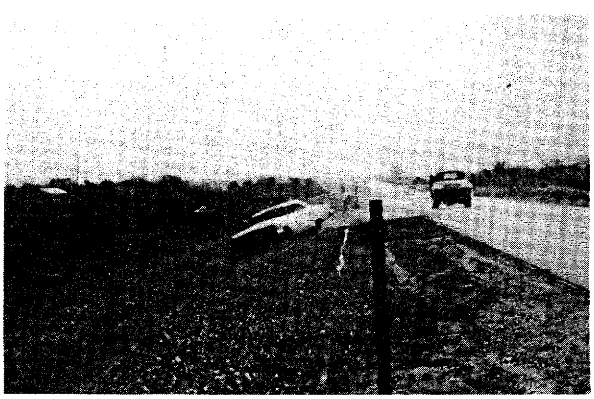

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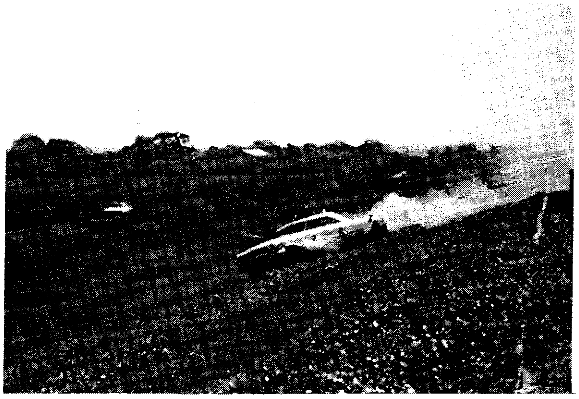
FIGURE C-3. TEST NO. 2 RESULTS, CAMERA NO. 2.



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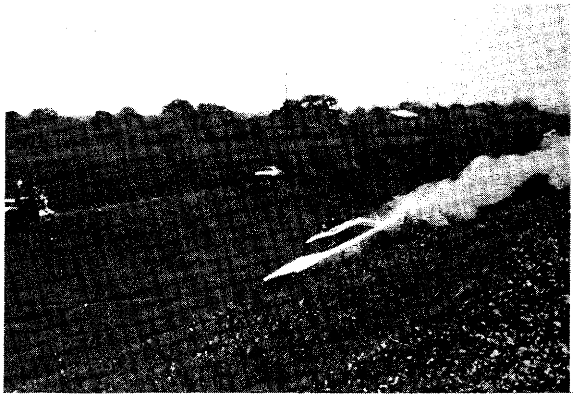

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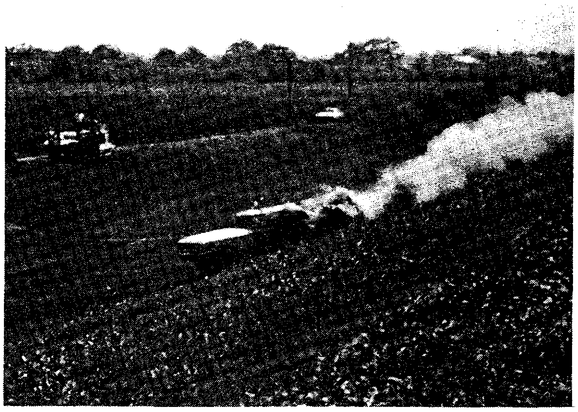

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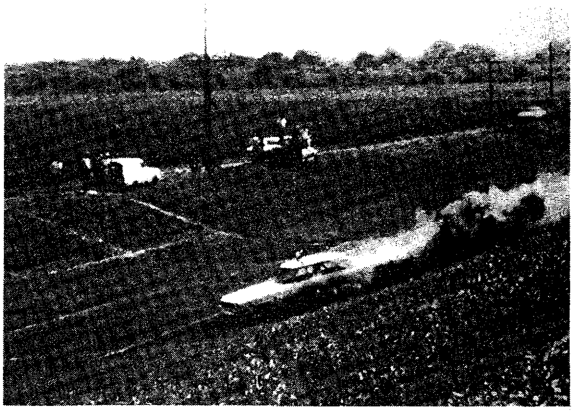

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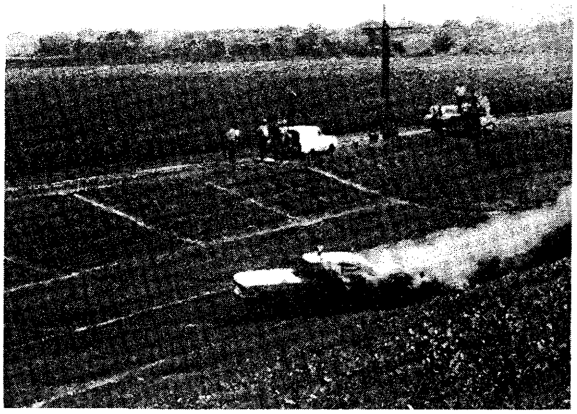

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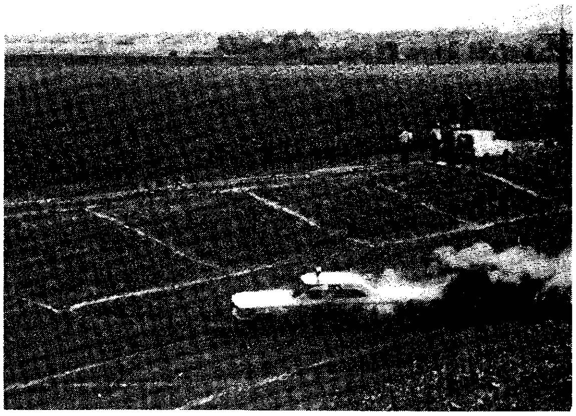

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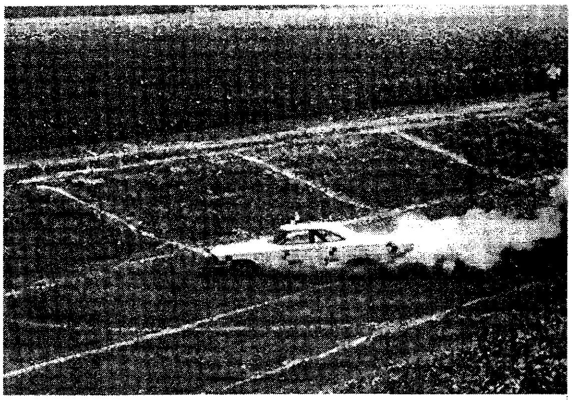
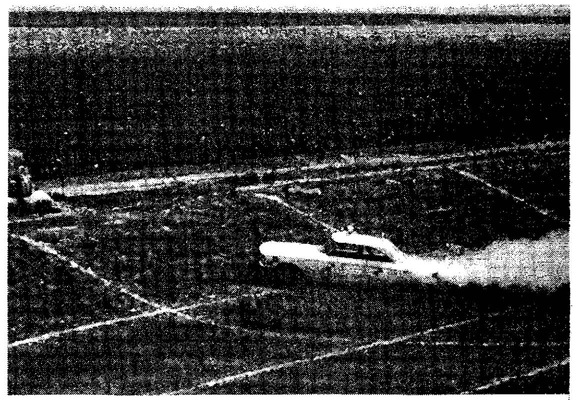
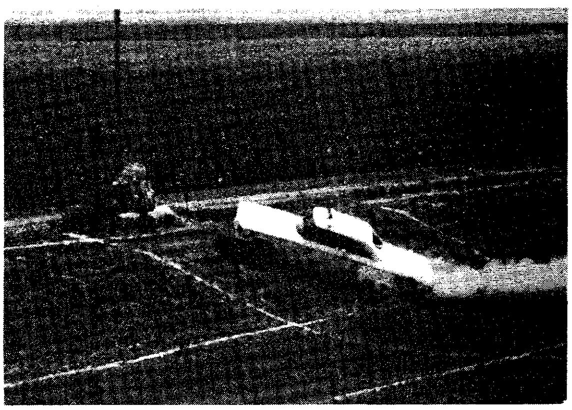
FIGURE C-3. CONTINUED.



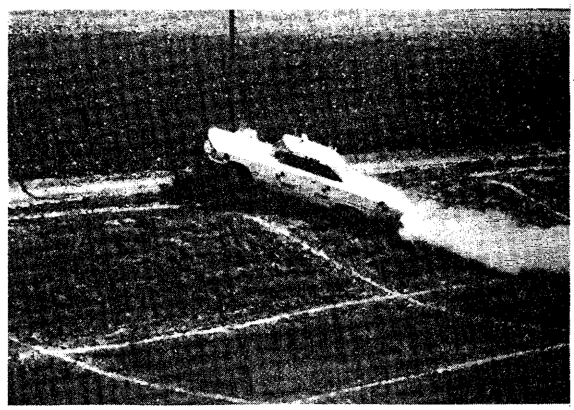
T = 3.60 SEC



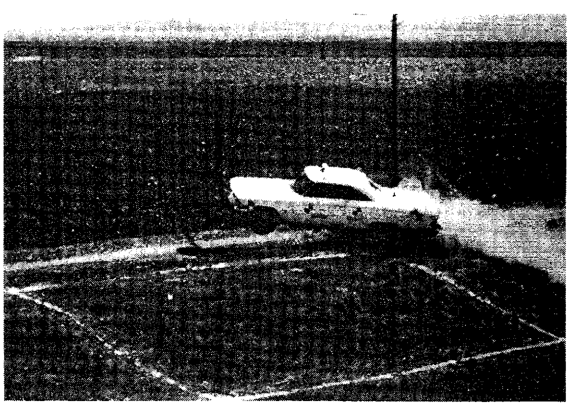
T = 3.90 SEC



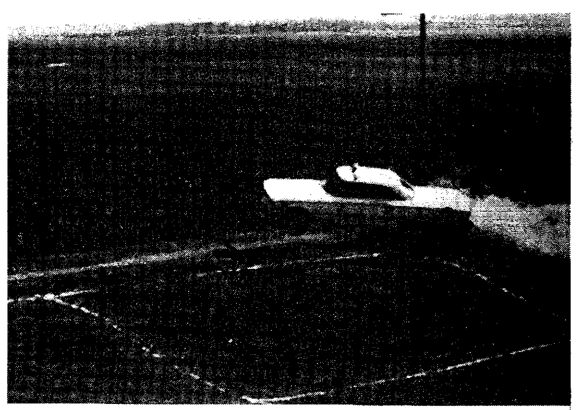
T = 4.20 SEC



T = 4.50 SEC



T = 4.80 SEC



T = 5.10 SEC

FIGURE C-3. CONTINUED.

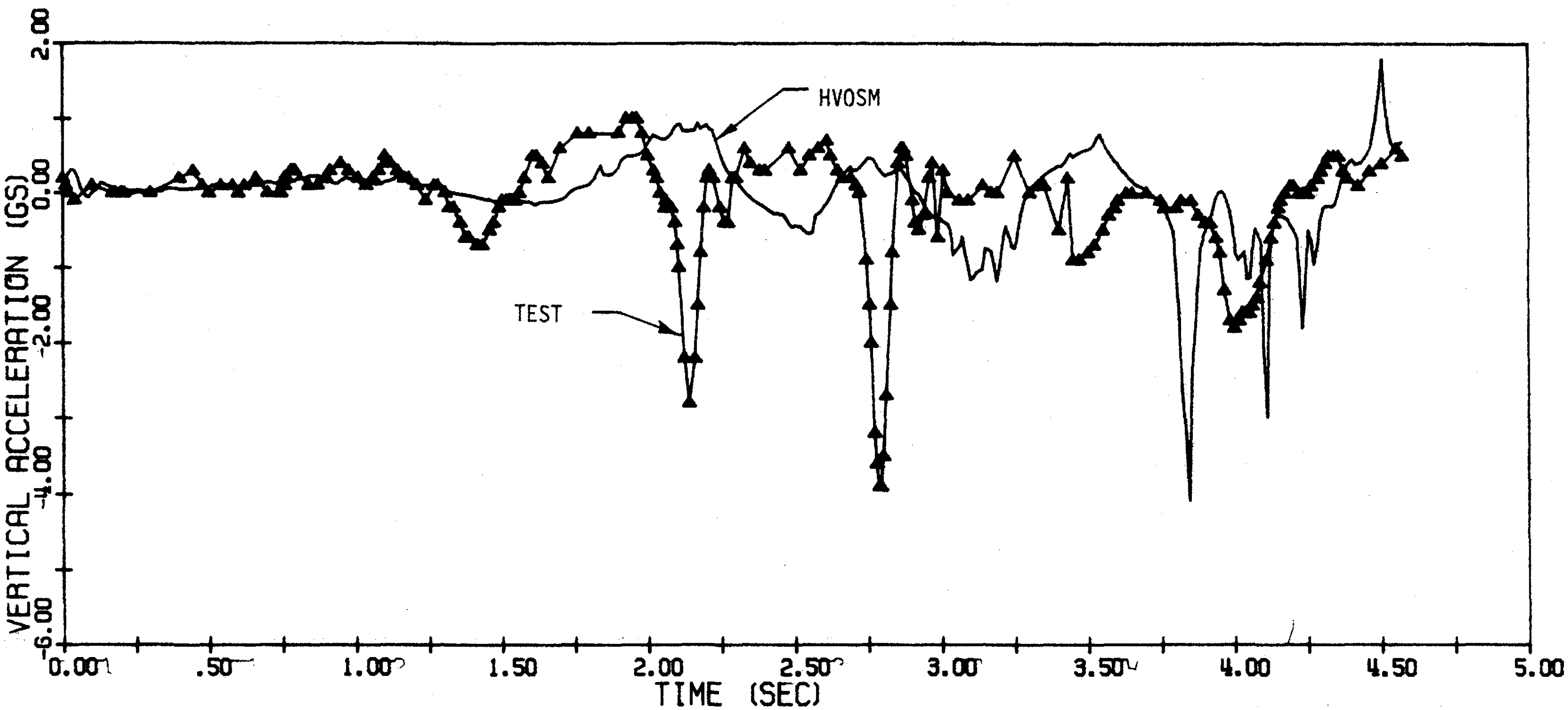


FIGURE C-4. VERTICAL ACCELERATION VERSUS TIME, TEST NO. 2.

TEST NO. 3

ENCROACHMENT ANGLE = 9.8 DEGREES

ENCROACHMENT SPEED = 45.3 MPH

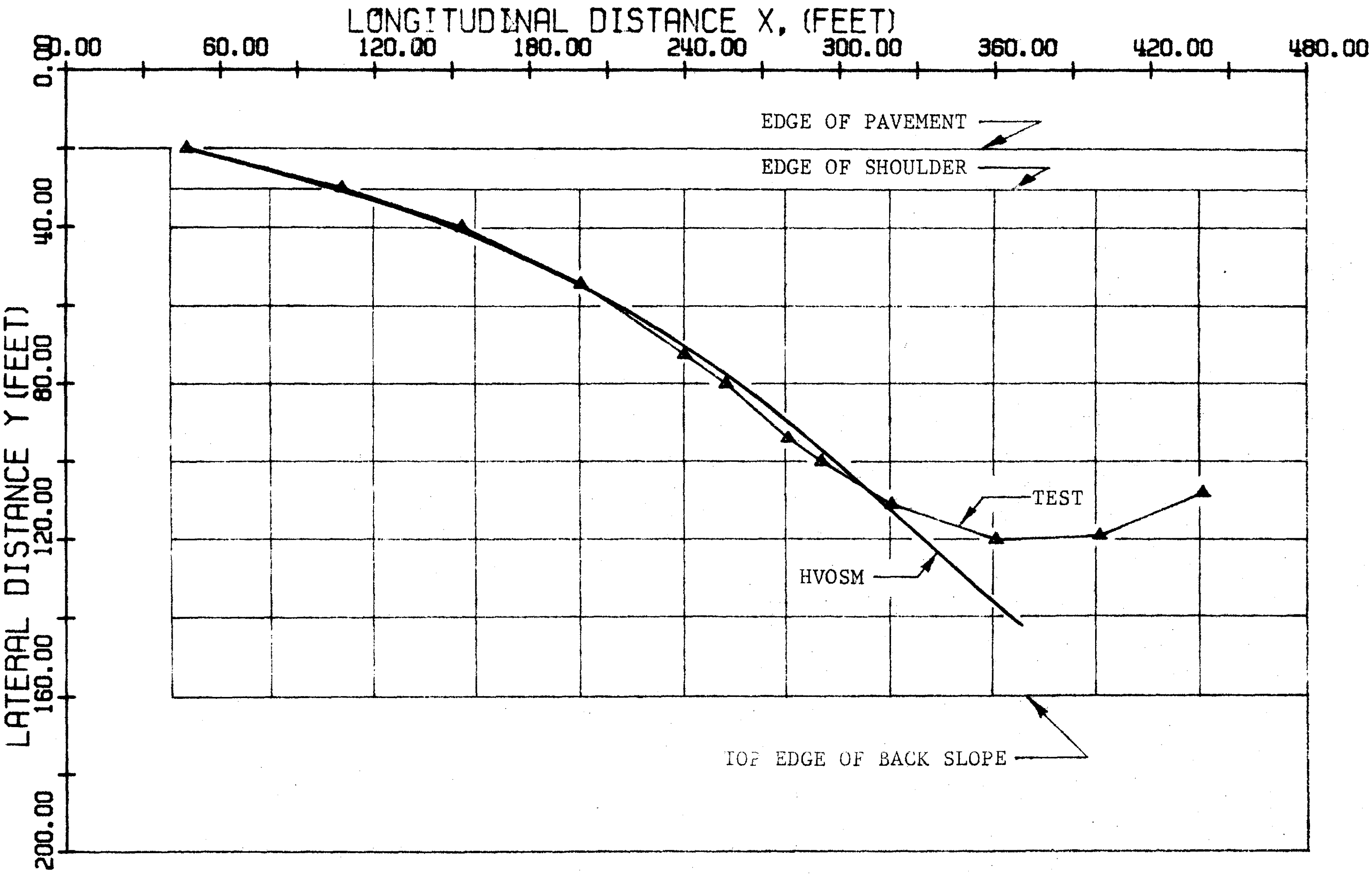
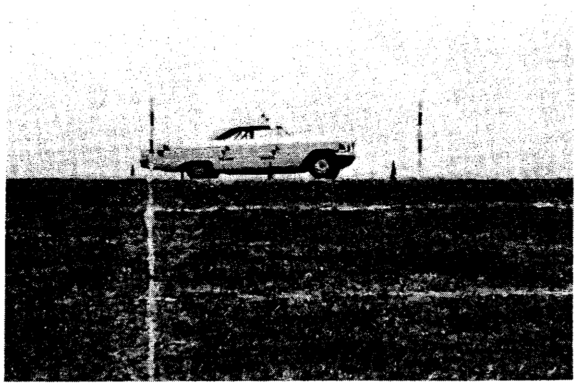
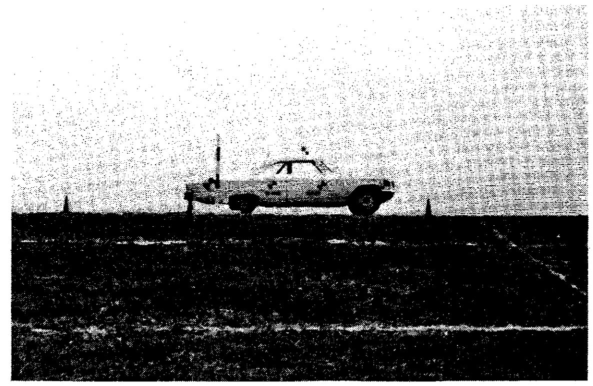


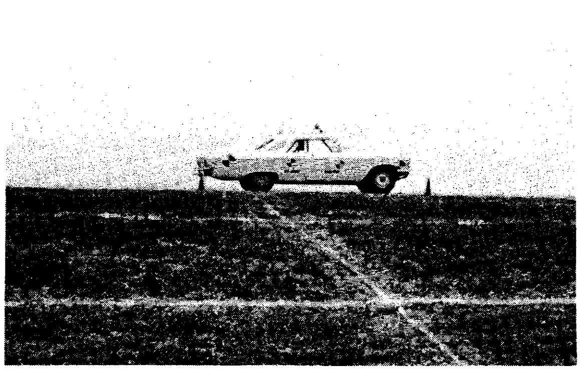
FIGURE C-5. RIGHT FRONT TIRE TRACK, TEST NO. 3.



