DYNAMIC IMPACT TESTING OF GUARDRAIL POSTS EMBEDDED IN SOIL

Submitted by

Brian A. Coon, B.S.M.E., E.I.T.
Graduate Research Assistant

John D. Reid, Ph.D.
Assistant Professor

John R. Rohde, Ph.D., P.E.
Associate Professor

MIDWEST ROADSIDE SAFETY FACILITY
University of Nebraska-Lincoln
1901 "Y" Street, Building "C"
Lincoln, Nebraska 68588-0601
(402) 472-6864

Submitted to

FEDERAL HIGHWAY ADMINISTRATION
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16. Abstract (Limit: 200 words)

Dynamic properties of steel and wooden guardrail posts rotating in AASHTO M 147-65 Gradation "B" specifications were obtained and documented (NCHRP Report 350 Strong Soil). The steel and wooden posts were impacted with a bogie vehicle at 5.5, 8.9, and 13.4 m/s (12.3, 20, and 30 mph). Devices used to collect data consisted of an accelerometer on the bogie vehicle, strain gauges, S-VHS video, and high speed photography. W150x13.5 (W6x9) posts were initially used for testing, later W150x23.5 (W6x16) posts were used to prevent post deformations and to ensure only soil failure behavior. 150x200mm (6x8 in.) Southern Yellow Pine posts of DS-65 grading were used for wooden post tests.

Dynamic effects were observed between the 5.5 and 8.9 m/s (12.3 and 20 mph) steel post tests. There were no measurable differences between the 5.9 and 13.4 m/s (20 and 30 mph) steel post tests.

No dynamic effects for wooden posts were obtained due to wooden post fractures that occurred at higher velocities. A significant decrease in energy absorption was observed when a wooden posts fracture instead of rotating in soil.

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This report replaces the draft report of October 14, 1998, entitled "Dynamic Impact Testing of Guardrail Posts Embedded in Soil Phase I: Wide Flange Steel Posts."

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Midwest Roadside Safety Facility

D.L. Sicking, Ph.D., P.E., MwRSF Director and Associate Professor
R.K. Faller, Ph.D., P.E., Research Assistant Professor
J.E. Herr, Graduate Research Assistant
J.C. Holloway, M.S.C.E., E.I.T., Research Associate Engineer
M.L. Hanau, Laboratory Mechanic I
E.A. Keller, B.S.M.E., E.I.T., Research Associate Engineer
K.L. Krenk, B.S.M.A. Field Operations Manager
Undergraduate and Graduate Assistants

Federal Highway Administration

Martin Hargrave, COTR, Turner-Fairbank Highway Research Center

TABLE OF CONTENTS

Page

List of Figures

List of Tables

1 INTRODUCTION

1.1 Background

The behavior of a guardrail system during an impact is a very complex event, requiring extensive analysis. One important aspect of this event is the post-soil interaction. The dynamic properties of this interaction are of great theoretical and practical importance in understanding how posts behave in soil. This understanding is also critical in determining parameters for computer simulation modeling.

The failure mode for a guardrail post drastically affects performance. Post rotation, fracture of the post, bending of the post, twisting of the post, or a combination of failure modes radically affect how much energy is absorbed by a post in a guardrail system. If the post is not allowed to rotate sufficiently and fractures or yields soon after impact, the force levels may be lower than what is commonly observed in full-scale vehicle crash tests on guardrail systems using strong posts embedded in soil (1). Because the interaction between the soil and guardrail posts is so important, it is necessary to conduct bogie testing to better quantify these parameters.

1.2 Objectives

The purpose of this study was to gather data for documenting the post-soil interaction of guardrail posts rotating in soil. The behavior of steel and wooden posts in both frontal impacts and frontal offset impacts are to be examined. Wide-flanged steel posts and wooden posts were tested to determine the dynamic properties of the post-soil interaction. Those results are included in this report.

2 LITERATURE REVIEW

2.1 Prior Post Testing Studies

Due to the complexity of post-soil interaction, much effort has been devoted to the behavior of posts under lateral load. Many different aspects of the post and soil interaction have been studied in prior research projects (1). In 1961, General Motors studied the performance characteristics of various materials and found that reinforced concrete is undesirable for guardrail posts (2). However, wooden and steel posts were found to be acceptable for strong and weak post designs.

In 1967, the New York State Department of Public Works (3) found that the behavior of guardrail posts directly affects the performance of guardrails. This was determined using the results of dynamic post test results. They also found that a 20.3-cm wide by 61.0-cm high (8-in. wide by 24-in. high) steel plate attached to the posts was adequate at replacing a more expensive concrete footing.

In 1970, the Southwest Research Institute (4) conducted a study of the post-soil interaction behavior of guardrail posts. A total of 72 tests were conducted. Both dynamic and static tests were completed using two types of soils, four embedment depths, and three different types of posts. The study found that the dynamic response of the post and the energy absorbed by the soil is directly related to the shear strength of non-cohesive soils, embedment depth, and post width. Also, the study found that the dynamic response of guardrail posts was greater than what was indicated by static tests. Results also showed that the performance of a highway guardrail system is clearly affected by the post-soil characteristics of the system.

