PERFORMANCE EVALUATION OF KDOT W-BEAM SYSTEMS

Volume I: Full-Scale Crash Testing

Prepared by:
Midwest Roadside Safety Facility (MwRSF)
Center for Infrastructure Research
Civil Engineering Department
University of Nebraska-Lincoln
1901 Y Street, Building C
Lincoln, Nebraska 68588-0601
(401) 472-9198

May 1996

1. Performing Organization Report No.	2. Report Date	3. Type of Report
TRP-03-39-96	May 1996	Final Report

4. Title and Subtitle

Performance Evaluation of KDOT W-Beam Systems
Volume I: Full-Scale Crash Testing

5. Author(s)

Holloway, J.C., M.G. Bierman, B.G. Pfeifer, B.T. Rosson, and D.L. Sicking

6. Performing Organization Name and Address

Midwest Roadside Safety Facility (MwRSF)
Civil Engineering Department
University of Nebraska - Lincoln
1901 Y St., Bldg C
Lincoln, Nebraska 68588-0601
(402) 472-6864

7. Sponsoring Agency Name and Address

Midwest States Regional Pooled Fund
Nebraska Department of Roads
1500 Nebraska Highway 2
Lincoln, Nebraska 68509-4567

8. Contract or Grant No.

SPR-3(017), FY-94 Midwest States Regional Pooled Fund Program

9. Abstract

Four full-scale vehicle crash tests were performed on steel post W-beam guardrail installations for the Kansas Department of Transportation to determine the safety performance of the guardrail systems and the deflection characteristics due to nesting of the W-beam and reducing the post spacing. The four test installations that were evaluated consisted of: (1) a single W-beam with 6 ft - 3 in. post spacing; (2) a nested W-beam with 6 ft - 3 in. post spacing; (3) a single W-beam with 3 ft - 1½ in. post spacing; and (4) a nested W-beam with 3 ft - 1½ in. post spacing. The impact conditions for all four crash tests consisted of using a 4500-lb sedan impacting at 60 mph and 25 degrees.

The tests were conducted and reported in accordance with the requirements specified in the *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program (NCHRP) Report No. 230. The safety performance of each guardrail system was determined to be acceptable according to the NCHRP Report 230 criteria. The impact characteristics of the guardrails and vehicles from the full-scale crash tests will be used to aid in the decisions for the placement of W-beam guardrail. These results will also be used in the second phase of this study (Volume II), which utilizes component testing and computer simulation to predict the behavior of the same types of systems with wood posts instead of steel.

10. Keywords	11. Distribution Statement
Highway Safety, Crash Tests, Guardrail, Posts, Dynamic Post Testing, W-Beam	No restrictions. This document is available to the public from the sponsoring agency.

12. Security Classification (of this report)	13. Security Classification (of this page)	14. No. of Pages
Unclassified	Unclassified	

DISCLAIMER STATEMENT

ACKNOWLEDGEMENTS

The authors wish to express their appreciation and thanks to the Midwest Regional States Pooled Fund and the Center for Infrastructure Research for funding the research described herein. A special thanks is also given the following individuals who made a contribution to this research study.

Kansas Department of Transportation
Ron Seitz, P.E., Squad Leader

Nebraska Department of Roads
Larry Brown, Midwest States Regional Pooled Fund Chairman
Leona Kolbet, Research Coordinator

Missouri Highway Transportation Department
Pat McDaniel, P.E., Special Assignments Design Engineer

Minnesota Department of Transportation
Khani Sahebjam, P.E., State Aid Bridge Engineer

Center for Infrastructure Research
Maher Tadros, P.E., Ph.D.

Midwest Roadside Safety Facility
Ronald K. Faller, P.E., Research Associate Engineer
John R. Rohde, Ph. D., P.E., Associate Professor
John D. Reid, Ph.D., Assistant Professor
Graduate and Undergraduate Assistants

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONT.)

Page

LIST OF TABLES

1 INTRODUCTION

Guardrails are used to reduce the severity of ran-off-the-road accidents and to safely redirect errant vehicles. Guardrail systems are classified according to their lateral stiffness characteristics. A common barrier system used by many states, including Kansas, is the G4 longitudinal guardrail, a strong post design consisting of steel W-beam mounted on steel or wood posts (1). The top mounting height is usually 27 in. and the rail is blocked out from the posts to minimize vehicle snagging and vaulting potential. The G4 system is classified as a semi-rigid system and is utilized where small lateral deflections are required.

1.1 PROBLEM STATEMENT

Full-scale crash testing has shown that the W-beam system can effectively redirect vehicles with a 6 ft - 3 in. post spacing (2,3,4). However, there has not been a full-scale crash test program conducted to investigate the effects of using different combinations of nesting and half-post spacing on standard G4(1S) longitudinal guardrails. Many states would like to use the results of such a study to allow them to make more informed decisions on the placement of systems with these different combinations of nesting and half-post spacing.

1.2 OBJECTIVE

The objective of this study was to determine the effects on the lateral deflection and the corresponding safety performance of each railing due to nesting the guardrail and spacing the posts at 3 ft - 1 ½ in. on center. This study will help the roadway design engineer to determine whether or not the use of nesting or reduced post spacing is warranted in situations where it is necessary to minimize lateral deflections. The experimental data acquired from this testing will be used to validate the BARRIER VII (5) computer model for guardrail impacts. This information will be used in a follow up study to investigate the same four tests when using timber posts instead of steel posts.

2 Full-Scale Test Conditions

2.1 System Design Details

2.1.1 KSWB-1 (Single W-Beam and 6 ft - 3 in. Post Spacing)

An overall layout of the installation for Test KSWB-1 is shown in Figure 1, with design details shown in Figure 2. The test installation consisted of 175 ft (seven- 25 ft sections) of single 12 gauge W-beam guardrail. The total installation was constructed with twenty-nine steel posts. The post spacing over the entire length of the installation was 6 ft - 3 in. on center. Post Nos. 3 through 27 consisted of W6 x 9 by 6-ft long steel posts with W6 x 9 steel spacer blocks, while Post Nos. 1, 2, 28, and 29 consisted of 5½-in. x 7½-in. x 3-ft 6½-in. timber breakaway posts. The guardrail had a top mounting height of 2 ft - 3 in. The W-beam guardrail was anchored on each end with a pair of anchor tubes, a groundline strut, and a cable anchor assembly. This anchorage system was identical to that used in a BCT, but there was no flare in this system. Steel backup plates were placed between the guardrail and the posts at all non-splice locations.

The standard breakaway posts were inserted into a tube and had a 2 3/8-in. diameter hole 25-in. below the top of the post and parallel to the roadway. All of the posts were installed by augering holes and backfilling with native silty-clay topsoil material. The soil was tamped around the posts with approximate 6-12 in. lifts throughout the entire embedment depth of 44.4 in. Prior to full-scale crash testing, the soil conditions, from a visual inspection, were found to be dry and crumbly at a depth of 1 to 2 ft below the surface. The soil was not in conformance with either the strong soil (S-1) or the weak soil (S-2) defined in NCHRP 230 (7), in order to evaluate the appurtenance under typical soil conditions encountered in the state of Kansas.

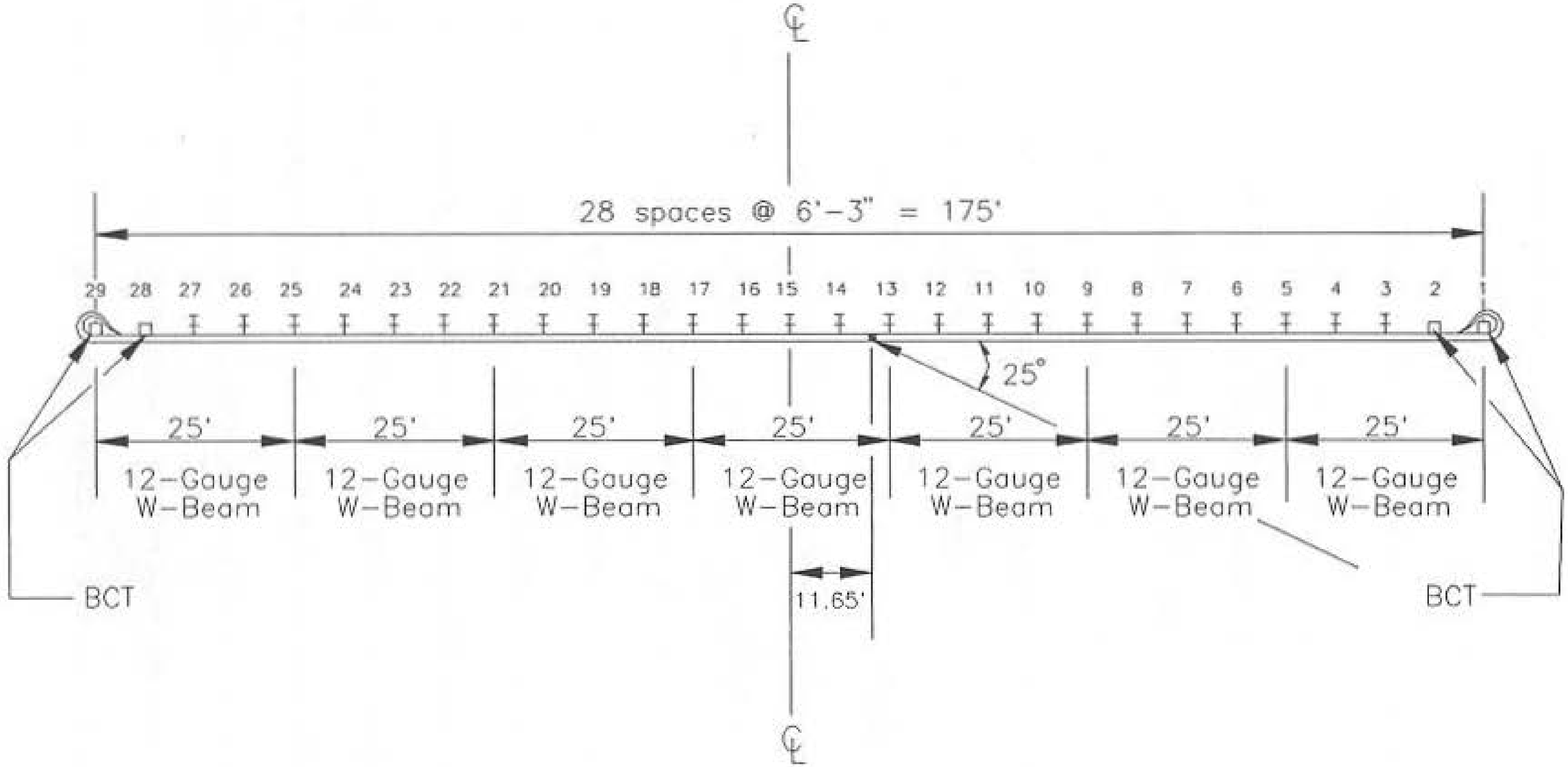


Figure 1. Guardrail Installation Layout, KSWB-1

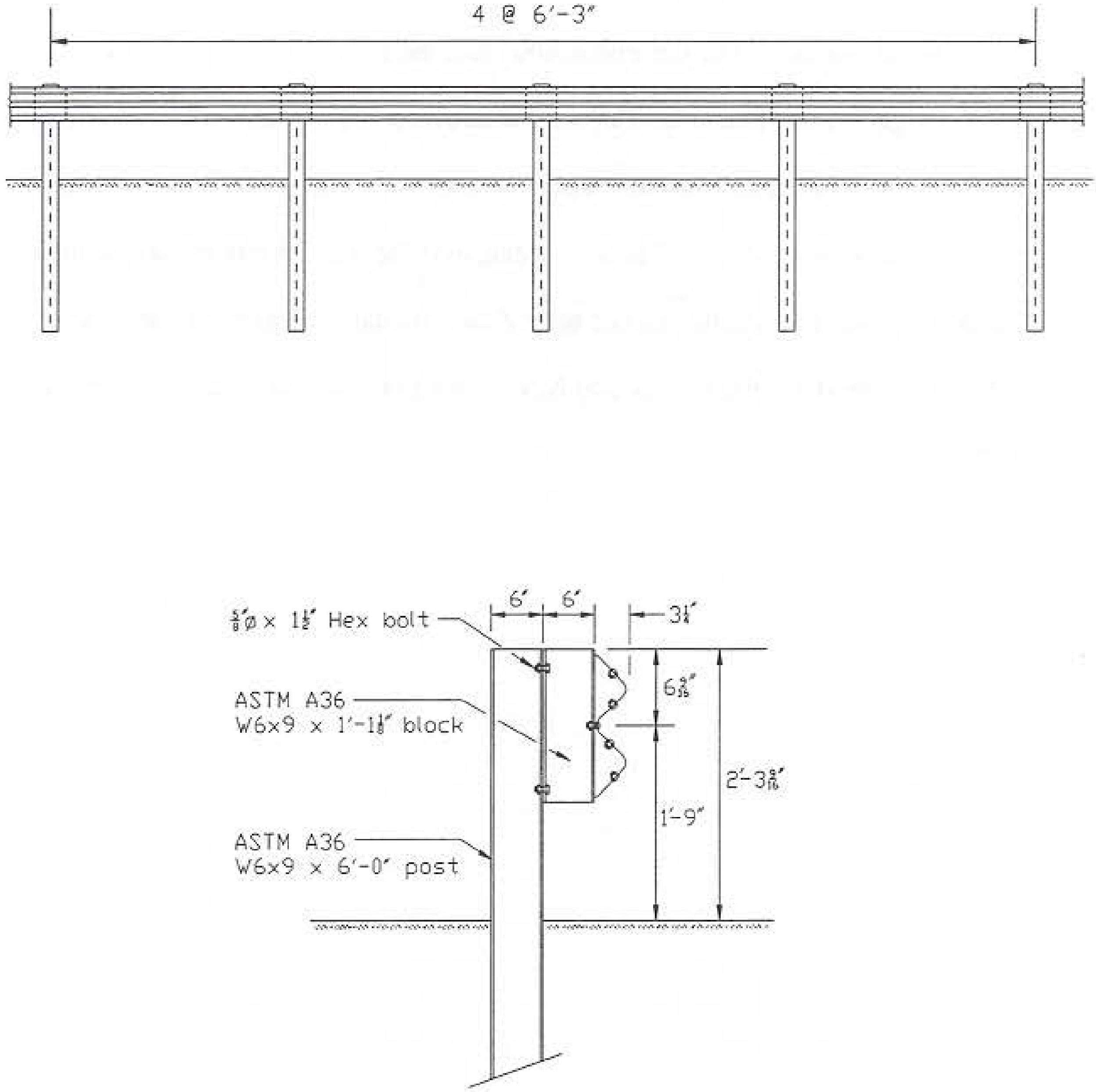


Figure 2. Guardrail Installation Details, KSWB-1

2.1.2 *KSWB-2 (Nested W-Beam and 6 ft - 3 in. Post Spacing)*

An overall layout of the installation for Test KSWB-2 is shown in Figure 3, with design details shown in Figure 4. The test installation consisted of 175 ft (twelve - 25 ft sections) of nested 12 gauge W-beam guardrail. The two end 25 ft sections of the installation consisted of a single layer of W-beam, and the five inner sections were nested. The total installation was constructed with twenty-nine posts. The post spacing over the entire length of the installation was 6 ft - 3 in. on center. Post installation and other details are the same as previously discussed for KSWB-1. Steel backup plates were placed between the guardrail and posts at all non-splice and non-nested locations.

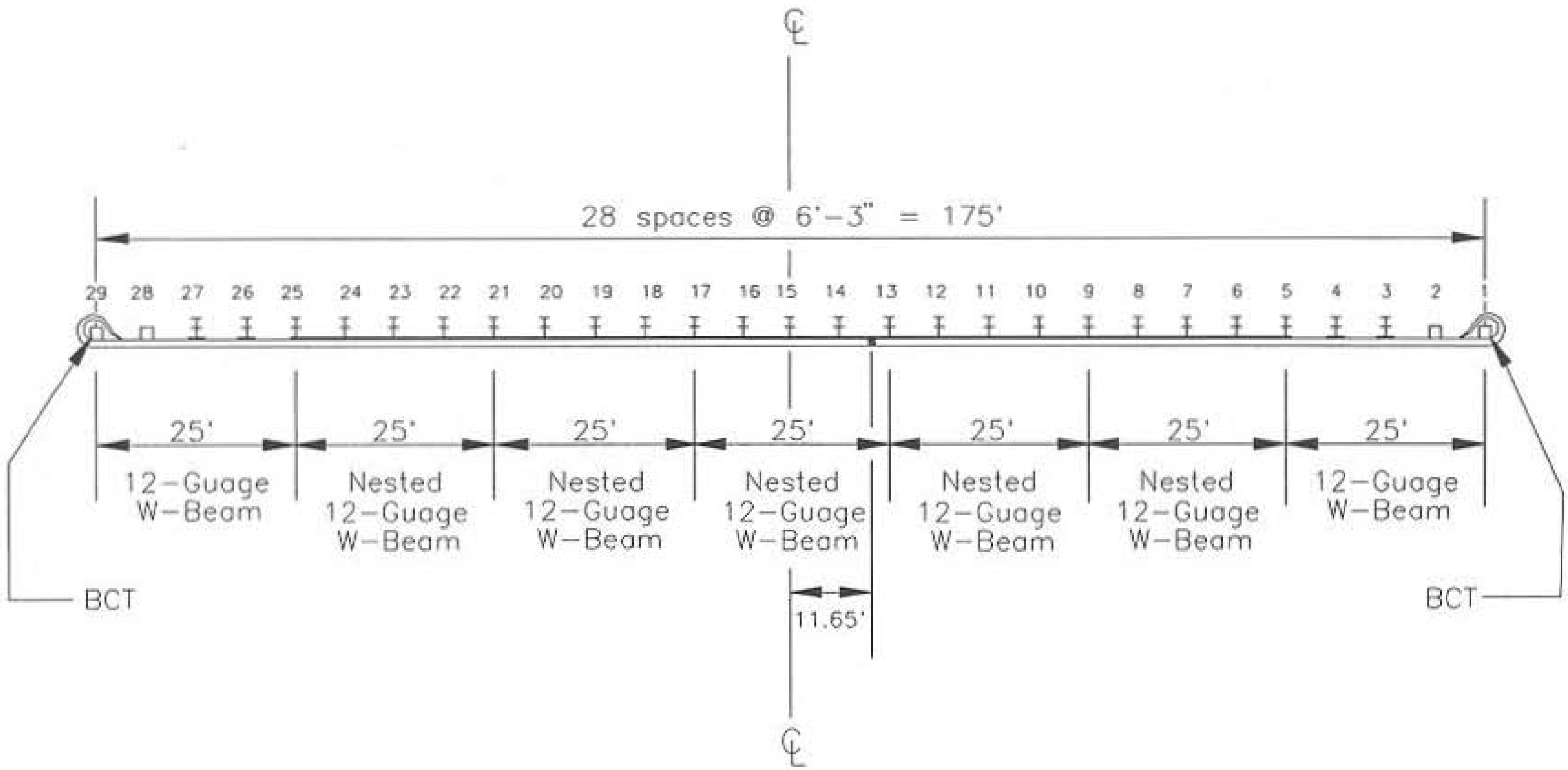


Figure 3. Guardrail Installation Layout, KSWB-2

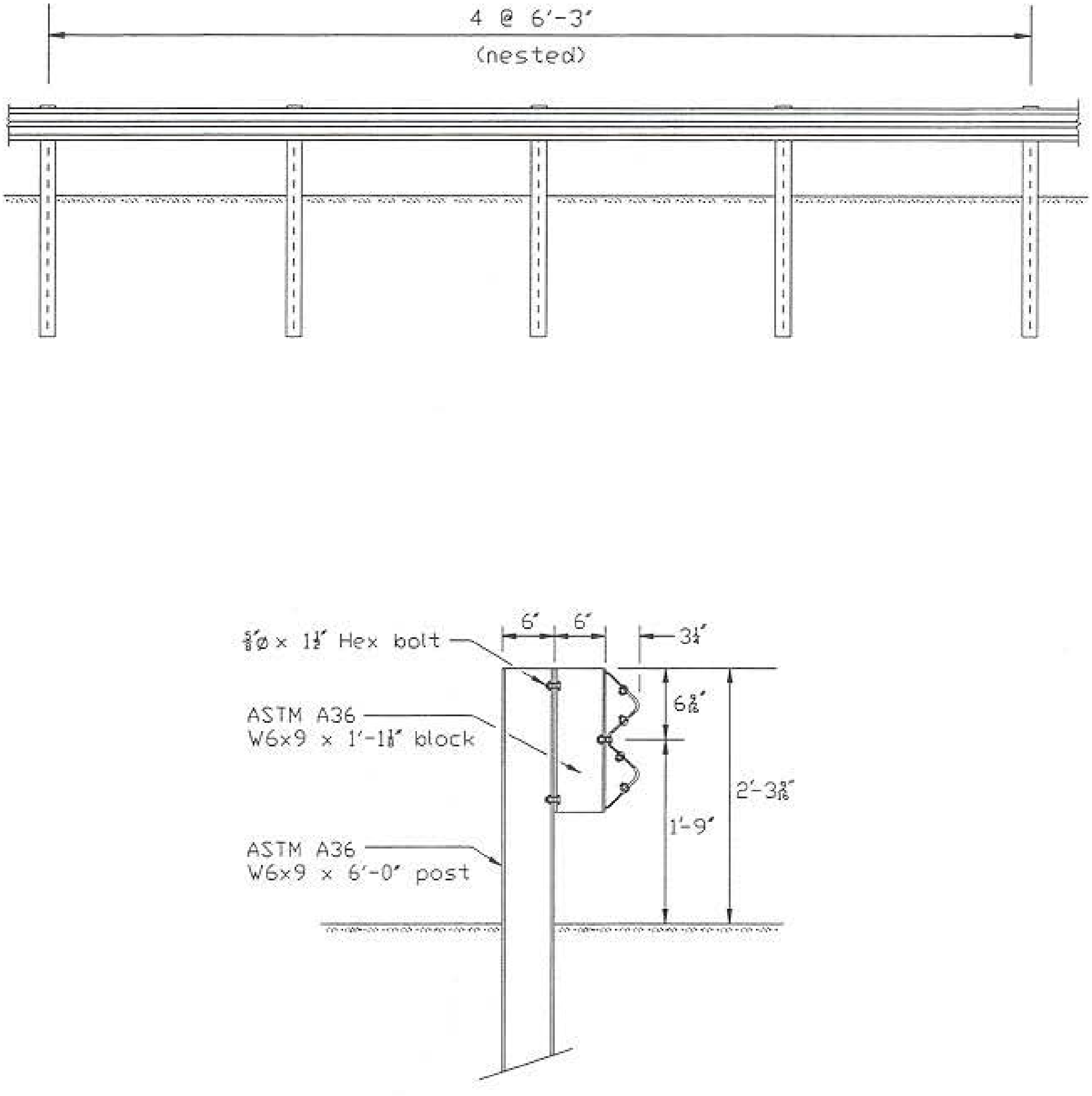


Figure 4. Guardrail Installation Details, KSWB-2

2.1.3 KSWB-3 (SINGLE W-BEAM AND 3 FT - 1½ IN. POST SPACING)

An overall layout of the installation for Test KSWB-3 is shown in Figure 5, with design details shown in Figure 6. The test installation consisted of 175 ft (seven- 25 ft sections) of single 12 gauge W-beam guardrail. The total installation was constructed with forty-nine posts. The post spacing over the inner five sections was 3 ft - 1½ in. and the two end sections contained 6 ft - 3 in. spacing on center. Post Nos. 3 through 47 consisted of W6 x 9 by 6-ft long steel posts with W6 x 9 steel spacer blocks, while Post Nos. 1, 2, 48, and 49 consisted of 5½-in. x 7½-in. x 3-ft 6½-in. timber breakaway posts. Steel backup plates were placed between the guardrail and the posts at all non-splice locations. All other pertinent details are the same as previously discussed.

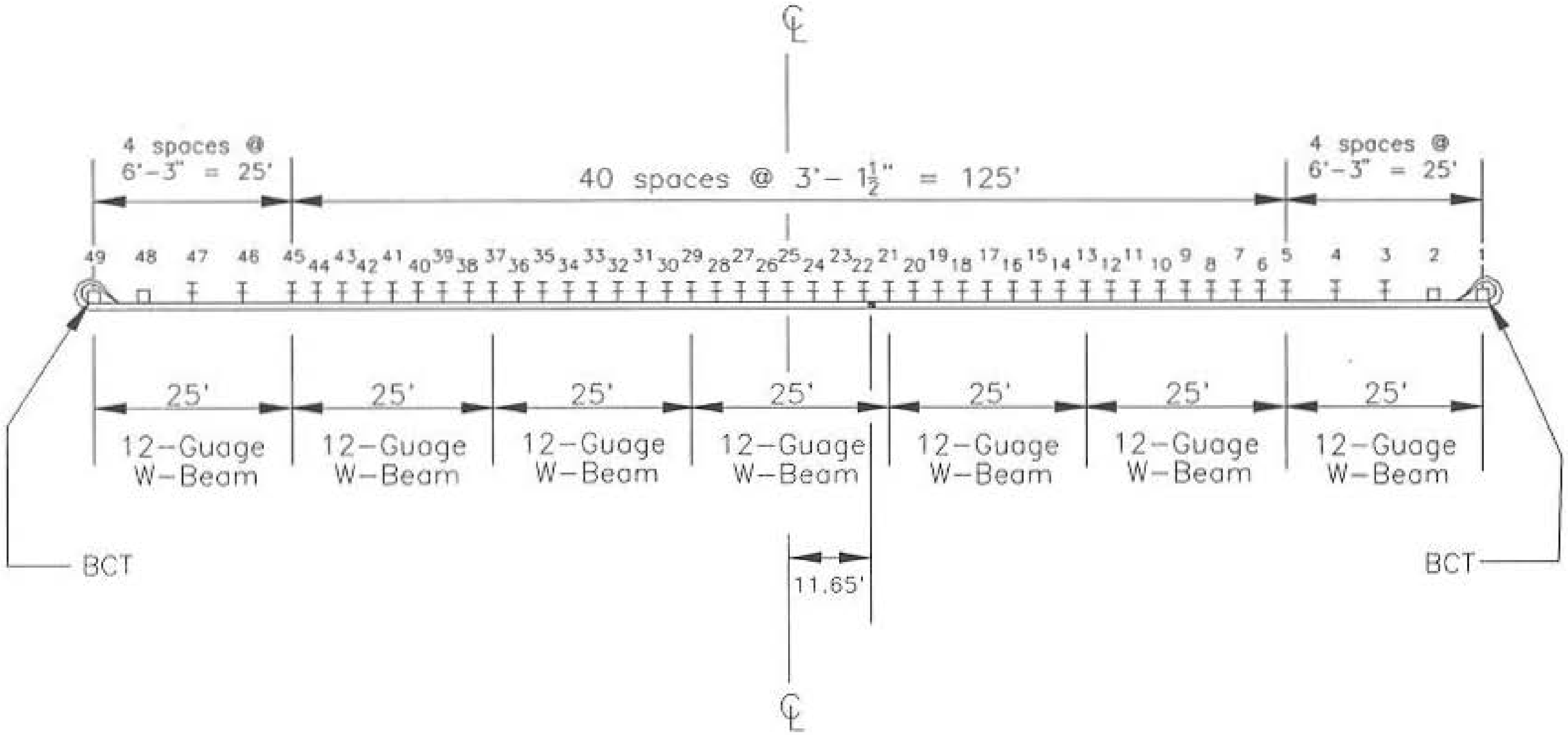


Figure 5. Guardrail Installation Layout, KSWB-3

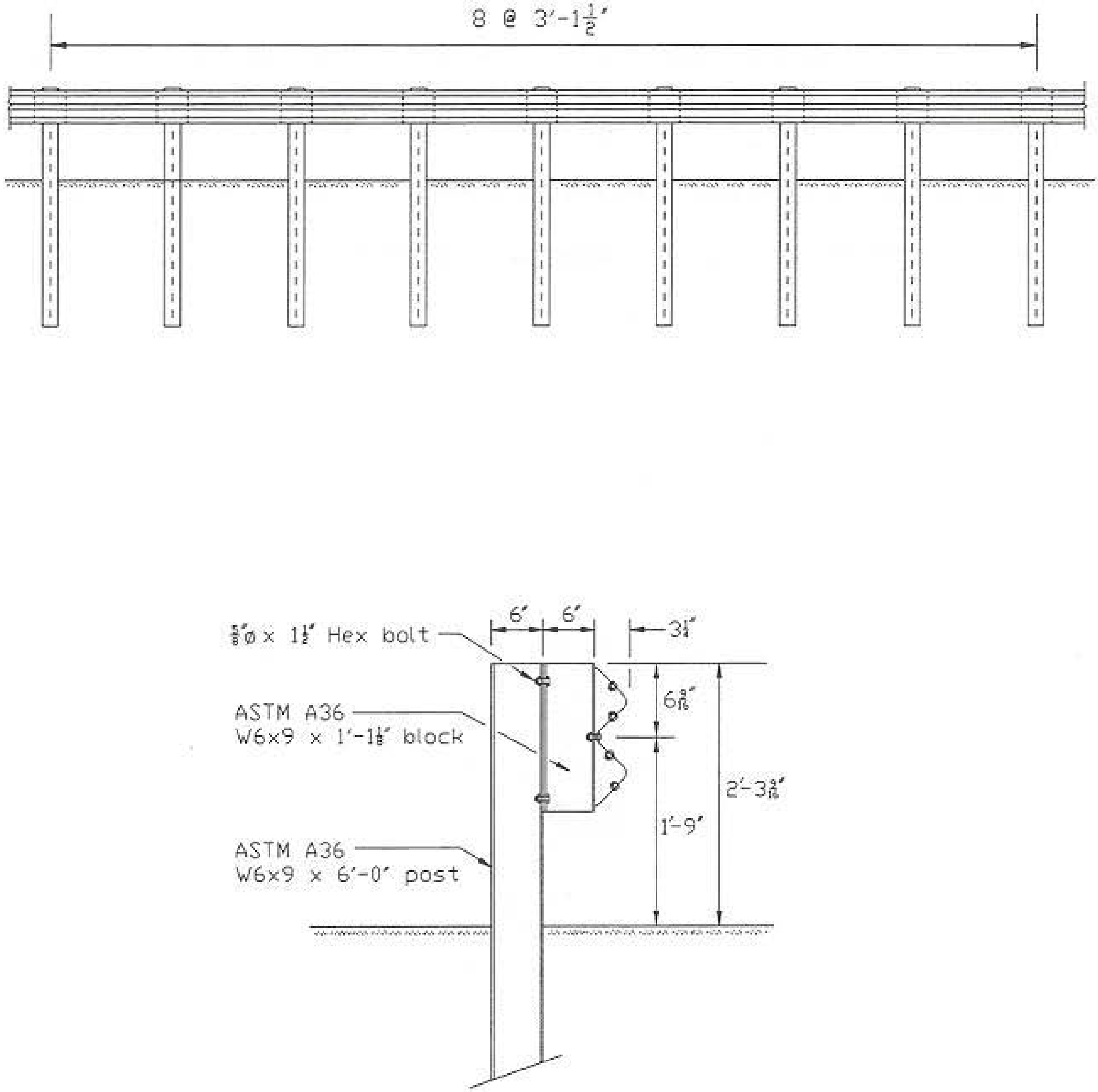


Figure 6. Guardrail Installation Details, KSWB-3

2.1.4 *KSWB-4 (Nested W-Beam and 3 ft - 1½ in. Post Spacing)*

An overall layout of the installation for Test KSWB-4 is shown in Figure 7, with design details shown in Figure 8. The test installation consisted of 175 ft (twelve - 25 ft sections) of nested 12 gauge W-beam guardrail. The two end 25 ft sections of the installation consisted of a single layer of W-beam and the five inner sections were nested. Steel backup plates were placed between the guardrail and posts at all non-splice and non-nested locations. All other details, including post details, are the same as discussed for KSWB-3.