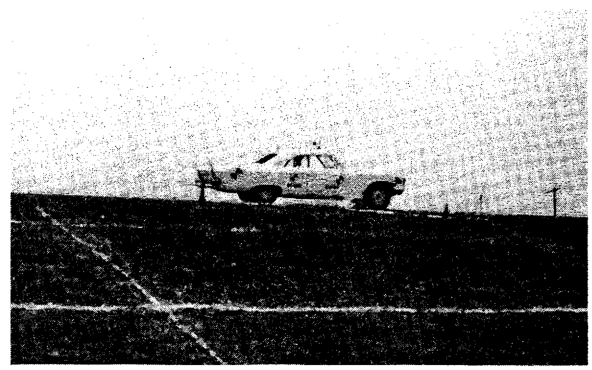
T = 0.00 SEC



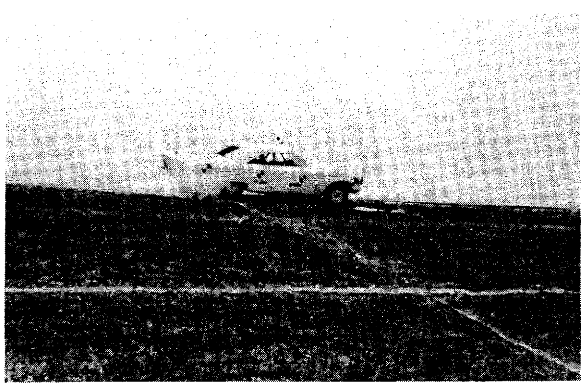
T = 0.30 SEC



T = 0.60 SEC



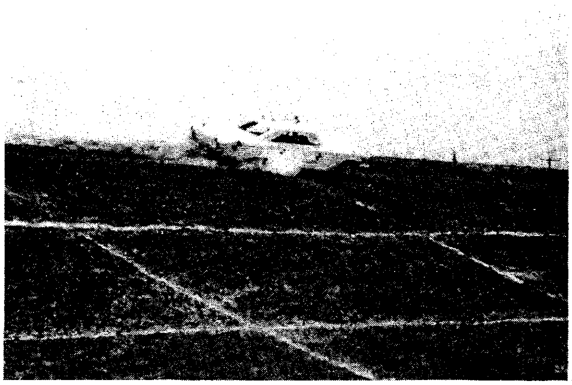
T = 0.90 SEC



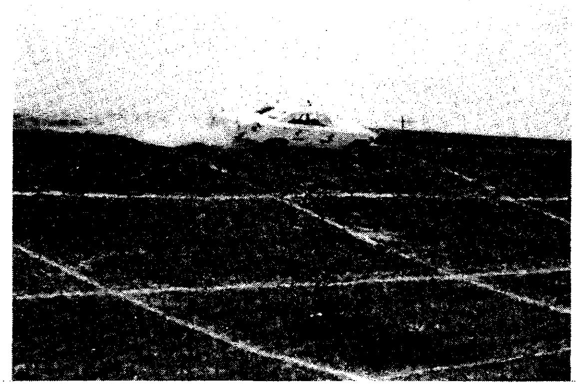
T = 1.20 SEC

T = 1.50 SEC

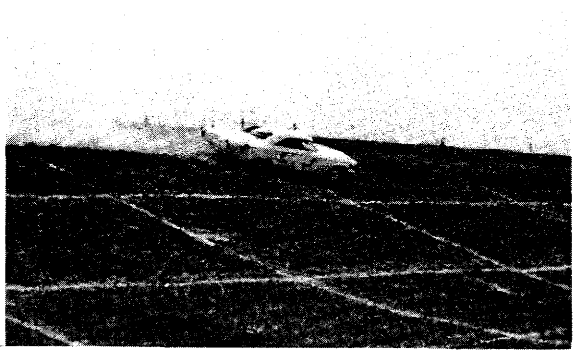
FIGURE C-6. TEST NO. 3 RESULTS, CAMERA NO. 1.



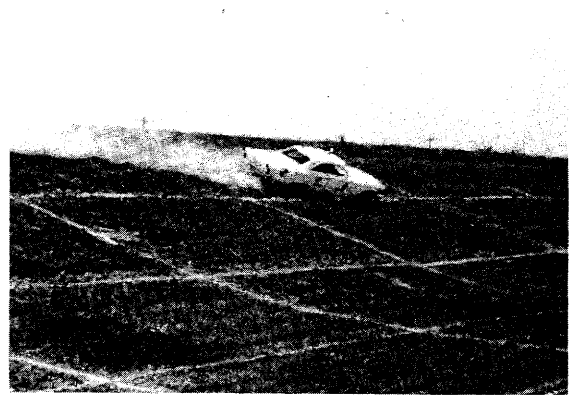
T = 1.80 SEC



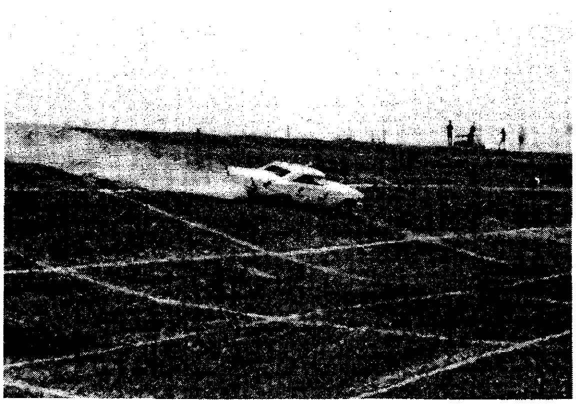
T = 2.10 SEC



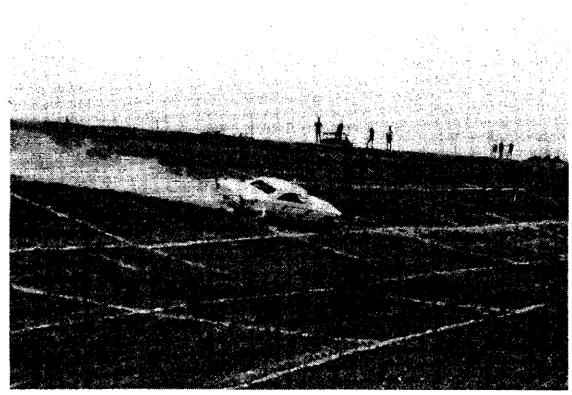
T = 2.40 SEC



T = 2.70 SEC



T = 3.00 SEC

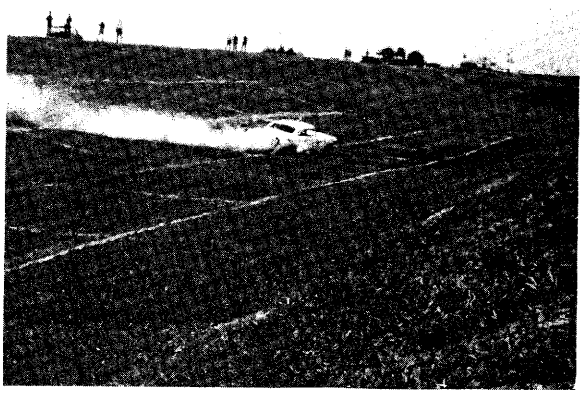


T = 3.30 SEC

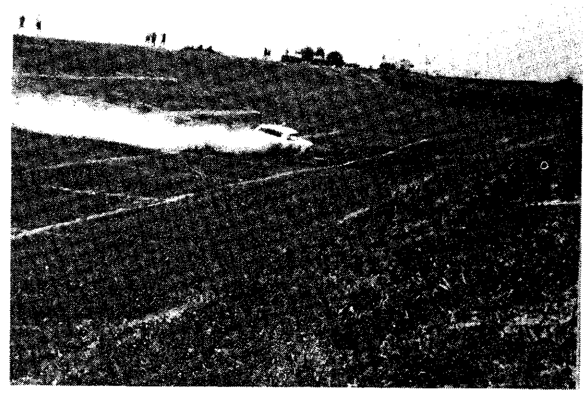
FIGURE C-6. CONTINUED.

T = 3.60 SEC

T = 3.90 SEC



T = 4.20 SEC

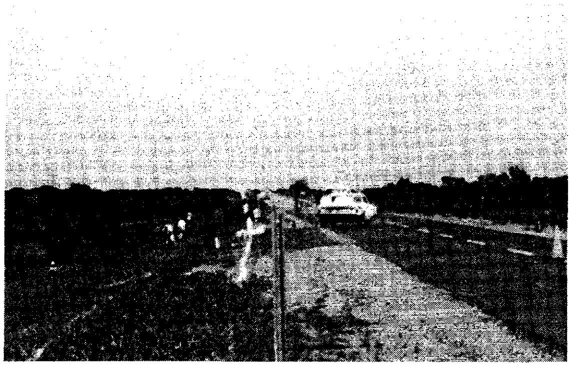


T = 4.50 SEC

T = 4.80 SEC

T = 5.10 SEC

FIGURE C- 6. CONTINUED.



T = 0.00 SEC

T = 0.30 SEC

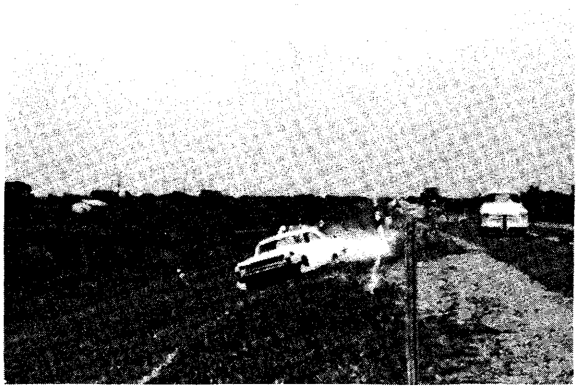
T = 0.60 SEC

T = 0.90 SEC

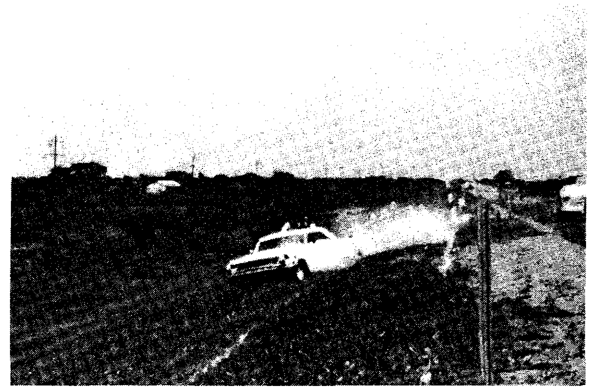
T = 1.20 SEC

T = 1.50 SEC

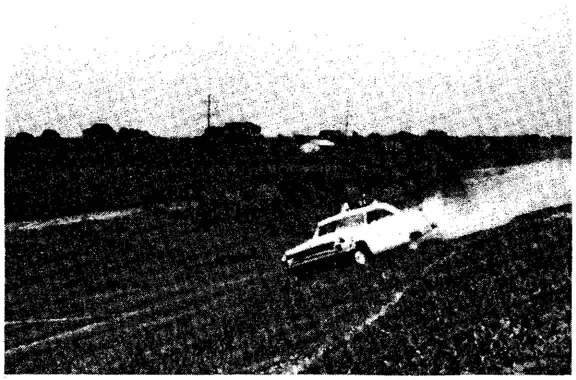
FIGURE C-7. TEST NO. 3 RESULTS, CAMERA NO. 2.



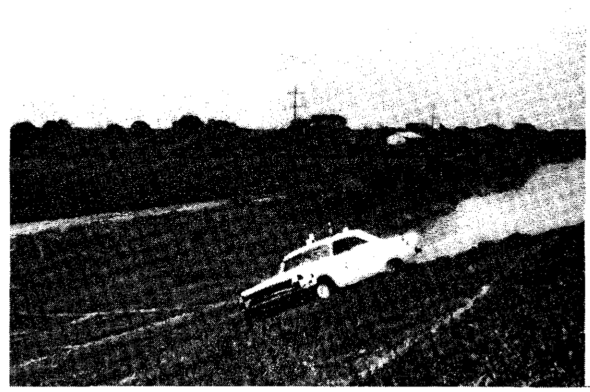
T = 1.80 SEC



T = 2.10 SEC



T = 2.40 SEC

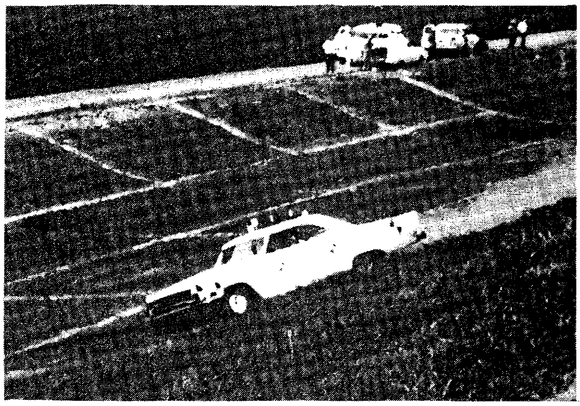


T = 2.70 SEC

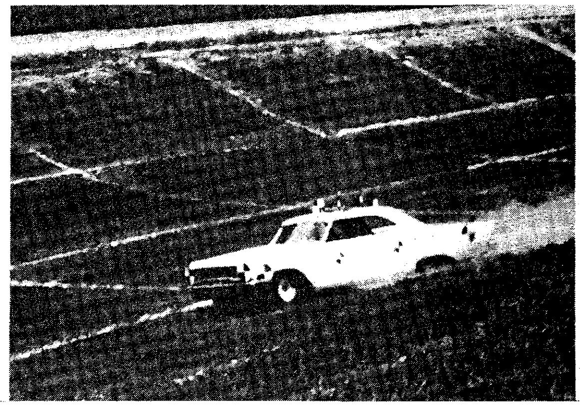
T = 3.00 SEC

T = 3.30 SEC

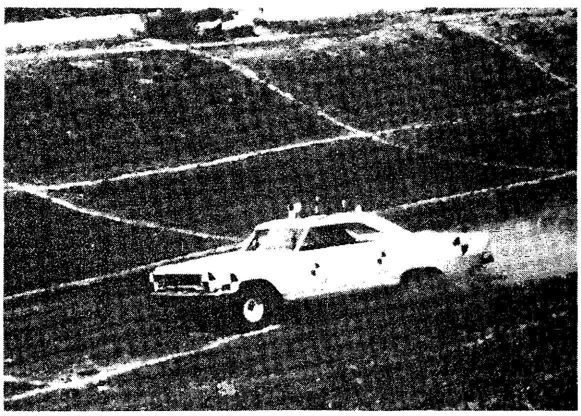
FIGURE C- 7. CONTINUED.



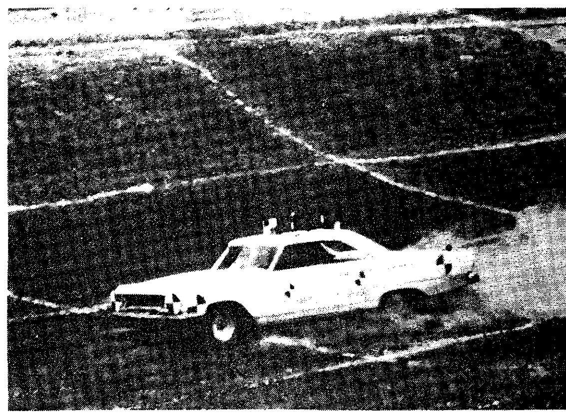
T = 3.60 SEC



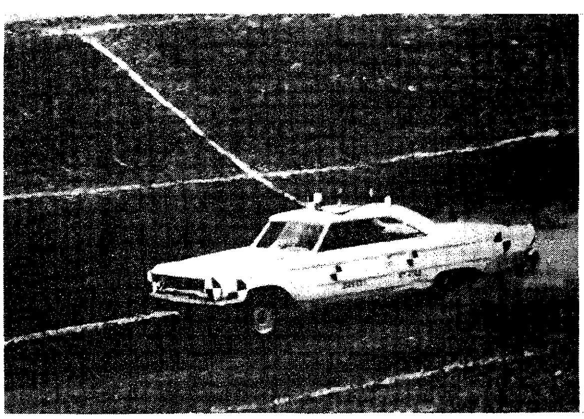
T = 3.90 SEC



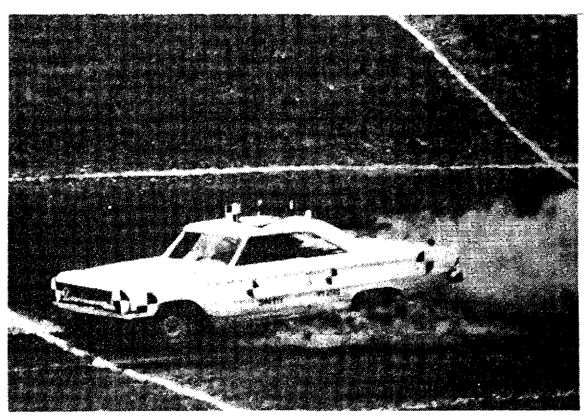
T = 4.20 SEC



T = 4.50 SEC



T = 4.80 SEC



T = 5.10 SEC

FIGURE C-7. CONTINUED.

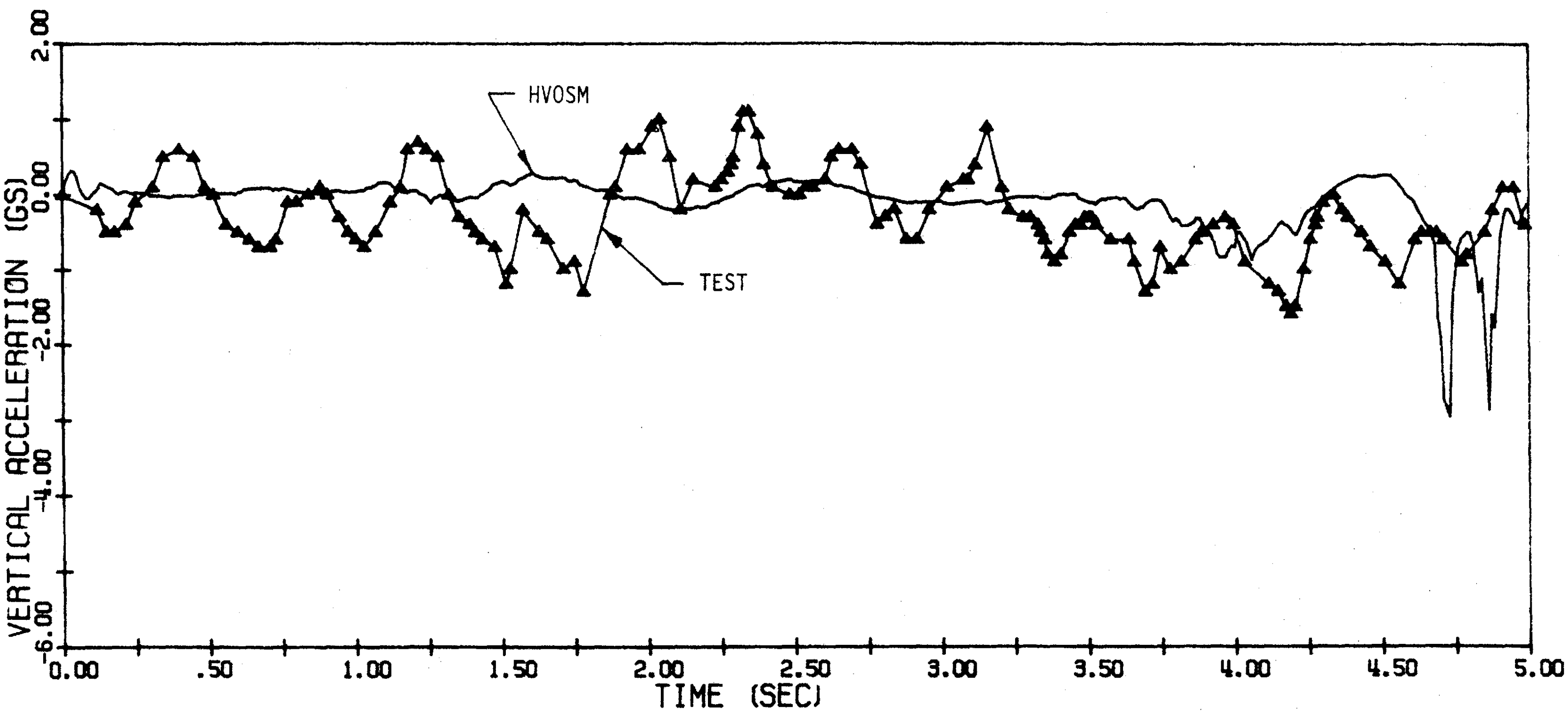


FIGURE C- 8. VERTICAL ACCELERATION VERSUS TIME, TEST NO. 3.

TEST NO. 4

ENCROACHMENT ANGLE = 20.4 DEGREES

ENCROACHMENT SPEED = 47.0 MPH

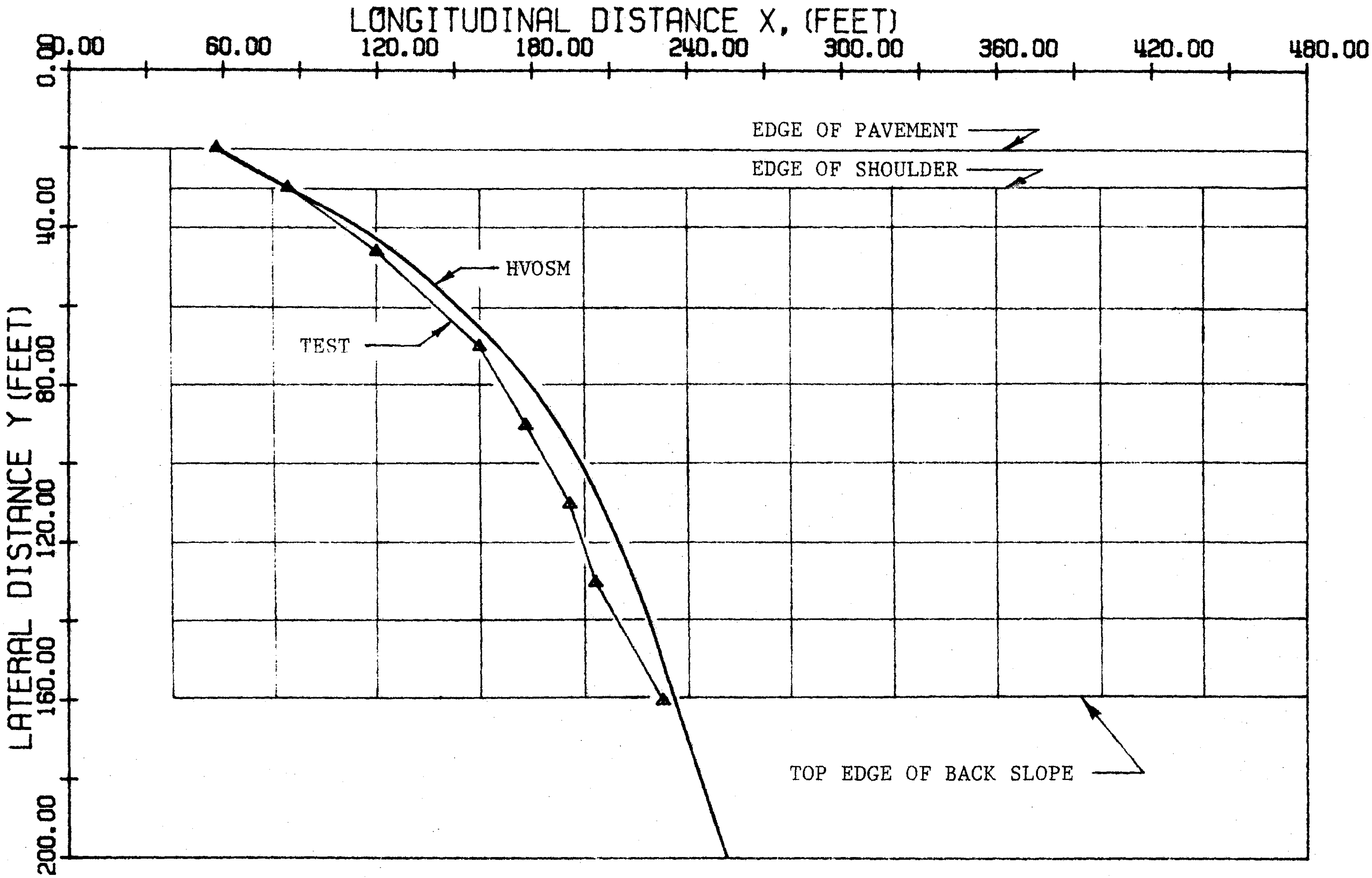


FIGURE C-9. RIGHT FRONT TIRE TRACK, TEST NO. 4.

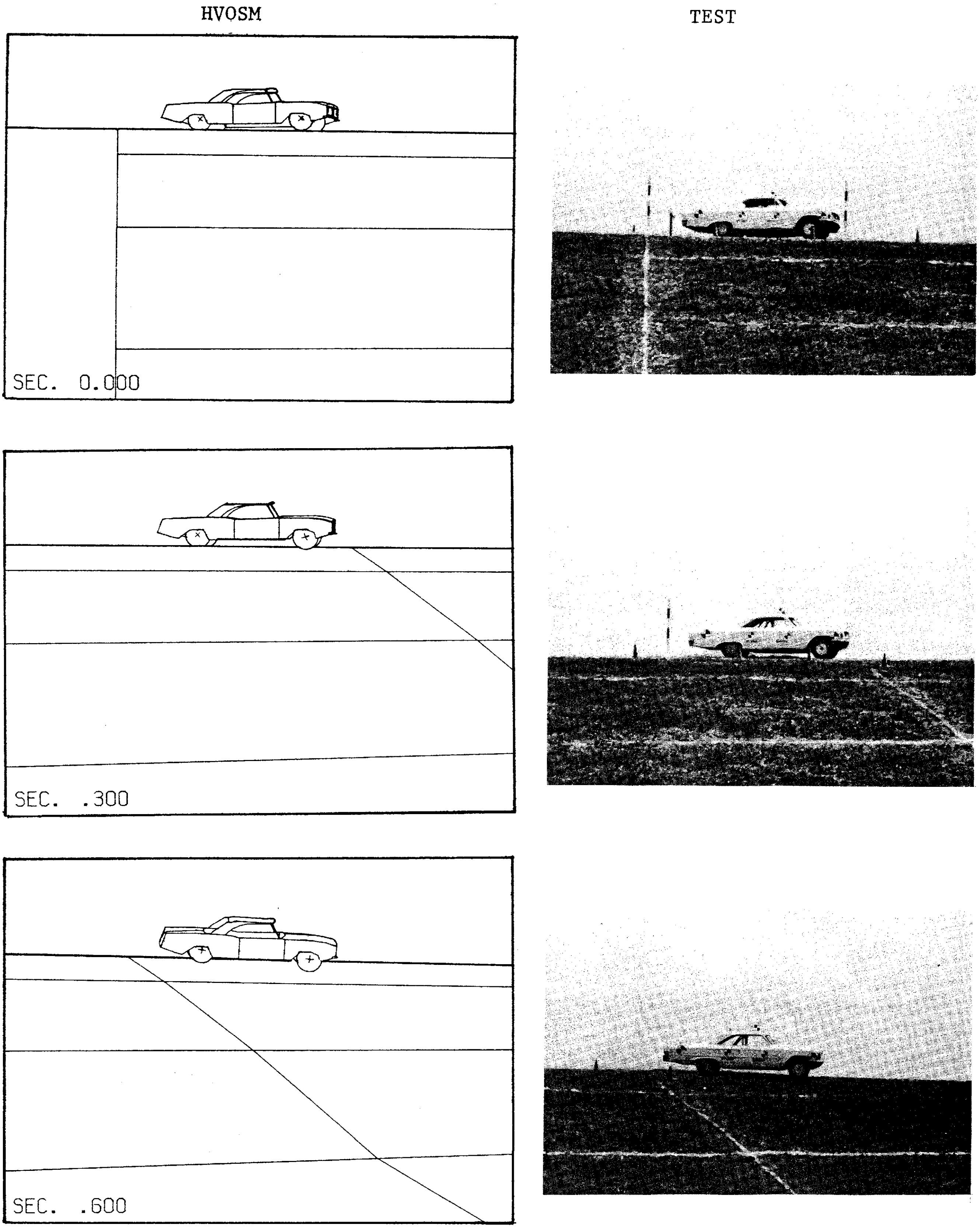


FIGURE C- 10. HVOSM VERSUS TEST RESULTS, TEST NO. 4, CAMERA NO. 1 .

HVOSM TEST

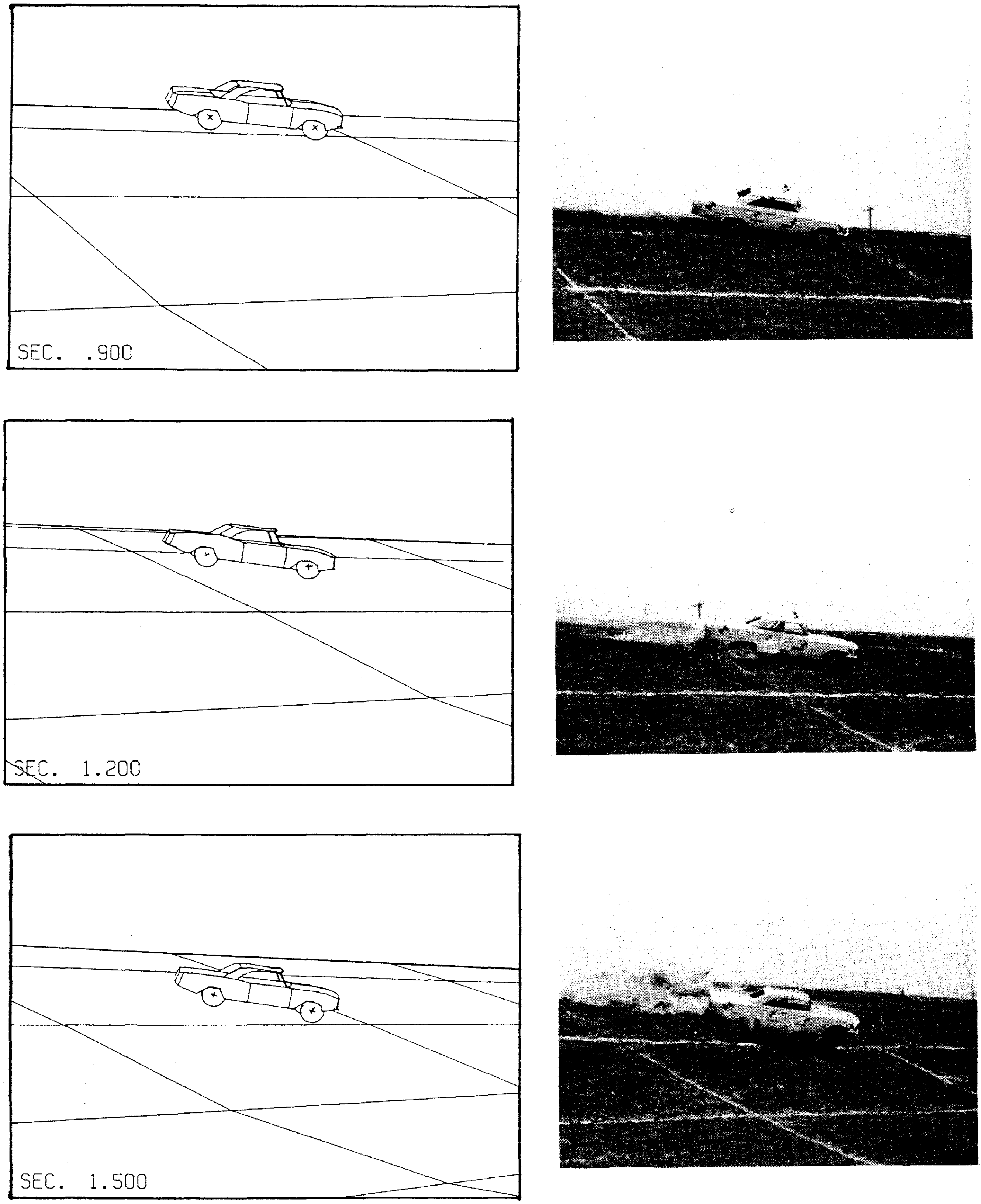


FIGURE C-10. CONTINUED.

HVOSM TEST

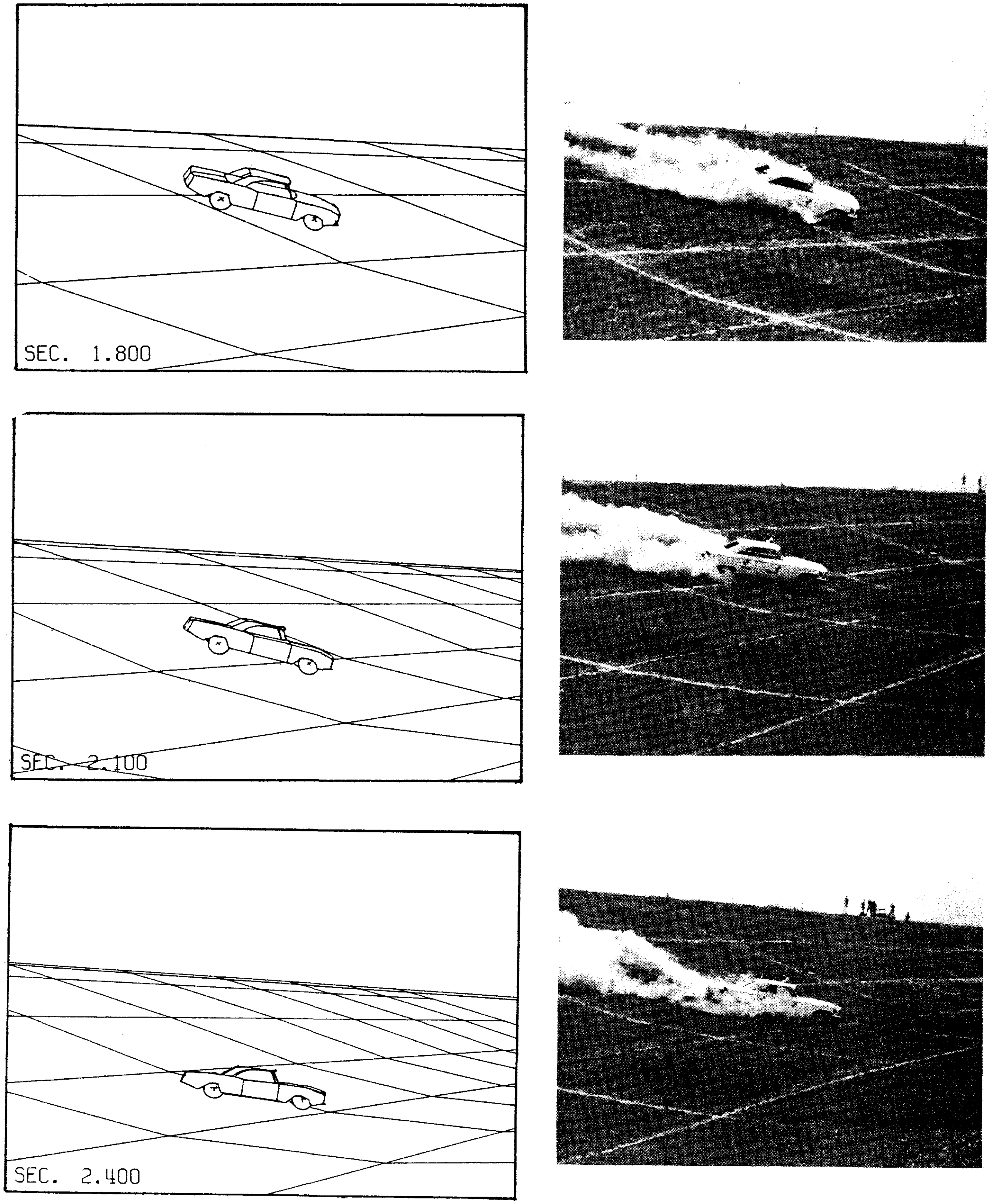


FIGURE C-10. CONTINUED.

HVOSM TEST

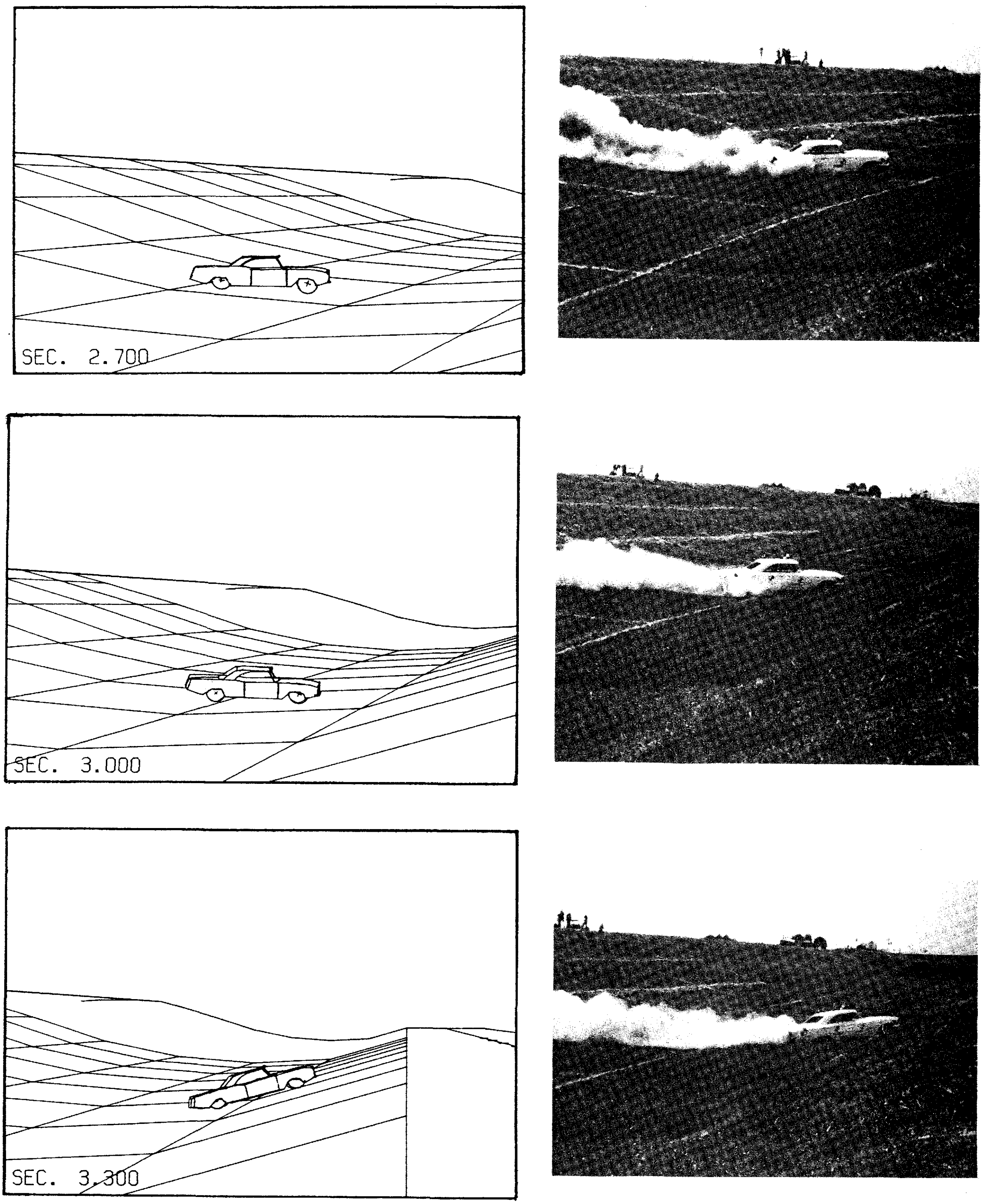


FIGURE C- 10. CONTINUED.