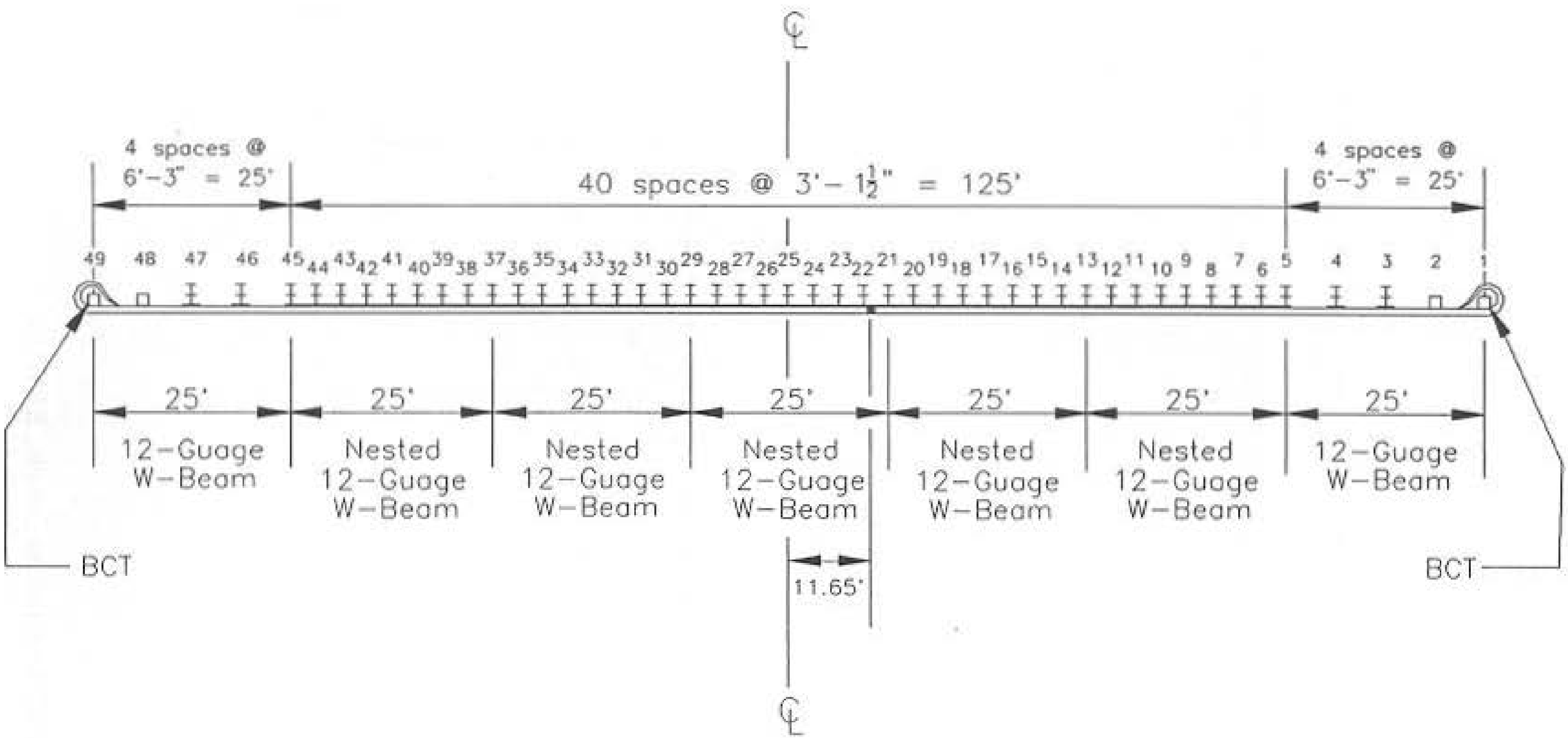


Figure 7. Guardrail Installation Layout, KSWB-4

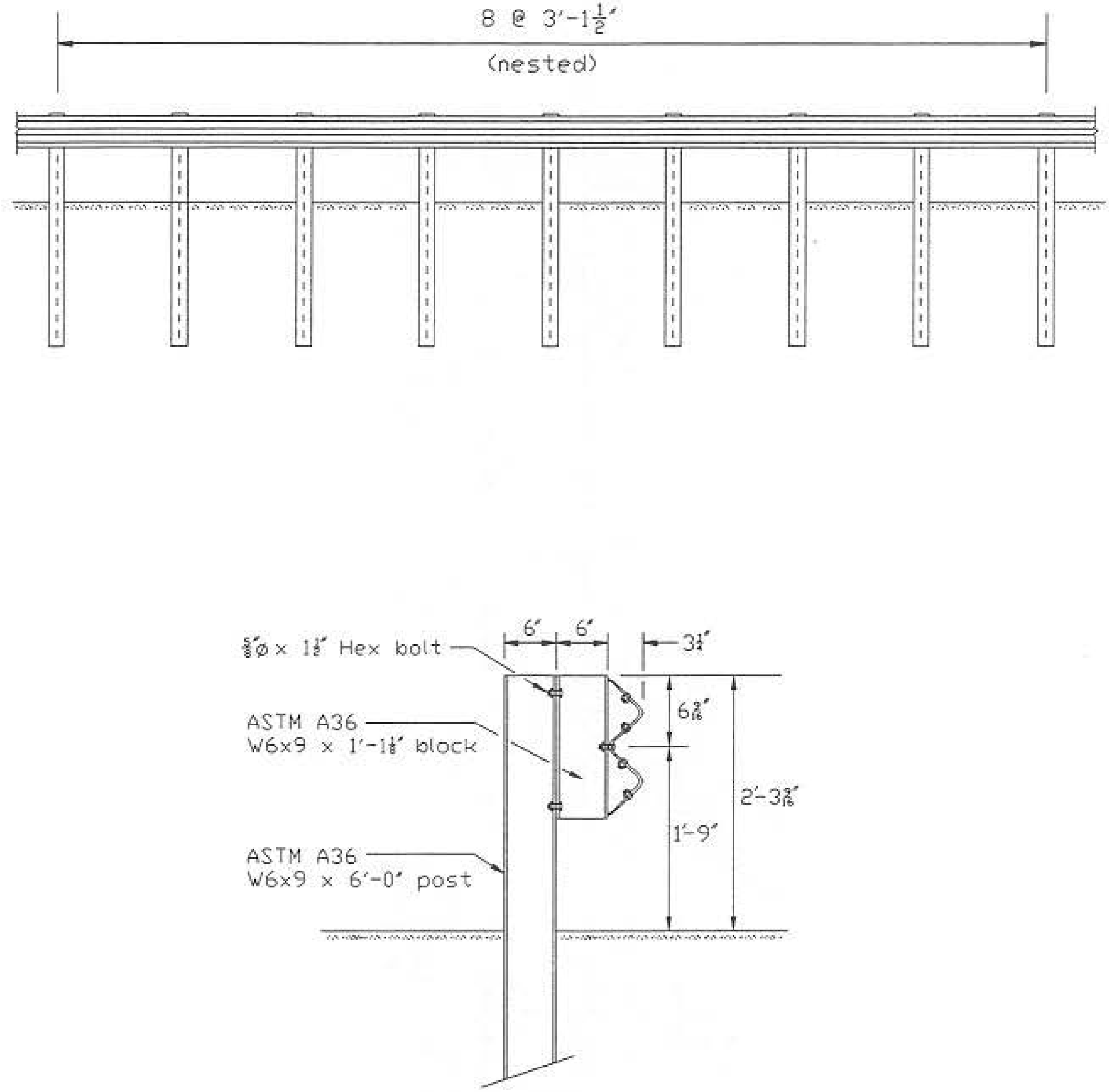


Figure 8. Guardrail Installation Details, KSWB-4

2.2 Test Vehicles

The vehicles used in this testing program are summarized in Table 1. Photographs of these vehicles and all dimensions and other pertinent information are located in Appendix A.

Table 1. Test Vehicles

Test No.	Vehicle	Test Inertial Weight (lbs)
KSWB-1	1985 Ford LTD	4399
KSWB-2	1984 Ford LTD	4486
KSWB-3	1985 Mercury Grand Marquis	4486
KSWB-4	1985 Mercury Grand Marquis	4501

The front wheels of the test vehicles were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs, fired by a pressure tape switch on the front bumper, were mounted on the roof of the vehicle to establish the time of impact on the high-speed film.

The Elevated Axle Method (8) was used to determine the vertical component of the center of gravity of each of the vehicles. This method converts measured wheel weights at different elevations to the location of the vertical component of the center of gravity. The longitudinal component of the center of gravity was determined using the measured axle weights. Ballast consisted of steel plates rigidly attached to the floor near the vertical center of gravity of the vehicle.

2.3 Data Acquisition Systems

Vehicle reactions during the full-scale testing program were monitored through video and high-speed photography, accelerometers, rate gyro, and tape pressure switches. Each of these components of the data acquisition system are described below.

2.3.1 High Speed Photography

Four high-speed 16-mm cameras (500 frames/sec), one 16-mm documentary camera (64 frames/sec), two documentary VHS cameras, and a high speed 35-mm camera were used to record the full-scale tests. Schematics of the camera layouts are shown in Figures 9 through 12. A Red Lake Locam with a 12.5 mm lens was placed above the test installation to provide a field of view perpendicular to the ground. Another Red Lake Locam with a 76-mm lens was placed downstream from the impact point and had a field of view parallel to the guardrail. A Photec IV, with an 80-mm lens, was also placed downstream from the impact point. A Photec IV, with a 55-mm lens, was placed on the traffic side of the guardrail and had a field of view perpendicular to the barrier. The documentary 16-mm camera was used to provide a panning view of the tests. Visible reference systems were placed in the fields of view to use in the analysis of the high-speed film. The film was analyzed using a Vanguard Motion Analyzer, and all camera divergence effects were properly accounted for.

2.3.2 *Accelerometers*

Endevco triaxial piezoresistive accelerometers (Model 7264) with a range of $\pm$ 200 g's were used to measure the accelerations in the longitudinal, lateral, and vertical directions of the test vehicle.

2.3.3 *Rate Gyro*

A Humphrey 3-axis rate transducer with a range of 250 deg/sec in each of the three directions (pitch, roll and yaw) was used to measure the rotational rates of the test vehicle.

Both the accelerometers and rate gyro transducers were rigidly attached to the vehicle near the center of gravity of the test vehicle. Signals from the transducers were received and conditioned by an onboard Metraplex unit where the signals were multiplexed and then transmitted by radio telemetry to a Honeywell (101) Analog Tape Recorder in the control van. The data acquisition flowchart is shown in Figure 13. State-of-the-art computer software, "Enhanced Graphics Acquisition and Analysis" (EGAA) (9) was used to acquire the rate gyro data and "Data Analysis and Display Software" (DADISP) (10) was to analyze and plot the data. The software was also used to conduct low pass filtering and smoothing operations to eliminate high frequency noise from the experimental data. Vehicle rotations become coupled in the presence of high rotation rates, therefore the uncoupled angular velocities were reported where applicable.

2.3.4 *Tape Pressure Switches*

Tape pressure switches spaced at 5 ft intervals were used to determine the actual speed of the vehicle before impact. Each tape switch triggered a strobe light located near each switch as the left-front tire of the test vehicle passed over it. The average speed of the test vehicle between the tape switches was determined by knowing the distance between the tape switches, the calibrated camera speed, and the number of frames between flashes from the high-speed film. The average speed was also determined from electronic timing mark data which was transmitted through fiber optic cable and recorded on oscilloscope software.

2.4 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle are one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the bridge rail. A fifth wheel, built by the Nucleus Corporation, was used in conjunction with a digital speedometer to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (6) was used to steer the test vehicle. The guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact. The 3/8-in. diameter guide cable was tensioned to approximately 3,000 lbs, and supported laterally and vertically every 100 ft by hinged stanchions. The vehicle guidance cable was approximately 1,500-ft long.

2.5 Impact Location

The impact point for all four of the tests was located 11 ft - 8 in. upstream from the center of the installations. This impact point was determined using methods described in the update to NCHRP Report 230 (7), NCHRP Report 350 (11).

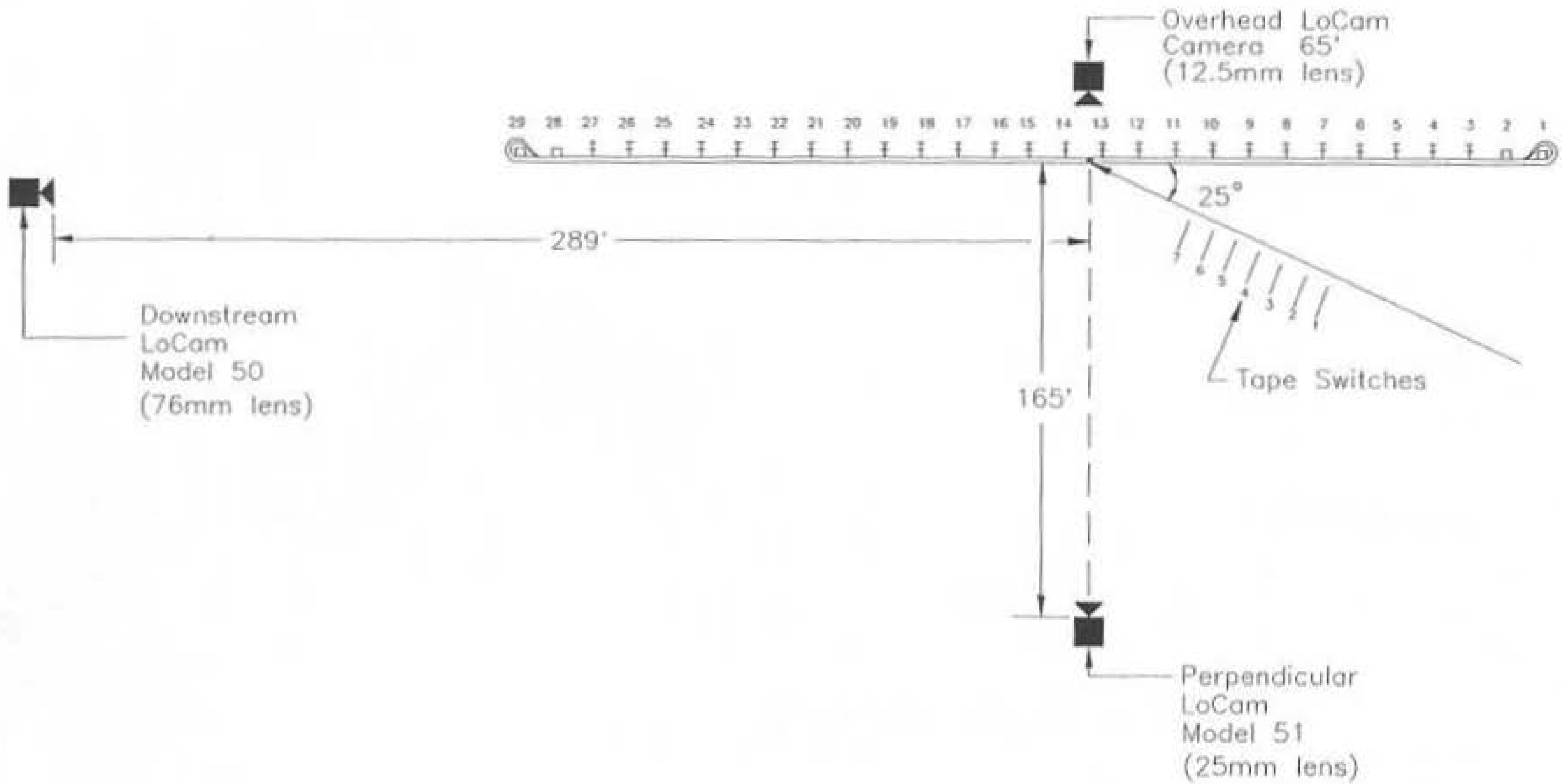


Figure 9. High-Speed Camera Layout, Test KSWB-1

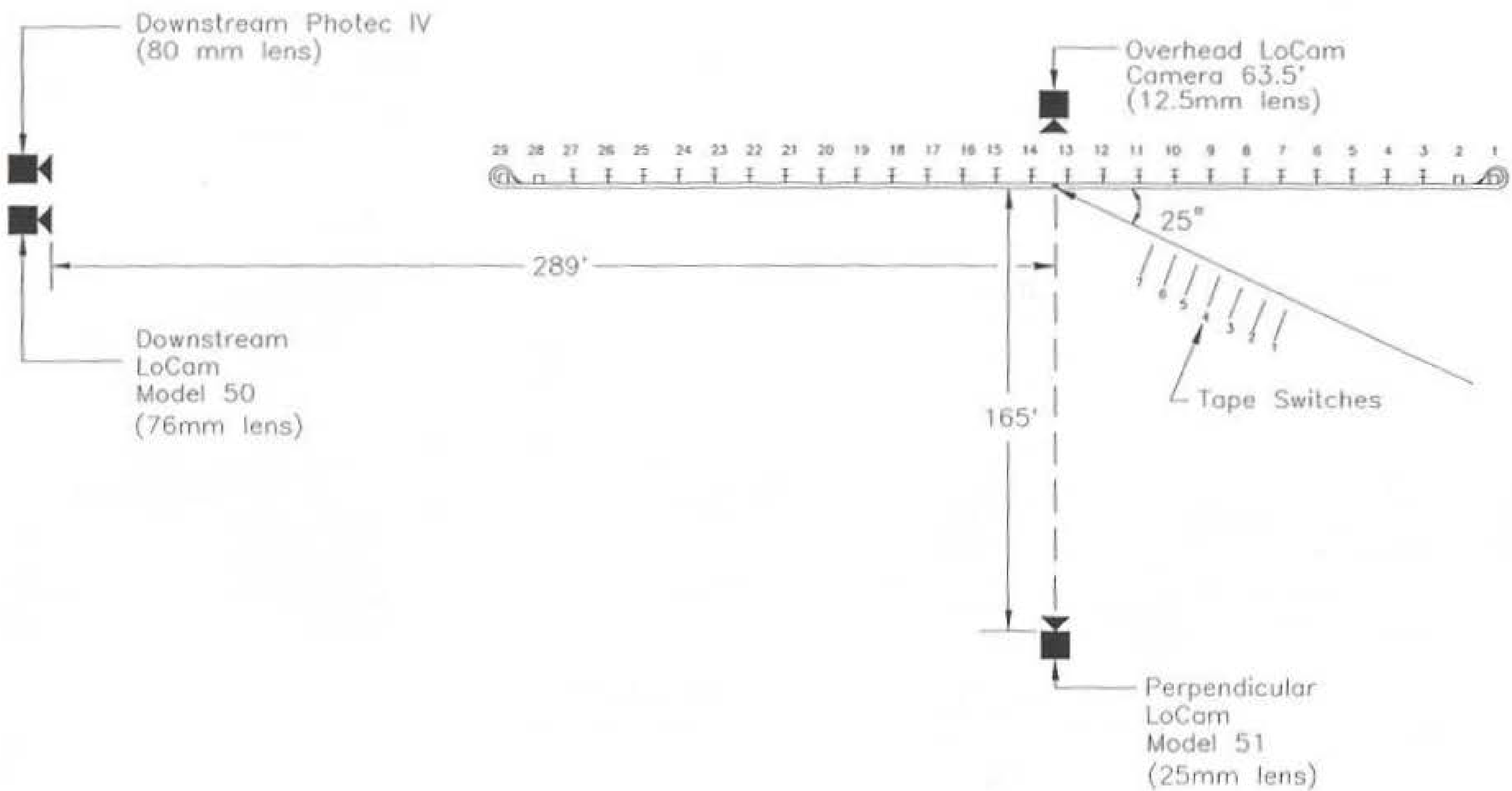


Figure 10. High-Speed Camera Layout, Test KSWB-2

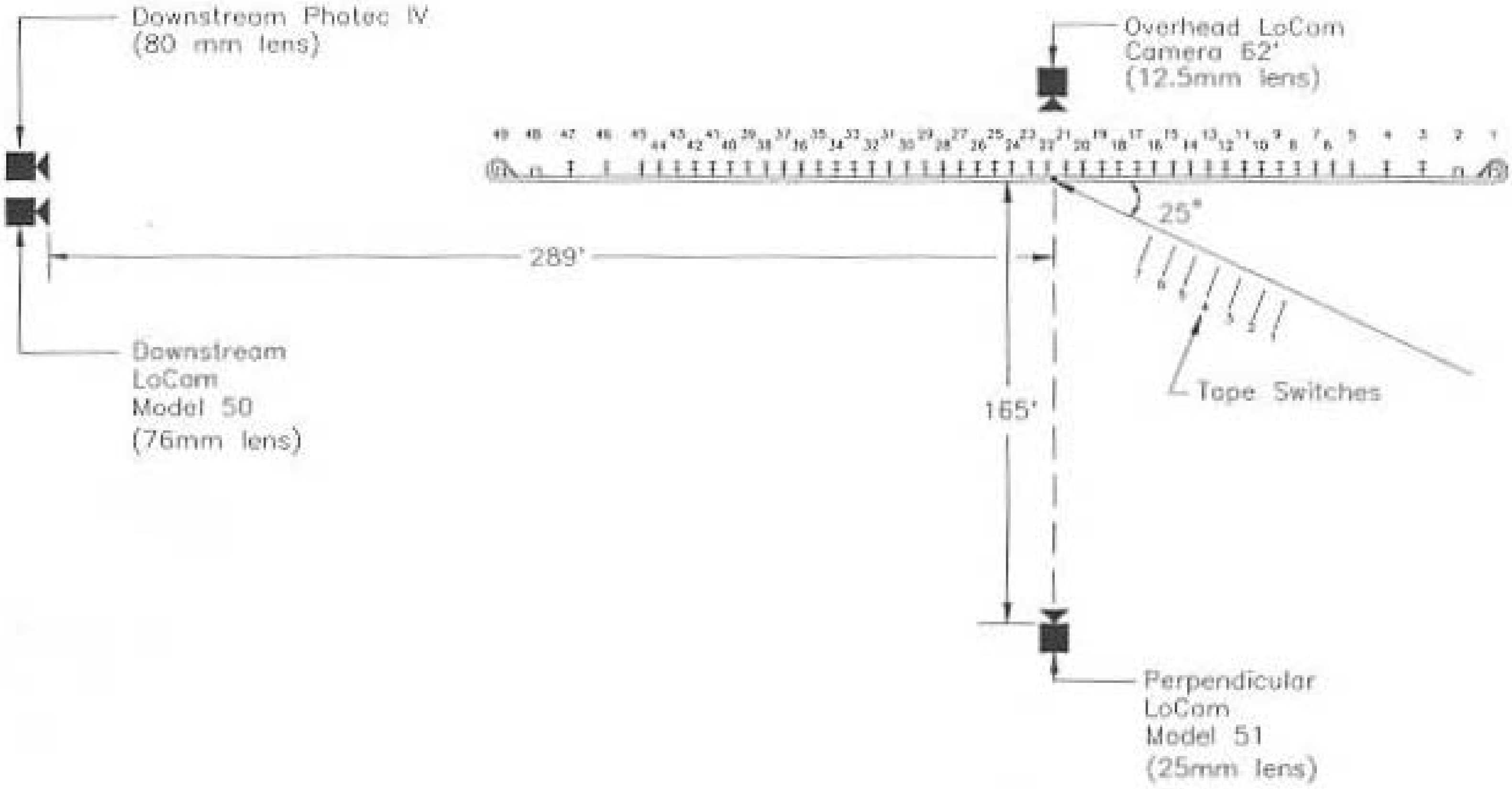


Figure 11. High-Speed Camera Layout, Test KSWB-3

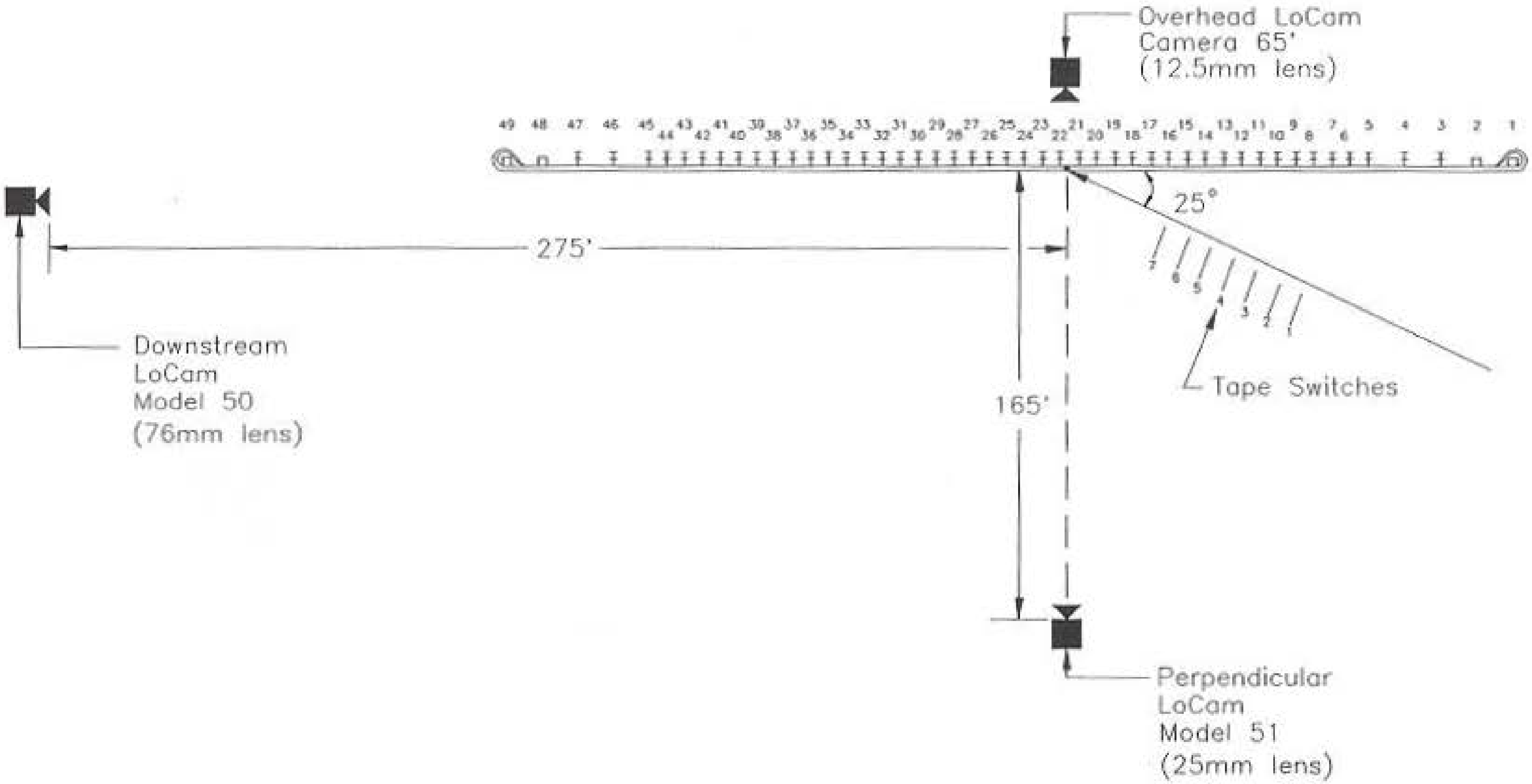


Figure 12. High-Speed Camera Layout, Test KSWB-4

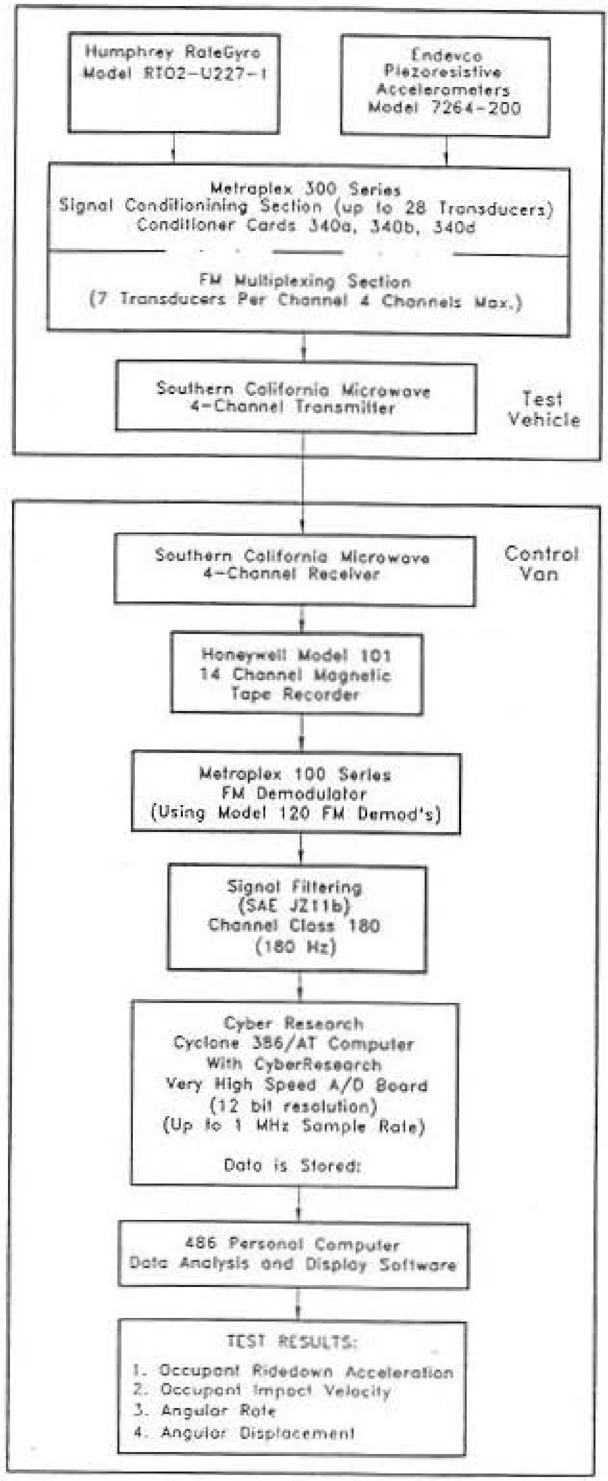


Figure 13. Data Acquisition Flowchart

3 Performance Evaluation Criteria

Longitudinal guardrail installations must satisfy the requirements provided in NCHRP Report No. 230 (7) in order to be accepted for use on new construction projects or as a replacement for existing installations. This criteria consists of two full-scale vehicle crash tests, the first of which is an impact with a small car at 60 mph and 15 degrees to evaluate the geometry of the system and identify any potential for snagging. The second test specified is conducted with a full-size sedan impacting the barrier at 60 mph and 25 degrees. This test evaluates the strength of the barrier, and provides engineers with maximum dynamic deflection values to use in determining where the installations should be placed. This is the test which was performed in this project. The criteria used to evaluate these tests are shown in Table 1. The full-scale crash tests were conducted and reported in accordance with the procedures provided in NCHRP 230. The vehicle damage was assessed by the traffic accident scale (TAD) (12) and the vehicle damage index (VDI) (13).

Table 2. NCHRP Report No. 230 Test Designation 10 Evaluation Criteria

Structural Adequacy	A. Test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.
	D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.
Occupant Risk	E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.
Vehicle Trajectory	H. After collision, vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.
	I. In tests where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of the test impact angle, both measured at time of vehicle loss of contact with test device.

4 Test Results

4.1 Test KSWB-1 (4399 lbs, 61.9 mph, 25.1 deg)

Test KSWB-1 was conducted with a 1985 Ford LTD weighing 4,399-lbs at an impact speed of 61.9 mph and impact angle of 25.1 degrees. The impact location was approximately 12 ft. upstream of post No. 15. The test installation was G4(1S) system consisting of single 12-gauge W-beam and 6 ft - 3 in. post spacing. A summary of the test results and sequential photographs are presented in Figure 14. Additional sequential photographs are shown in Figure 15. Documentary photographs of the crash test are shown in Figures 16 and 17.

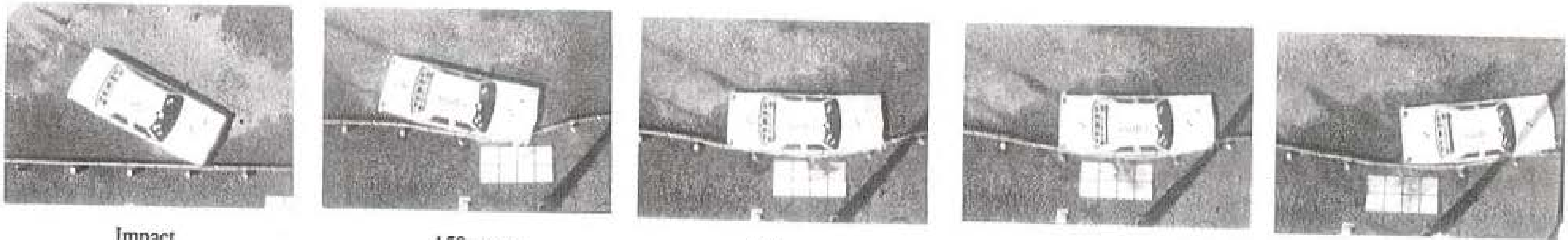
After the initial impact with the W-beam guardrail, the vehicle began to redirect coinciding with the first post after impact (Post No. 14) at approximately 70 msec. At 150 msec after impact the right front wheel contacted Post No. 15, disengaging it from the system and causing the right front tire to blow out. At 230 msec proceeding impact the vehicle was approximately parallel to the guardrail. The maximum dynamic lateral deflection of the system was 29.7 in. and occurred at approximately 270 msec after impact. The vehicle exited the guardrail at approximately 604 msec with an exit speed and angle of 40.1 mph and 14.5 deg respectively. As shown in Figure 14, the vehicle came to rest approximately 128 ft downstream from impact and had a maximum rebound distance of approximately 17 ft.

Vehicle damage is shown in Figure 18, and consisted primarily of right front corner crush, including tire blowout and rim damage, and passenger side W-beam interlock damage. There was no interior occupant compartment damage detected. The guardrail damage is shown in Figure 19. Guardrail damage was moderate and consisted of deformation of the impacted 25-ft beam section.

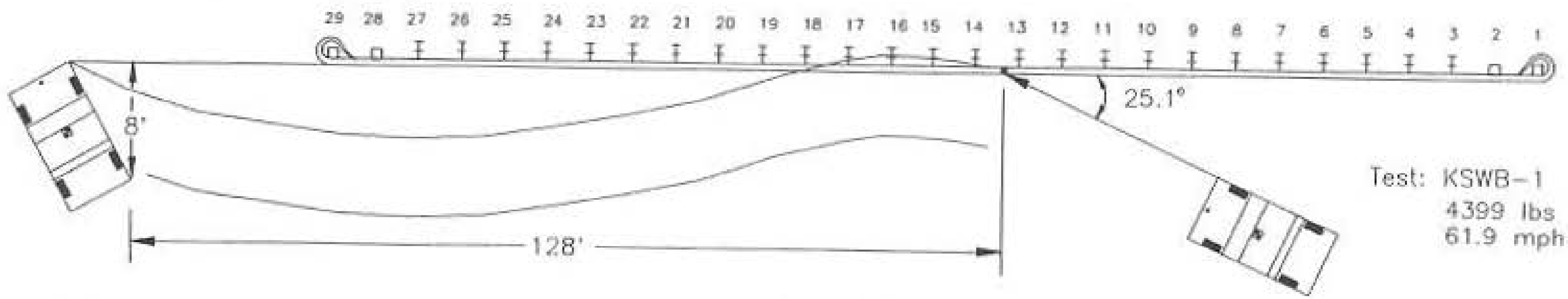
The measured contact length was between the vehicle and the rail was 24 ft. The maximum permanent set deflection of 22.0 in. occurred at Post No. 15 and the maximum dynamic deflection of the system (29.7 in.) occurred in the rail midway between Post Nos. 15 and 16. Maximum deflections (permanent set and dynamic) of the system at the post and midspan locations are shown in Figure 20. Post Nos. 15 and 16 were disengaged from the system and Post No. 15 was permanently twisted. A small tear occurred in the lower portion of the rail at Post No. 15.