HVOSM TEST

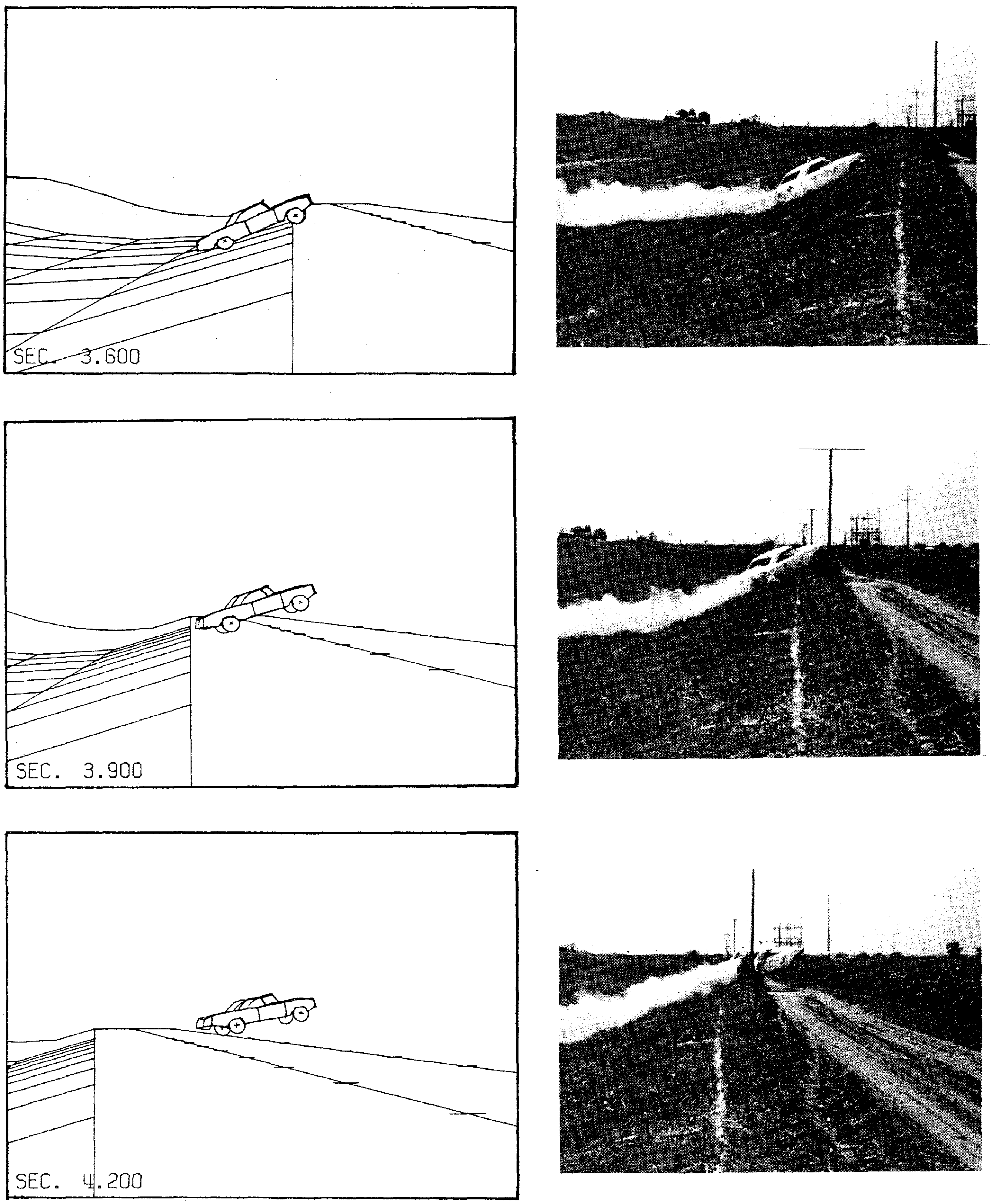
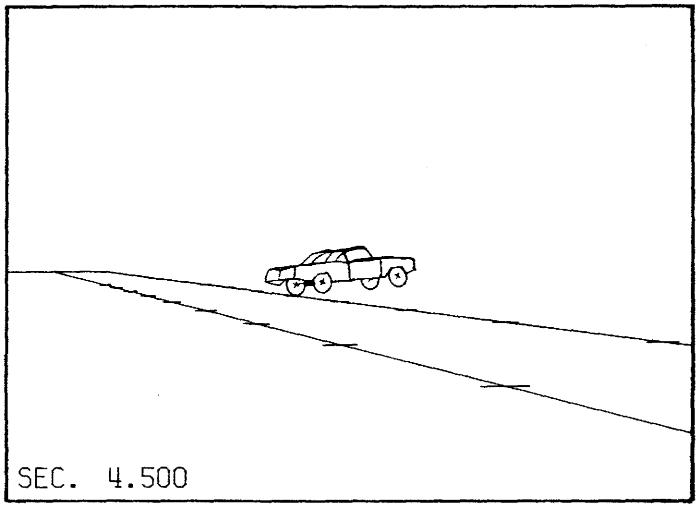


FIGURE C-10. CONTINUED.

HVOSM



TEST

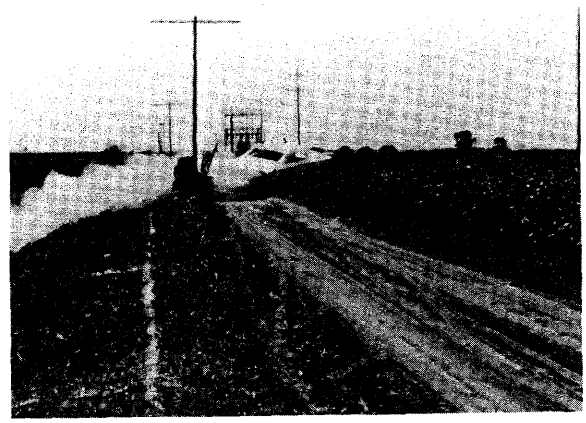


FIGURE C-10. CONTINUED.

HVOSM TEST

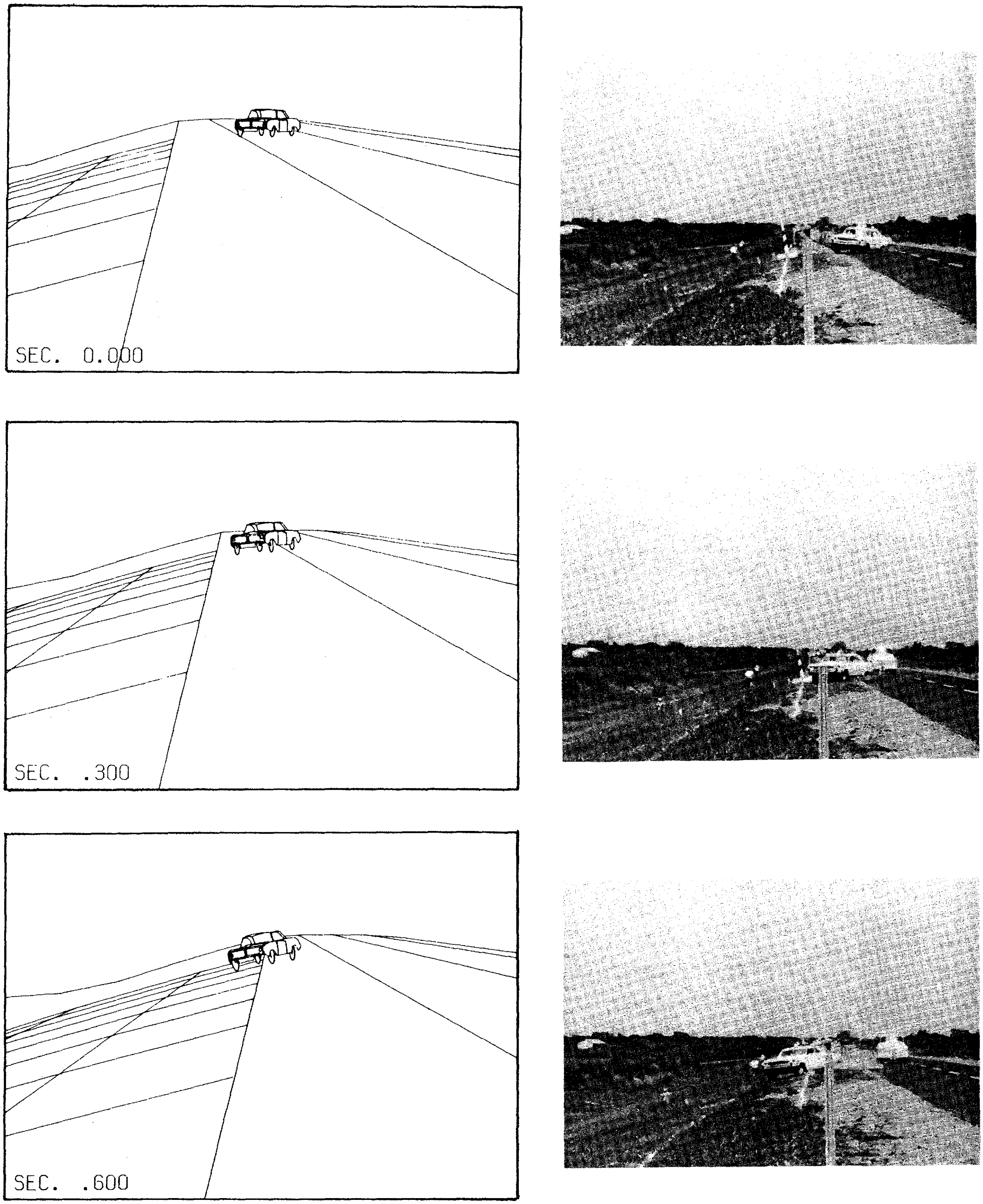


FIGURE C-11. HVOSM VERSUS TEST RESULTS, TEST NO. 4, CAMERA NO. 2.

HVOSM TEST

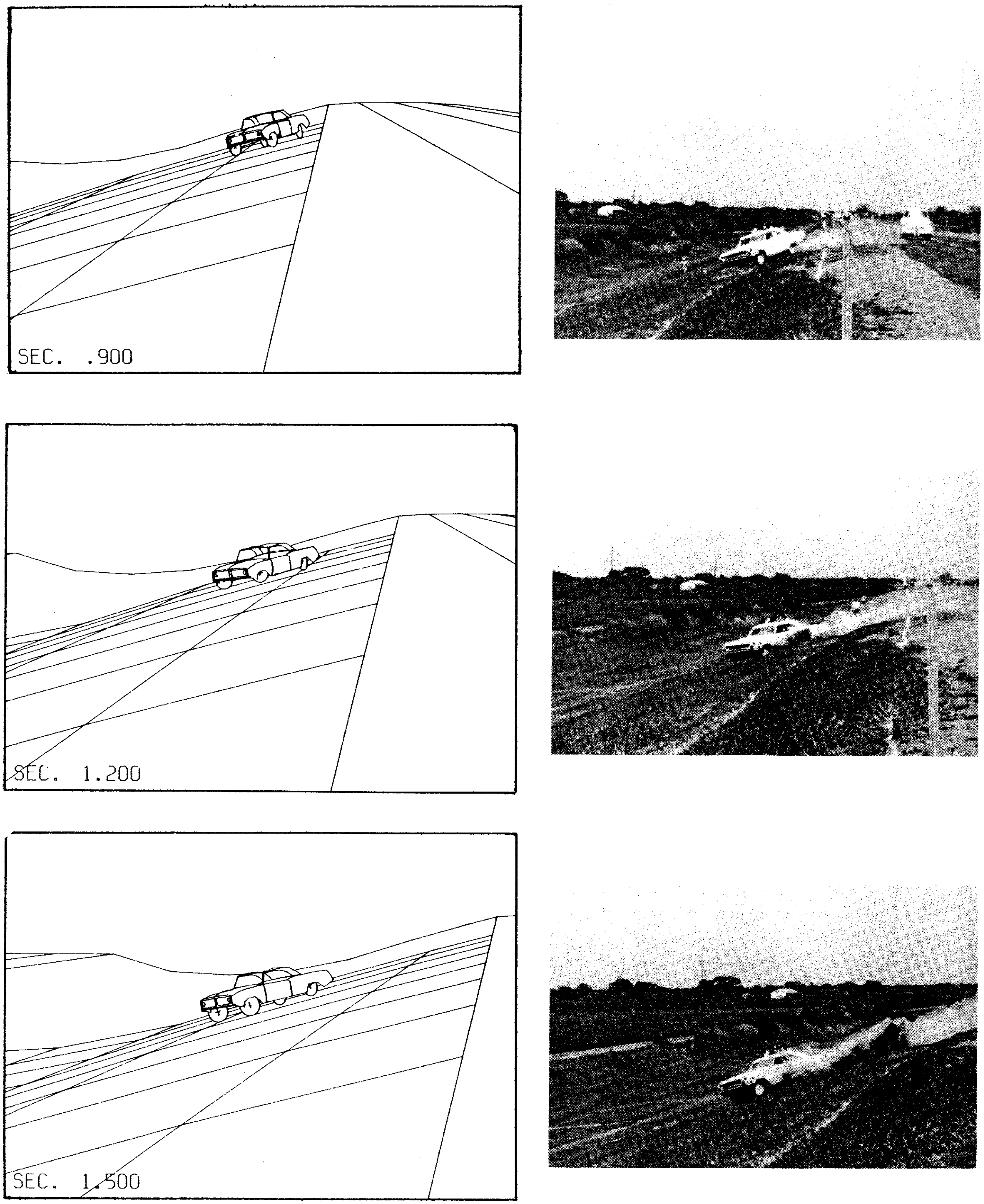


FIGURE C-11. CONTINUED.

HVOSM TEST

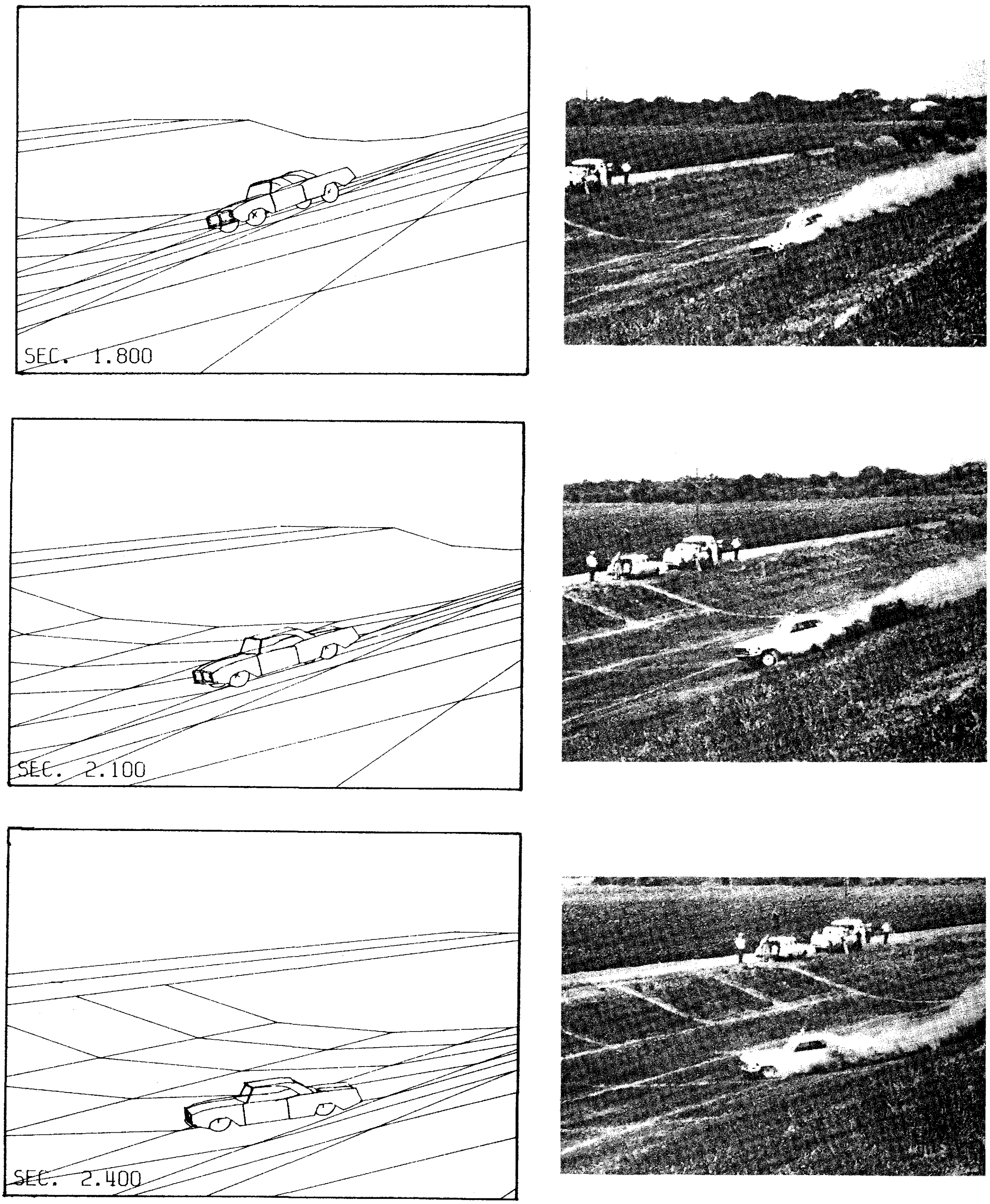


FIGURE C-11. CONTINUED.

HVOSM TEST

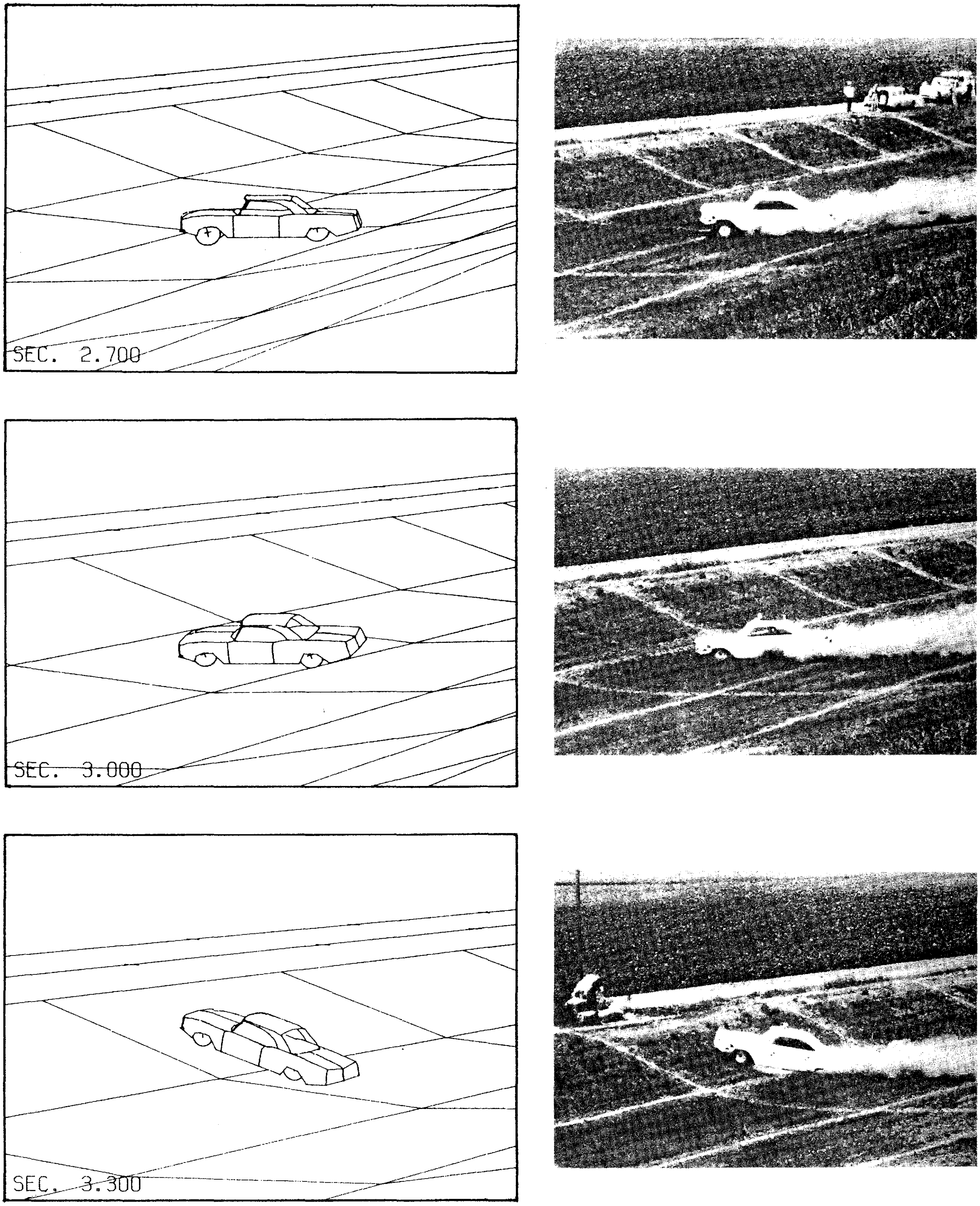


FIGURE C-11. CONTINUED.