The normalized longitudinal and lateral occupant impact velocities were determined to be 21.3 fps and 17.7 fps, respectively. The highest 10-msec average occupant ridedown decelerations in the longitudinal and lateral directions were 8.8 g's and 11.9 g's, respectively. The results of the occupant risk assessment, determined from accelerometer data, are summarized in Figure 14. The results are also shown graphically in Appendix B. Angular rates and displacements are also shown graphically in Appendix B.

This test passed all of the required criteria set forth in NCHRP Report 230 (7) for the full-size sedan redirectional test.



Impact 150 msec 230 msec 270 msec 370 msec



Test Number	KSWB-1
Date	5/27/93
Installation	Single 12-Gauge W-Beam with 6 ft-3 in. Post Spacing
Installation Length	175 ft
Post	
Size	W6x9
Length	6 ft
Guardrail	
Material	7 - 25 ft sections of 12 gauge W-beam
Post Spacing	6 ft - 3 in.
End Treatments	Breakaway Cable Terminal With Strut
Test Vehicle	1985 Ford LTD
Test Inertial Weight	4399 lbs
Gross Static Weight	4399 lbs

Impact Speed	61.9 mph
Impact Angle	25.1 deg
Impact Location	11.7 ft Upstream of Post No. 15
Exit Speed	40.1 mph
Exit Angle	14.5 deg
Normalized Occupant Impact Velocity	
Longitudinal	21.3 fps
Lateral	17.7 fps
Occupant Ridedown Deceleration	
Longitudinal	8.8 g's
Lateral	11.9 g's
Vehicle Damage	
TAD	1-RFQ-3, 1-RD-2
VDI	01RDES2
Maximum Permanent Set Deflection	22.0 in. @ Post No. 15
Maximum Dynamic Deflection	29.7 in. btwn Post Nos. 15 & 16
W-Beam Contact Length	24 ft

Figure 14. Summary of Test Results, KSWB-1

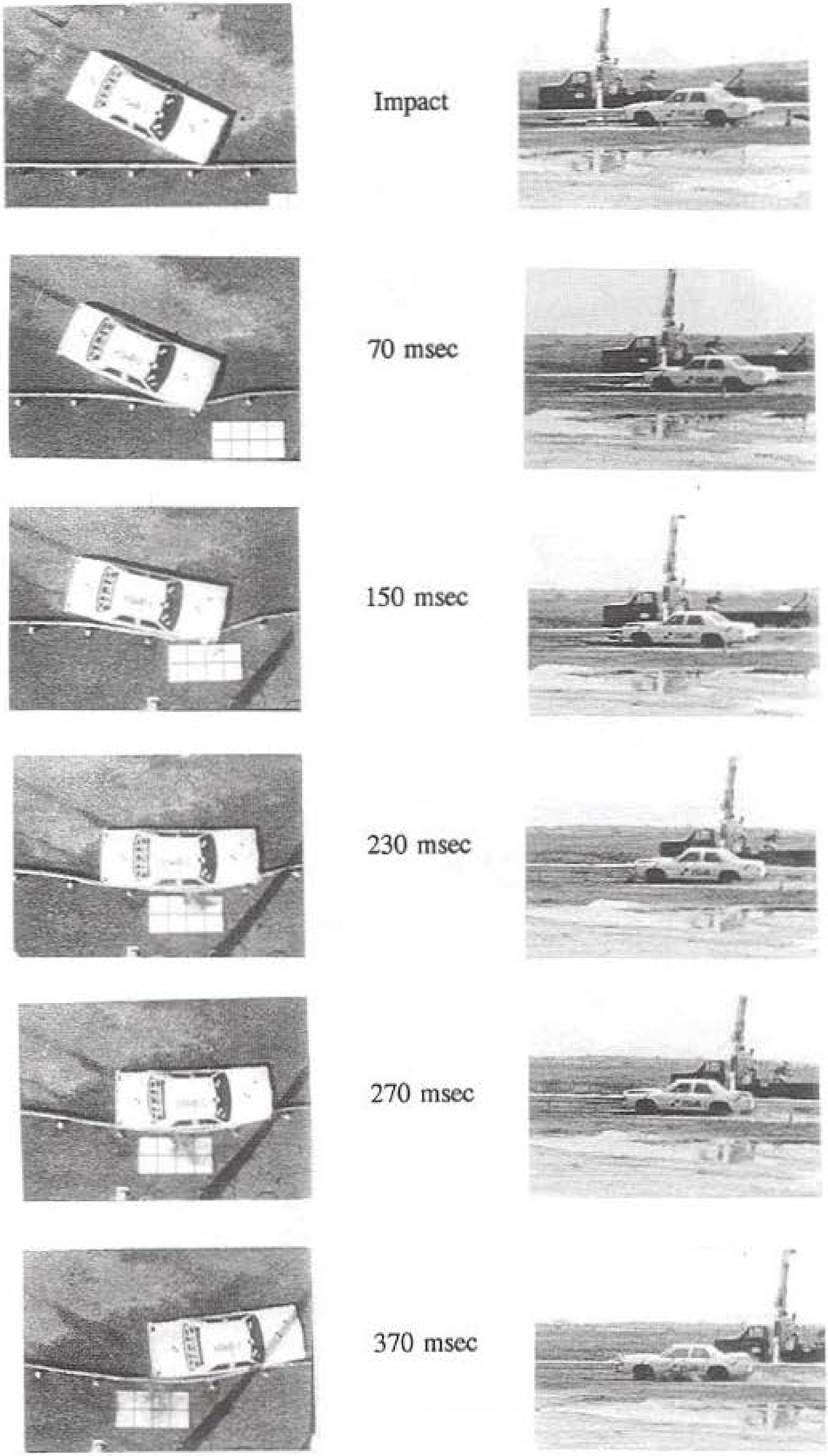


Figure 15. Sequential Photographs, KSWB-1

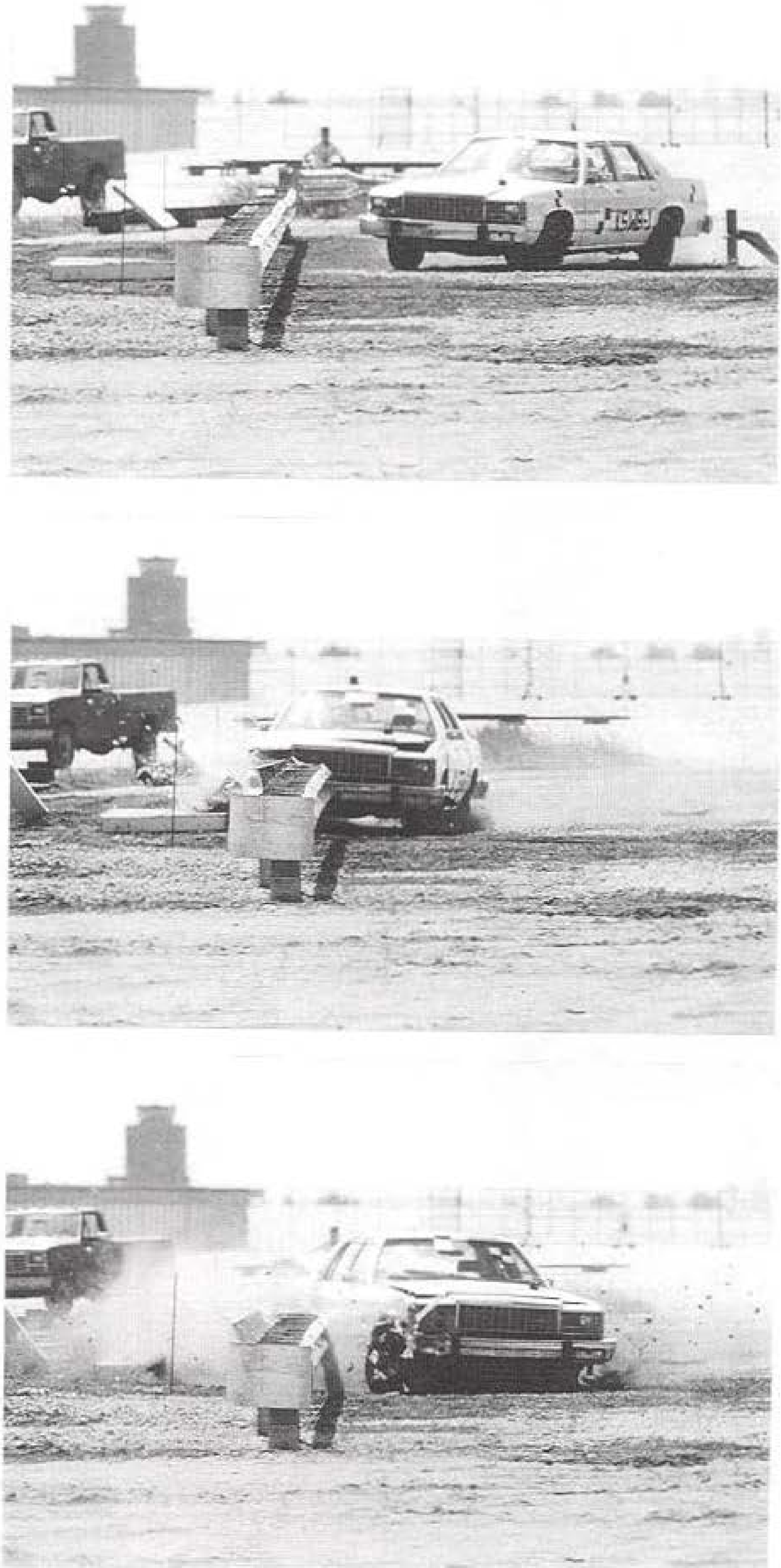


Figure 16. Full-Scale Crash Test, KSWB-1

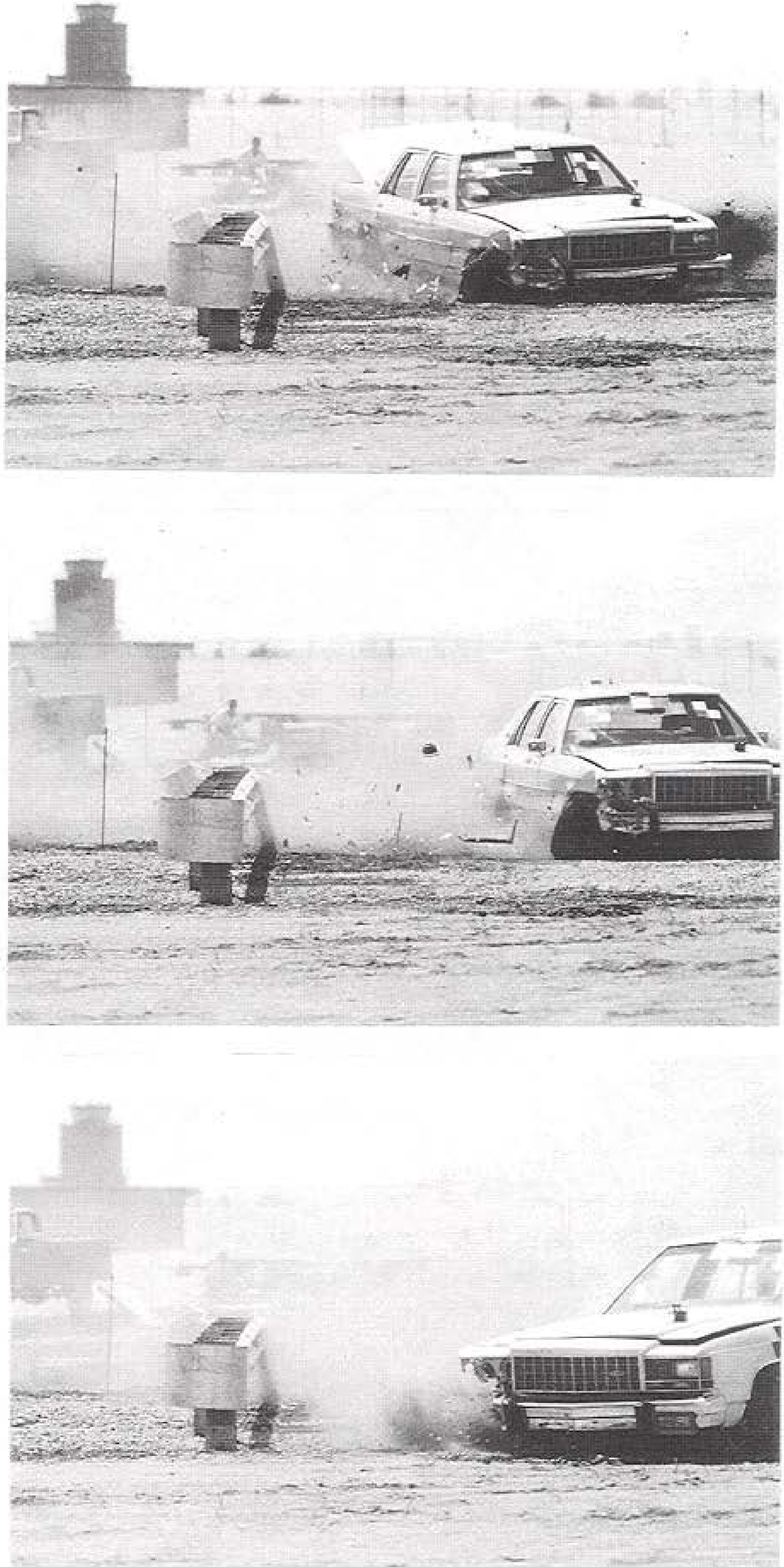


Figure 17. Full-Scale Crash Test (continued), KSWB-1

Figure 18. Test Vehicle Damage, KSWB-1

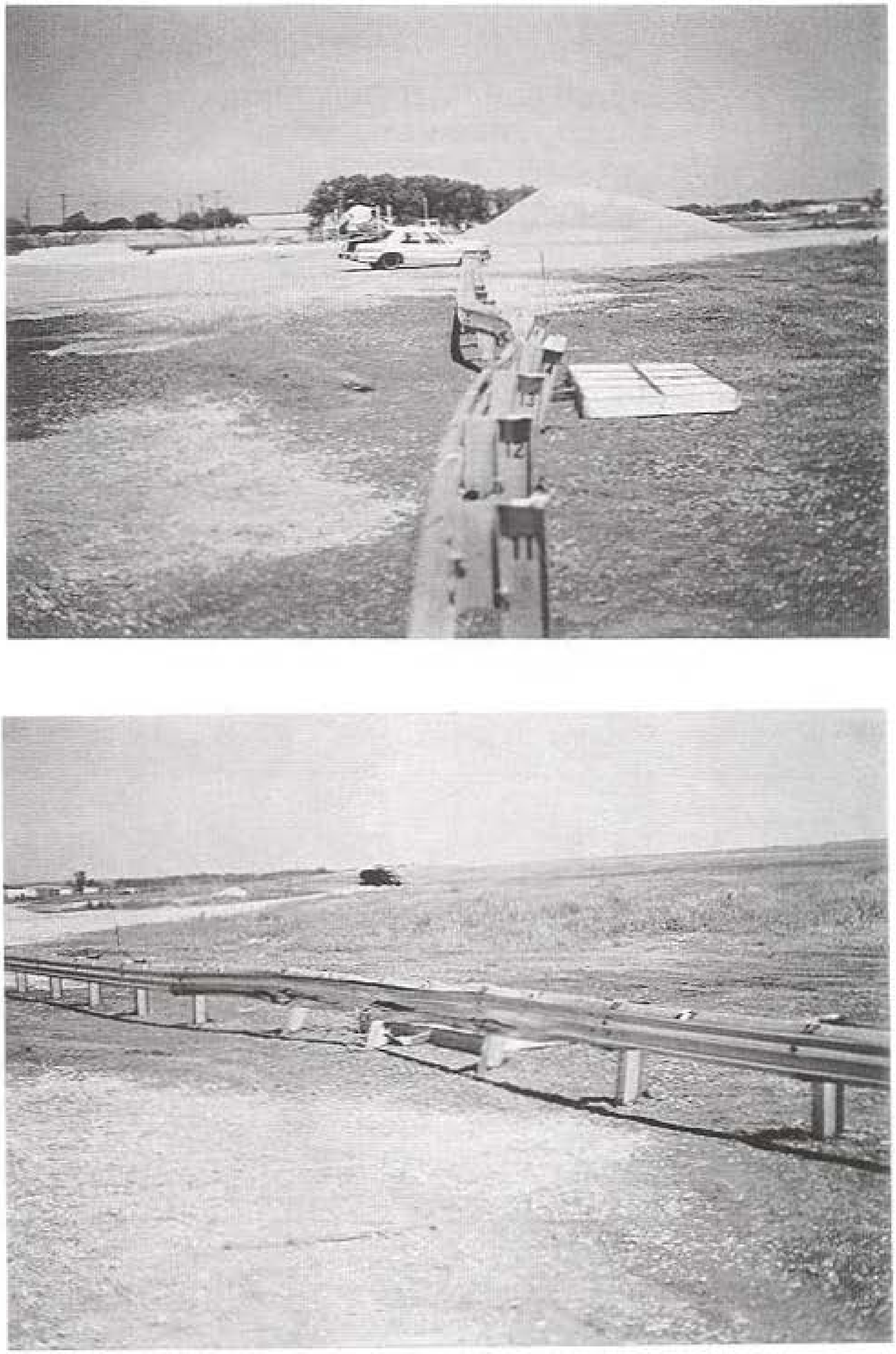


Figure 19. Installation Damage, KSWB-1

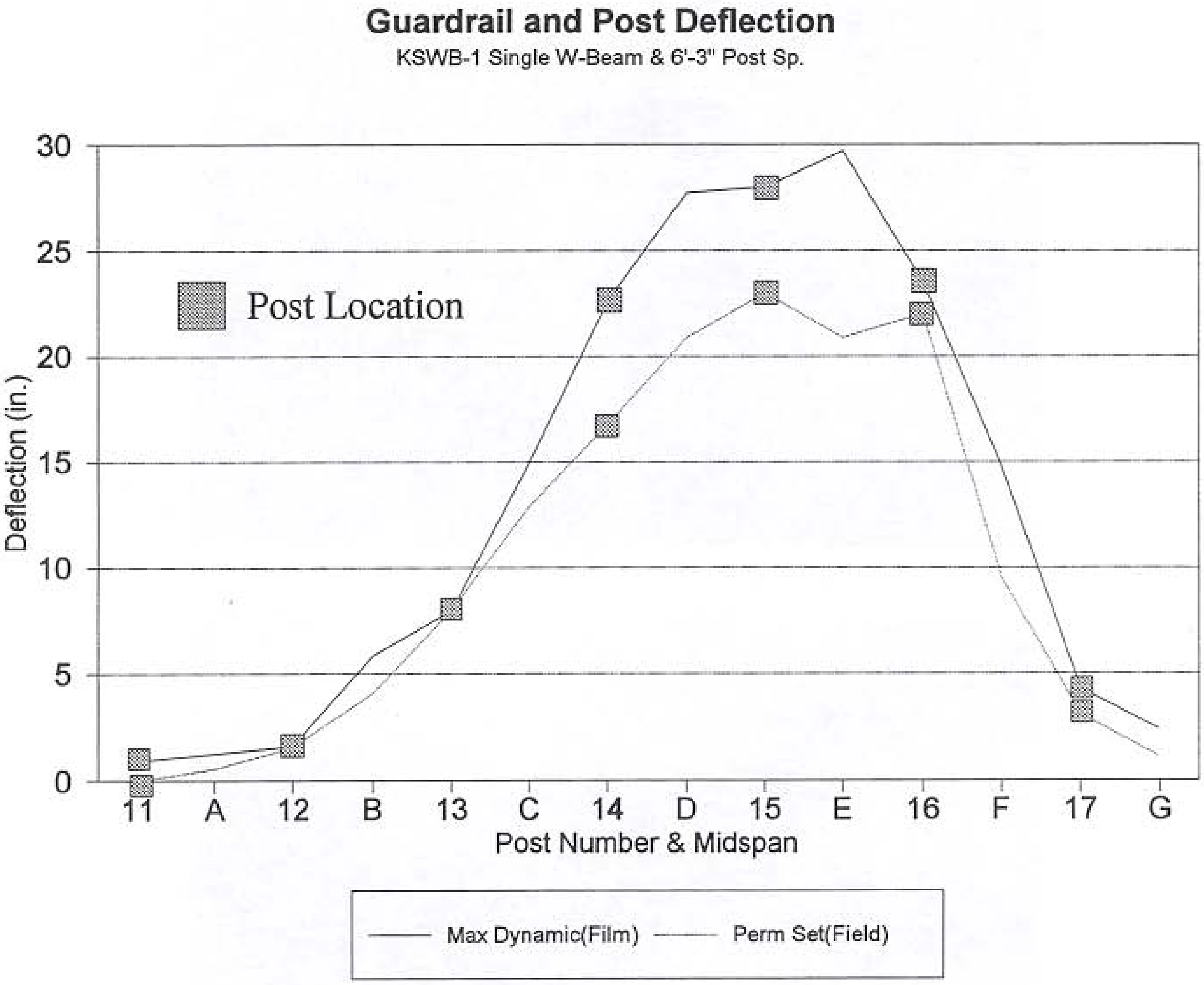


Figure 20. Guardrail and Post Maximum Deflections, KSWB-1

4.2 Test KSWB-2 (4486 lbs, 60.5 mph, 25.4 deg)

Test KSWB-2 was conducted with a 1984 Ford LTD weighing 4,486-lbs at an impact speed of 60.5 mph and impact angle of 25.4 degrees. The impact location was approximately 12 ft. upstream of post No. 15. The test installation was a G4(1S) system consisting of nested 12-gauge W-beam and 6 ft - 3 in. post spacing. A summary of the test results and sequential photographs are presented in Figure 21. Additional sequential photographs are shown in Figure 22. Documentary photographs of the crash test are shown in Figures 23 and 24.

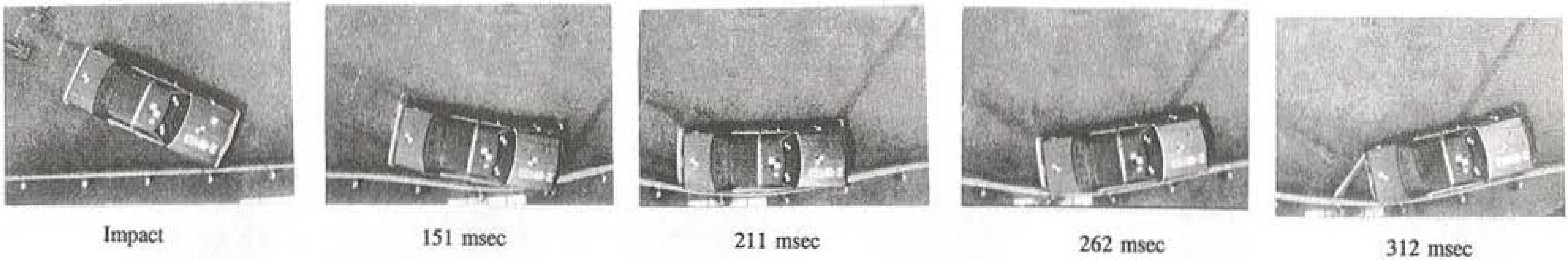
After the initial impact with the W-beam guardrail, the vehicle began to redirect coinciding with the first post after impact (Post No. 14) at approximately 70 msec. At 151 msec after impact the right front wheel coincided with Post No. 15. At 211 msec proceeding impact the vehicle was approximately parallel to the guardrail. The maximum dynamic lateral deflection of the system was 35.5 in., which occurred approximately 262 msec after impact. The vehicle exited the guardrail at approximately 481 msec with an exit speed and angle of 52.6 mph and 12.9 deg respectively. As shown in Figure 21, the vehicle came to rest approximately 265 ft downstream from impact and had a maximum rebound distance of approximately 35 ft.

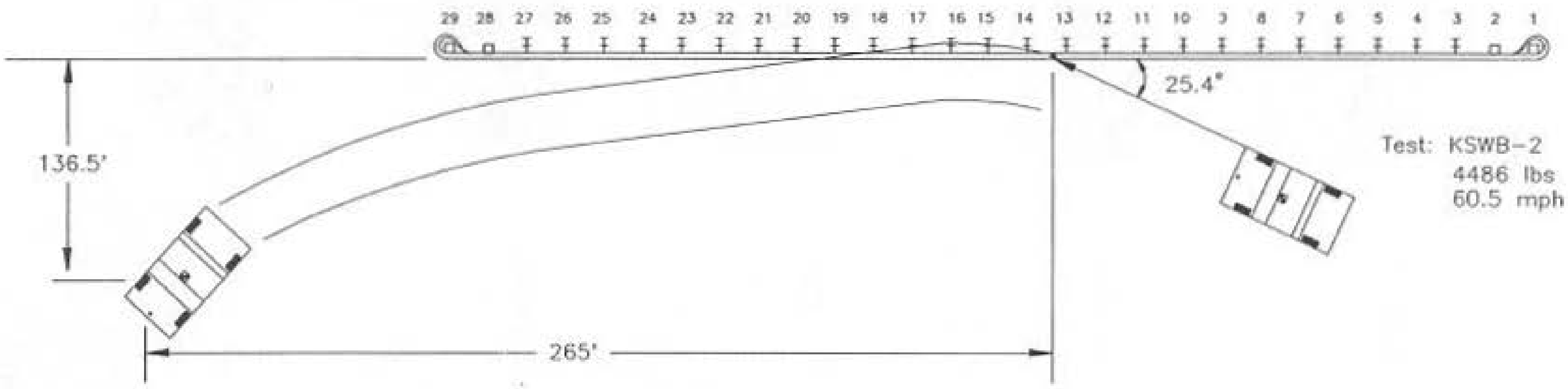
Vehicle damage is shown in Figure 25, and consisted primarily of right front corner crush and passenger side W-beam interlock damage. There was no interior occupant compartment damage detected. The rear bumper was disengaged and the right rear tire was blown during tail slap impact with the rail. Guardrail damage is shown in Figure 26, and consisted of only moderate deformation and flattening of the lower portion of the impacted 25-ft nested beam section. The measured contact length between the vehicle and the rail was approximately 22 ft. The maximum permanent set deflection of 24.8 in. occurred at Post No. 14, and the maximum dynamic deflection of 35.5 in.

occurred at the midspan between Post Nos. 14 and 15. Maximum deflections (permanent set and dynamic) of both the posts and midspan locations are shown in Figure 27. None of the posts were disengaged from the system, although Post No. 15 was permanently twisted and contained visible markings resulting from contact with the vehicle.

The maximum dynamic deflection of the rail in this test was approximately 15% higher than that observed in the previous test with the same post spacing and a single W-beam rail element. This, of course, is contrary to the behavior which would be expected when the rail element is stiffened. The main factor which contributed to this increase in the dynamic deflection is believed to be a difference in soil conditions. Despite attempts to control the soil conditions, rainfall occurring between the tests resulted in the soil moisture content being higher for Test KSWB-2. An increase in the soil moisture content reduces the rotational stiffness of the posts, allowing the rail to deflect farther for a given load. The results of this test indicate that the soil moisture content has a large influence on the behavior of guardrail systems. Under some conditions this effect even outweighs the benefits obtained by various strengthening techniques, as demonstrated in this test. This behavior will be investigated in more detail in the second phase of this study (17).

The normalized longitudinal and lateral occupant impact velocities were determined to be 11.0 fps and 16.5 fps, respectively. The highest 10 msec average occupant ridedown decelerations in the longitudinal and lateral directions were 5.7 g's and 14.3 g's, respectively. The results of the occupant risk, determined from accelerometer data, are summarized in Figure 21. The results are shown graphically in Appendix C. Angular rates and displacements are also shown graphically in Appendix C. This test passed all of the required criteria set forth in NCHRP Report 230 (7) for the full-size sedan redirectional test.





Test Number KSWB-2
Date 6/16/93
Installation . . . . Nested 12-Gauge W-Beam with 6 ft-3 in. Post Spacing
Installation Length . . . . 175 ft
Post
    Size W6x9
    Length . . . . 6 ft
Guardrail
    Material . . . . 12 - 25 ft sections of 12 gauge W-beam
Post Spacing . . . . 6 ft - 3 in.
End Treatments . . . . Breakaway Cable Terminal With Strut
Test Vehicle . . . . 1984 Ford LTD
    Test Inertial Weight . . . . 4486 lbs
    Gross Static Weight . . . . 4486 lbs

Impact Speed . . . . 60.5 mph
Impact Angle . . . . 25.4 deg
Impact Location . . . . 11.7 ft Upstream of Post No. 15
Exit Speed . . . . 52.6 mph
Exit Angle . . . . NA
Normalized Occupant Impact Velocity
    Longitudinal . . . . 11.0 fps
    Lateral . . . . 16.5 fps
Occupant Ridedown Deceleration
    Longitudinal . . . . 5.7 g's
    Lateral . . . . 14.3 g's
Vehicle Damage
    TAD 1-RFQ-3, 1-RD-2
    VDI 01RDES2
Maximum Permanent Set Deflection . . . . 24.8 in. @ Post No. 14
Maximum Dynamic Deflection . . . . 35.5 in. btwn. Post Nos. 14 & 15
W-Beam Contact Length . . . . 22 ft

Figure 21. Summary of Test Results, KSWB-2

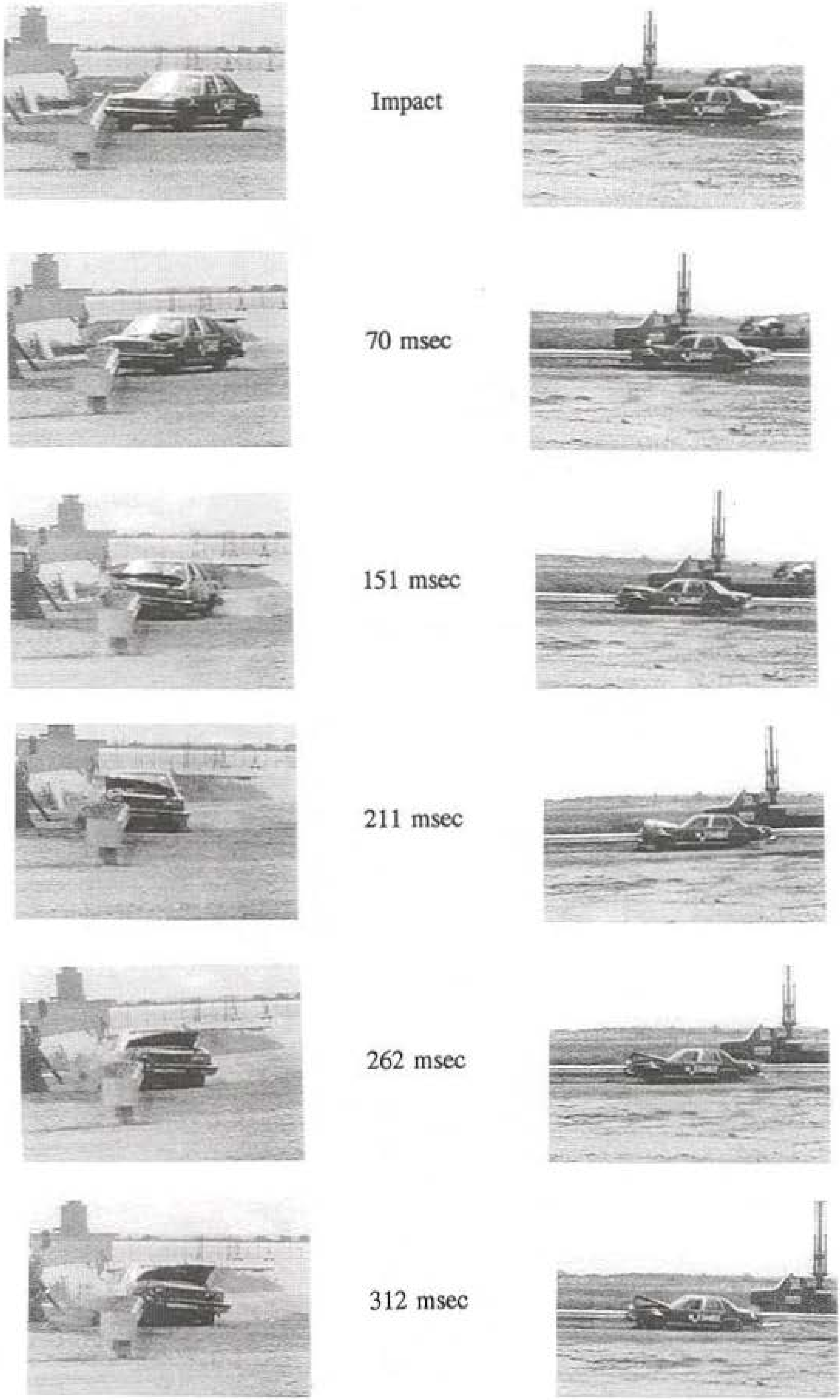


Figure 22. Sequential Photographs, KSWB-2

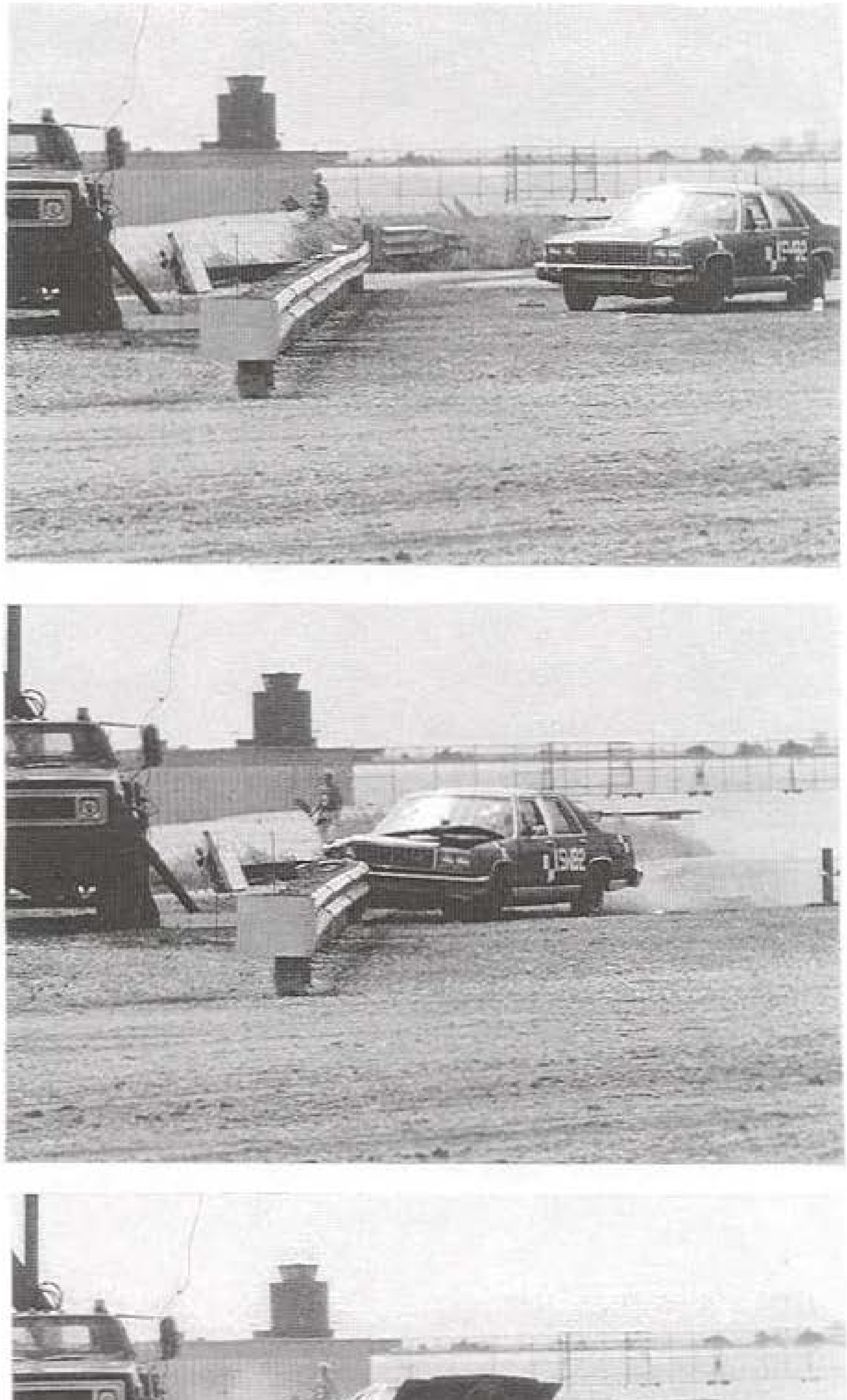


Figure 23. Full-Scale Crash Test, KSWB-2

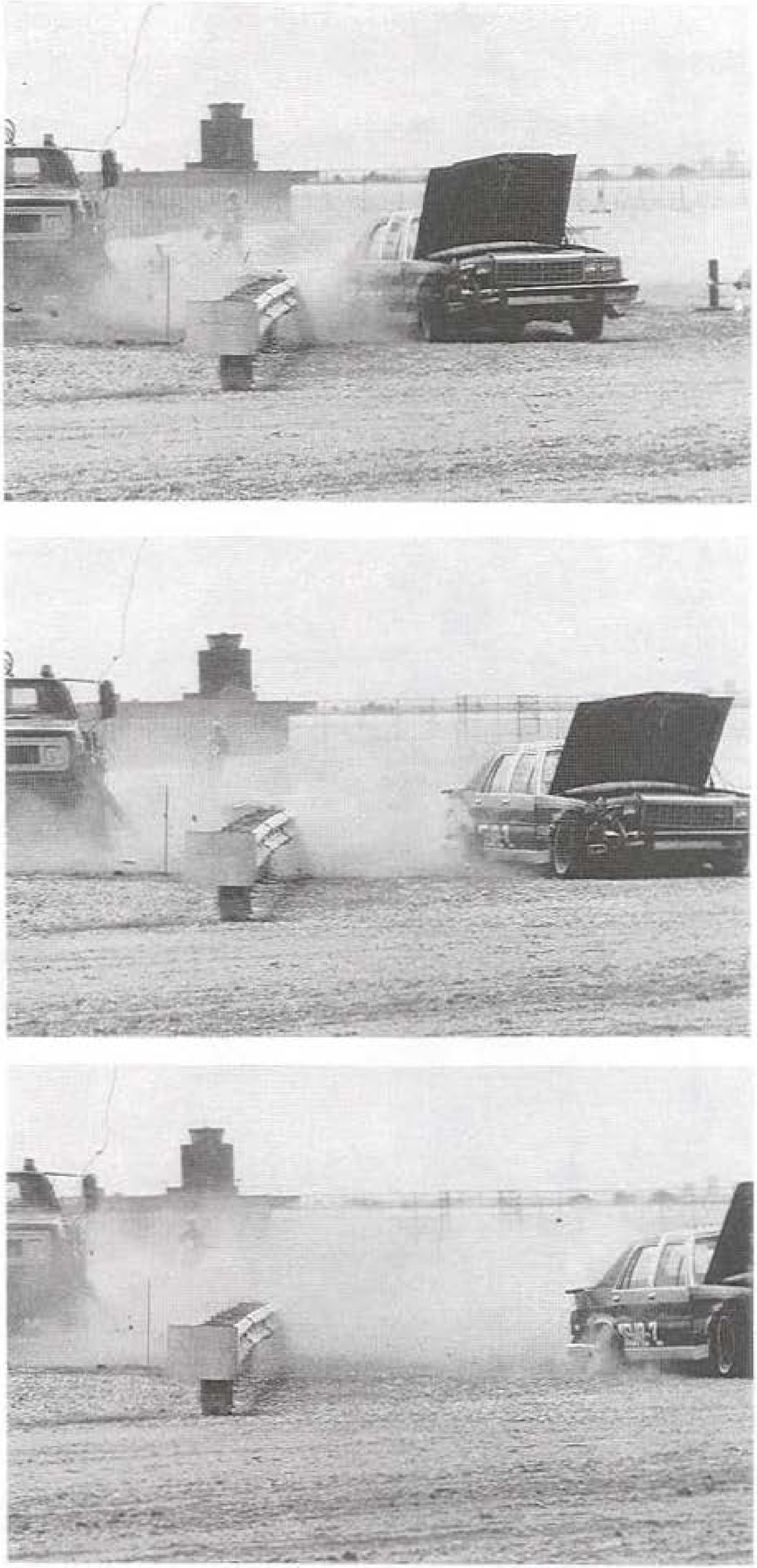


Figure 24. Full-Scale Crash Test (continued), KSWB-2

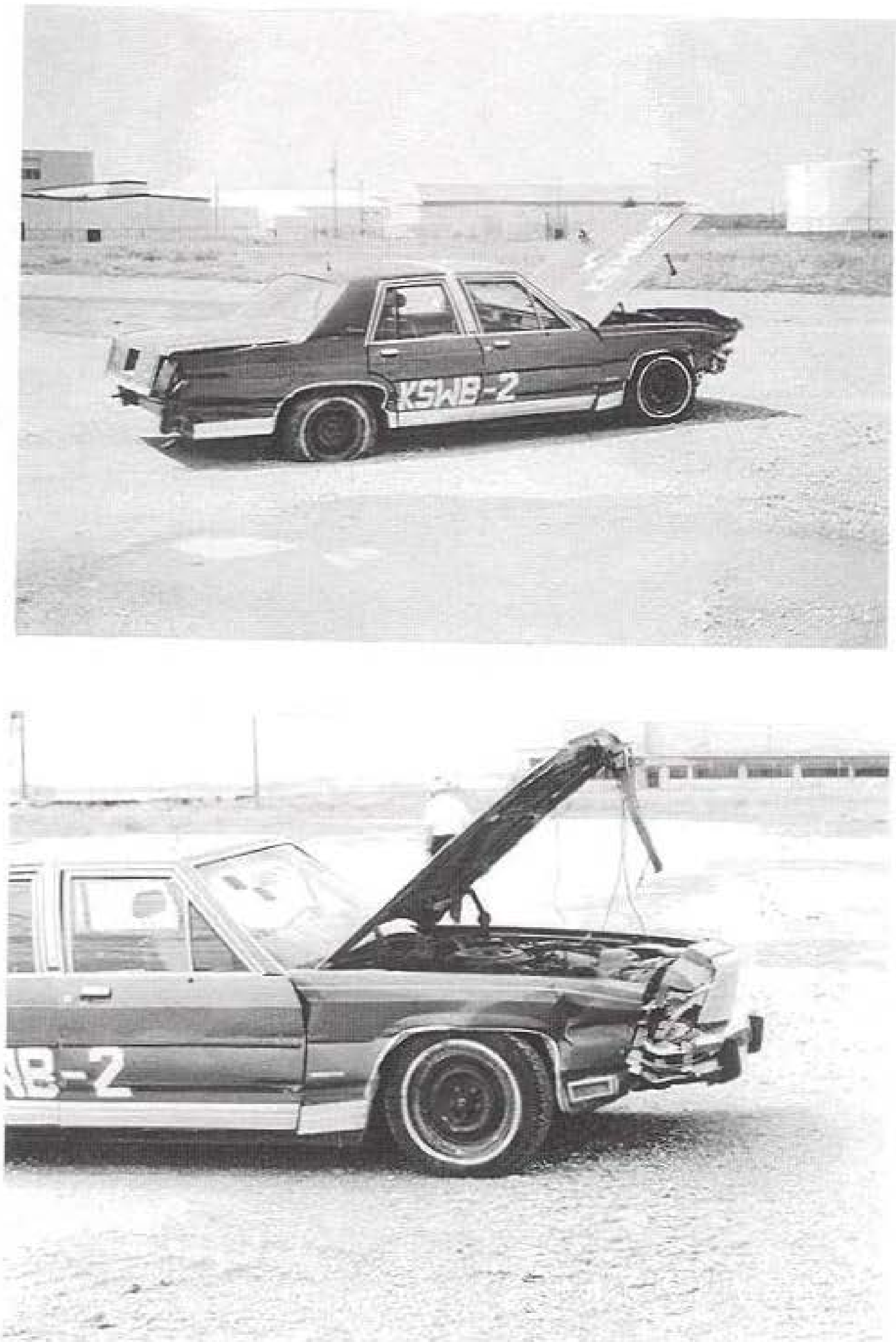


Figure 25. Test Vehicle Damage, KSWB-2

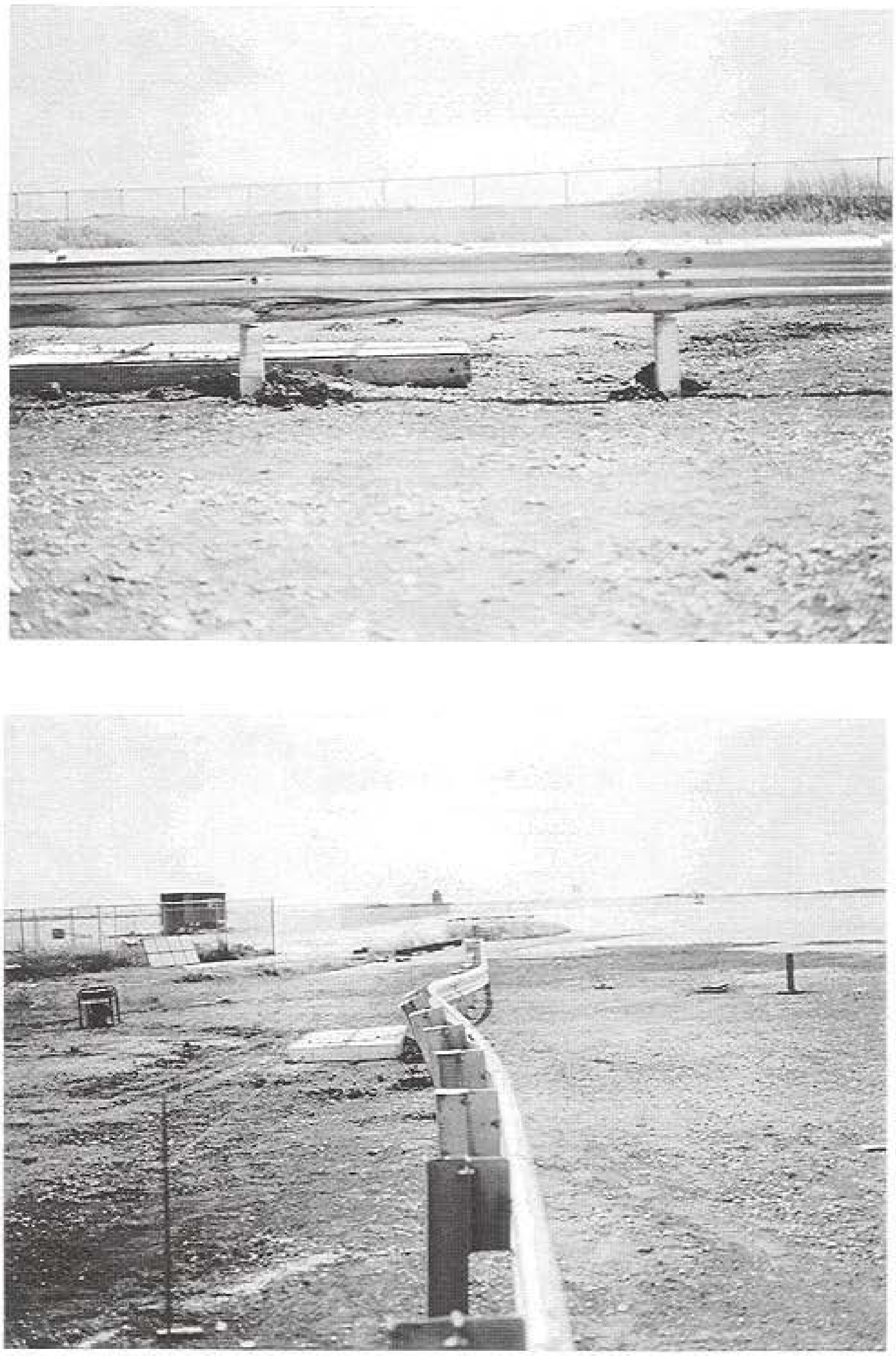


Figure 26. Installation Damage, KSWB-2

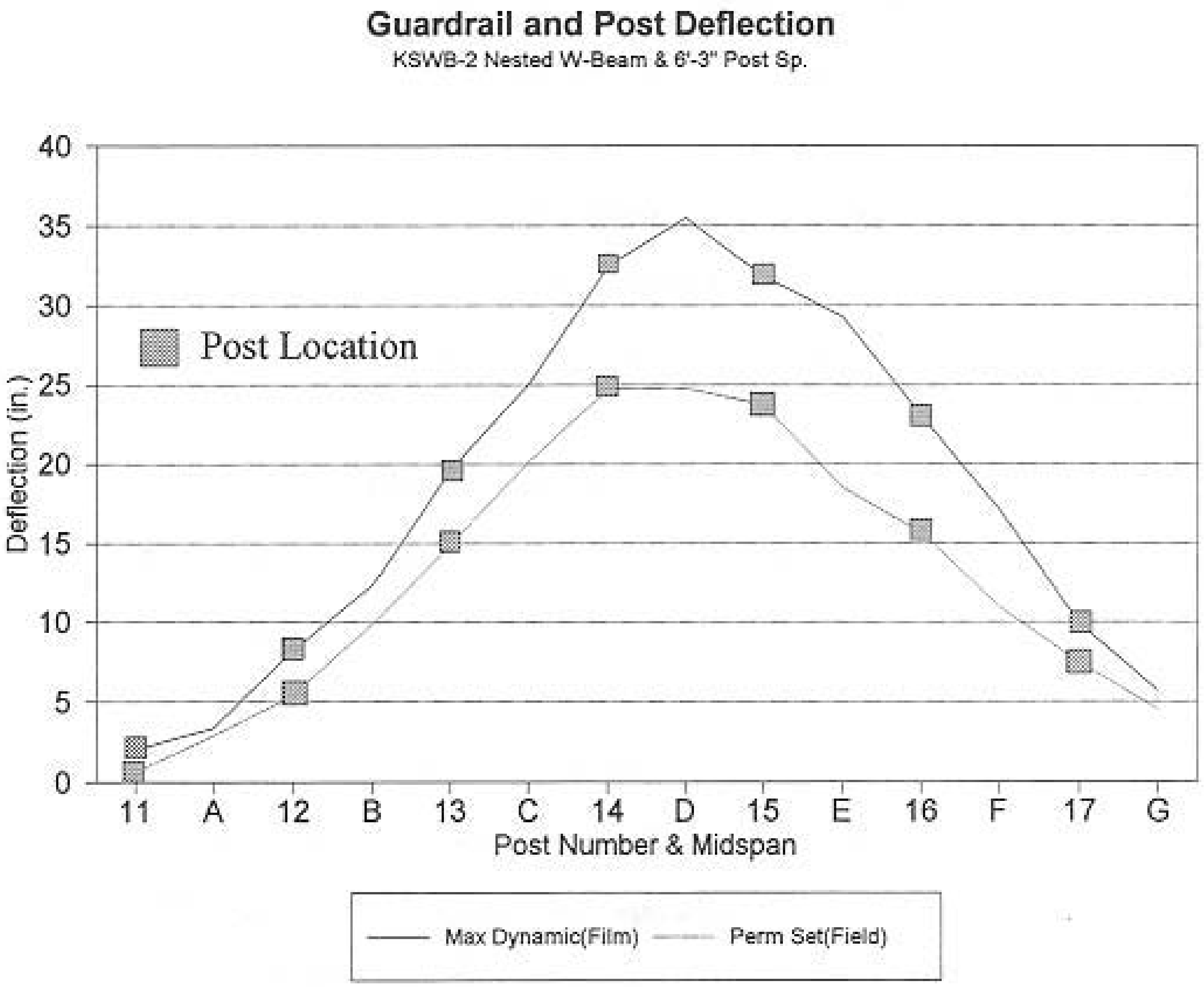


Figure 27. Guardrail and Post Maximum Deflections, KSWB-2

4.3 Test KSWB-3 (4486 lbs, 59.7 mph, 24.8 deg)

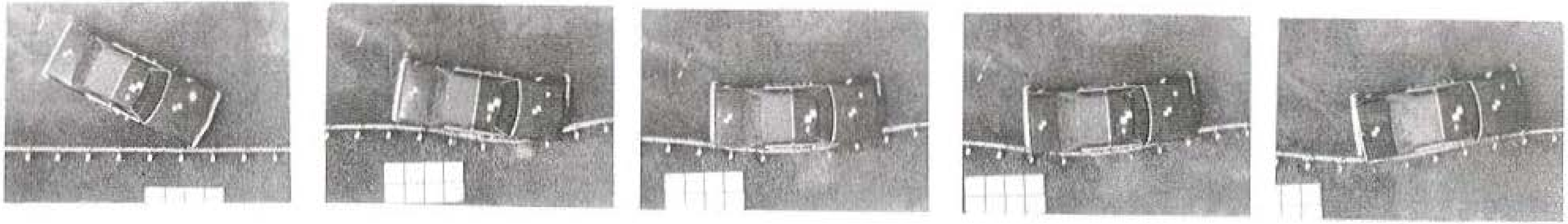
Test KSWB-3 was conducted with a 1985 Mercury Grand Marquis weighing 4,486-lbs at an impact speed of 59.7 mph and an angle of 24.8 degrees. The impact location was approximately 12 ft. upstream of post No. 25. The test installation was a G4(1S) system consisting of single 12-gauge W-beam and 3 ft - 1½ in. post spacing. A summary of the test results and sequential photographs are presented in Figure 28. Additional sequential photographs are shown in Figure 29. Documentary photographs of the crash test are shown in Figures 30 and 31.

After the initial impact with the W-beam guardrail, the vehicle began to redirect coinciding with Post No. 24 at approximately 101 msec after impact. At 151 msec after impact the right front wheel contacted Post No. 25, which caused tire blowout. At 201 msec proceeding impact the vehicle was approximately parallel to the guardrail. The maximum dynamic lateral deflection of the system of 23.5 in. occurred approximately 222 msec after impact at Post No. 24. The vehicle exited the guardrail at approximately 504 msec with an exit speed and angle of 46.1 mph and 9.6 deg respectively. As shown in Figure 28, the vehicle came to rest approximately 169.5 ft downstream from impact and had a maximum rebound distance of approximately 14 ft.

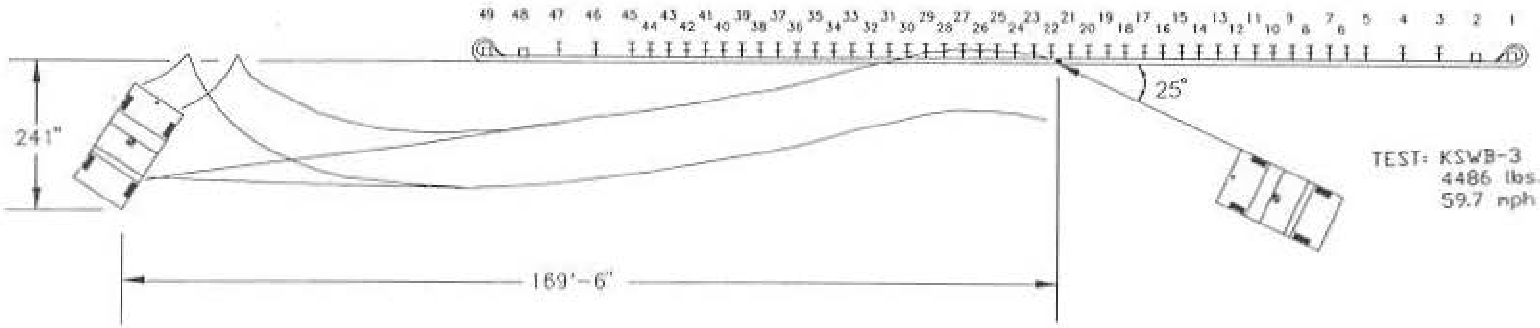
Vehicle damage is shown in Figure 32, and consisted primarily of right-front corner crush and passenger side W-beam interlock damage. There was no interior occupant compartment damage detected. The right front tire was blown and disengaged from the rim, and the rim contained excessive deformation. Guardrail damage is shown in Figure 33, and consisted of only moderate deformation and flattening of the lower portion of the impacted 25-ft beam section. The measured contact length between the vehicle and the rail was approximately 18 ft. The maximum permanent set deflection of 20.3 in. and the maximum dynamic deflection of 23.5 in. occurred at Post No. 24. Maximum deflections (permanent set and dynamic) of the system are shown in Figure 34. None of the posts were disengaged from the system, although Post Nos. 24 through 26 contained permanent deformations and marks near the bottom of the posts resulting from contact with the vehicle.

The normalized longitudinal and lateral occupant impact velocities were determined to be 16.9 fps and 18.8 fps, respectively. The highest average occupant ridedown decelerations in the longitudinal and lateral directions were 9.8 g's and 11.7 g's, respectively. The results of the occupant risk, determined from film analysis, are summarized in Figure 28. The results are shown graphically in Appendix D.

This test passed all of the required criteria set forth in NCHRP Report 230 (7) for the full-size sedan redirectional test.



Impact | 151 msec | 201 msec | 222 msec | 302 msec



Test Number	KSWB-3
Date	6/29/93
Installation	Single 12-Gauge W-Beam with 3 ft - 1½ in. Post Spacing
Installation Length	175 ft
Post	
Size	W6x9
Length	6 ft
Guardrail	
Material	7 - 25 ft sections of 12 gauge W-beam
Post Spacing	3 ft - 1½ in.
End Treatments	Breakaway Cable Terminal With Strut
Test Vehicle	1985 Mercury Marquis
Test Inertial Weight	4486 lbs
Gross Static Weight	4486 lbs

Impact Speed	59.7 mph
Impact Angle	24.8 deg
Impact Location	11.7 ft Upstream of Post No. 25
Exit Speed	46.1 mph
Exit Angle	NA
Normalized Occupant Impact Velocity	
Longitudinal	16.9 fps
Lateral	18.8 fps
Occupant Ridedown Deceleration	
Longitudinal	9.8 g's
Lateral	11.7 g's
Vehicle Damage	
TAD	1-RFQ-4, 1-RD-2
VDI	01RDES2
Maximum Permanent Set Deflection	20.3 in. @ Post No. 24
Maximum Dynamic Deflection	23.5 in. @ Post No. 24
W-Beam Contact Length	18 ft