HVOSM TEST

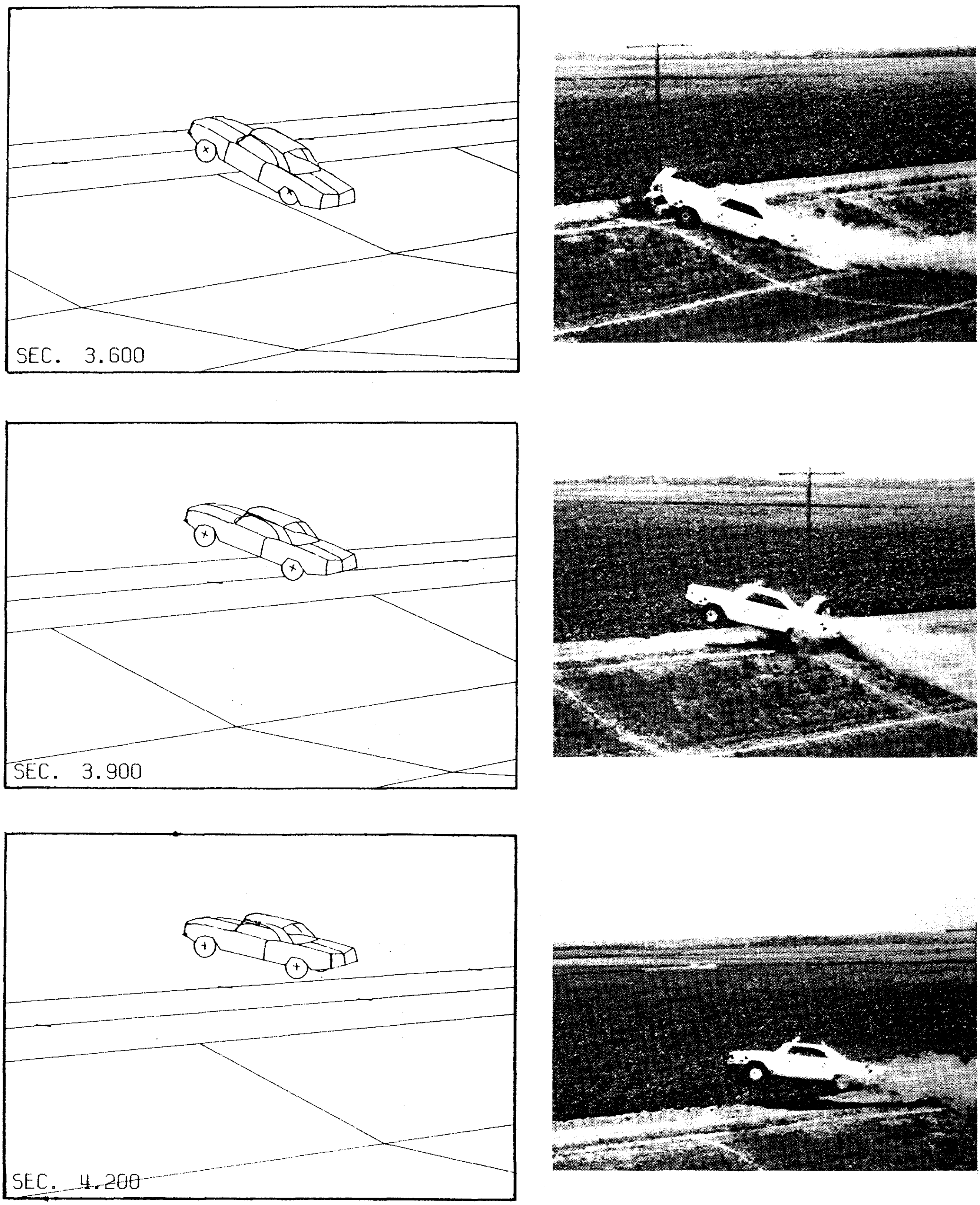


FIGURE C-11. CONTINUED.

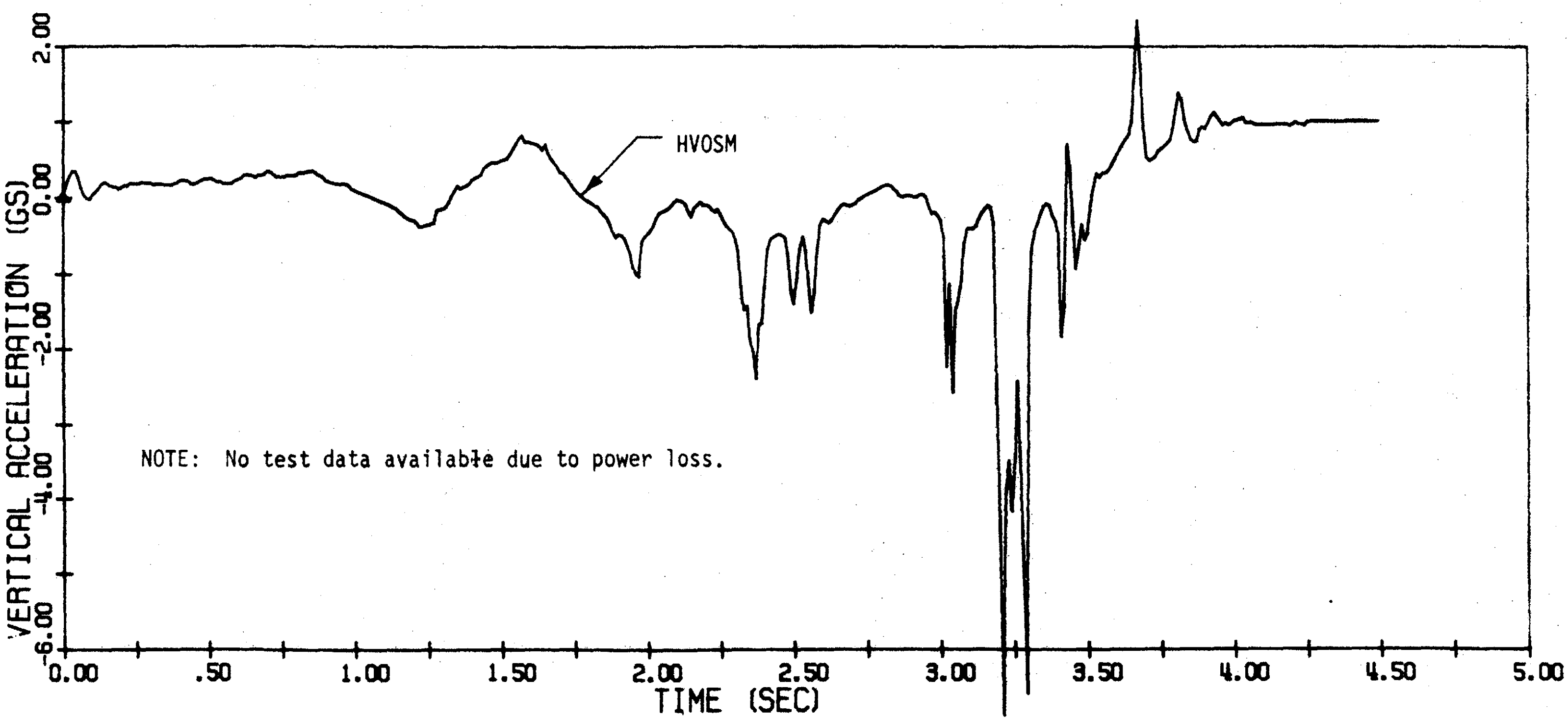


FIGURE C-12. VERTICAL ACCELERATION VERSUS TIME, TEST NO. 4.

TEST NO. 5

ENCROACHMENT ANGLE = 8.6 DEGREES

ENCROACHMENT SPEED = 59.9 MPH

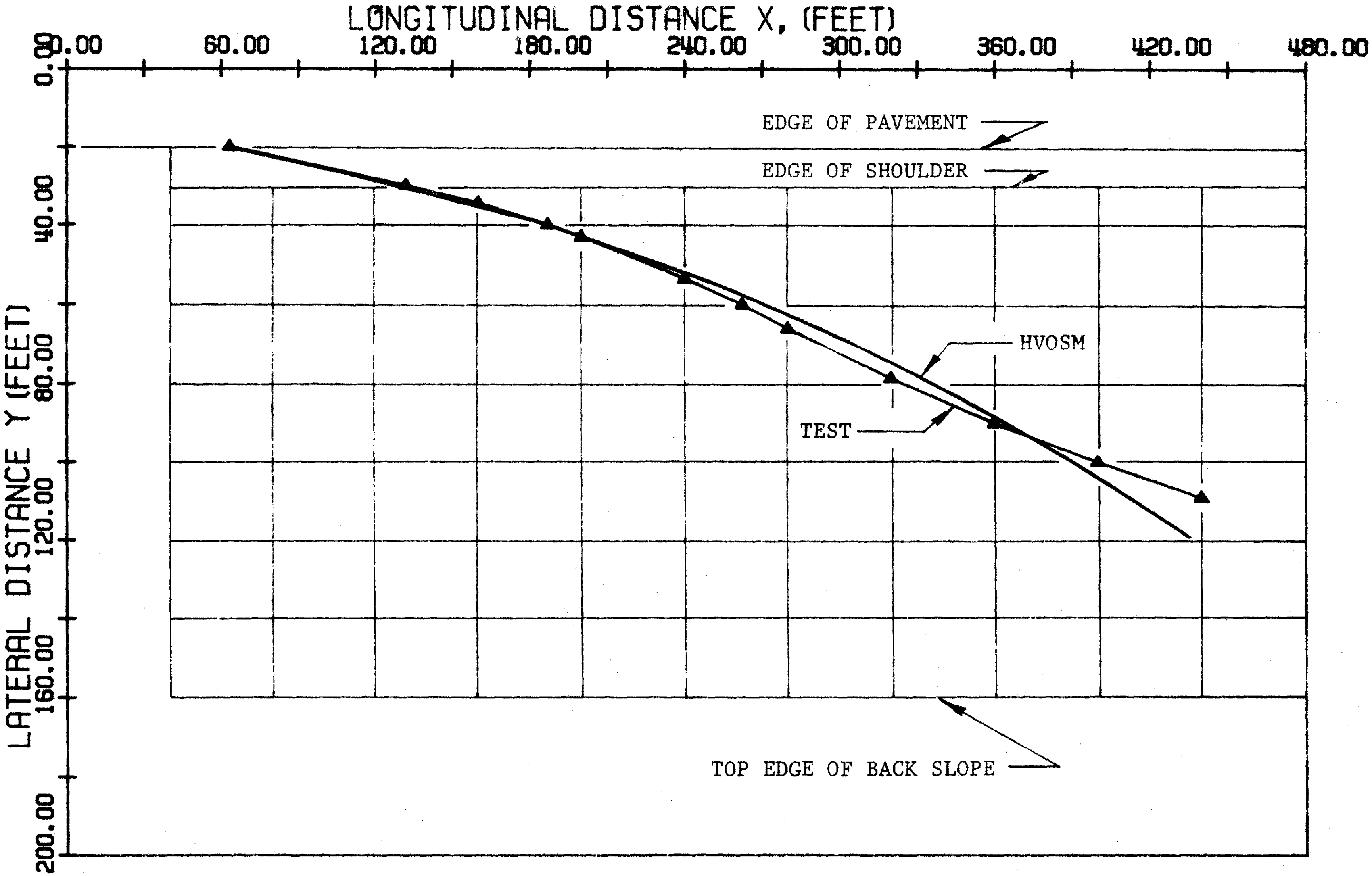
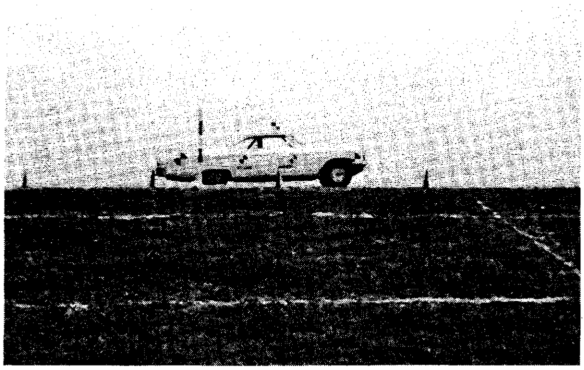
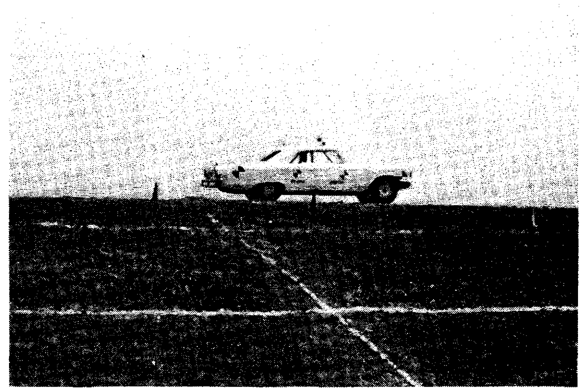


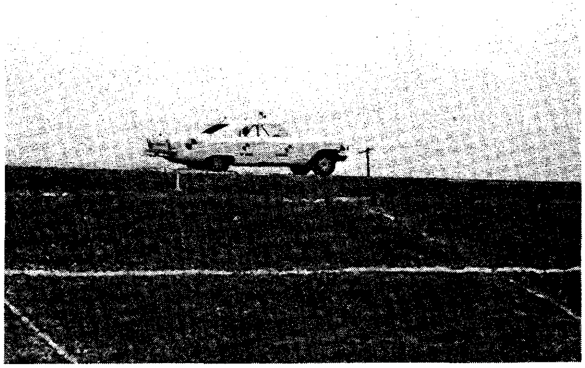
FIGURE C-13. RIGHT FRONT TIRE TRACK, TEST NO. 5.



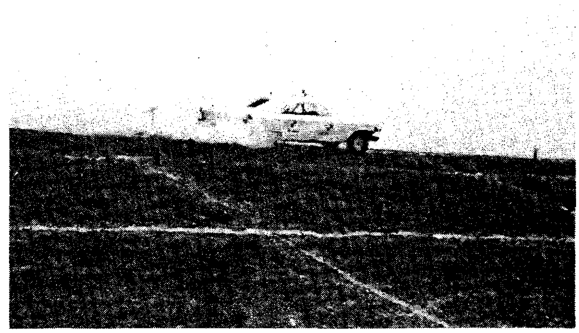
T = 0.00 SEC



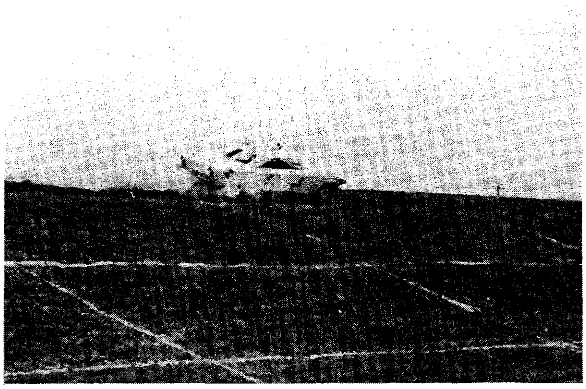
T = 0.30 SEC



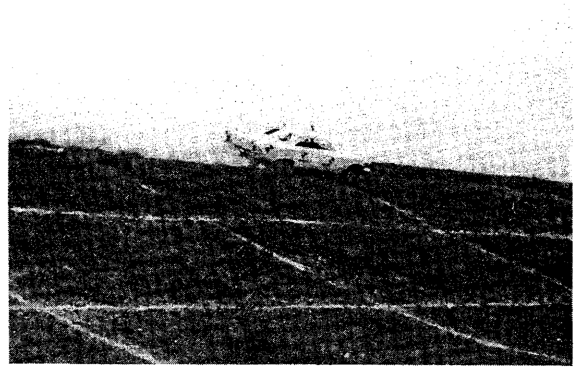
T = 0.60 SEC



T = 0.90 SEC

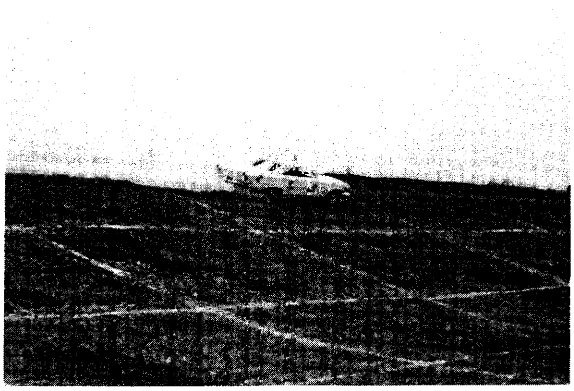


T = 1.20 SEC



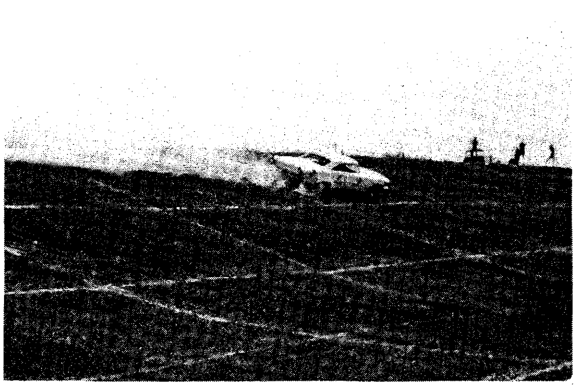
T = 1.50 SEC

FIGURE C-14. TEST NO. 5 RESULTS, CAMERA NO. 1.

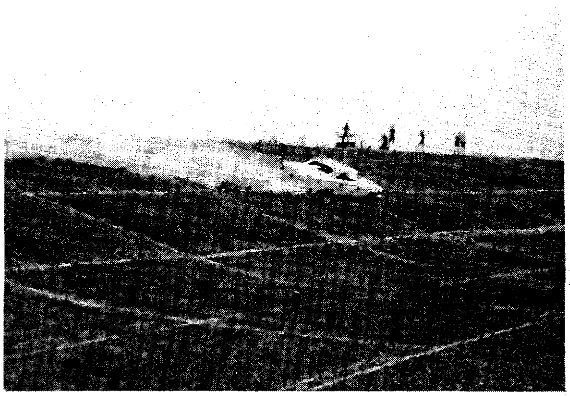


T = 1.80 SEC

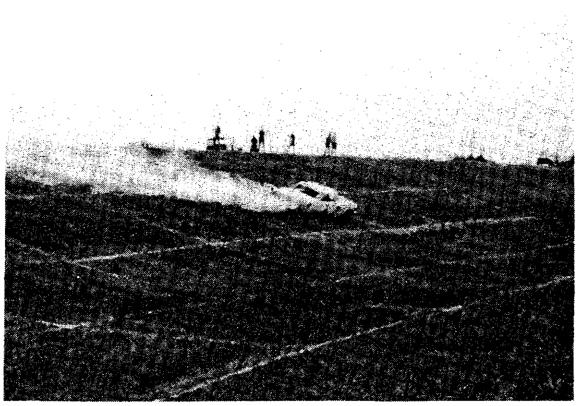
T = 2.10 SEC



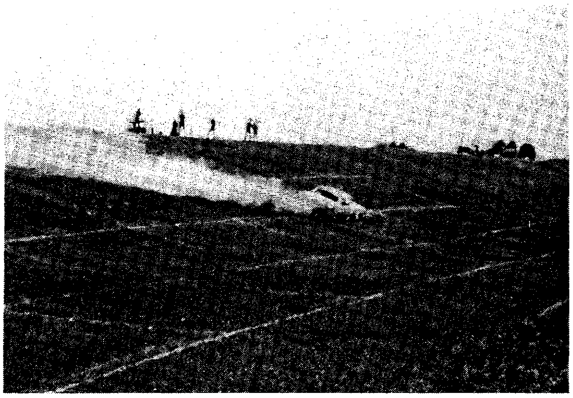
T = 2.40 SEC



T = 2.70 SEC

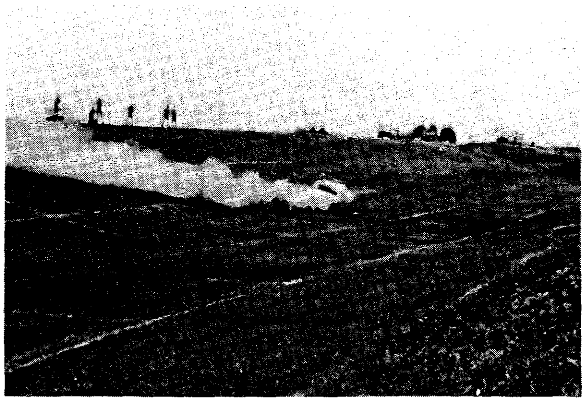


T = 3.00 SEC



T = 3.30 SEC

FIGURE C-14. CONTINUED.