Figure 28. Summary of Test Results, KSWB-3

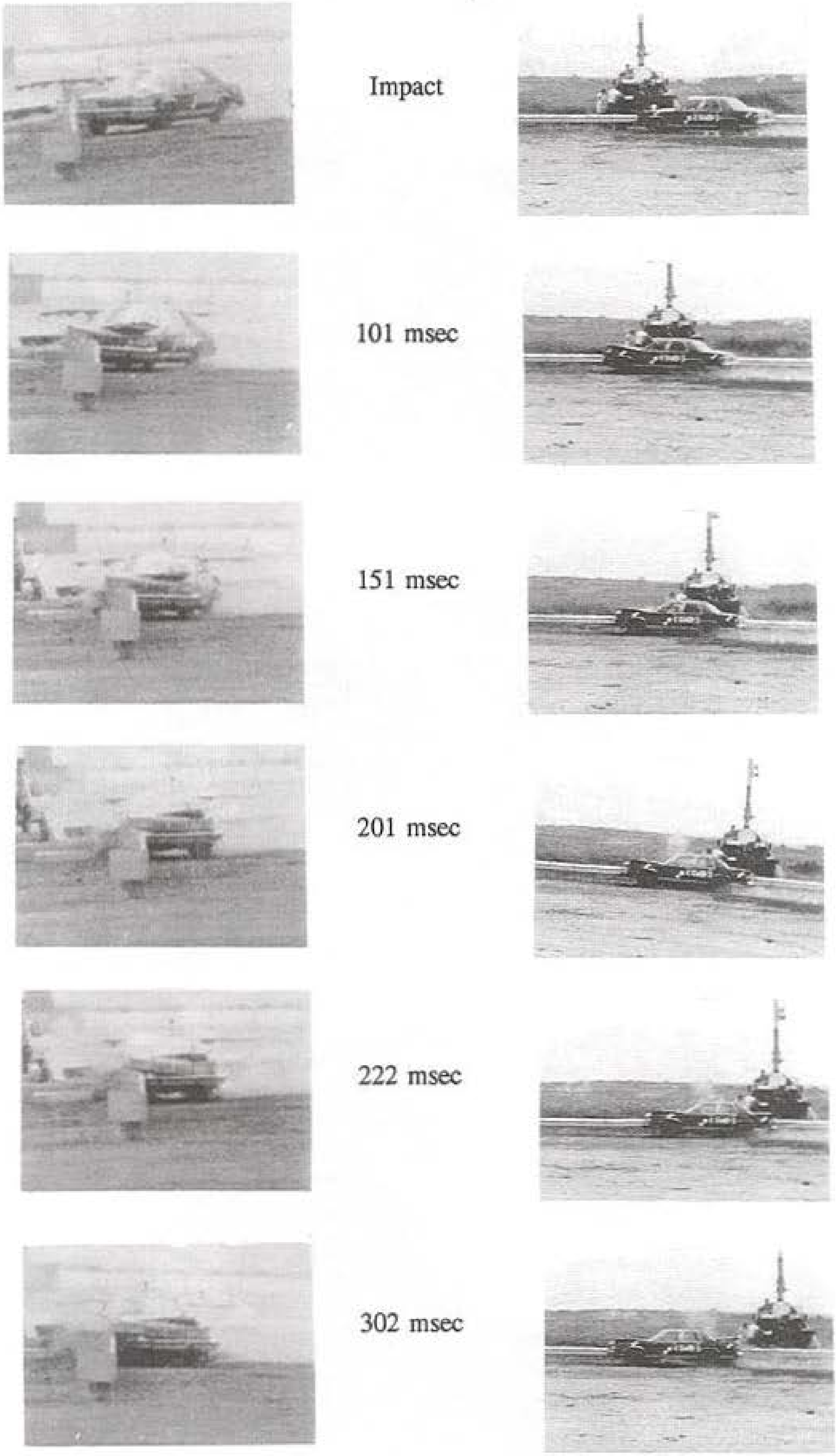


Figure 29. Sequential Photographs, KSWB-3

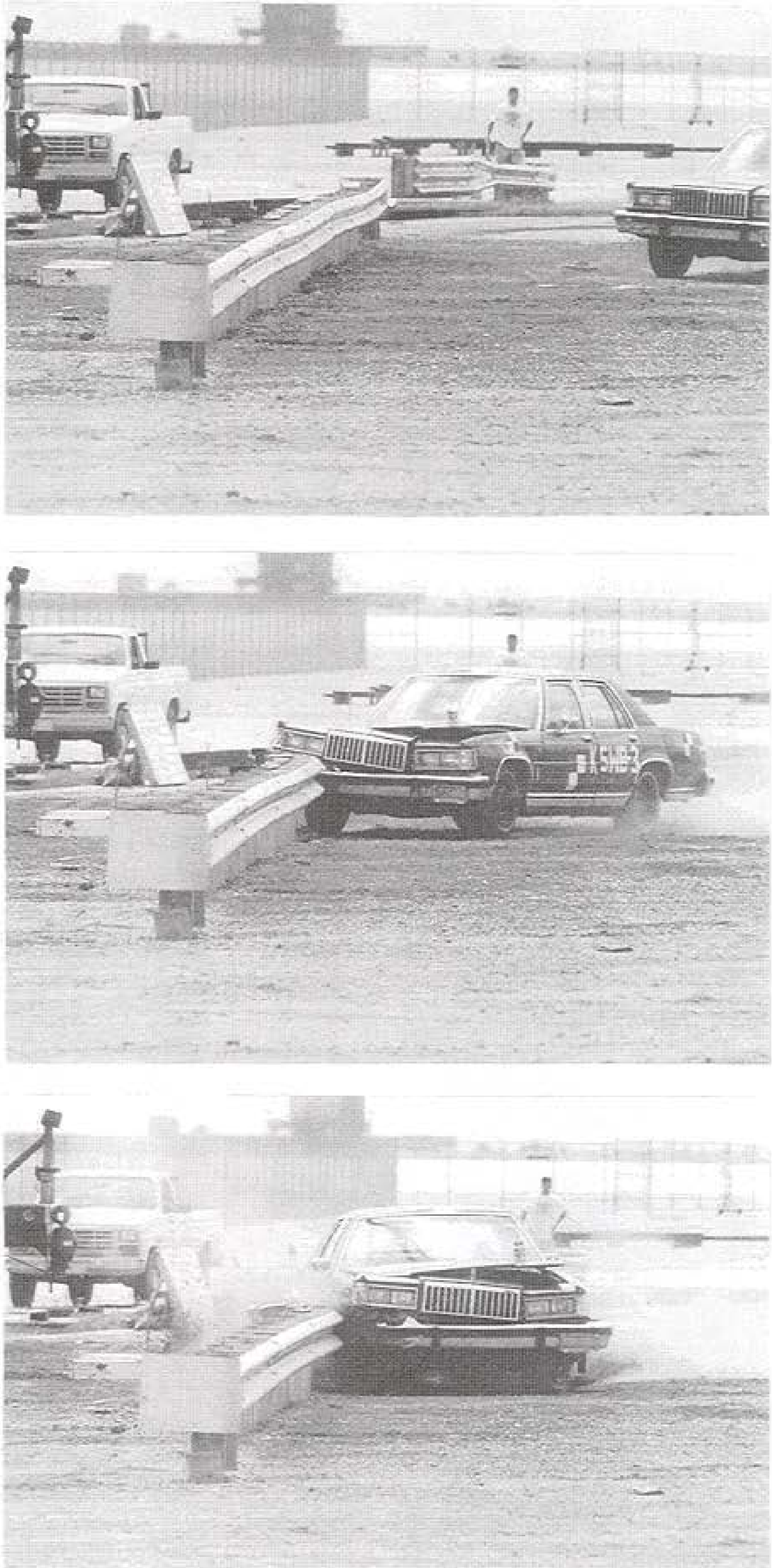


Figure 30. Full-Scale Crash Test, KSWB-3

Figure 31. Full-Scale Crash Test (continued), KSWB-3

Figure 32. Test Vehicle Damage, KSWB-3

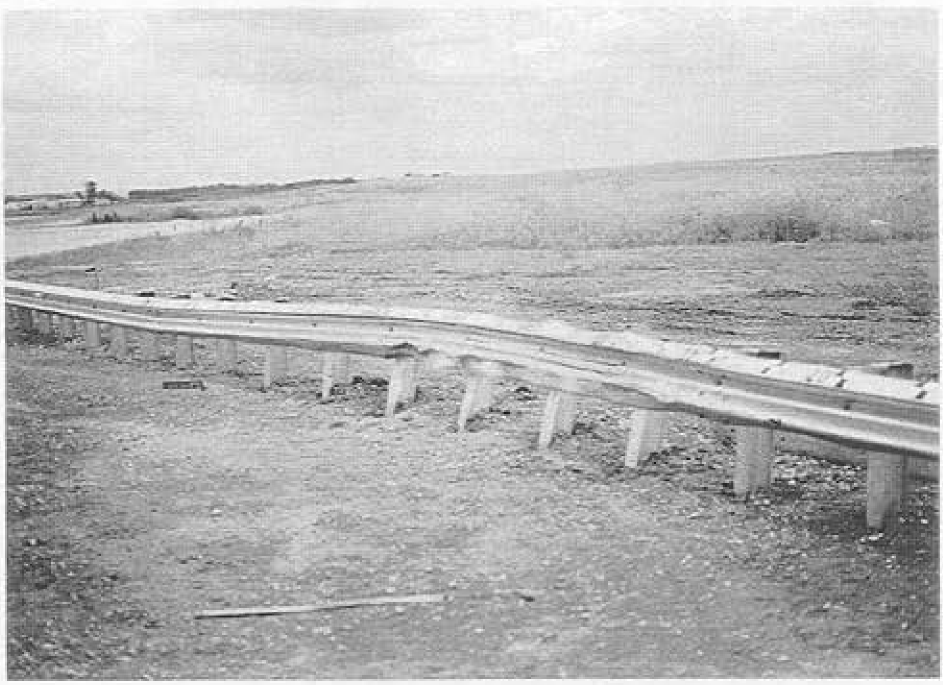


Figure 33. Installation Damage, KSWB-3

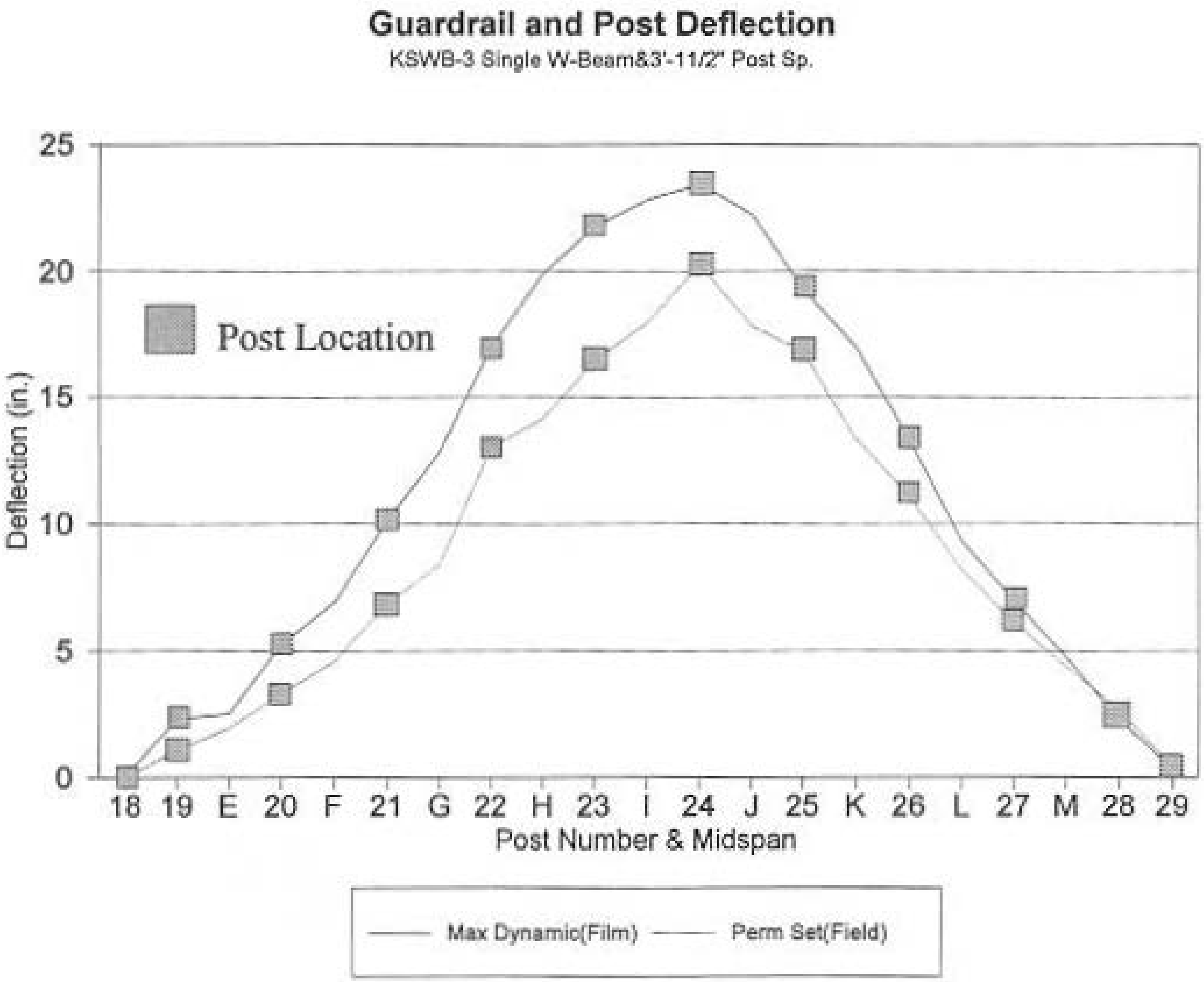


Figure 34. Guardrail and Post Maximum Deflections, KSWB-3

4.4 Test KSWB-4 (4501 lbs, 60.4 mph, 28.4 deg)

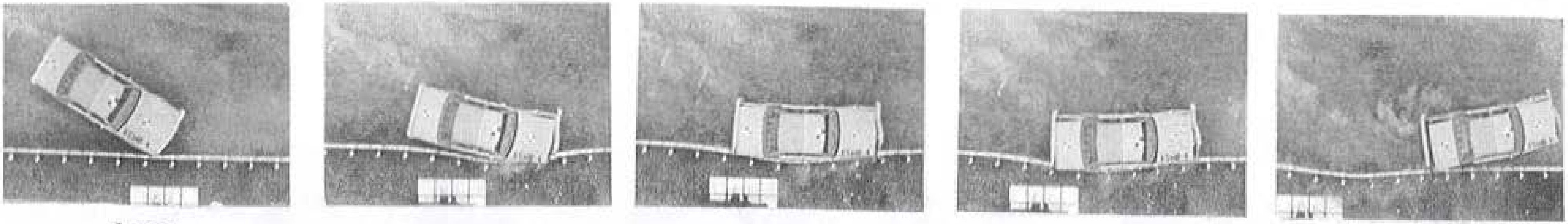
Test KSWB-4 was conducted with a 1985 Mercury Grand Marquis weighing 4,501-lbs at an impact speed of 60.4 mph and impact angle of 28.4 degrees. The impact location was approximately 12 ft. upstream of post No. 25. The test installation was a G4(1S) system consisting of nested 12-gauge W-beam and 3 ft - 1½ in. post spacing. A summary of the test results and sequential photographs are presented in Figure 35. Additional sequential photographs are shown in Figure 36. Documentary photographs of the crash test are shown in Figures 37 and 38.

Following the initial impact with the W-beam guardrail, the vehicle began to redirect coinciding with Post No. 24 at approximately 112 msec after impact. At 143 msec after impact the right-front wheel contacted Post No. 25. At 194 msec proceeding impact the vehicle was approximately parallel to the guardrail. The maximum dynamic lateral deflection of 19.6 in. occurred approximately 225 msec after impact between Post Nos. 23 and 24. The vehicle exited the guardrail at approximately 429 msec with a speed and angle of 46.8 mph and 14.1 deg respectively. As shown in Figure 36, the vehicle came to rest approximately 163.5 ft downstream from impact and had a maximum rebound distance of approximately 14 ft.

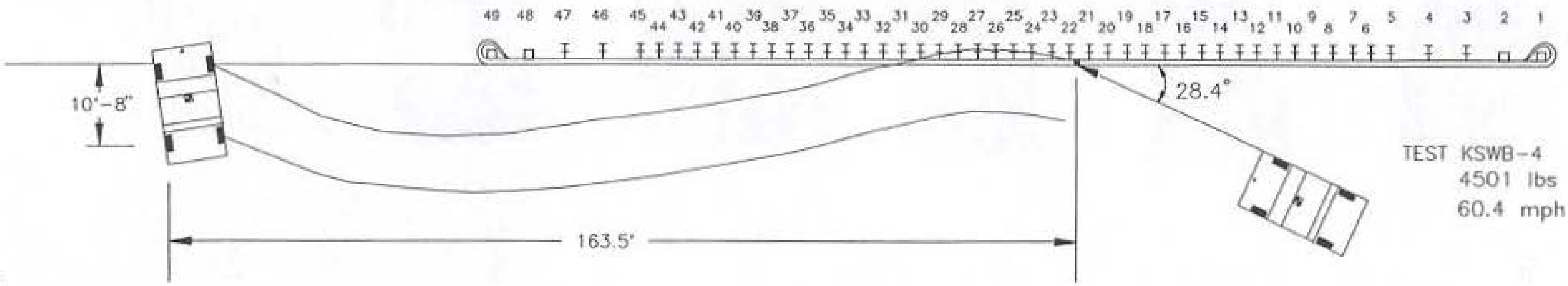
Vehicle damage is shown in Figure 39, and consisted primarily of right front corner crush and passenger side W-beam interlock damage. There was minor interior occupant damage to the right front floor board. The right front tire was blown and the rim contained considerable deformation. Guardrail damage is shown in Figure 40, and consisted of only moderate deformation and flattening of the lower portion of the impacted 25 ft beam section. The measured contact length between the vehicle and the rail was approximately 15 ft. The maximum permanent set deflection of 15.9 in. occurred at Post No. 24. Maximum deflections (permanent set and dynamic) are shown in Figure 41. Post No. 24 was pulled away from the guardrail and Post Nos. 23 through 25 contained permanent deformations and marks near the bottom of the posts resulting from contact with the vehicle.

The normalized longitudinal and lateral occupant impact velocities were determined to be 14.4 fps and 19.4 fps, respectively. The highest average occupant ridedown decelerations in the longitudinal and lateral directions were 5.9 g's and 9.9 g's, respectively. The results of the occupant risk, determined from film analysis, are summarized in Figure 46. The results are shown graphically in Appendix E.

This test passed all of the required criteria set forth in NCHRP Report 230 (7) for the full-size sedan redirectional test.



Impact 143 msec 194 msec 225 msec 419 msec



Test Number	KSWB-4
Date	8/5/93
Installation	Nested 12-Gauge W-Beam with 3 ft - 1½ in. Post Spacing
Installation Length	175 ft
Post	
Size	W6x9
Length	6 ft
Guardrail	
Material	12 - 25 ft sections of 12 gauge W-beam
Post Spacing	3 ft - 1½ in.
End Treatments	Breakaway Cable Terminal With Strut
Test Vehicle	1985 Mercury Marquis
Test Inertial Weight	4501 lbs
Gross Static Weight	4501 lbs

Impact Speed	60.4 mph
Impact Angle	28.4 deg
Impact Location	11.7 ft Upstream of Post No. 25
Exit Speed	46.8 mph
Exit Angle	14.1 deg
Normalized Occupant Impact Velocity	
Longitudinal	14.4 fps
Lateral	19.4 fps
Occupant Ridedown Deceleration	
Longitudinal	5.9 g's
Lateral	9.9 g's
Vehicle Damage	
TAD	1-RFQ-4, 1-RD-2
VDI	01RDES2
Maximum Permanent Set Deflection	15.9 in. @ Post No. 24
Maximum Dynamic Deflection	23.5 in. btwn Post Nos. 23 and 24
W-Beam Contact Length	15 ft

Figure 35. Summary of Test Results, KSWB-4

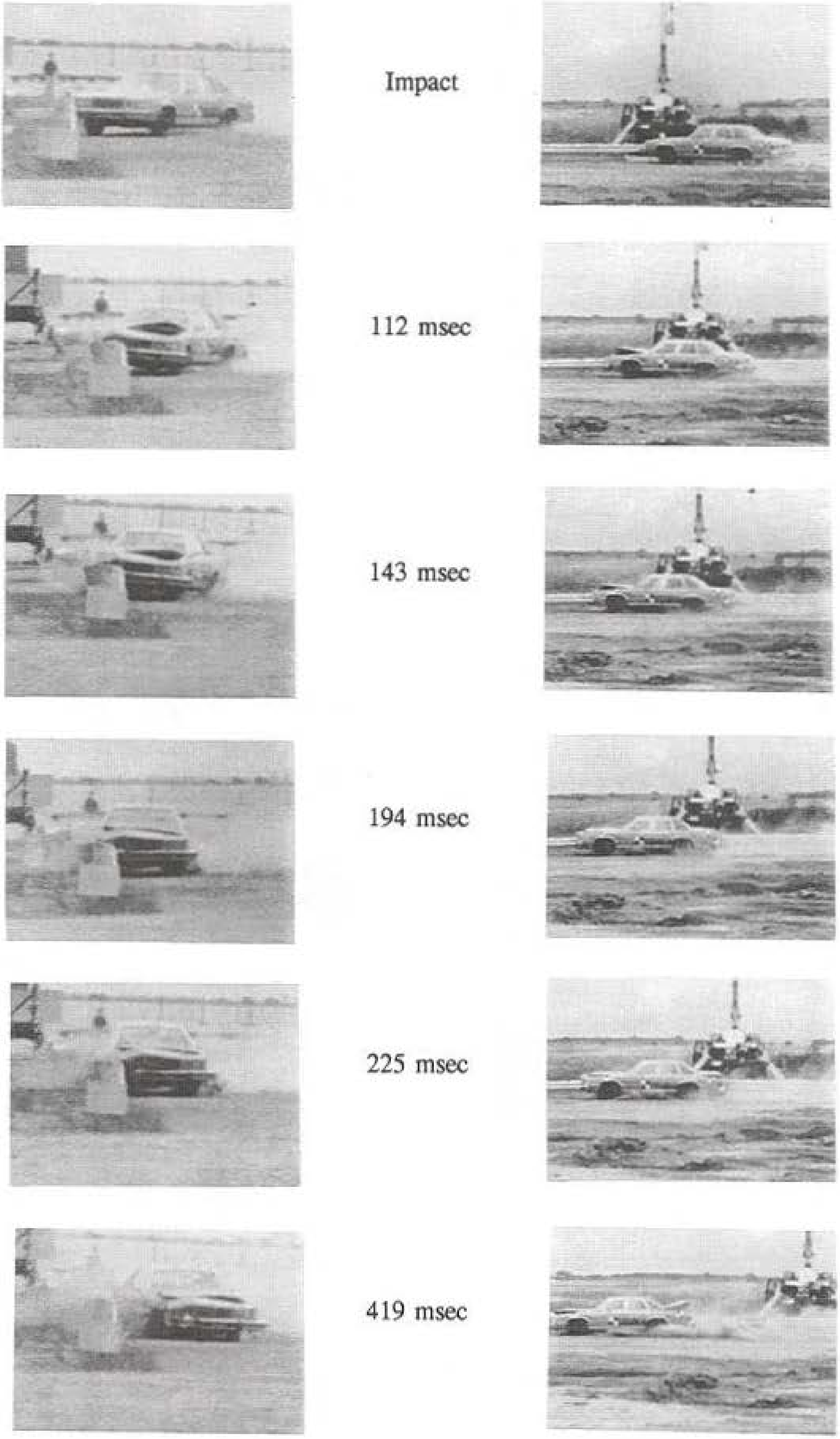


Figure 36. Sequential Photographs, KSWB-4

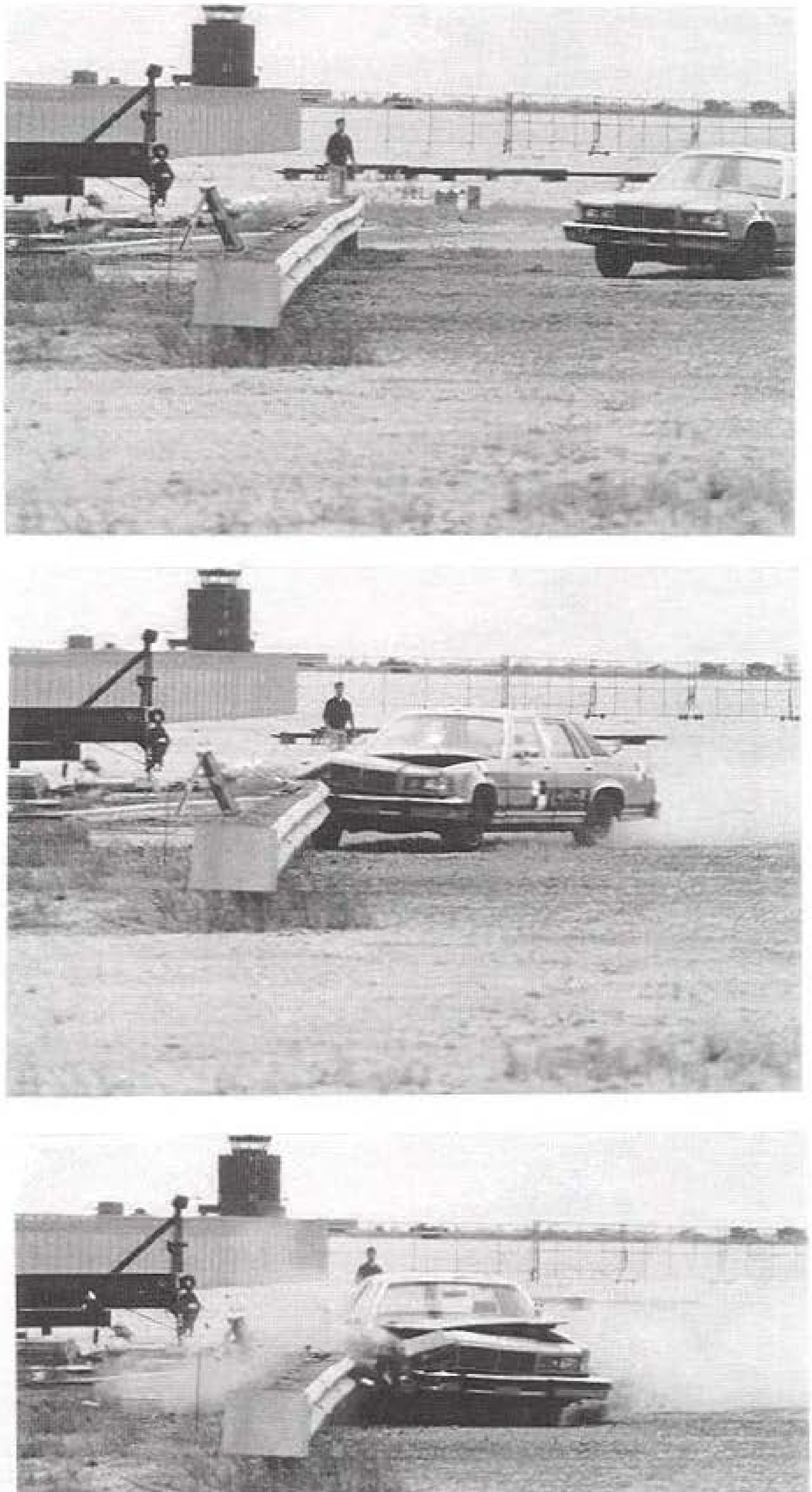


Figure 37. Full-Scale Crash Test, KSWB-4

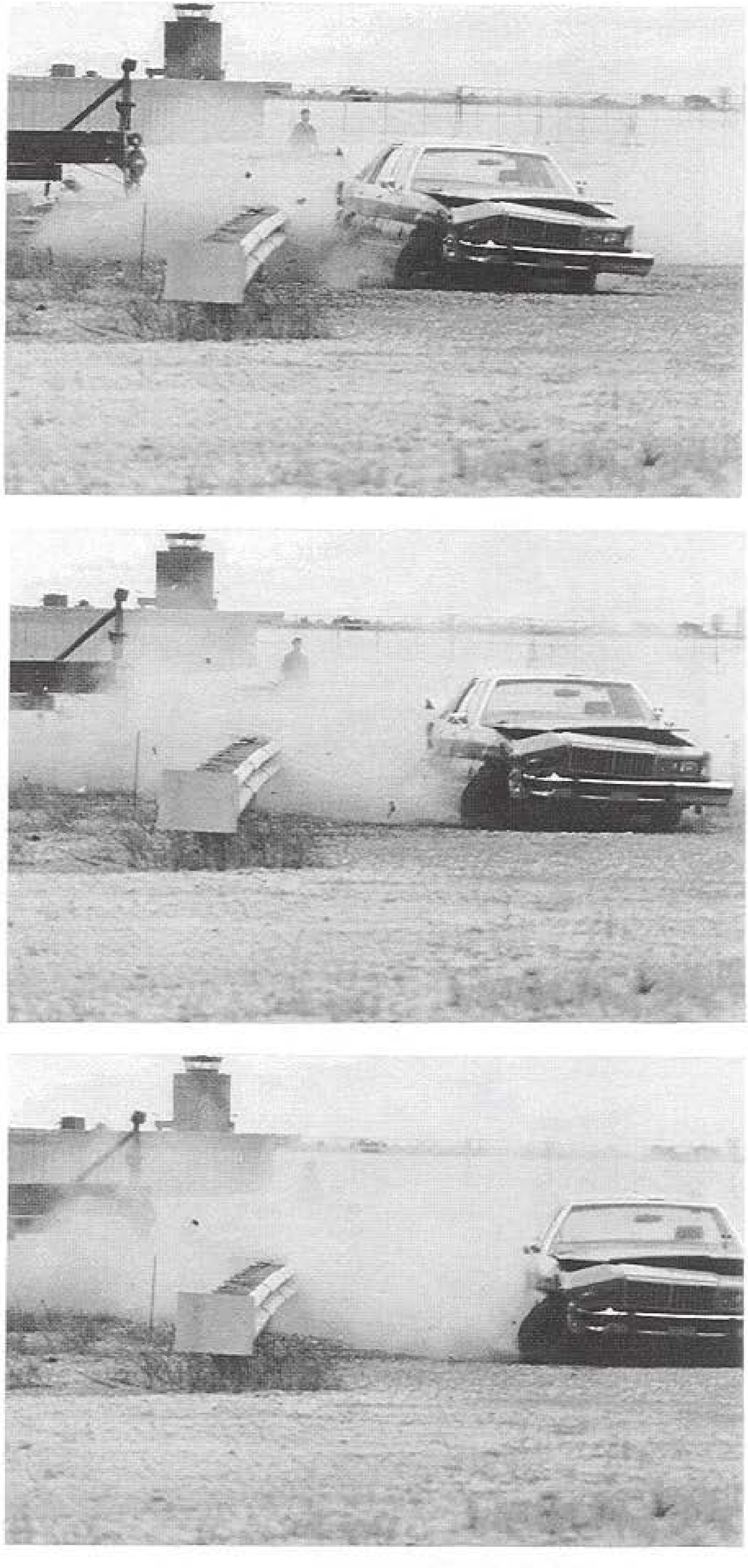
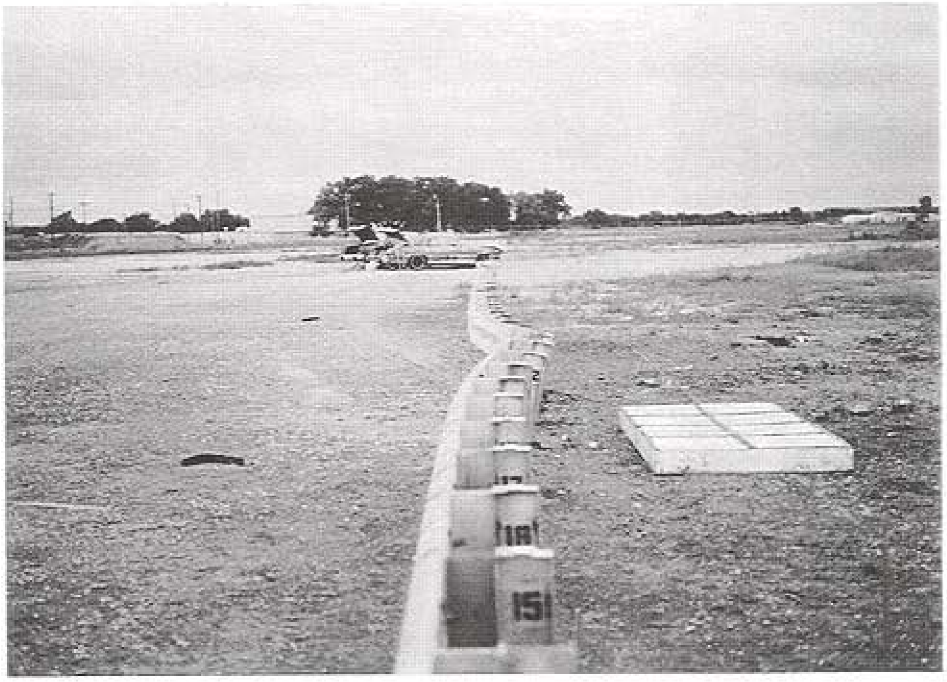


Figure 38. Full-Scale Crash Test (continued), KSWB-4

Figure 39. Test Vehicle Damage, KSWB-4



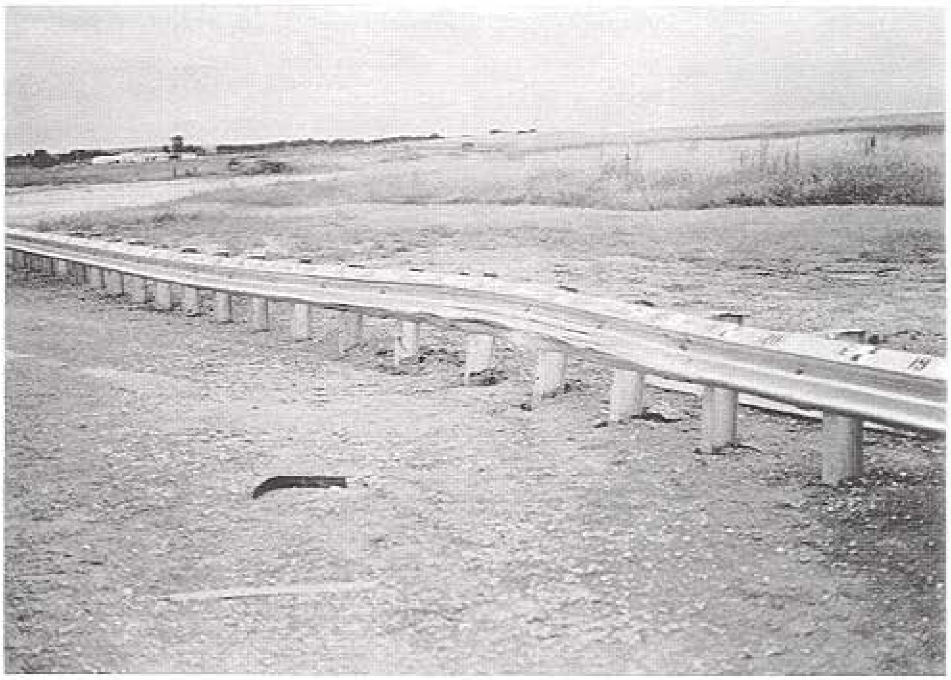


Figure 40. Installation Damage, KSWB-4

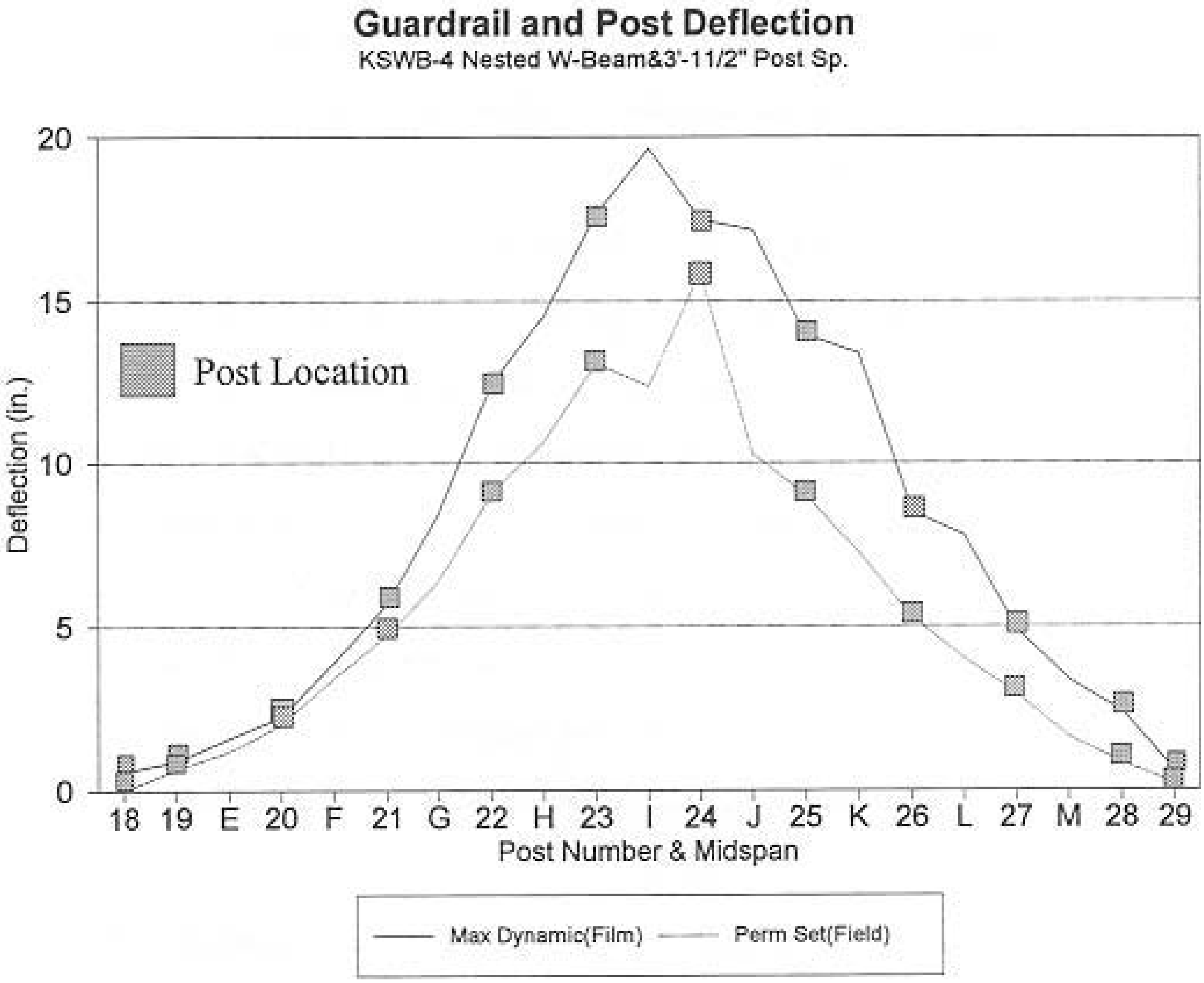


Figure 41. Guardrail and Post Maximum Deflections, KSWB-4

4.5 Comparison of Results

With the exception of Test KSWB-2, where the rail deflection increased slightly, the increase in stiffness resulting from the nesting of the beam and/or the increase in post spacing resulted in a decrease in the permanent set and dynamic deflections, as shown in Figures 42 and 43. The maximum lateral dynamic deflections, as well as other pertinent information from this testing is summarized in Table 3.

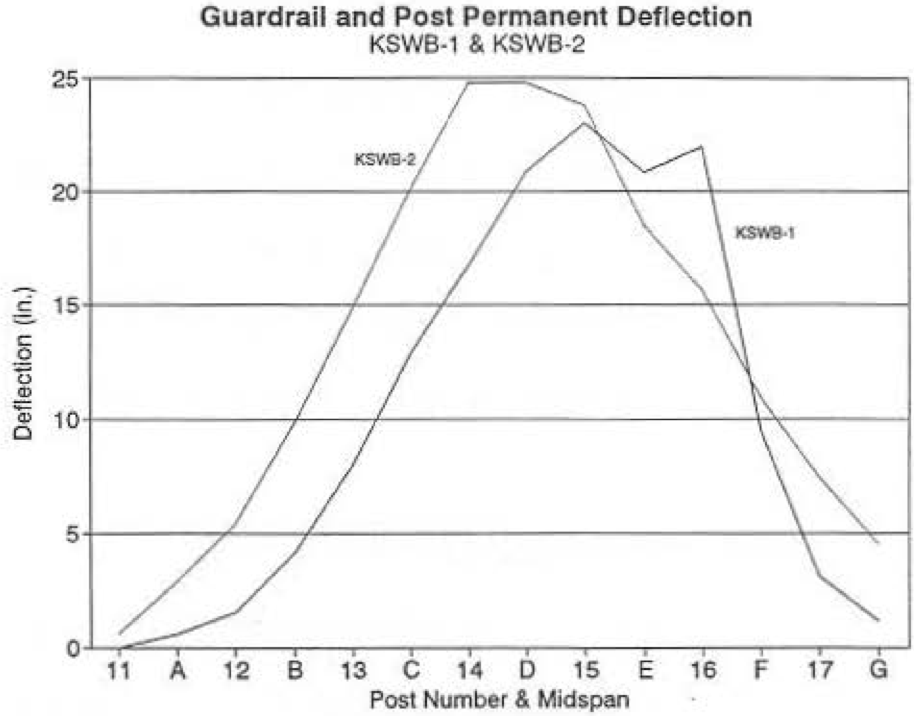
Table 4 is comprised of the results of previous testing which has been conducted on similar systems. These results were used to provide comparisons of maximum lateral deflections between similar systems and to compare the effects of strengthening the systems.

Previous testing included one full-scale crash test conducted at the Southwest Research Institute (SwRI) on a G4(1S) system (2). This test resulted in excessive lateral deflections as a result of poor soil conditions, length of installation, and the method of anchoring the end of the rail. A second test which was used for comparison was conducted at the California Highway Department (CALTRANS) (3). This G4(1S) system was stiffer than the previous test conducted by SwRI, and provided much more reasonable results which compared favorably with Test KSWB-1.

Additional testing used for comparison included a series of full-scale crash tests conducted at SwRI. This series of tests investigated the effects of soil conditions on the performance of standard G4(1S) systems (4). The first test (SPI-1) was a baseline test used to evaluate the performance of the W-beam system with adequate soil conditions. The second test (SPI-2) was conducted to evaluate the effects of substandard soil compaction effects, and test SPI-3 was conducted to evaluate the behavior of the system with substandard soil strength.

The final series of tests used for comparisons was conducted at Analysis Group Inc.(14), using the NARD computer simulation model (15). The deflection results obtained in these computer simulations were presented in a FHWA technical memorandum (16) and are used nationwide to guide engineers in the placement of W-beam systems. Three of the computer simulations from this study were used for comparisons because of their test condition similarities. These tests include: Run No.1 (single W-beam with 6 ft - 3 in. post spacing); Run No.4 (single W-beam with 3 ft - 1½ in. post spacing); and Run No. 6 (nested W-beam with 3 ft - 1½ in. post spacing).

A comparison of these tests indicates that the results obtained from the full-scale vehicle crash tests conducted during this research project are reasonable. All dynamic deflection values are within 20% of the values obtained in previous studies, which is reasonable given the variance in actual test conditions and computer simulation results.