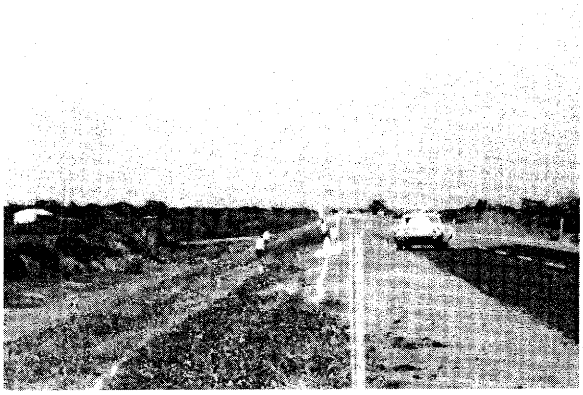


T = 3.60 SEC

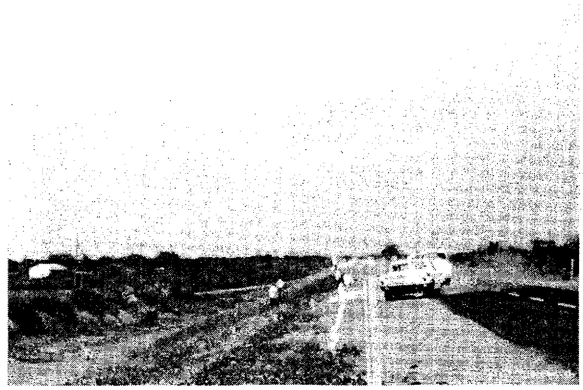
T = 3.90 SEC

T = 4.20 SEC

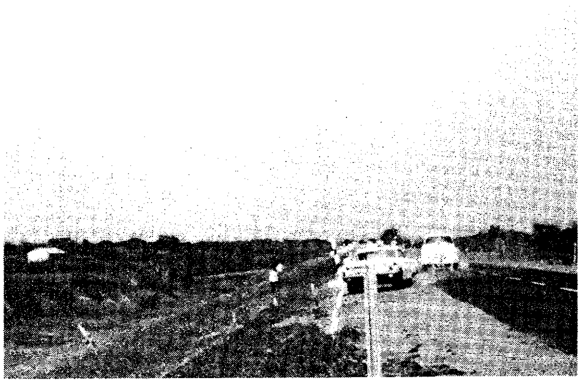
FIGURE C-14. CONTINUED.



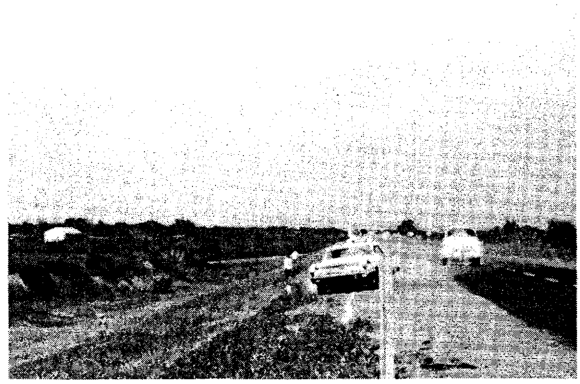
T = 0.00



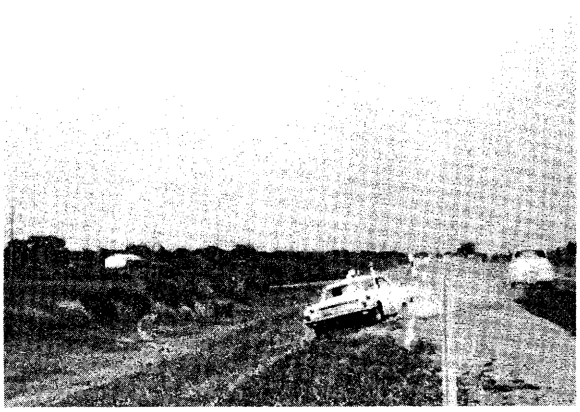
T = 0.30



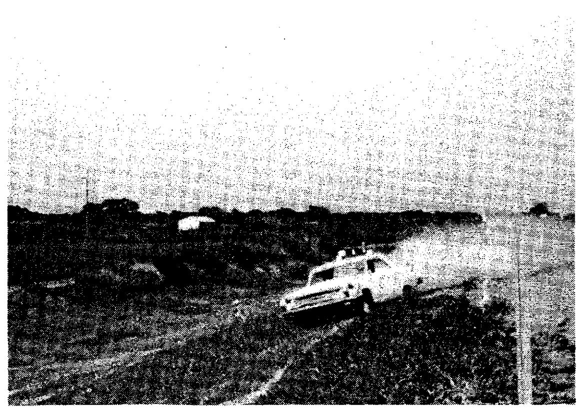
T = 0.60



T = 0.90



T = 1.20



T = 1.50

FIGURE C-15. TEST NO. 5 RESULTS, CAMERA NO. 2.

T = 1.80

T = 2.10

NOTE: Remainder of photos not available due to camera no. 2 malfunction.

FIGURE C-15. CONTINUED.

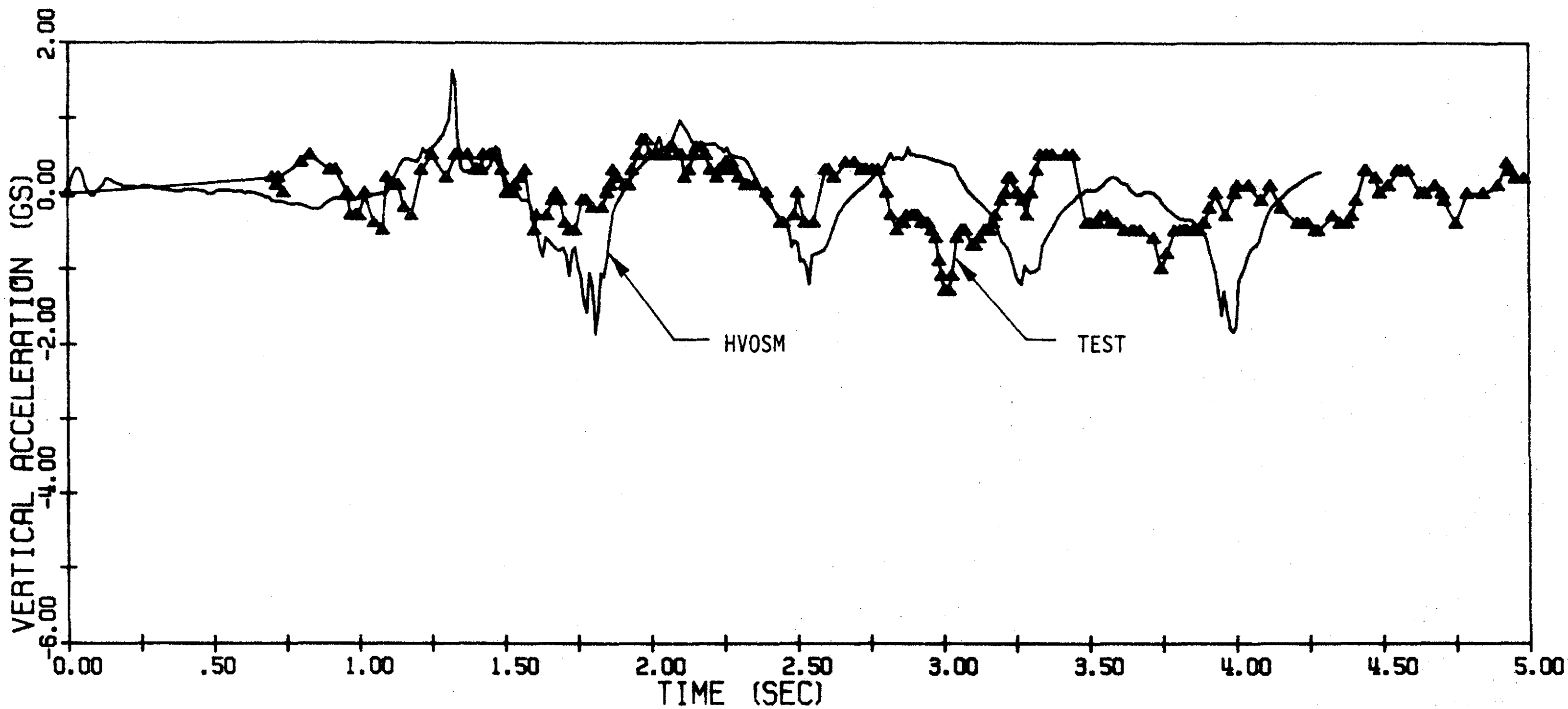


FIGURE C-16. VERTICAL ACCELERATION VERSUS TIME, TEST NO. 5.

TEST NO. 6

ENCROACHMENT ANGLE = 13.3 DEGREES

ENCROACHMENT SPEED = 63.6 MPH

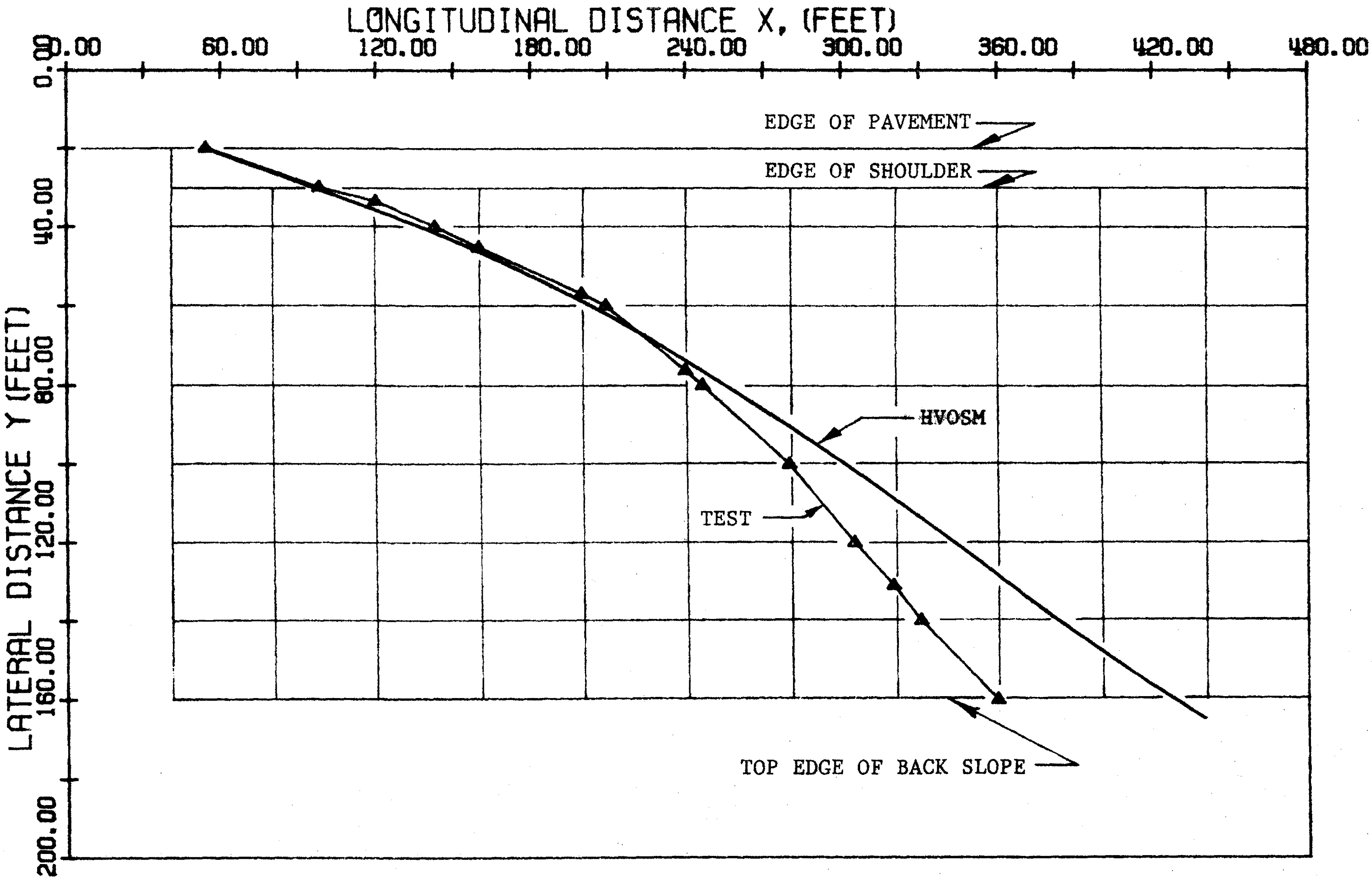


FIGURE C-17. RIGHT FRONT TIRE TRACK, TEST NO. 6.

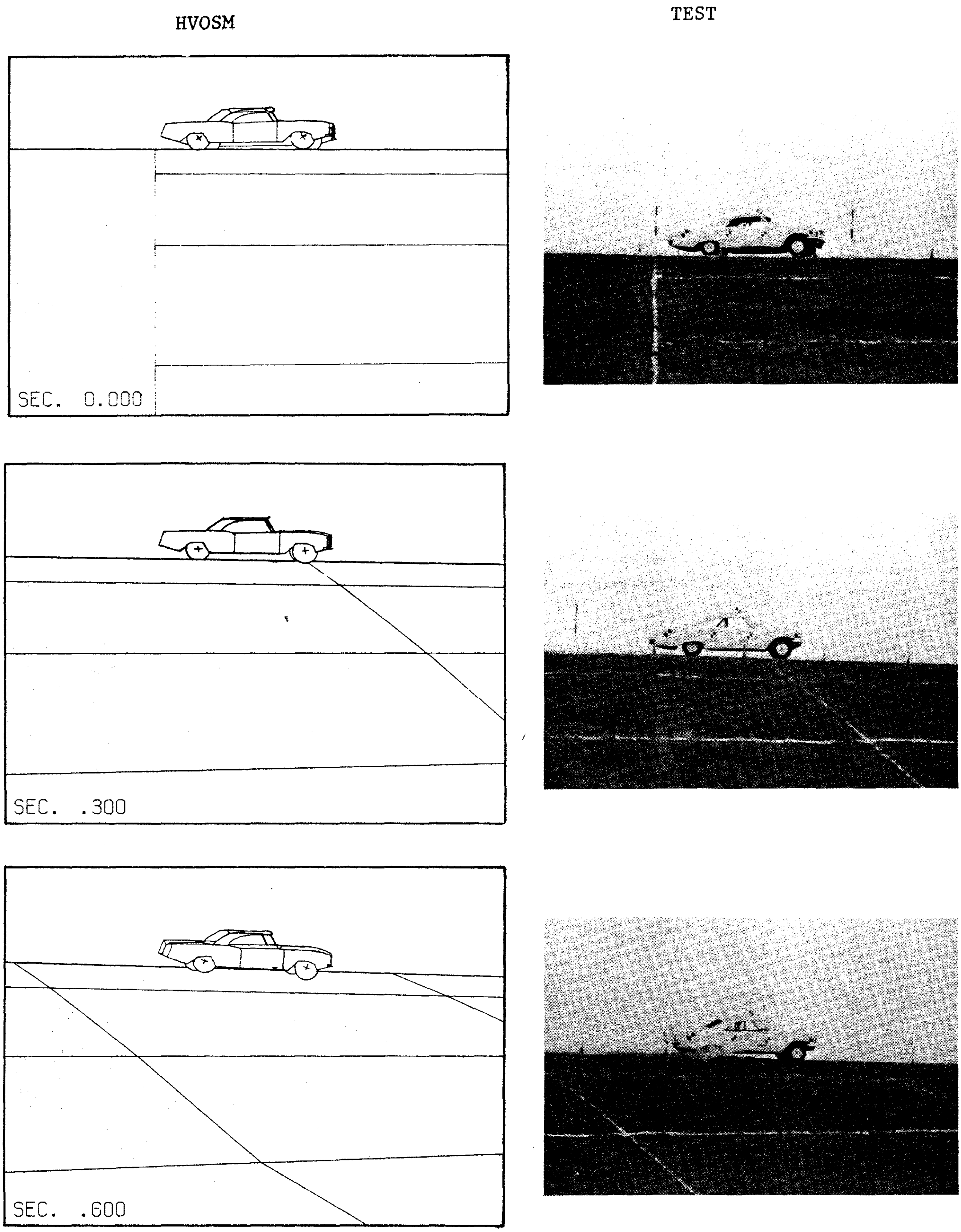
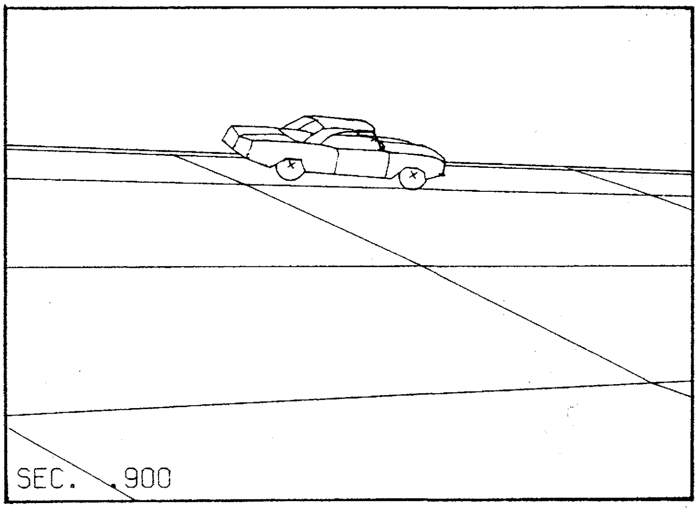
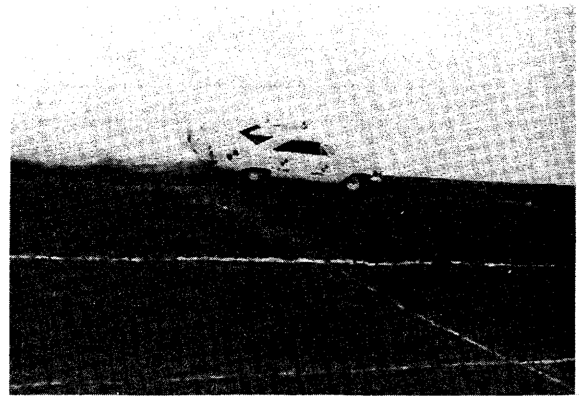
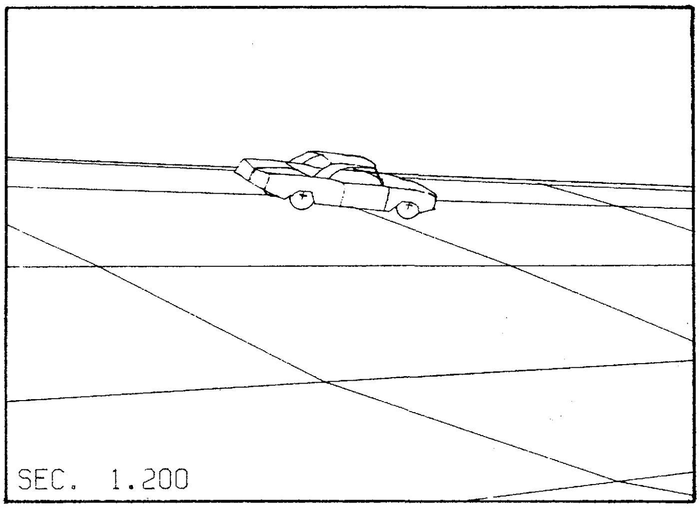


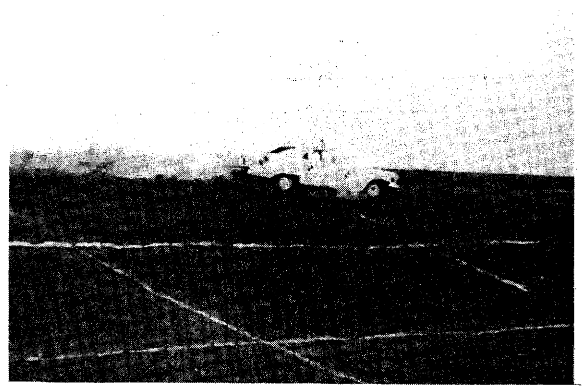
FIGURE C-18. HVOSM VERSUS TEST RESULTS, TEST NO. 6, CAMERA NO. 1.

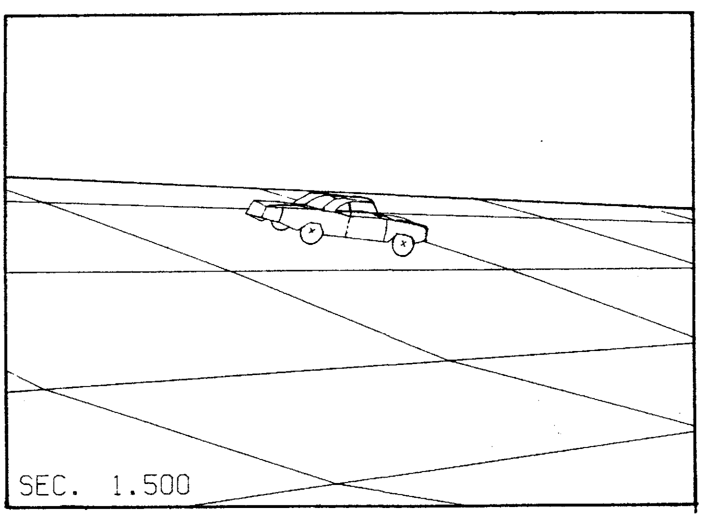
HVOSM TEST











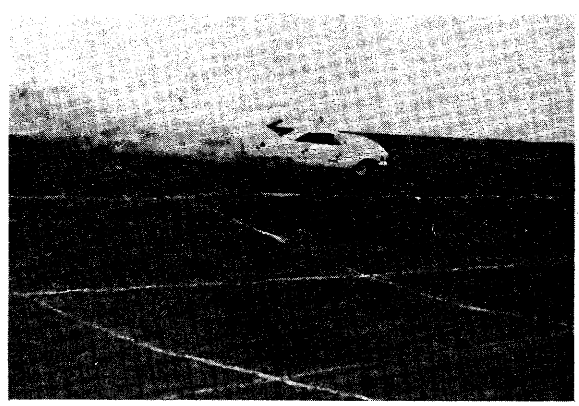


FIGURE C-18. CONTINUED.

HVOSM TEST

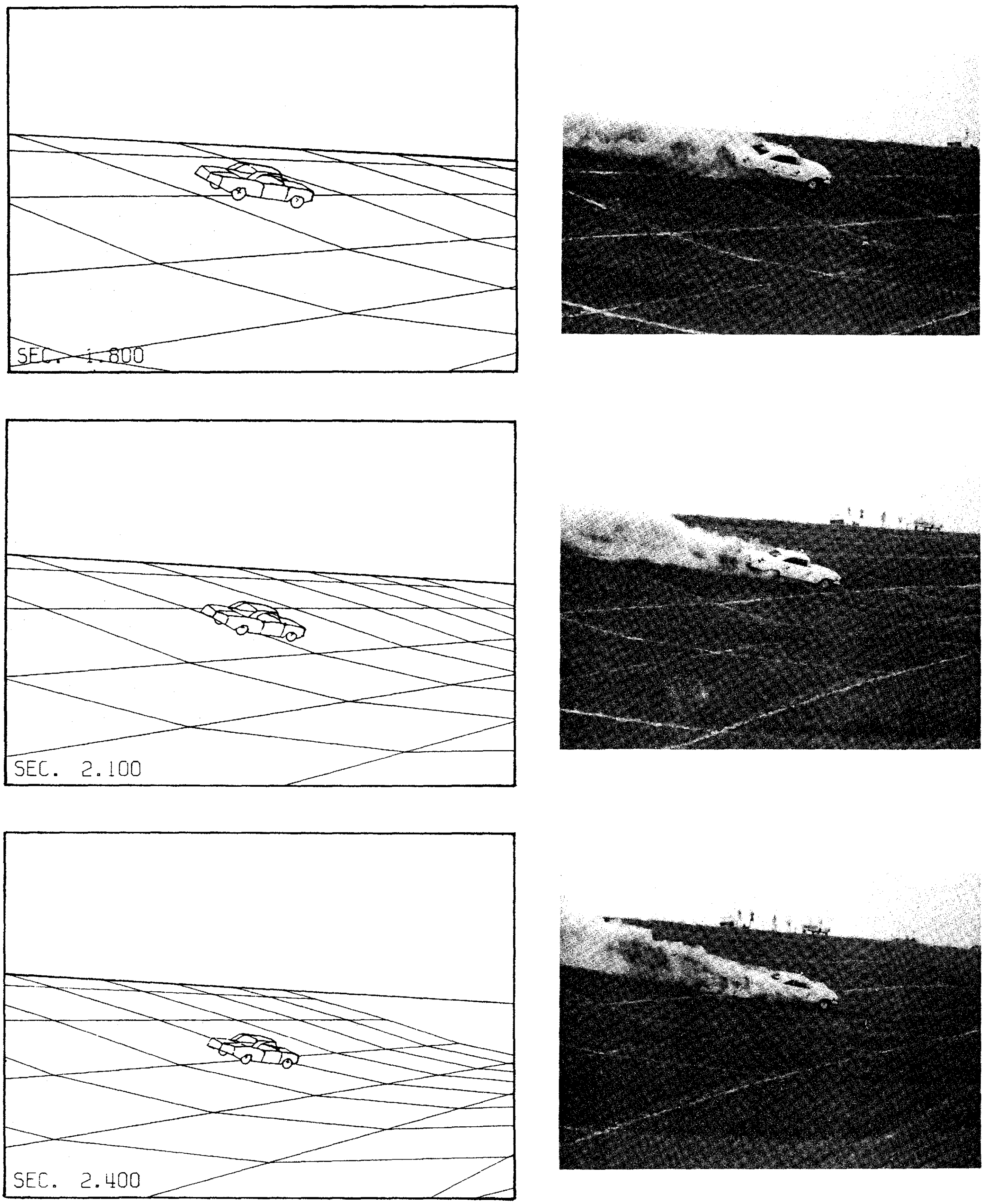


FIGURE C-18 . CONTINUED.

HVOSM TEST

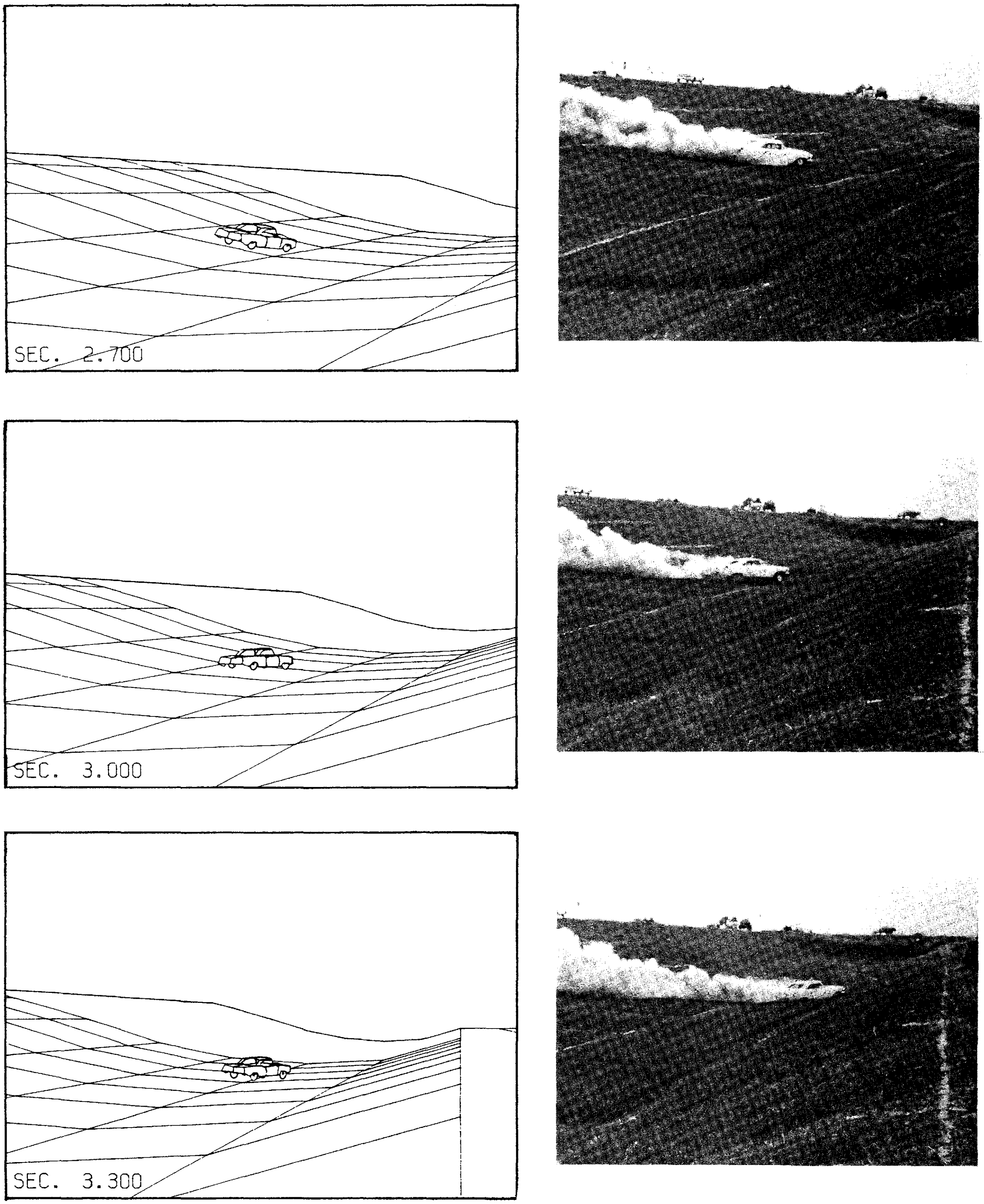


FIGURE C-18. CONTINUED.

HVOSM TEST

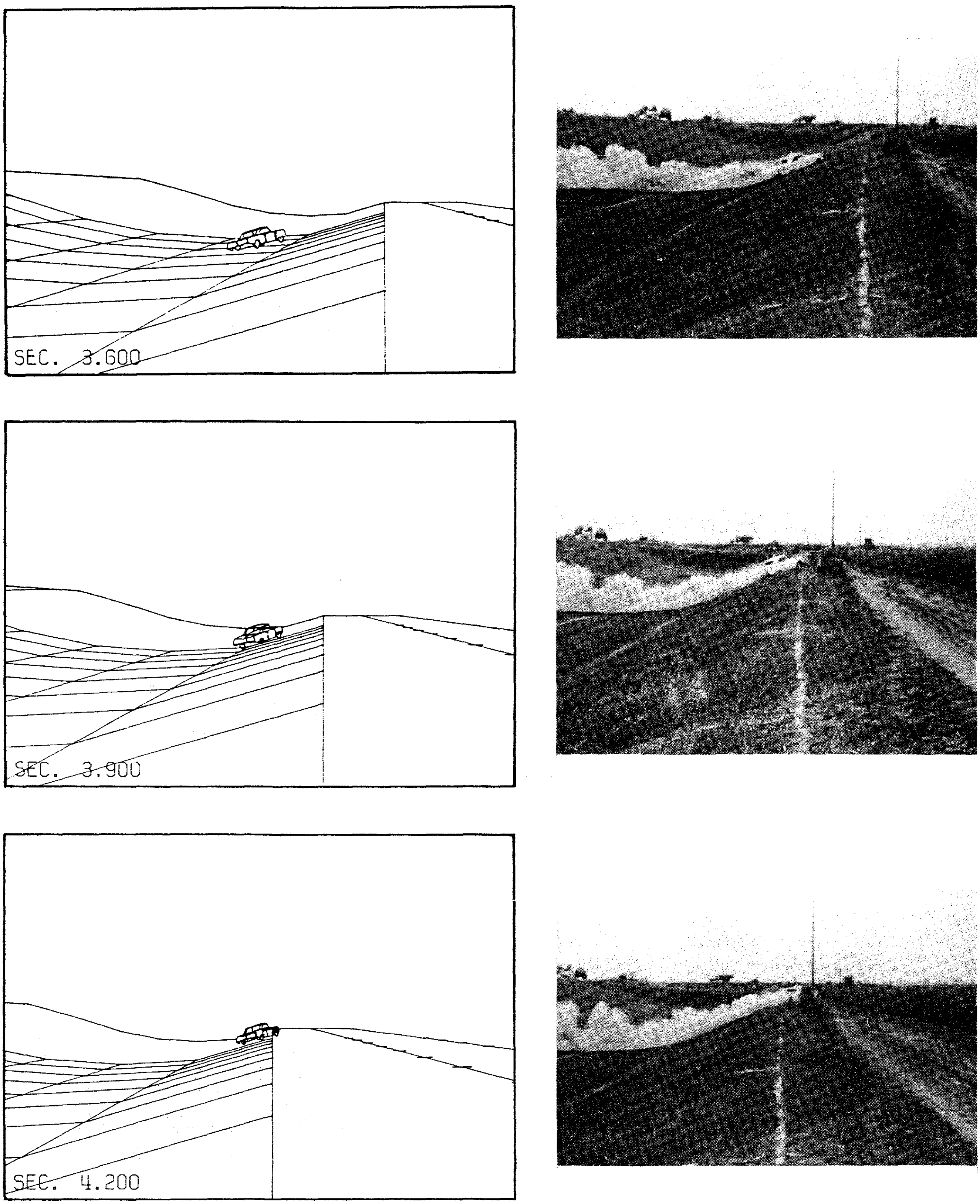


FIGURE C-18. CONTINUED.

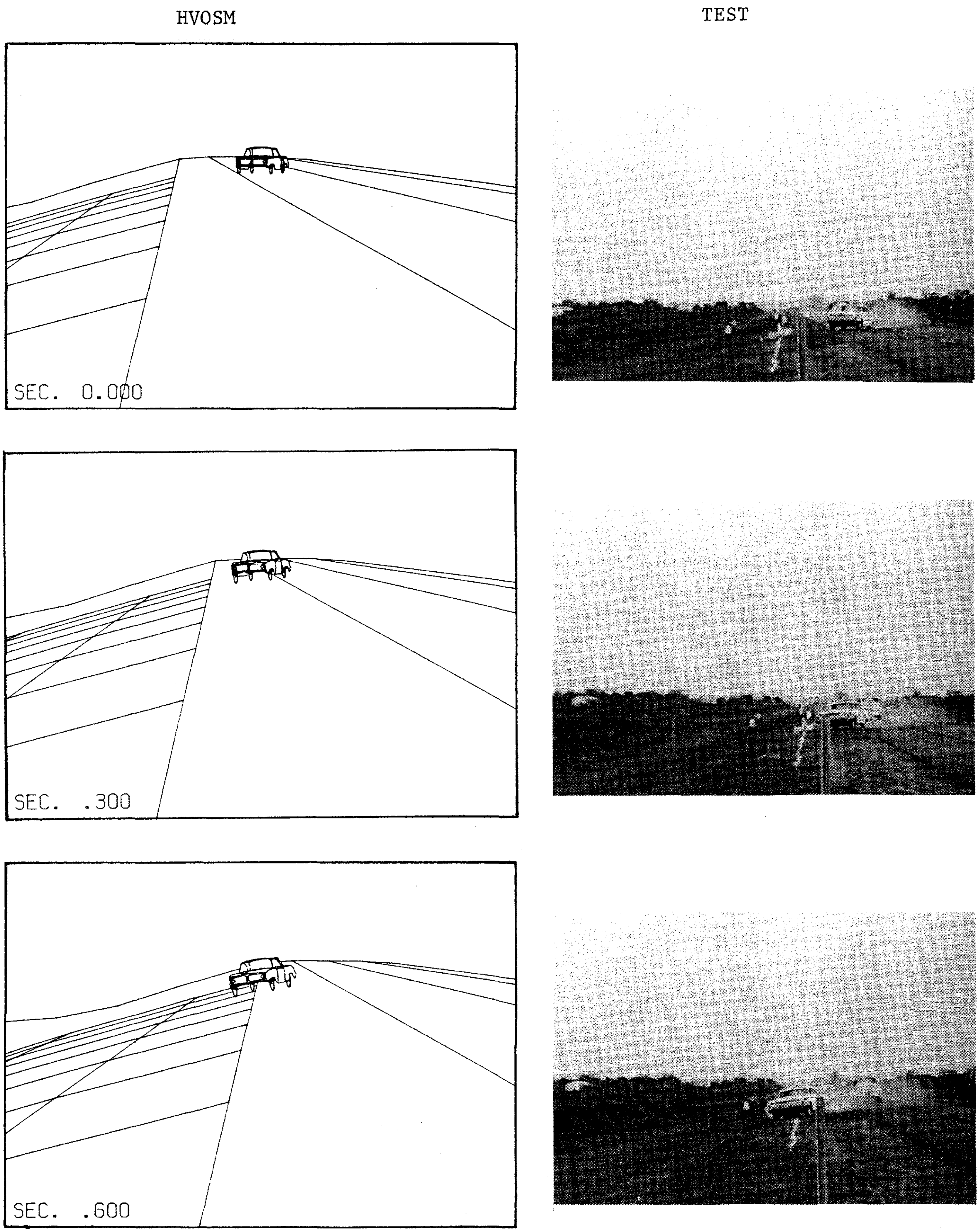


FIGURE C-19. HVOSM VERSUS TEST RESULTS, TEST NO. 6, CAMERA NO. 2.

HVOSM TEST

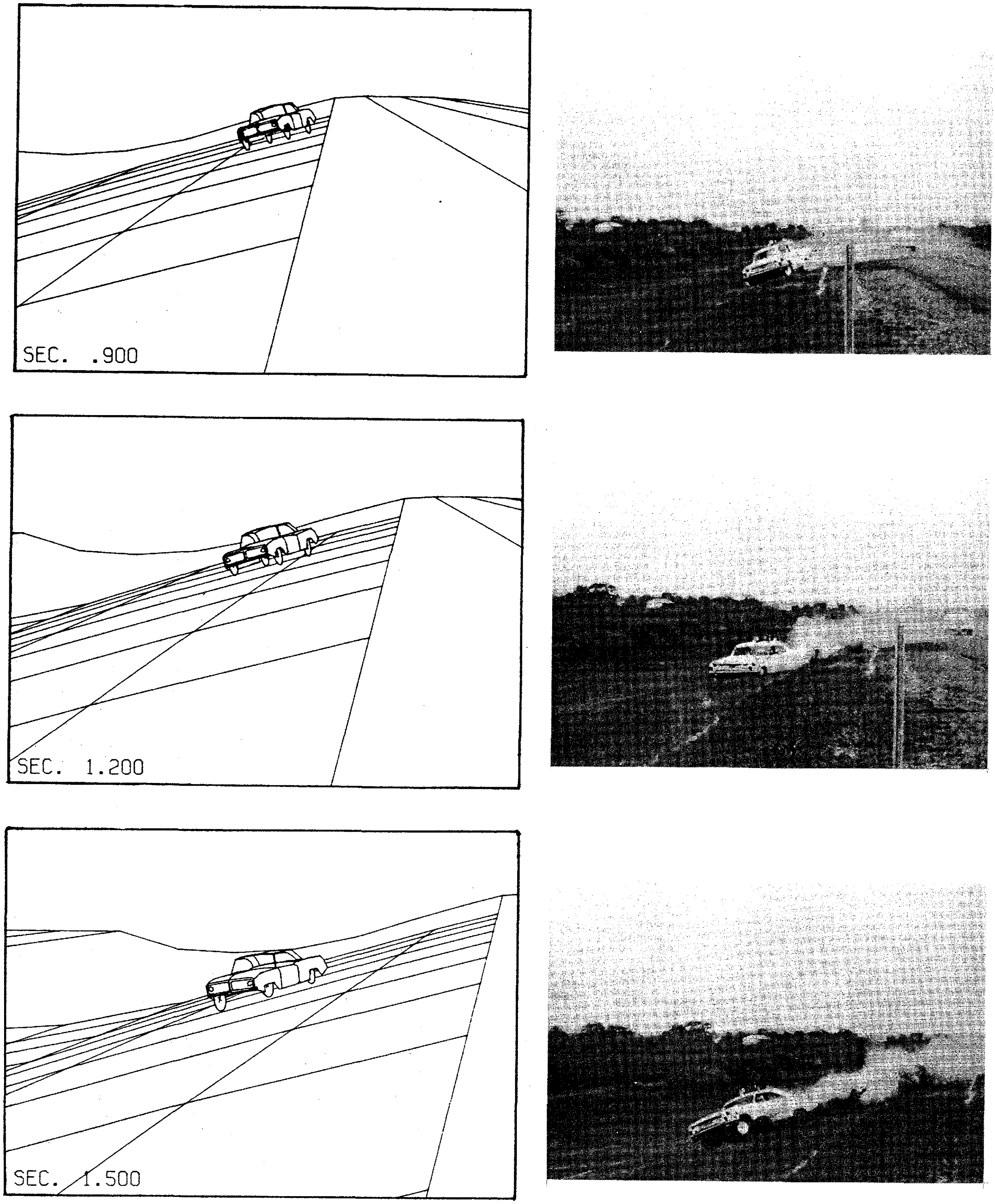


FIGURE C-19. CONTINUED.