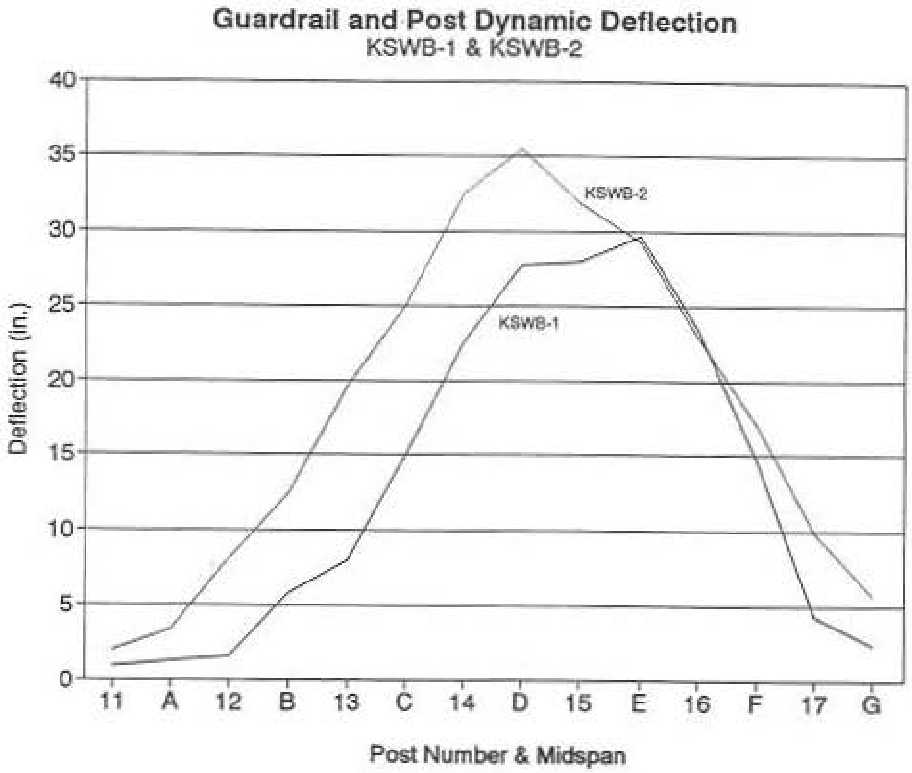
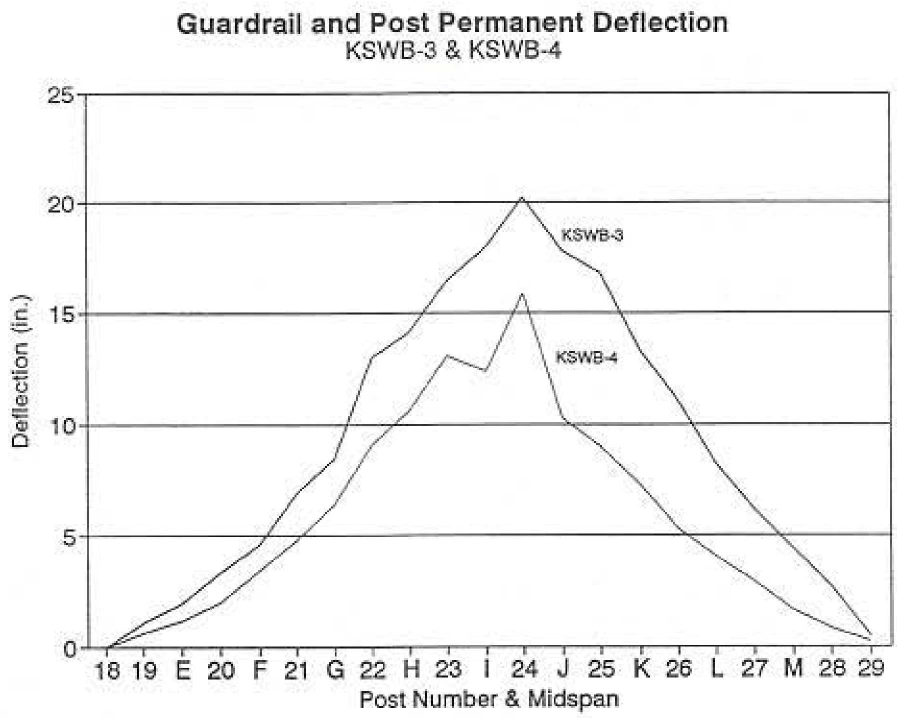


Figure 42. Deflection Comparisons, KSWB-1 and KSWB-2



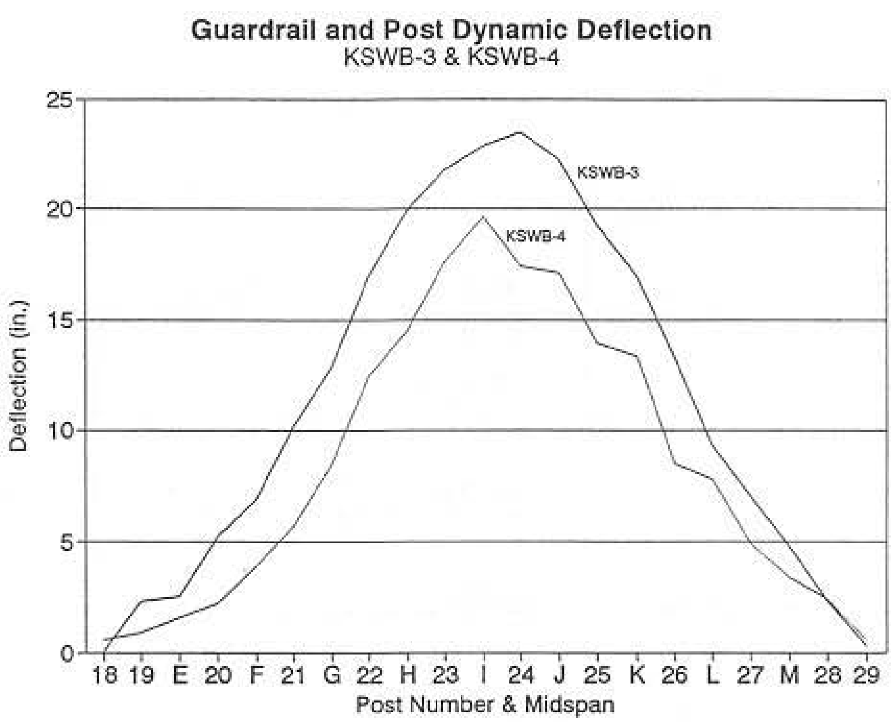


Figure 43. Deflection Comparisons, KSWB-3 and KSWB-4

Table 3. Comparison of Test Results

Test Parameter	KSWB-1 (Single W-beam & 6'-3" P.S.)	KSWB-2 (Nested W-beam & 6'-3" P.S.)	KSWB-3 (Single W-beam & 3'-1½" P.S.)	KSWB-4 (Double W-beam & 3'-1½" P.S.)
Test Inertial Weight	4399 lb	4486 lb	4486 lb	4501 lb
Impact Speed	61.9 mph	60.5 mph	59.7 mph	60.4 mph
Impact Angle	25.1 deg	25.4 deg	24.8 deg	28.4 deg
Impact Severity	101.8 k-ft	101.3 k-ft	94.5 k-ft	124.7 k-ft
Exit Angle	14.5 deg	12.9 deg	9.6 deg	14.1 deg
Exit Speed	40.1 mph	52.6 mph	46.1 mph	46.8 mph
Max Perm. Set Deflection	22.0 in.	24.8 in.	20.3 in.	15.9 in.
Max Dynamic Deflection	29.7 in.	35.5 in.	23.5 in.	19.6 in.
Longitudinal OIV	21.3 fps	11.0 fps	16.9 fps	14.4 fps
Lateral OIV	17.7 fps	16.5 fps	18.8 fps	19.4 fps
Longitudinal Deceleration	8.8 g's	5.7 g's	9.8 g's	5.9 g's
Lateral Deceleration	11.9 g's	14.3 g's	11.7 g's	9.9 g's
Vehicle Rebound Dist.	17 ft	35 ft	14 ft	14 ft

Table 4. Maximum G4(1S) Guardrail Deflection Comparisons

TEST PARAMETER	KSWB-1	KSWB-2	KSWB-3	KSWB-4	SwRI[1]	CAL[2]	SPI-1[3]	SPI-2[3]	SPI-3[3]	RUN 1[4]	RUN 4[4]	RUN 6[4]
Test Vehicle Inertial Weight (lb)	4399	4486	4486	4501	3813	4960	4490	4490	4490	4500	4500	4500
Impact Angle (deg)	25.1	25.4	24.8	28.4	28.4	25.0	25.3	23.6	23.1	25.0	25.0	25.0
Impact Speed(mph)	61.9	60.5	59.7	60.4	56.8	66.0	59.6	58.6	59.6	60.0	60.0	60.0
Rail Type (12 ga.)	Single	Nested	Single	Nested	Single	Single	Single	Single	Single	Single	Single	Nested
Post Type (Steel)	W6x9	W6x9	W6x9	W6x9	6x8.5	6x8.5	6x8.5	6x8.5	6x8.5	6x8.5	6x8.5	6x8.5
Post Spacing	6'-3"	6'-3"	3'-1½"	3'-1½"	6'-3"	6'-3"	6'-3"	6'-3"	6'-3"	6'-3"	3'-1½"	3'-1½"
Maximum Dynamic Deflection (in.)	29.7	35.5	23.5	19.6	48.6	31.2	35.6	45.1	29.6	35.7	21.3	17.2
Maximum Permanent Set (in.)	22.0	24.8	20.3	15.9	34.8	NA	27.3	27.3	24.5	NA	NA	NA

[1] SwRI (2)
[2] CALTRAN (3)
[3] SwRI (4)
[4] Analysis Group Inc. (14)
NA - Not Available

5 CONCLUSIONS

All of the full-scale tests conducted during this research project satisfied the performance criteria set forth by NCHRP Report No. 230 (7), and the tests have provided well established deflection distances resulting from the effects of nesting and half-post spacing. These tests indicate that soil moisture content can have a significant effect on the behavior of guardrail systems. It was also evident that nesting W-beam does not affect the lateral dynamic deflection of the guardrail as significantly as half-post spacing does. These deflection results will be beneficial for the computer model calibration conducted in the second phase of this project (17), and will ultimately aid in decisions on the location of W-beam barrier placement.

6 References

1. *Guide For Selecting, Locating, and Designing Traffic Barriers*, American Association of State Highway and Transportation Officials (AASHTO), 1977.

2. Michie, J.D., Calcote, L.R., and Bronstad, M.E., *Guardrail Performance and Design*, National Cooperative Highway Research Program Report 115, Highway Research Board, 1971.

3. Stoughton, R.L., Stocker, J.R., and Nordlin, E.F., *Dynamic Tests of Metal Beam Guardrail*, Paper presented at the 54th Annual Transportation Research Board Meeting, Washington, D.C., 1975.

4. Ray, M.H., *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware - Volume II, The Effect of Soil Strength on Longitudinal Barrier Performance*, Southwest Research Institute, San Antonio, Texas, July 1987.

5. Powell, G.H., *BARRIER VII: A Computer Program For Evaluation Of Automobile Barrier Systems*, Prepared for: Federal Highway Administration, Report No. FHWA RD-73-51, April 1973.

6. Hinch, J., Yang, T-L, and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, VA, 1986.

7. Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program Report No. 230, Transportation Research Board, Washington, D.C., March 1981.

8. Taborck, J.J., "*Mechanics of Vehicles - 7*", Machine Design Journal, May 30, 1957.

9. Enhanced Graphics Acquisition and Analysis (EGAA), Operation Guide and Reference Manual, Version 3.34.1, R.C. Electronics, Goleta, CA, December 1990.

10. The DADISP Worksheet, Data Analysis and Display Software, User and Reference Manuals, Version 3.0, DSP Development Corporation, Cambridge MA, December 1991.

11. Ross, H.E., Jr., Sicking, D.L., Zimmer, R.A., and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Research Program Report No. 350, Transportation Research Board, Washington, D.C., 1993.

12. *Vehicle Damage Scale for Traffic Investigators*, Traffic Accident Data Project Technical Bulletin No. 1, National Safety Council, Chicago, IL, 1971.

13. *Collision Deformation Classification, Recommended Practice J224 March 1980*, SAE Handbook Vol. 4, Society of Automotive Engineers, Warrendale, Penn., 1985.

14. Hancock, K.L., *Determination of Strengthened Guardrail Deflection*, Analysis Group Inc., Washington, D.C., January 1989.

15. Chou, C.C., Hancock, K., and Basu, S., *NARD: Numerical Analysis of Roadside Design, Version 2.0*, Final Report on Contract DTFH61-87-Z-00116, Federal Highway Administration, Washington, D.C., July 1989.

16. *Determination of Strengthened Guardrail Deflection*, FHWA Memorandum dated May 18, 1989, Director of the Office of Highway Safety, Wahington, D.C.

17. Holloway, J.C., Bierman, M.G., Pfeifer, B.G., Rosson, B.T., and Sicking, D.L., *Performance Evaluation of KDOT W-beam Systems Volume II: Component Testing and Computer Simulation*, Research Report No. TRP-03-56-96, Draft Report to the Kansas Department of Transportation, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Ne., March 1996.

Appendix A

Test Vehicle Information

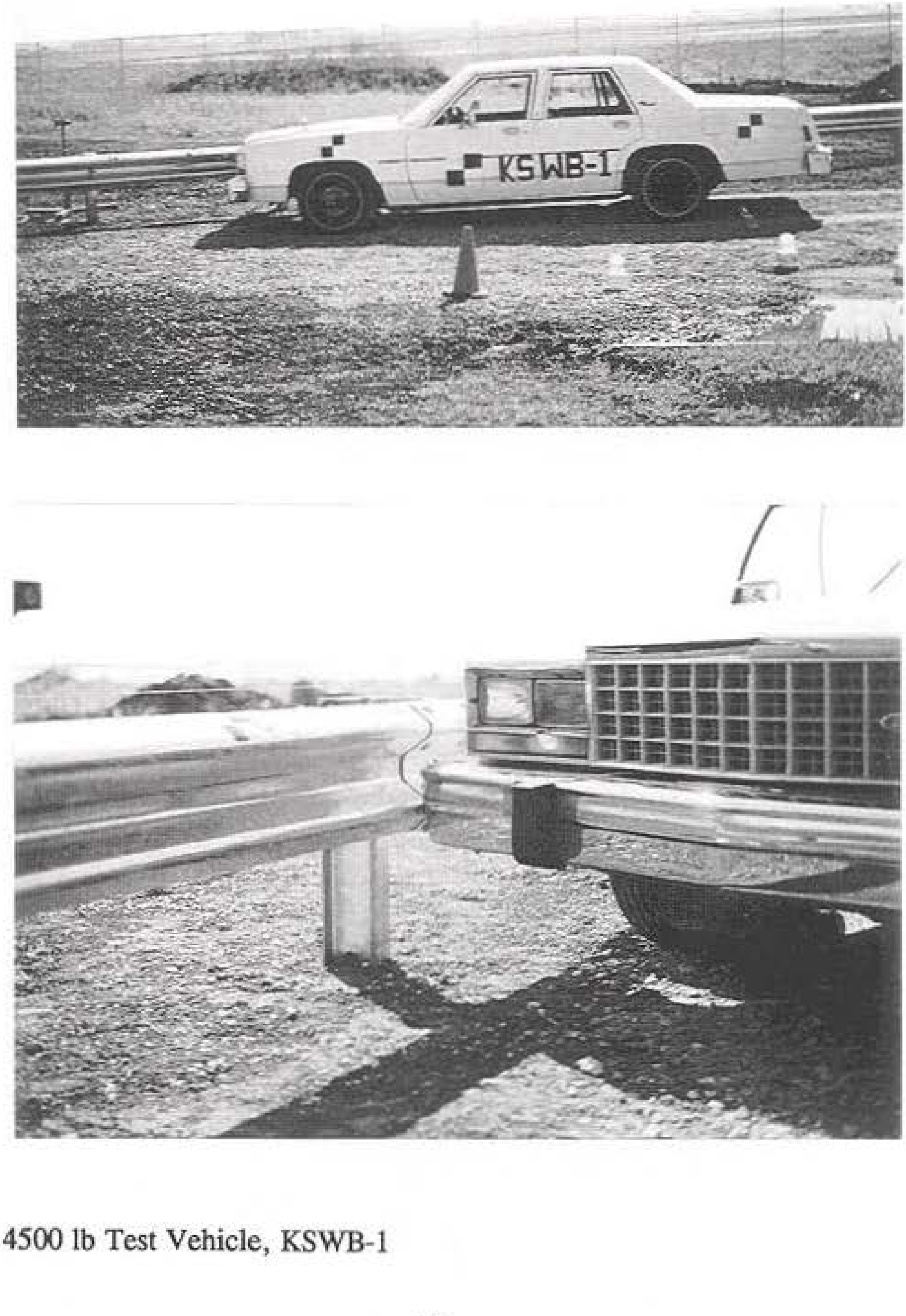
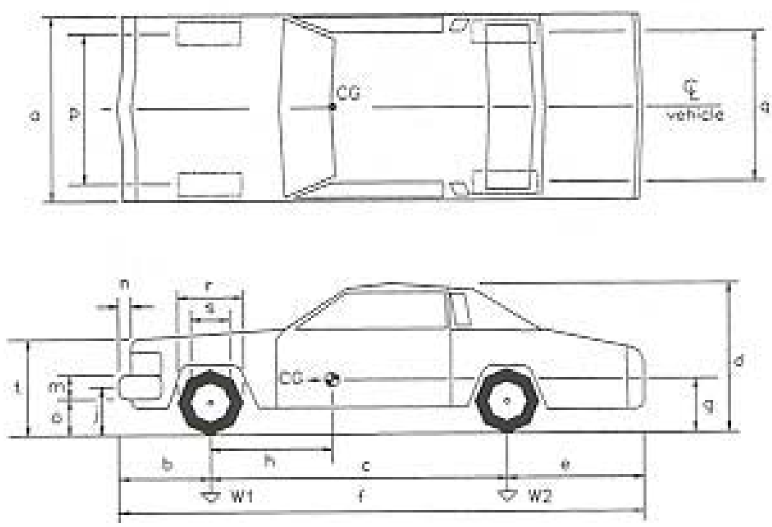


Figure A-1. 4500 lb Test Vehicle, KSWB-1

Make: Ford	Test No.: KSWB-1		
Model: LTD Crown Victoria	Tire Size: P215-75R15		
Year: 1985	VIN: 2FABP43G5FX172657		

Vehicle Geometry
Inches

a	76.75	b	41.0
c	114.0	d	55.75
e	61.0	f	216.0
g	22.0	h	48.35
j	17.0	m	8.0
n	6.5	o	13.5
p	62.75	q	62.0
r	27.0	s	16.25
t	34.5		



Engine Size: 351 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2265	2533	2533
W2	1445	1866	1866
Wtotal	3710	4399	4399

Damage prior to test: None

Figure A-2. 4500 lb Test Vehicle Dimensions, KSWB-1

Figure A-3. 4500 lb Test Vehicle, KSWB-2

Make: Ford

Model: LTD Crown Victoria

Year: 1984

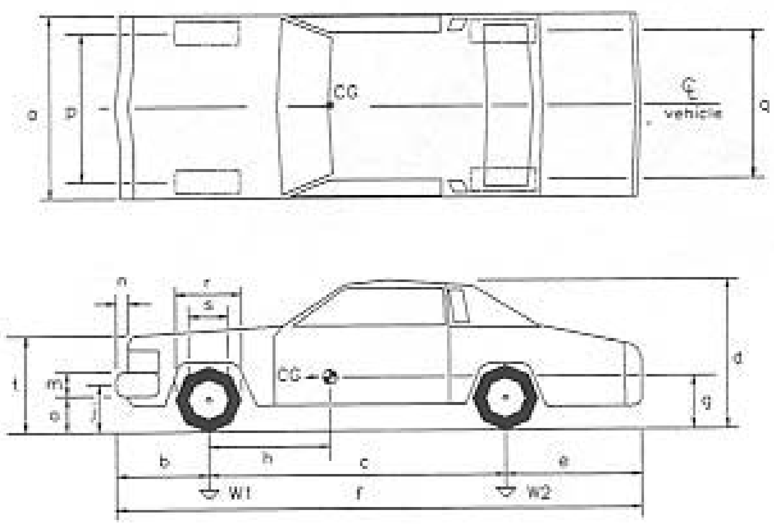
Test No.: KSWB-2

Tire Size: P215-70R15

VIN: 2FABP43FXEX121970

Vehicle Geometry
Inches

a	76.75	b	41.0
c	114.0	d	55.75
e	60.0	f	215.0
g	22.0	h	51.4
j	17.25	m	8.0
n	6.5	o	13.25
p	62.25	q	62.0
r	27.0	s	16.25
t	34.5		



Engine Size: 302 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2170	2286	2286
W2	1410	2200	2200
Wtotal	3580	4486	4486

Damage prior to test: None

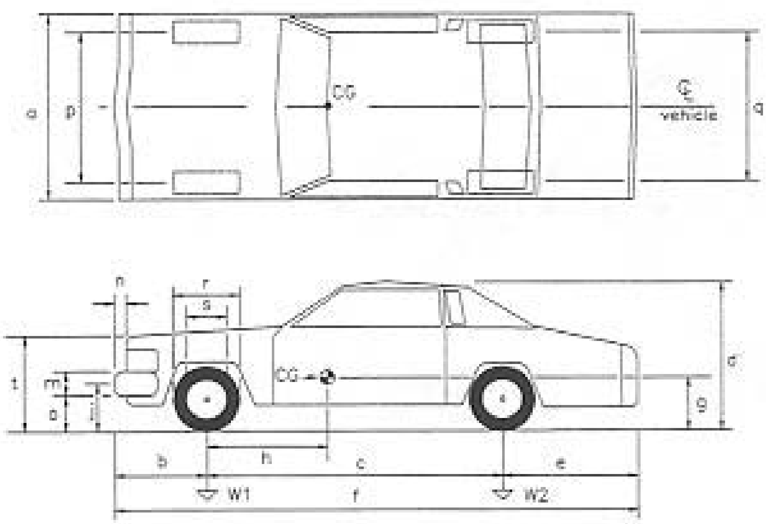
Figure A-4. 4500 lb Test Vehicle Dimensions, KSWB-2

Figure A-5. 4500 lb Test Vehicle, KSWB-3

Make: Mercury	Test No.: KSWB-3		
Model: Grand Marquis	Tire Size: P215-75R15		
Year: 1985	VIN: 2MEBP95F1FX658621		

Vehicle Geometry
Inches

a — 77.0	b — 44.25		
c — 114.0	d — 55.75		
e — 56.75	f — 215.0		
g — 22.0	h — 50.45		
j — 17.0	m — 8.0		
n — 6.5	o — 13.0		
p — 62.5	q — 62.0		
r — 27.0	s — 16.25		
t — 34.5			



Engine Size: 302 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2190	2501	2501
W2	1420	1985	1985
Wtotal	3610	4486	4486

Damage prior to test: ______

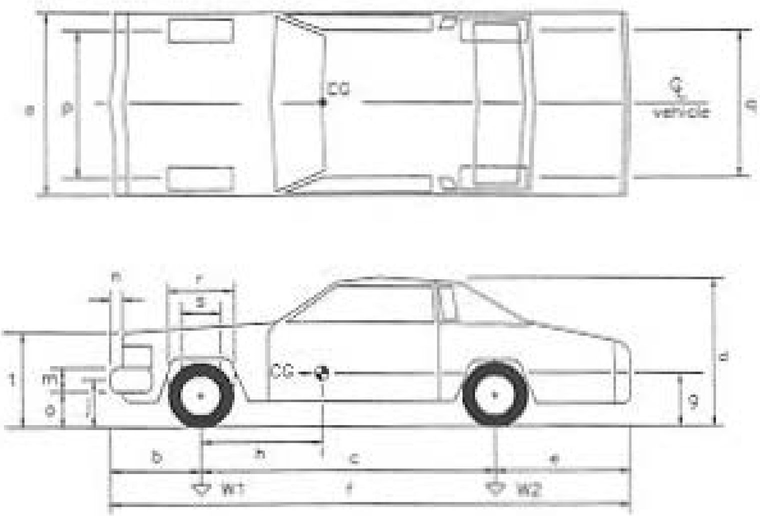
Figure A-6. 4500 lb Test Vehicle Dimensions, KSWB-3

Figure A-7. 4500 lb Test Vehicle, KSWB-4

Make: Mercury	Test No.: KSWB-4		
Model: Grand Marquis	Tire Size: P215-75R15		
Year: 1985	VIN: 2MEBP95F1FX635162		

Vehicle Geometry
Inches

a — 77.0	b — 44.25
c — 114.0	d — 55.75
e — 56.75	f — 215.0
g — 22.0	h — 50.2
j — 17.0	m — 8.0
n — 7.0	o — 13.0
p — 62.5	q — 62.0
r — 27.0	s — 16.25
t — 34.5	



Engine Size: 302 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2220	2519	2519
W2	1450	1982	1982
Wtotal	3670	4501	4501

Damage prior to test: None

Figure A-8. 4500 lb Test Vehicle Dimensions, KSWB-4

Appendix B

KSWB-1 Data Analysis

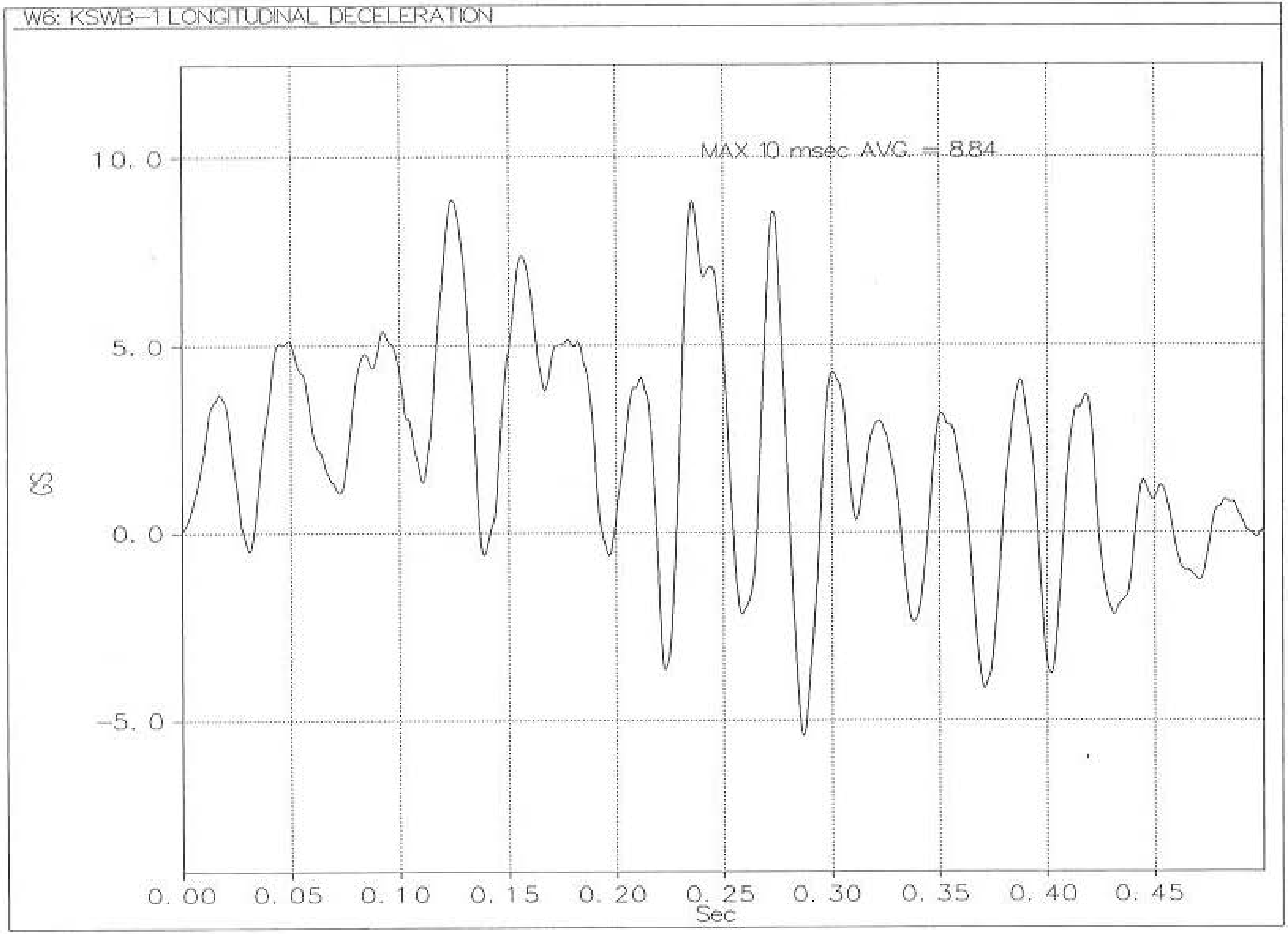


Figure B-1. Graph of KSWB-1 Longitudinal Deceleration

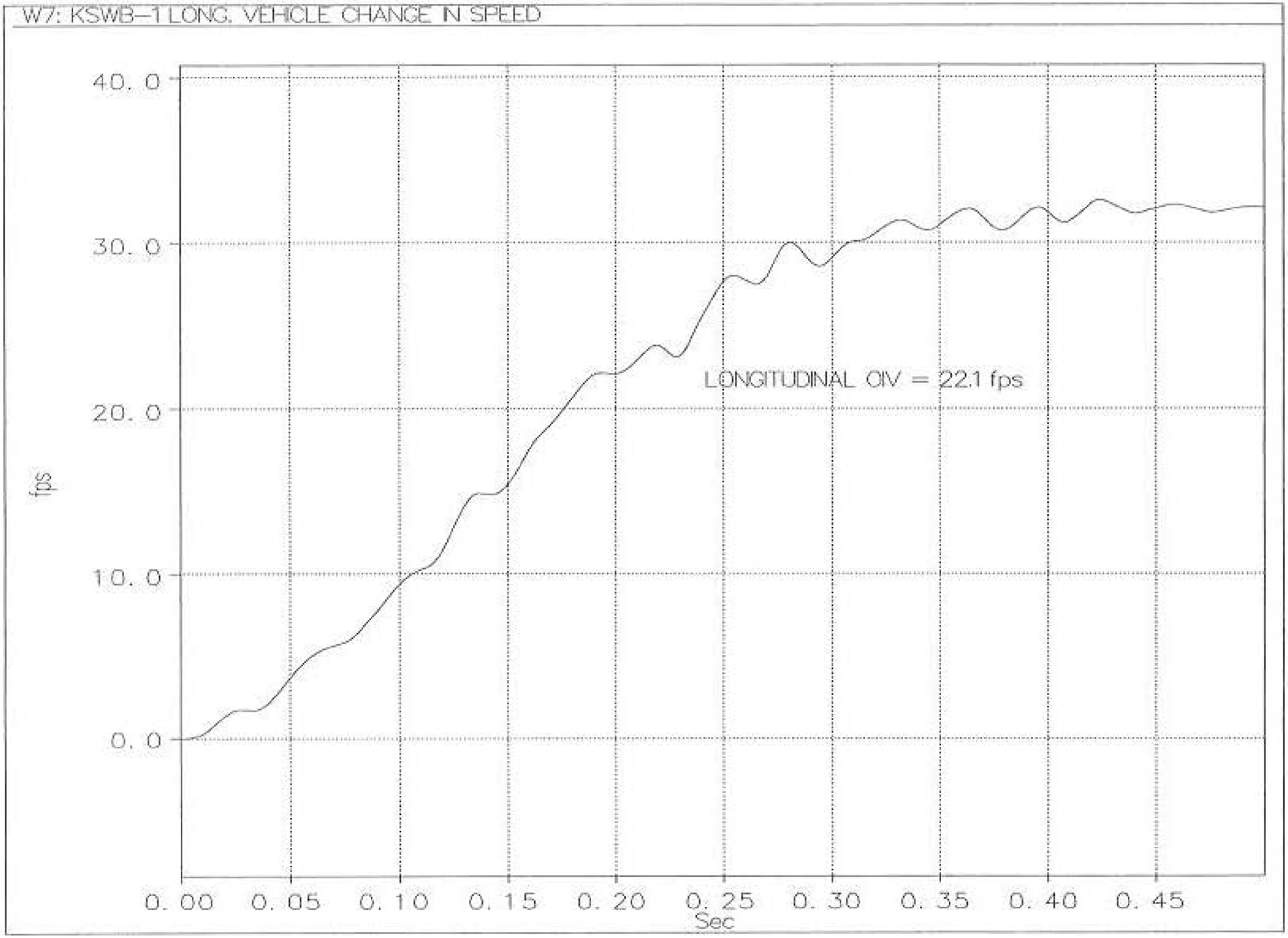


Figure B-2. Graph of KSWB-1 Longitudinal Vehicle Change in Speed

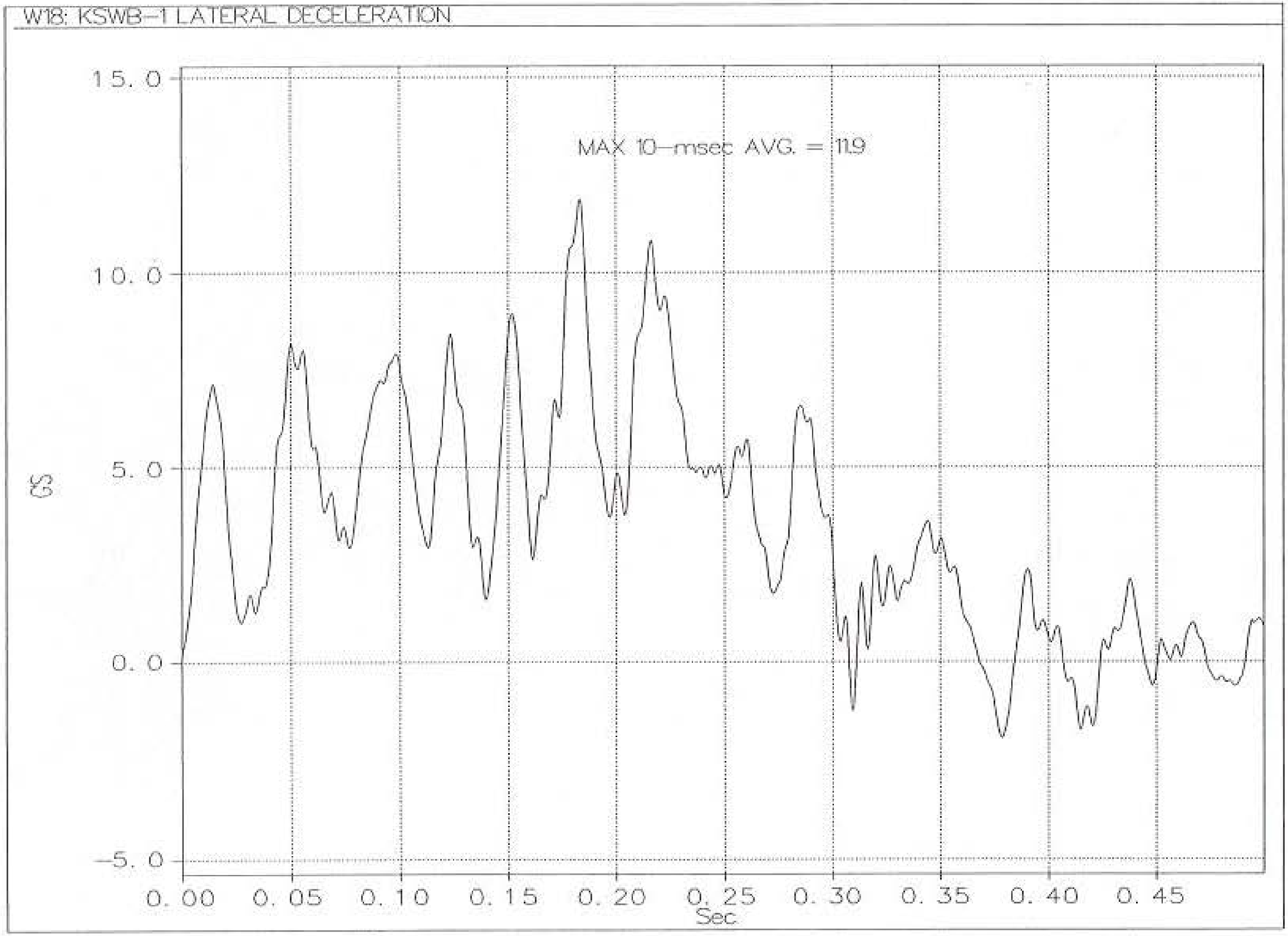


Figure B-3. Graph of KSWB-1 Lateral Deceleration

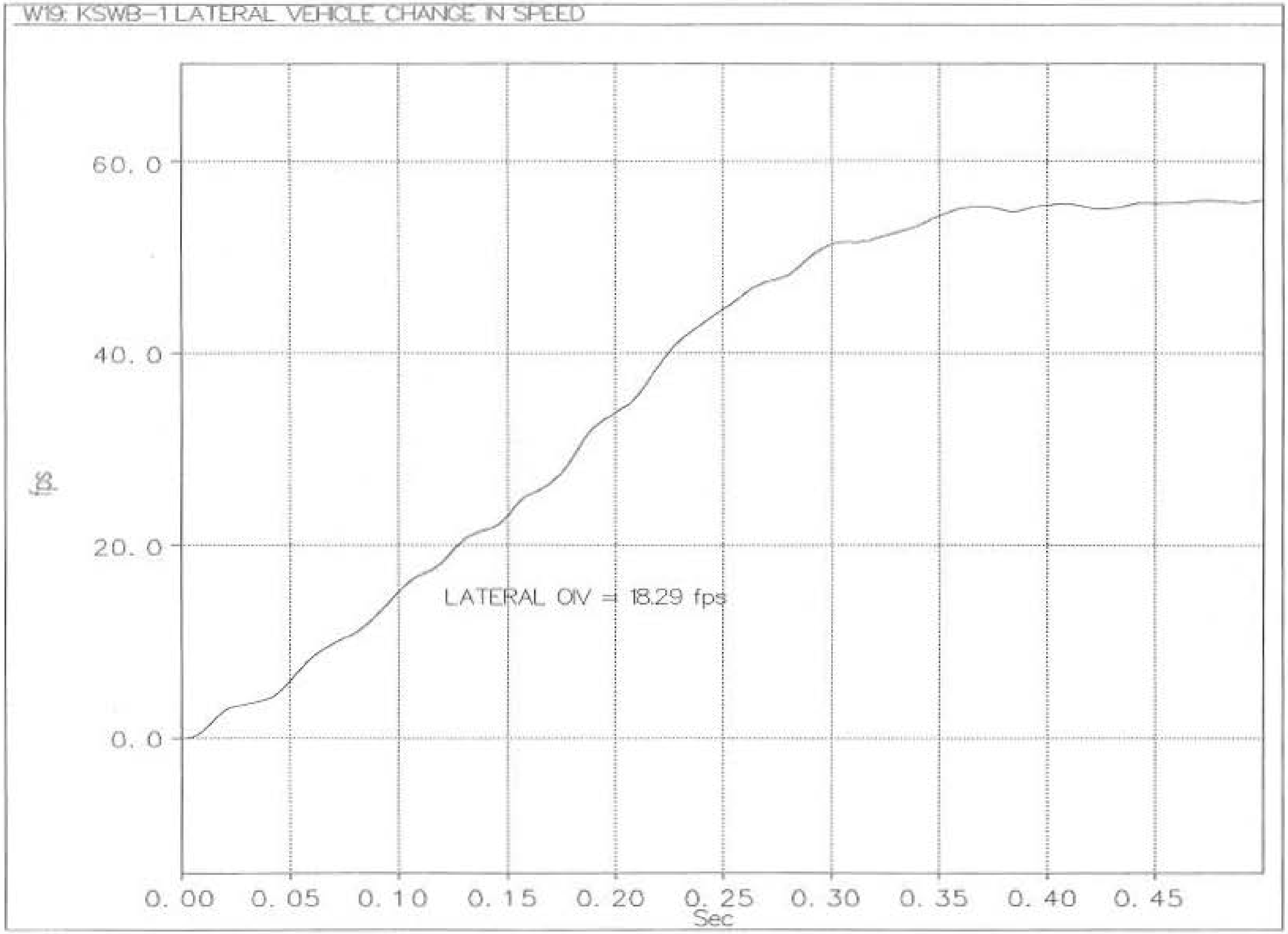


Figure B-4. Graph of KSWB-1 Lateral Vehicle Change in Speed

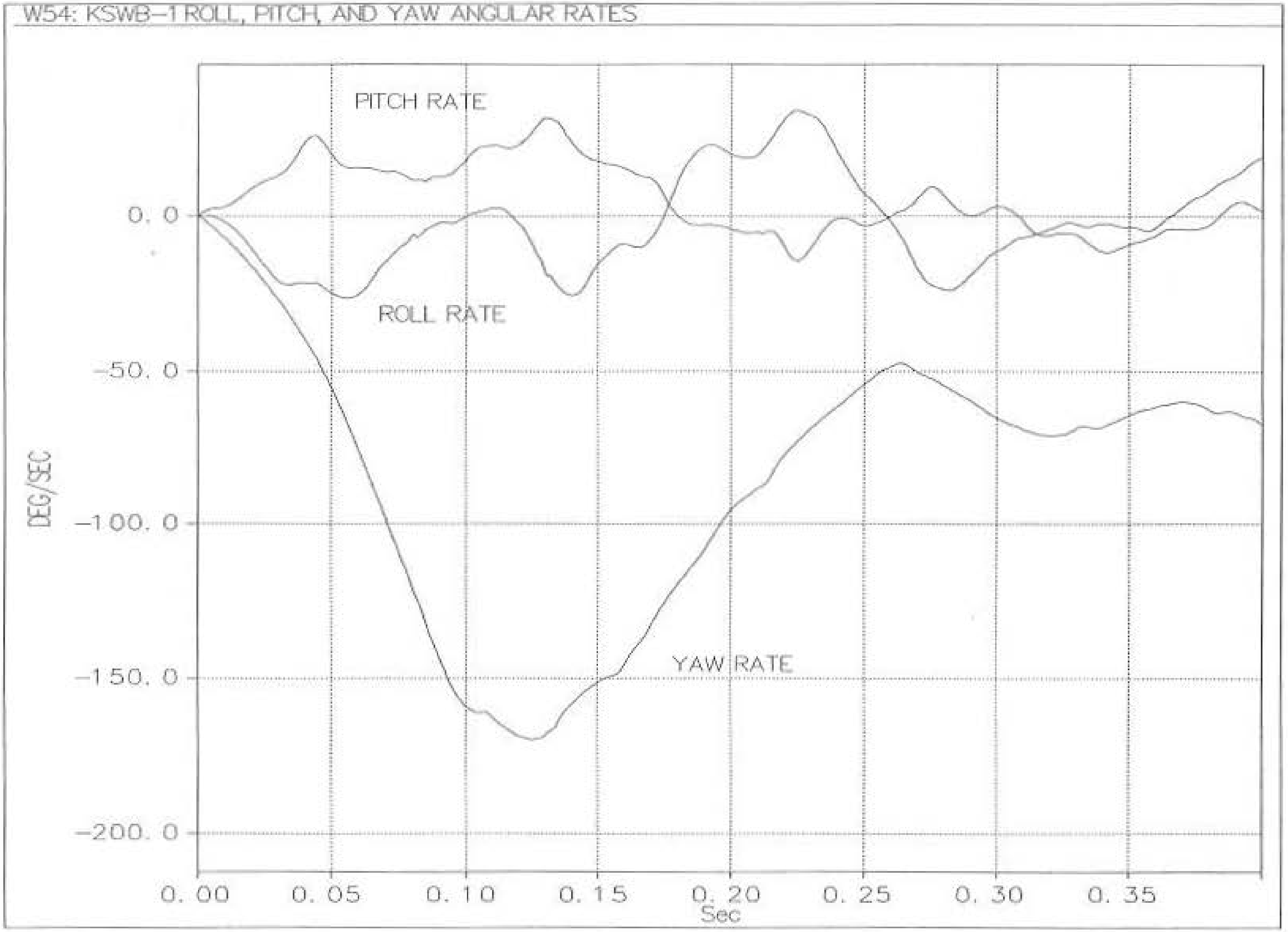


Figure B-5. Graph of KSWB-1 Roll, Pitch, and Yaw Angular Rates

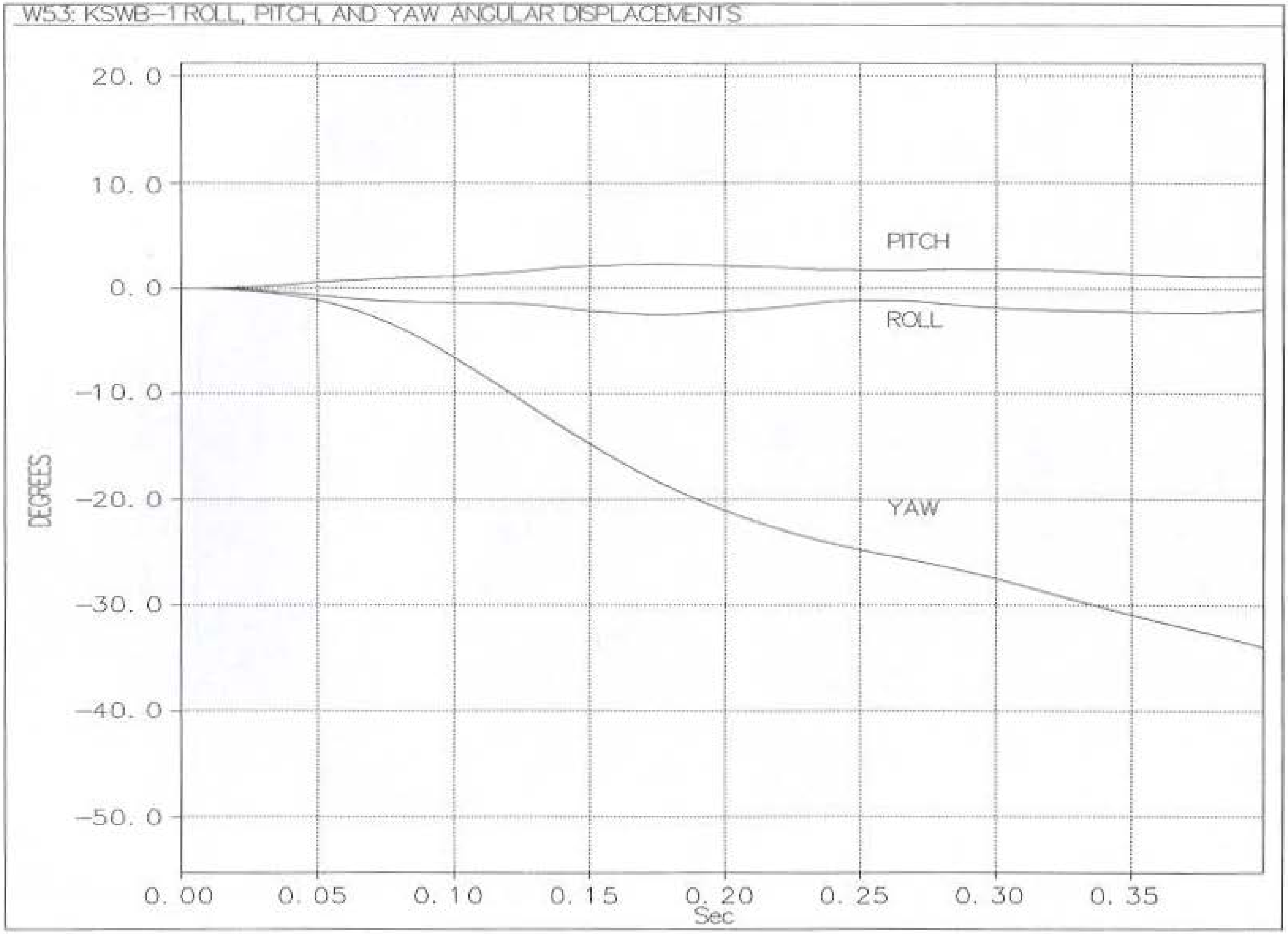


Figure B-6. Graph of KSWB-1 Roll, Pitch, and Yaw Angular Displacements

Appendix C

KSWB-2 Data Analysis

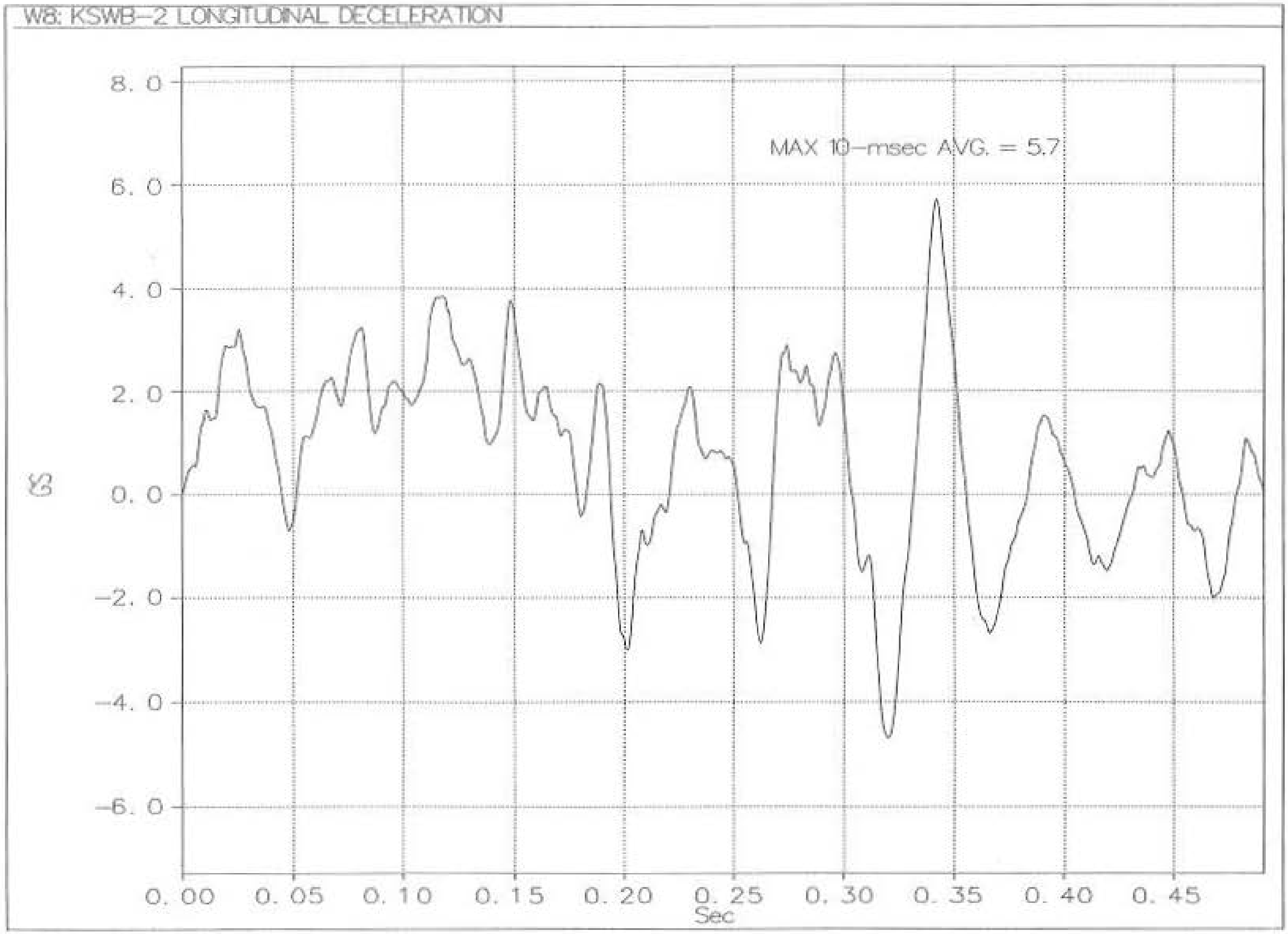


Figure C-1. Graph of KSWB-2 Longitudinal Deceleration

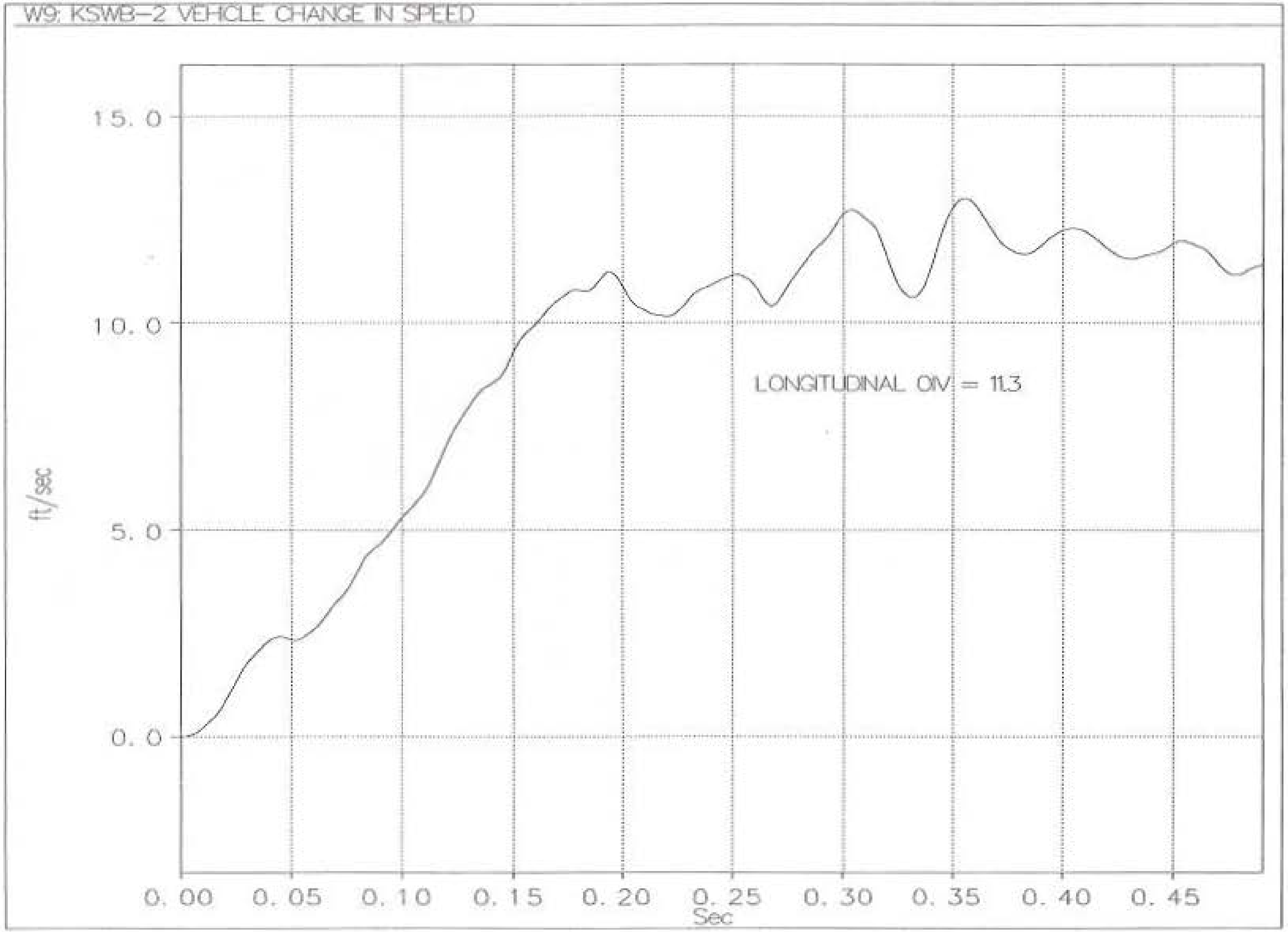


Figure C-2. Graph of KSWB-2 Vehicle Change in Speed

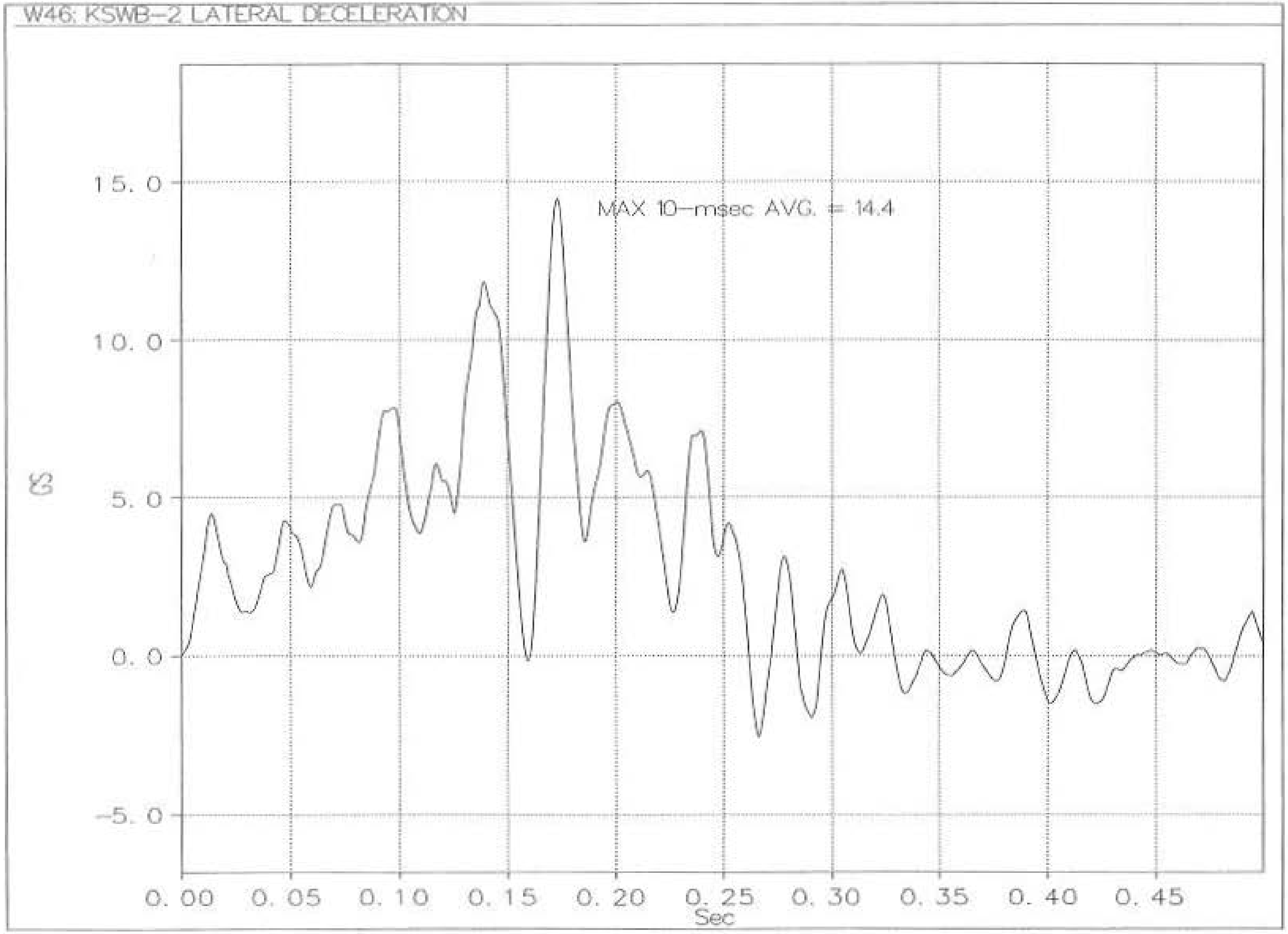


Figure C-3. Graph of KSWB-2 Lateral Deceleration

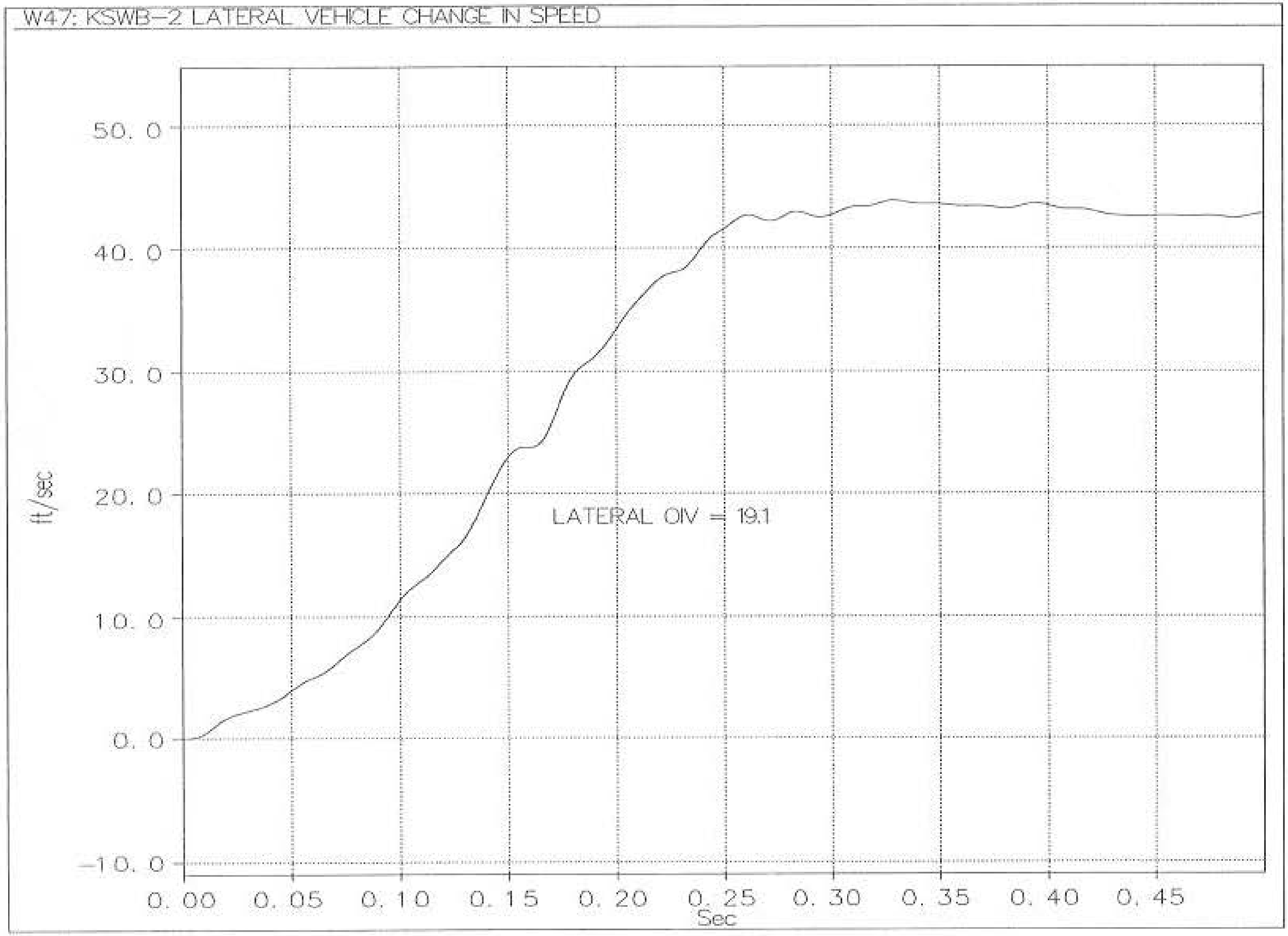