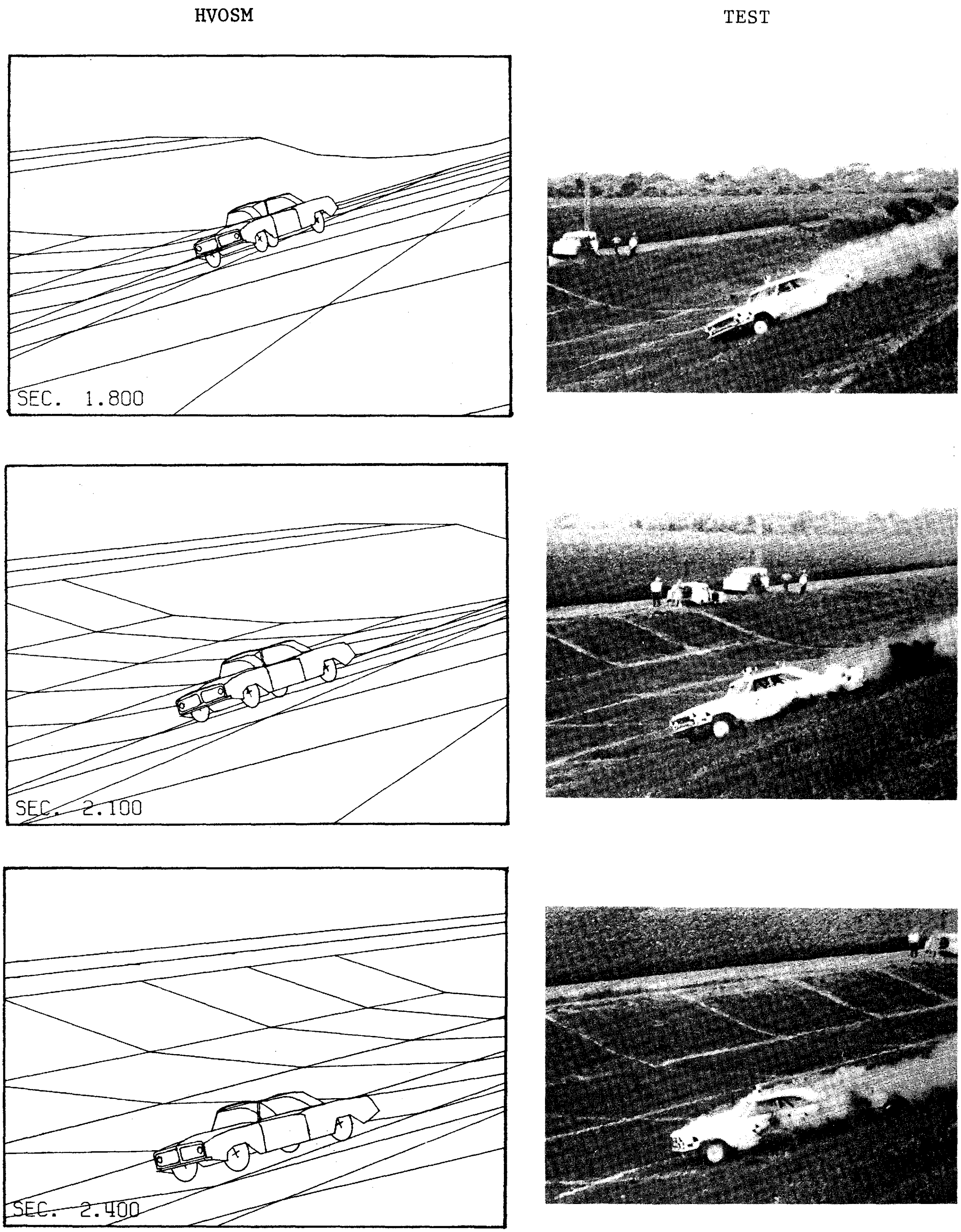


FIGURE C-19. CONTINUED.

HVOSM TEST

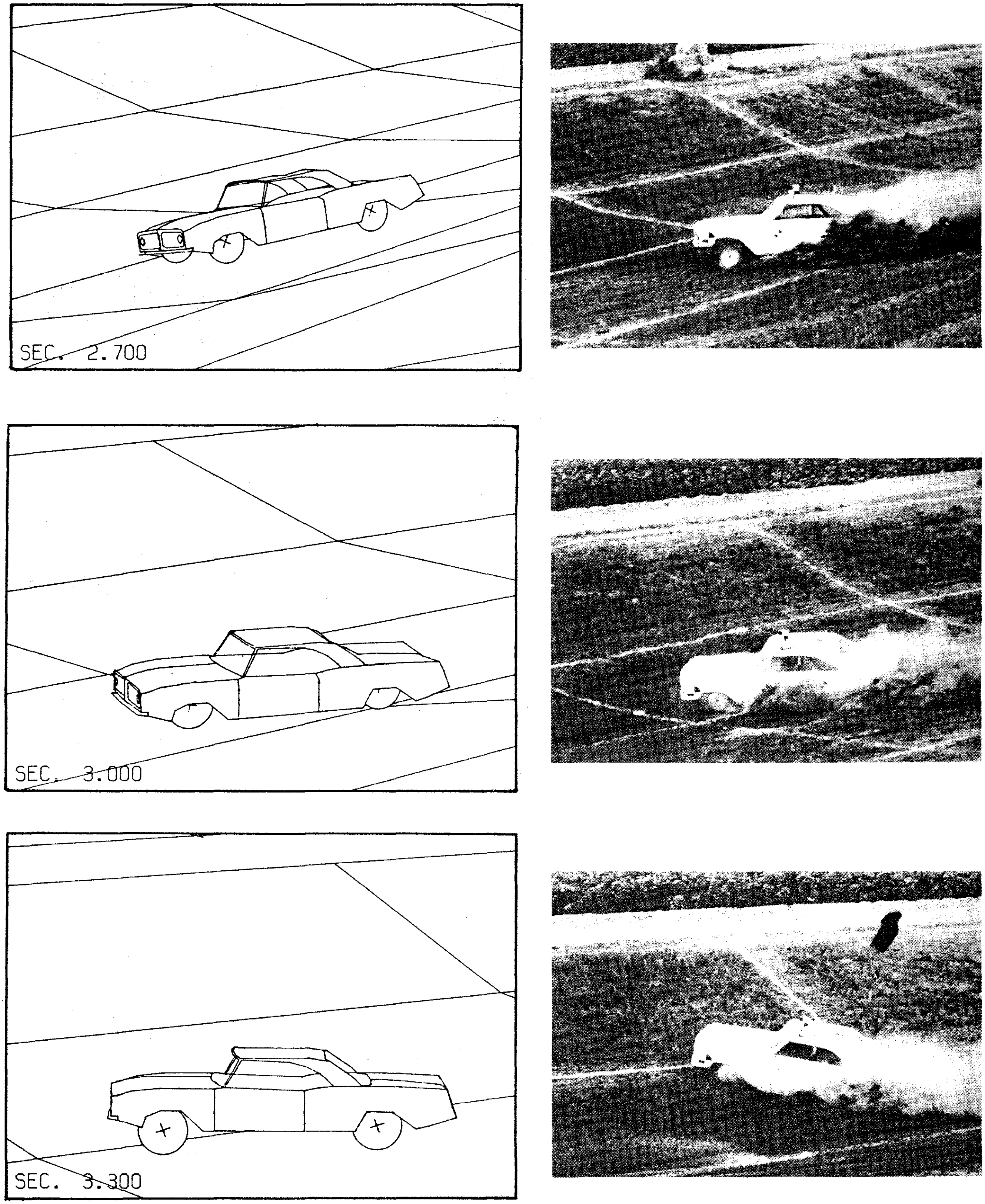


FIGURE C-19. CONTINUED.

HVOSM TEST

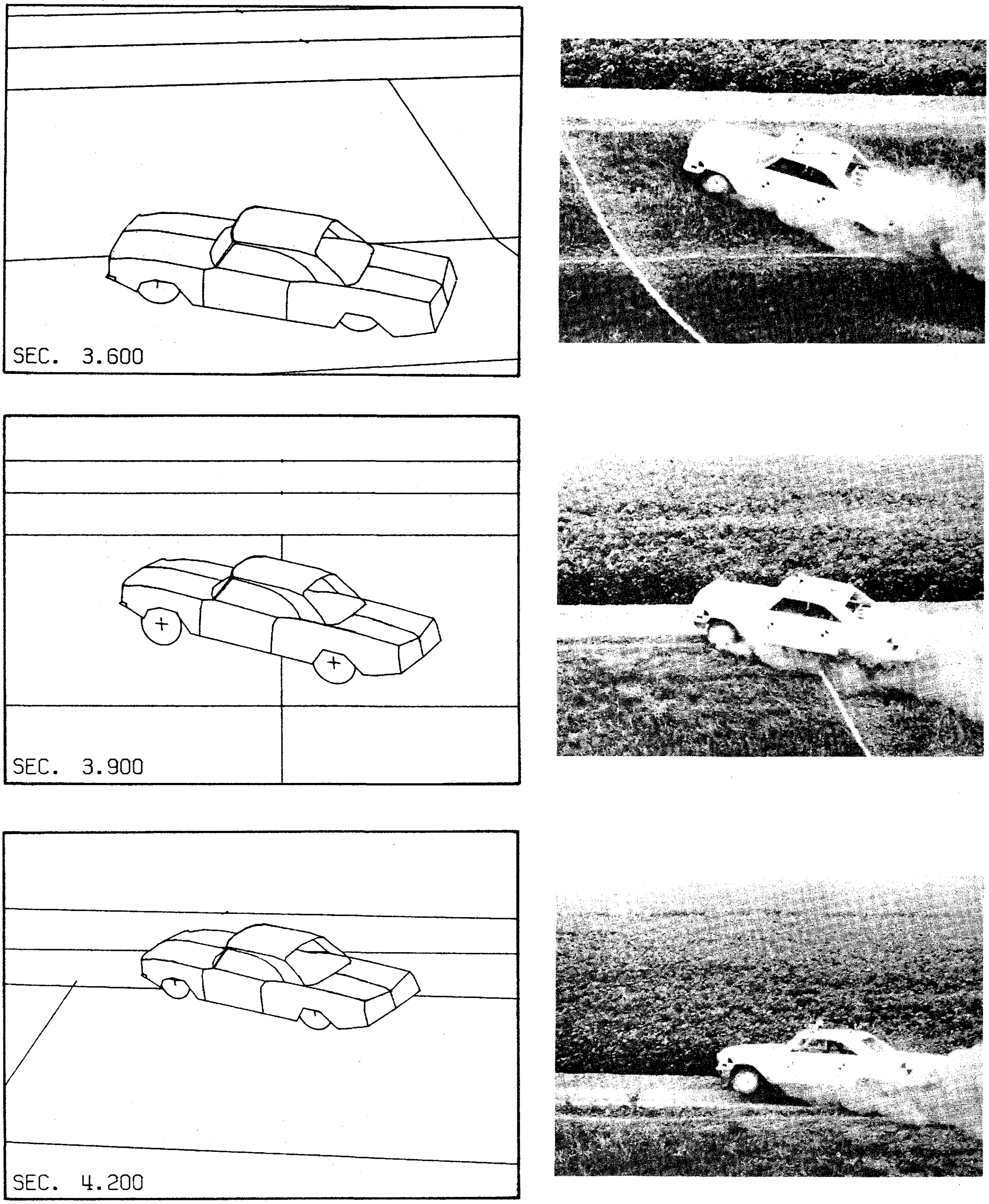
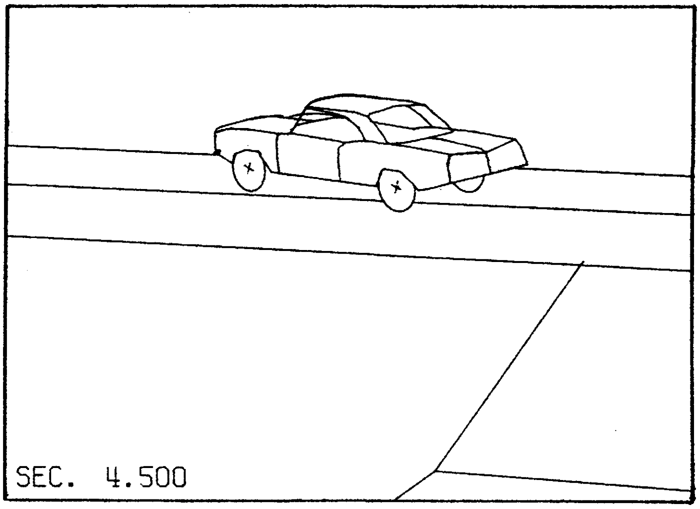
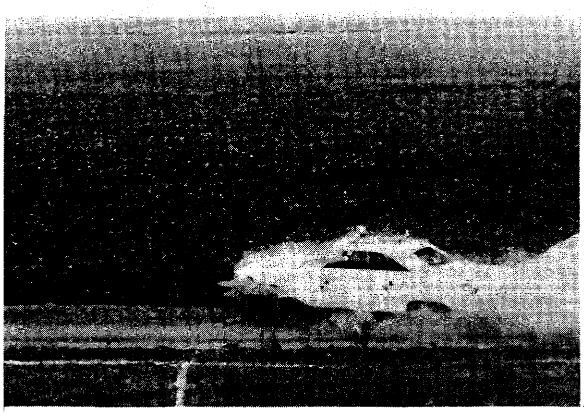


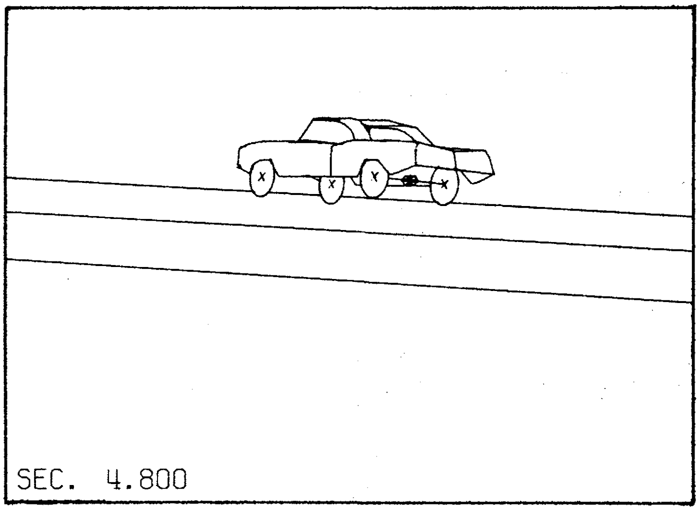
FIGURE C-19. CONTINUED.

HVOSM

TEST







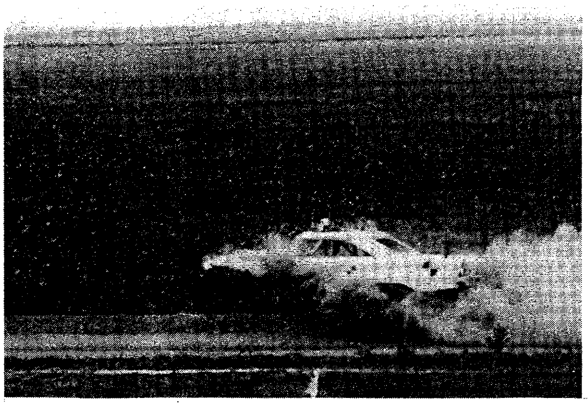


FIGURE C-19. CONTINUED.

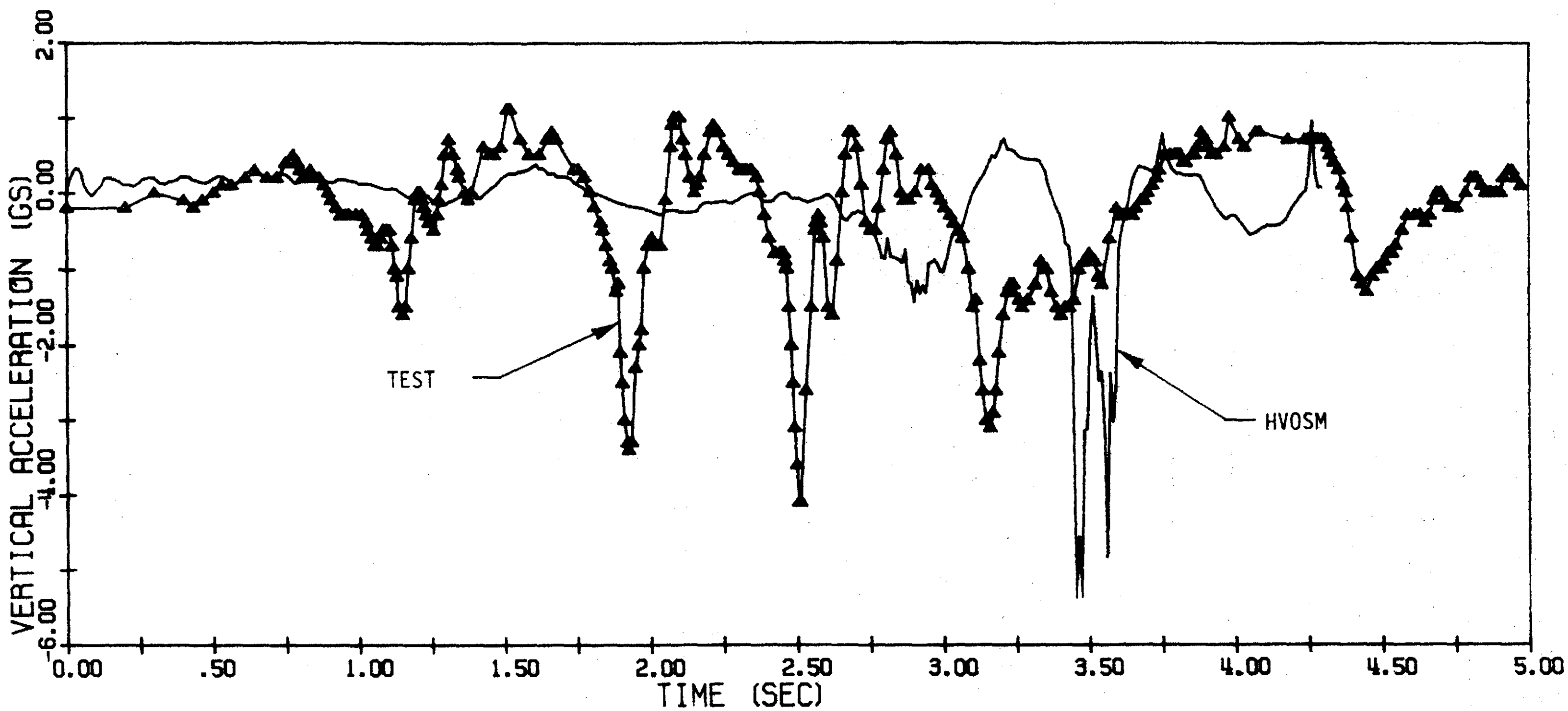


FIGURE C-20. VERTICAL ACCELERATIONS VERSUS TIME, TEST NO. 6.