Figure C-4. Graph of KSWB-2 Lateral Vehicle Change in Speed

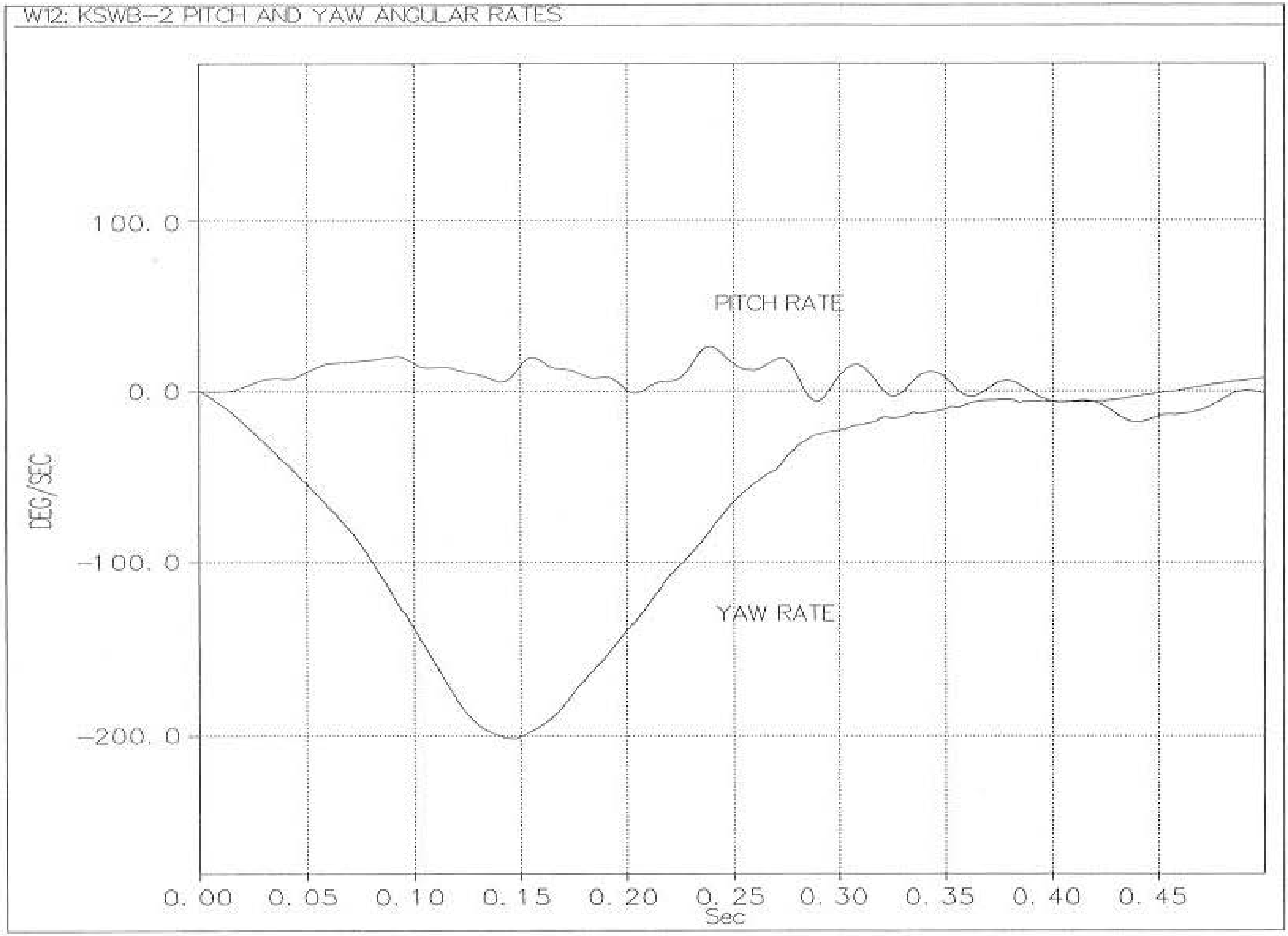


Figure C-5. Graph of KSWB-2 Pitch and Yaw Angular Rates

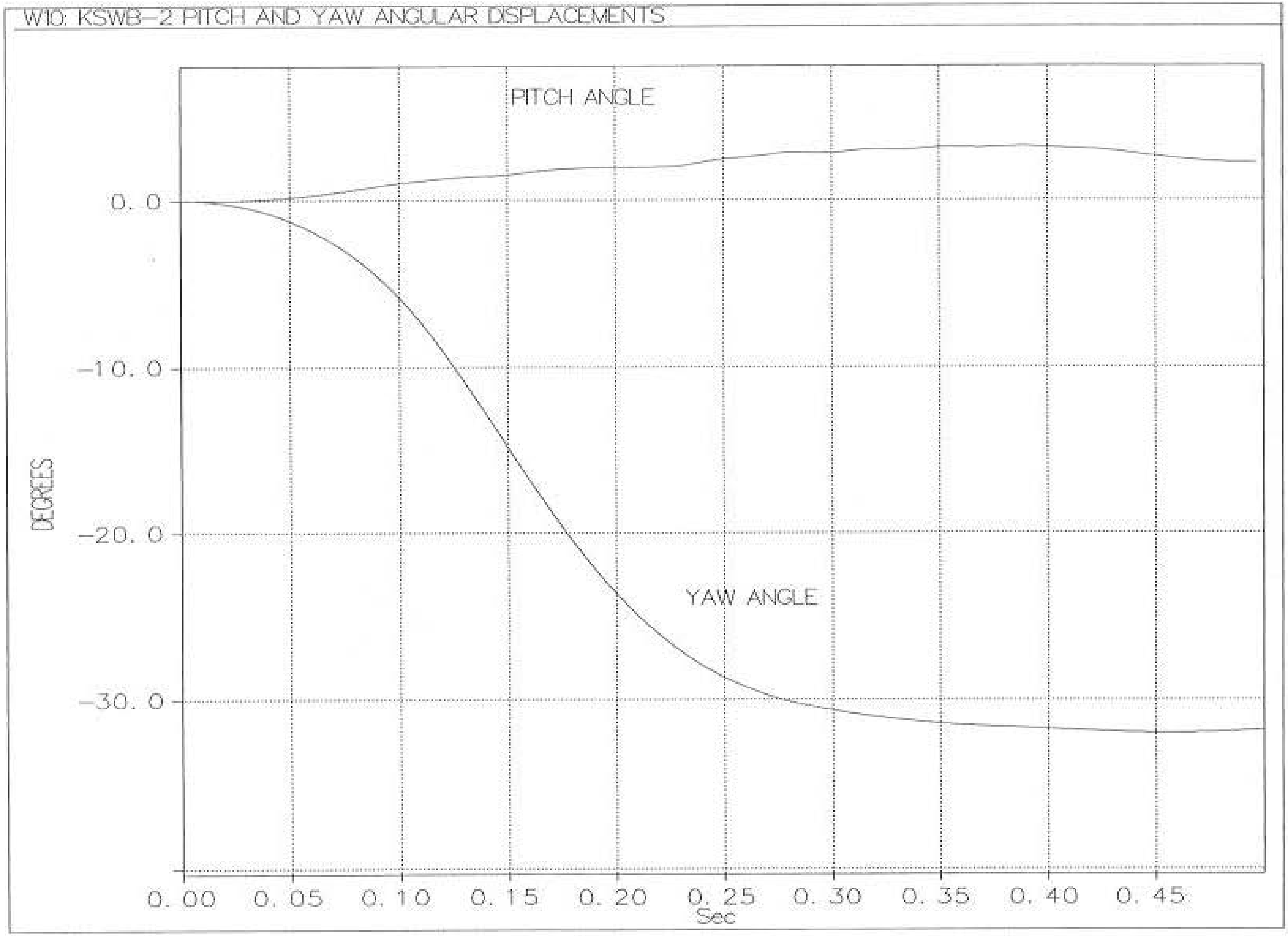


Figure C-6. Graph of KSWB-2 Pitch and Yaw Angular Displacements

Appendix D

KSWB-3 Data Analysis

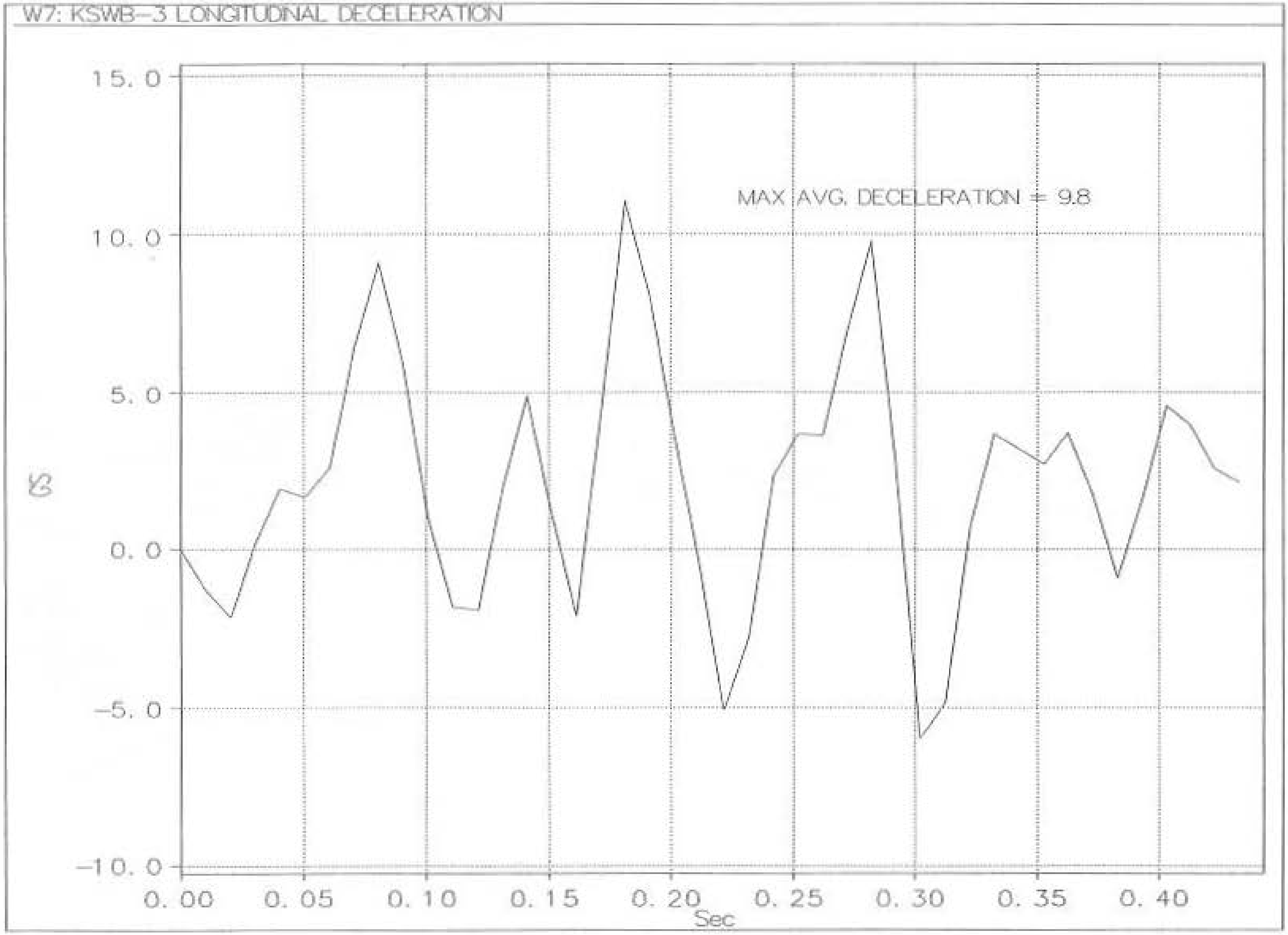


Figure D-1. Graph of KSWB-3 Longitudinal Deceleration

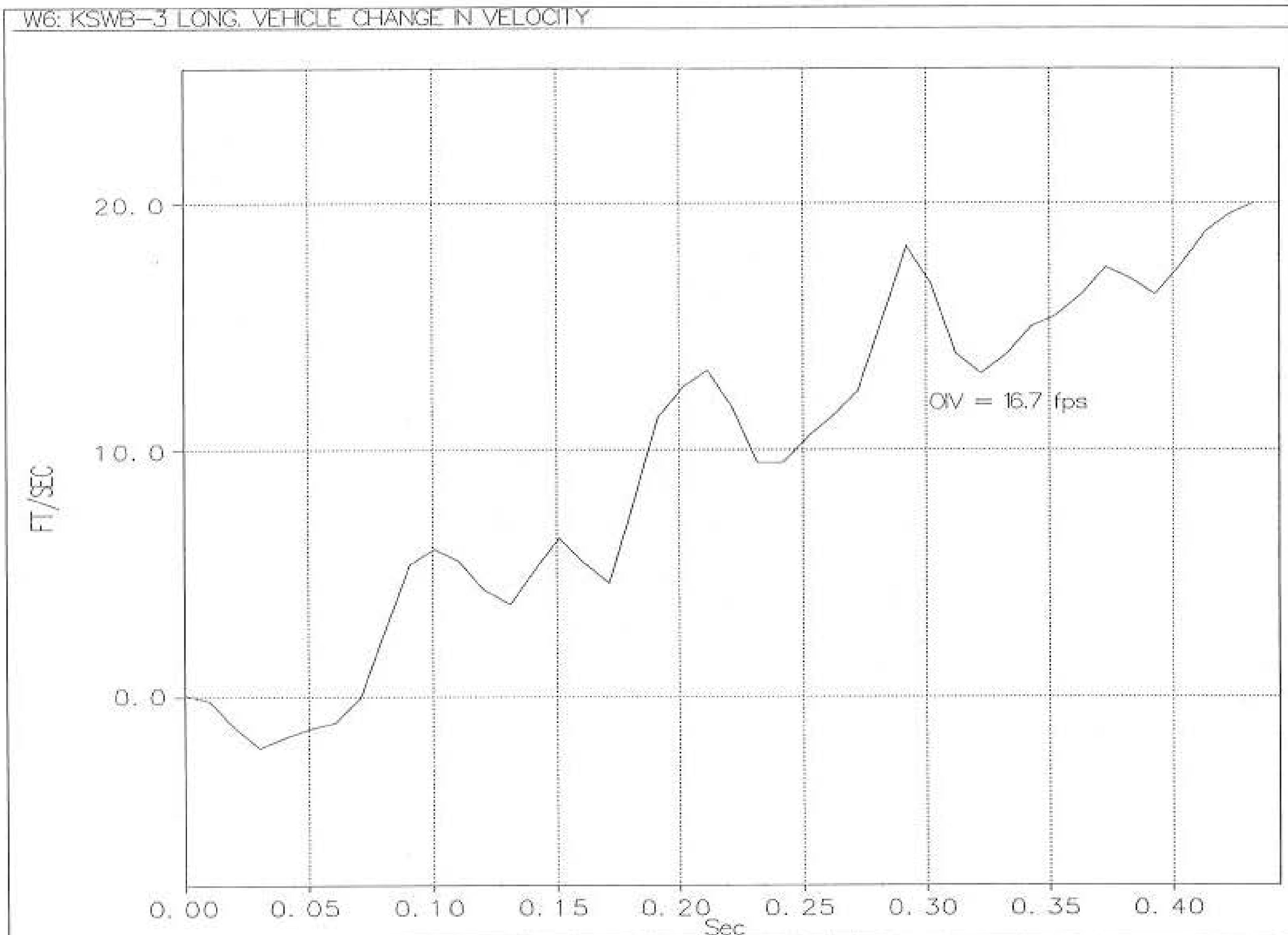


Figure D-2. Graph of KSWB-3 Longitudinal Vehicle Change in Velocity

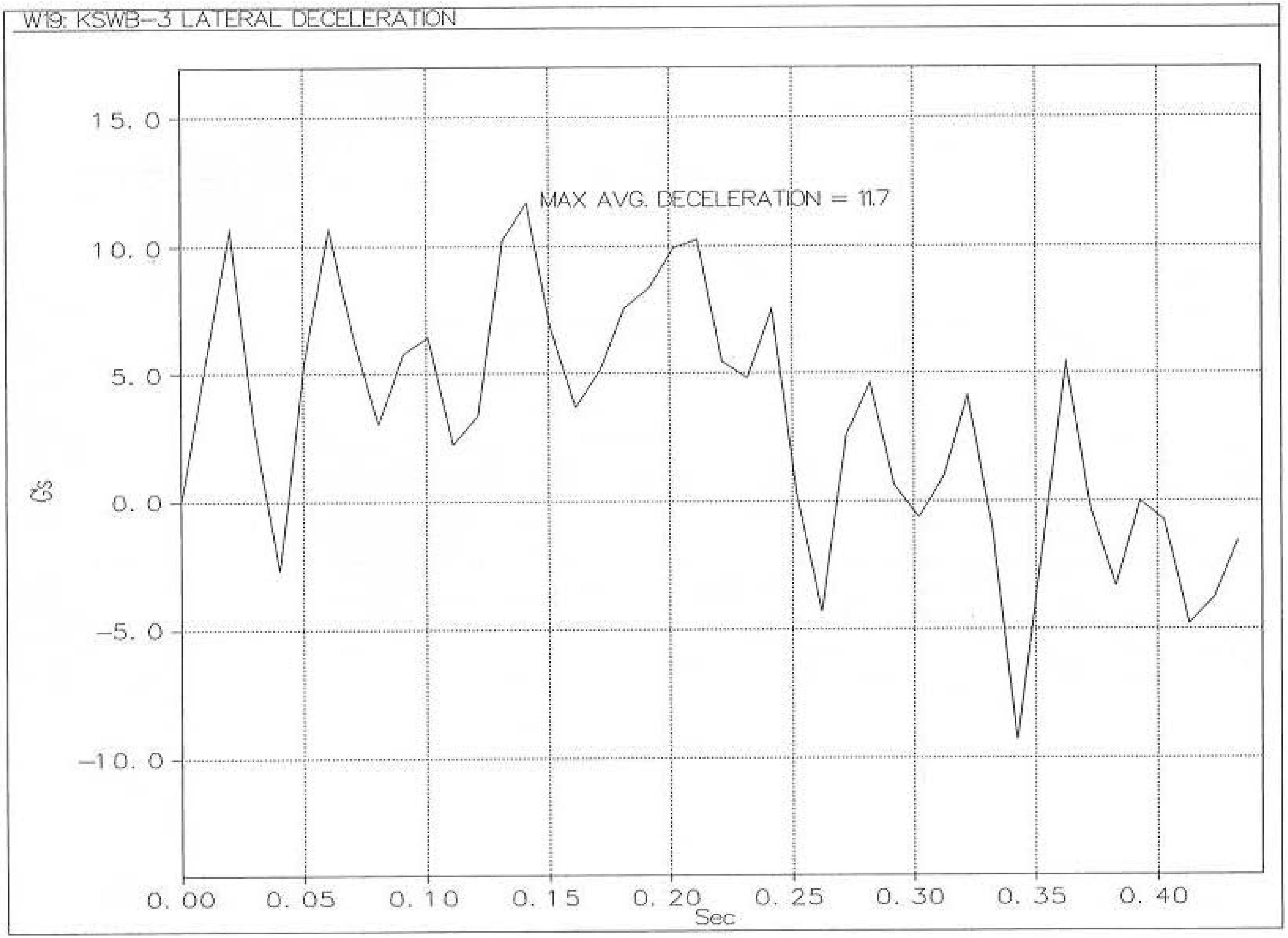


Figure D-3. Graph of KSWB-3 Lateral Deceleration

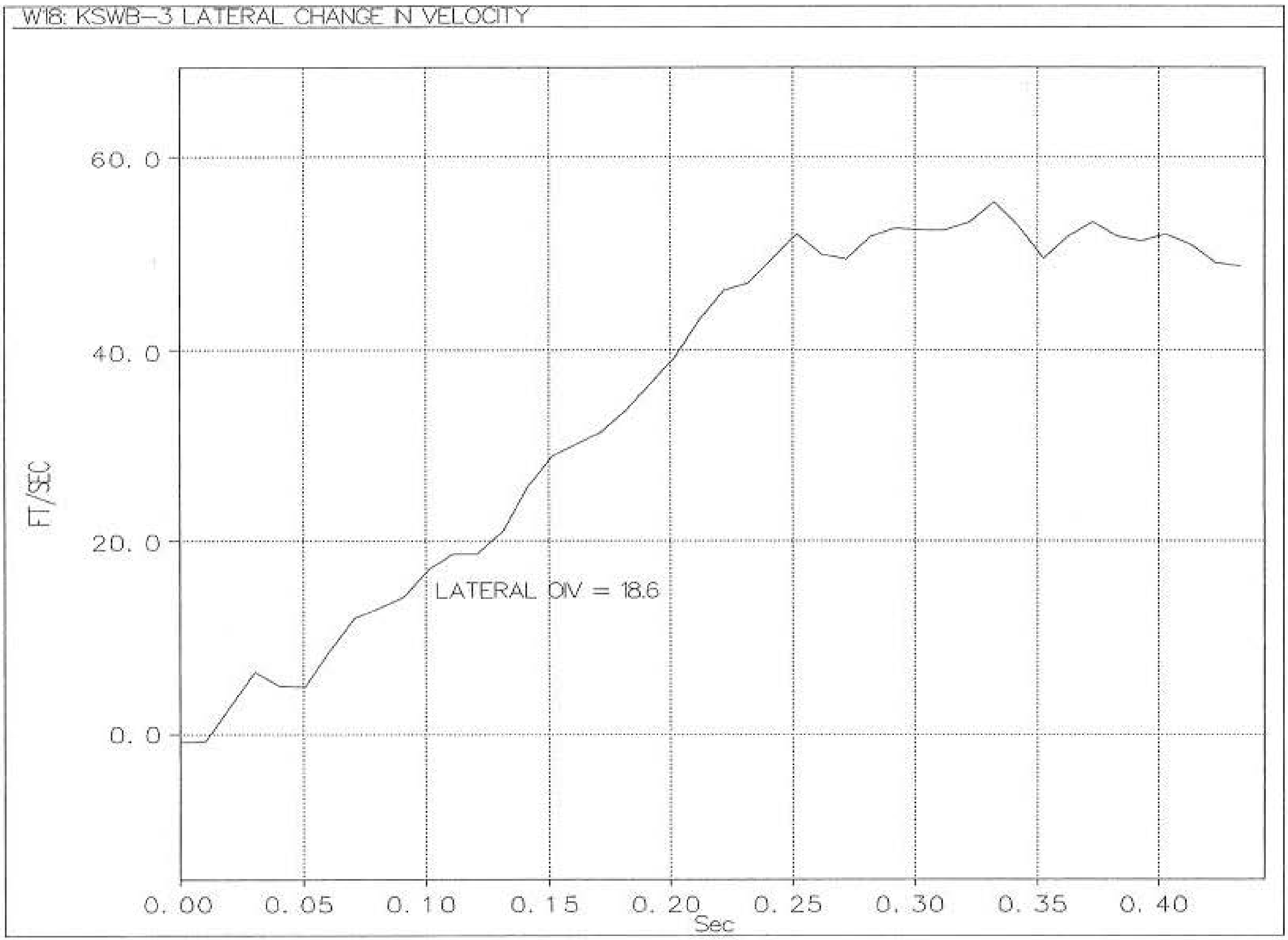


Figure D-4. Graph of KSWB-3 Lateral Change in Velocity

Appendix E

KSWB-4 Data Analysis

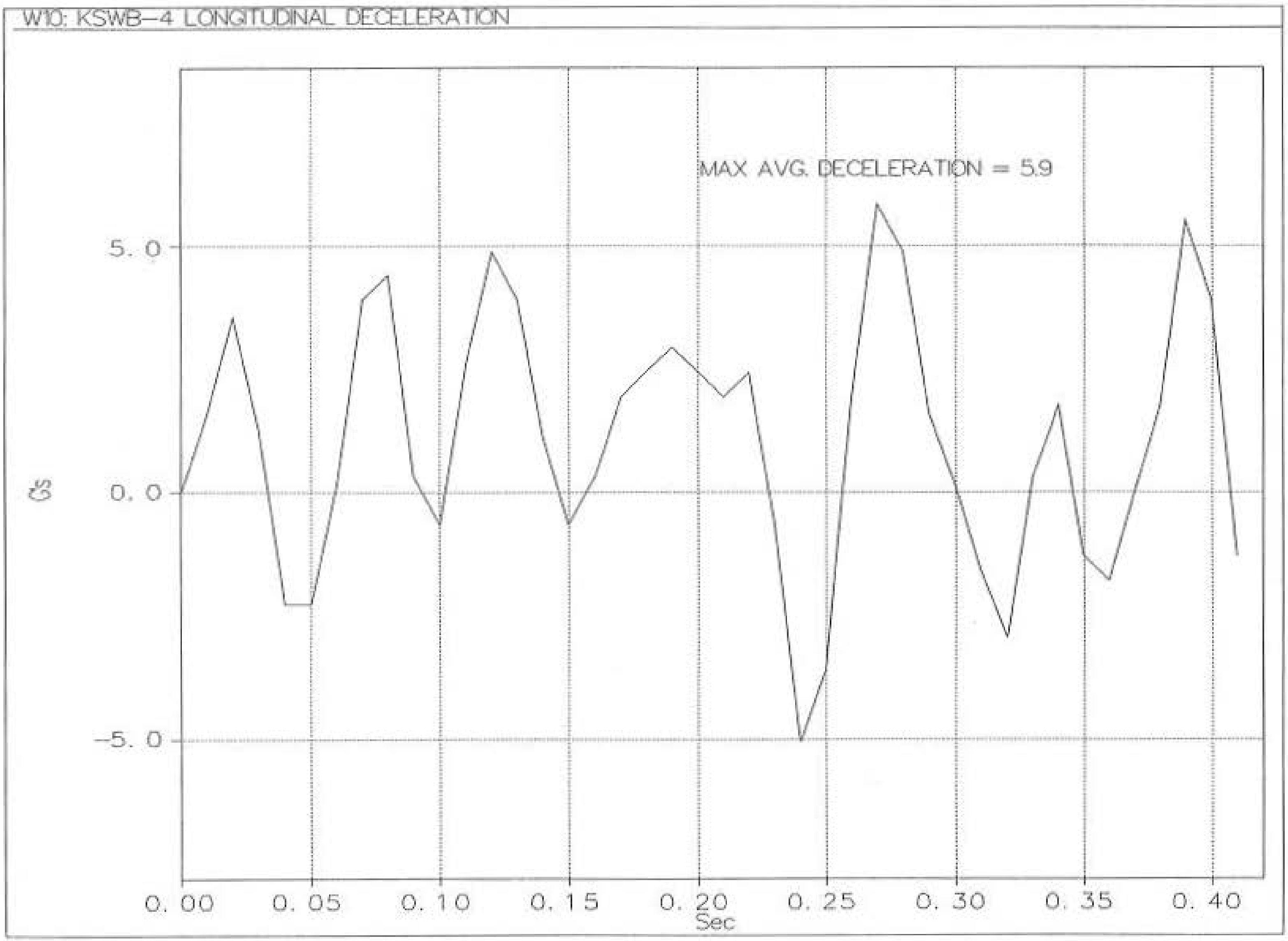


Figure E-1. Graph of KSWB-4 Longitudinal Deceleration

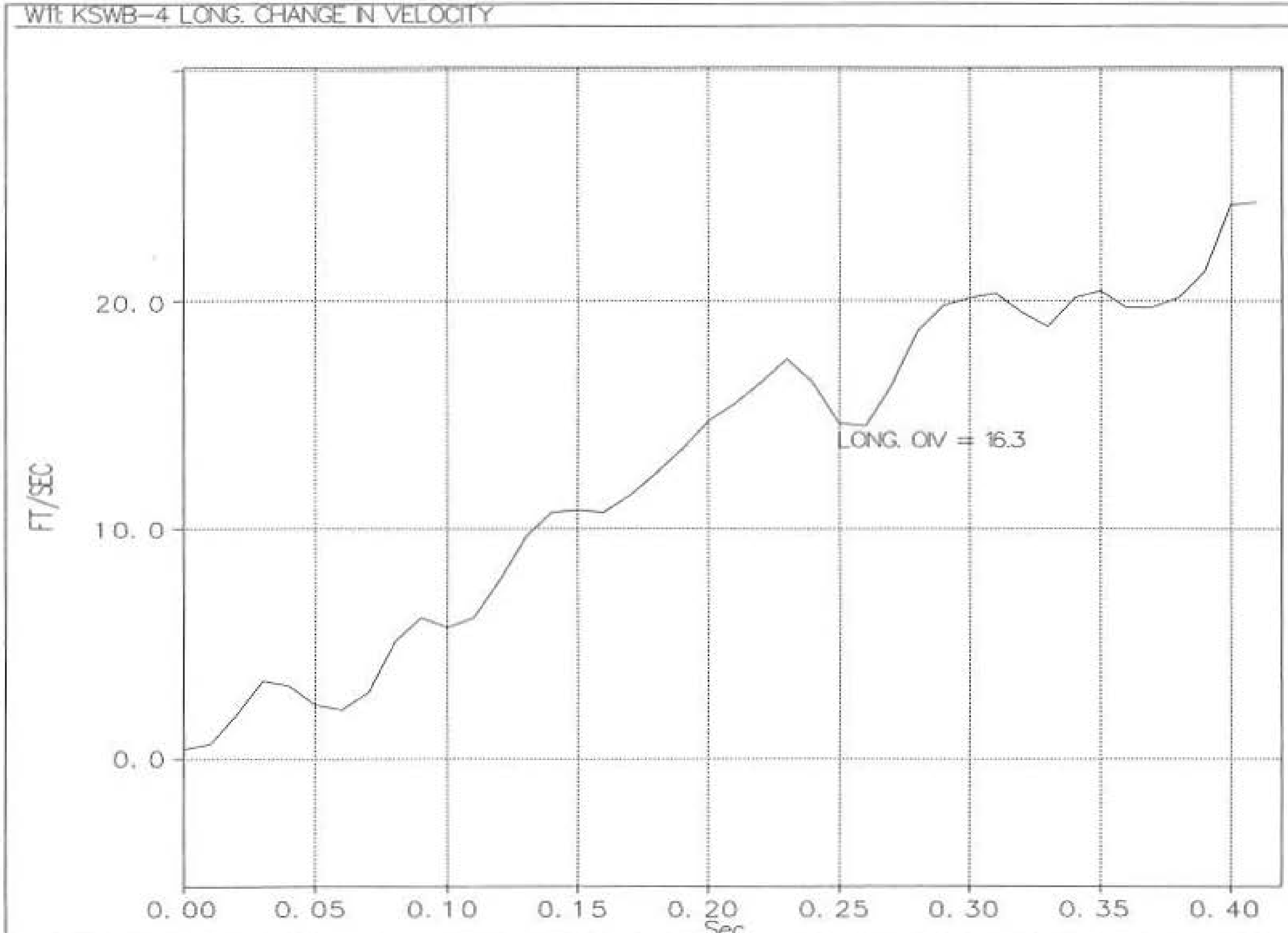


Figure E-2. Graph of KSWB-4 Longitudinal Change in Velocity

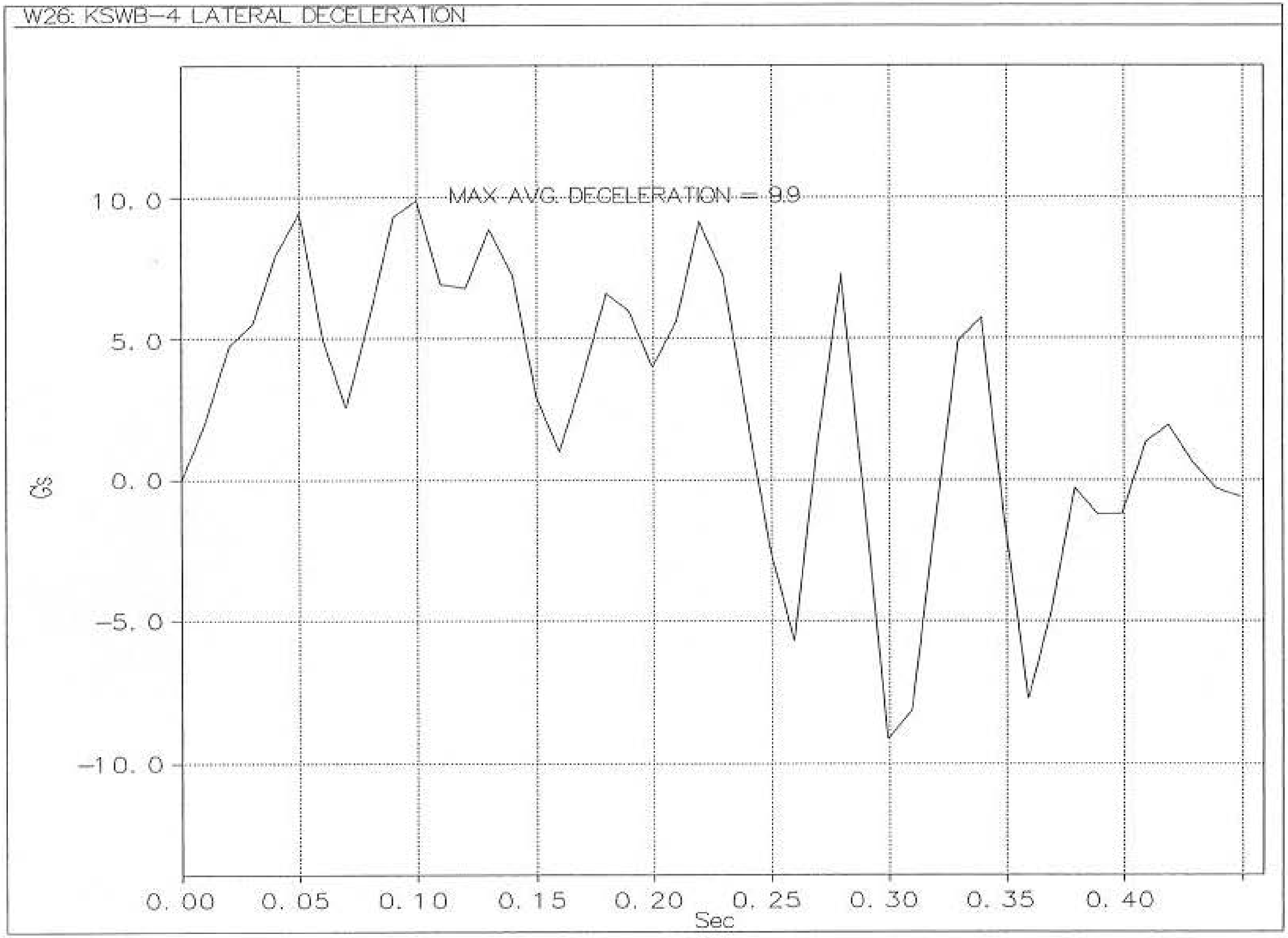


Figure E-3. Graph of KSWB-4 Lateral Deceleration

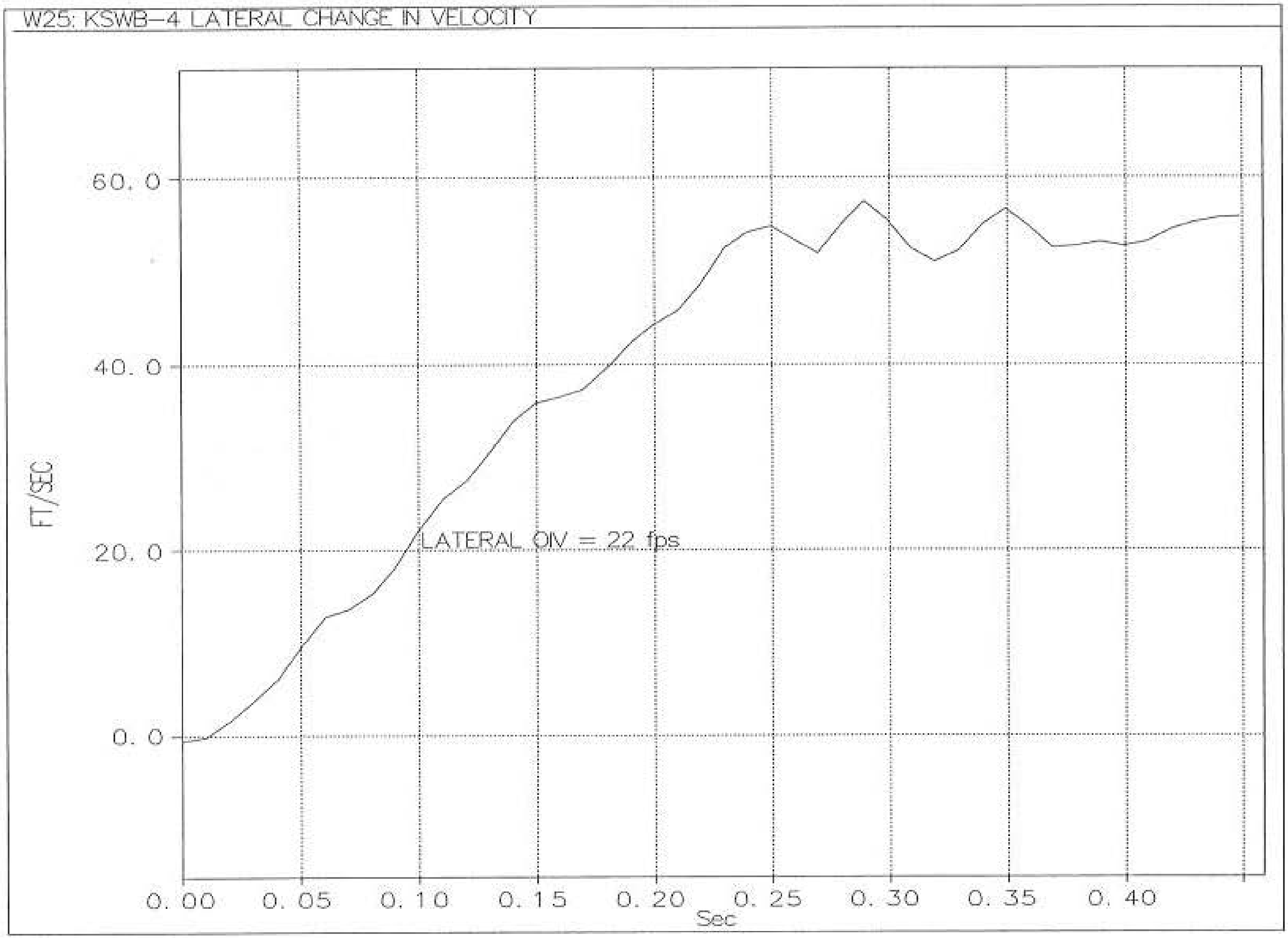


Figure E-4. Graph of KSWB-4 Lateral Change in Velocity