Michie et al. (5) conducted pendulum tests to experimentally determine the performance properties of guardrail posts under impact loads. Steel and wooden posts were also tested for comparison. The posts were secured to a rigid fixture to test the post strength and not the more complex post-soil composite properties. The post dynamic peak force, average force and fracture energy were found to vary directly with the moment of inertia. Presented in Table 1 is a summary of the results obtained from the study.

Table 1. Michie Post Test Results.

Post Material	Dimensions or Specifications cm (in.)	Average Force kN (kips)	Deflection cm (in.)
Douglas Fir	20.3 x 20.3 (8 x 8)	40.39 (9.08)	29.7 (11.7)
Douglas Fir	15.2 x 20.3 (6 x 8)	30.43 (6.84)	24.9 (9.8)
Douglas Fir	10.2 x 15.2 (4 x 6)	13.34 (3.00)	23.1 (9.1)
Douglas Fir	10.2 x 10.2 (4 x 4)	7.92 (1.78)	22.6 (8.9)
Steel	152B12.8 (6B8.5)	32.92 (7.40)	24.6 (9.7)
Steel	762I8.6 (3I5.7)	15.92 (3.58)	30.5 (12.0)

In 1974, a series of pendulum tests was performed by Gatchell (6) to evaluate the dynamic performance of wooden guardrail posts. The major finding was that specifications for wooden guardrail posts based on grades or stress ratings can be eliminated. Wooden guardrail post specifications should be based on the amount of knot-associated grain distortion in the middle third of the tension face. Such knot-associated grain distortion should not exceed one-third the width of the tension face.

A series of 102 pendulum tests on two typical guardrail posts installed in five different soil types was performed by Calcote, et al. (7-8) of the Southwest Research Institute (SwRI) in 1978. The purpose of the tests was to determine post property variations as a function of soil conditions. The results were then used as post parameters in the BARRIER VII computer program to estimate the ultimate effect soil conditions have on guardrail performance. It was concluded that guardrail failure could be expected for severe impacts on short installations, less than 45.7 m (150 ft), with poor soil conditions and that guardrails of this length or shorter should not be used unless precautions are taken to ensure the integrity of each post, particularly if the available space behind the barrier is limited. It was felt that embedding the post in a concrete footing or lengthening the embedment depth in the soil could provide the necessary integrity of the posts. The parameters developed as a result of this study are shown in Table 2.

Table 2. Calcote Post Test Results.

		Soil and Post Type									
		Fixed Support		Base Material		Stiff Clay		Sat Clay		Sandy Loam	
Parameter		Steel	Wood	Steel	Wood	Steel	Wood	Steel	Wood	Steel	Wood
Stiffness Strong Axis, KA	kN/m (k/in.)	178.6 (1.02)	623.5 (3.56)	201.4 (1.15)	341.5 (1.95)	106.8 (0.61)	206.6 (1.18)	129.6 (0.74)	245.2 (1.40)	136.6 (0.78)	274.9 (1.57)
Stiffness Weak Axis, KB	kN/m (k/in.)	691.8 (3.95)	796.8 (4.55)	430.8 (2.46)	273.2 (1.56)	203.1 (1.16)	248.7 (1.42)	197.9 (1.13)	213.7 (1.22)	339.7 (1.94)	224.2 (1.28)
Base Yield Moment Strong Axis, MB	kN*m (k*in.)	39.89 (353)	38.40 (340)	26.10 (231)	19.50 (173)	14.20 (126)	12.30 (109)	8.10 (71.7)	8.30 (73.5)	15.70 (139)	12.10 (107)
Base Yield Moment Weak Axis, MA	kN*m (k*in.)	12.09 (107)	28.02 (248)	10.09 (96.5)	21.81 (193)	8.10 (71.7)	11.64 (103)	6.39 (56.6)	8.80 (77.9)	8.30 (73.5)	13.56 (120)
Shear Force Strong Axis, FA	kN (kips)	476 (5.10)	1103 (11.8)	429 (4.61)	859 (9.19)	319 (3.39)	458 (4.90)	252 (2.70)	347 (3.71)	327 (3.51)	534 (5.71)
Shear Force Weak Axis, FB	kN (kips)	74.3 (16.7)	72.1 (16.2)	48.9 (11.0)	36.5 (8.21)	26.7 (6.00)	23.1 (5.19)	15.1 (3.39)	15.6 (3.51)	29.4 (6.61)	22.7 (5.10)
Max. Deflection Strong Axis, DA	cm (in.)	12.6 (4.96)	8.4 (3.31)	10.1 (3.98)	12.0 (4.72)	14.1 (5.55)	10.6 (4.17)	9.3 (3.66)	6.7 (2.64)	11.4 (4.49)	9.2 (3.62)
Max. Deflection Weak Axis, DB	cm (in.)	10.8 (4.25)	9.0 (3.54)	11.4 (4.49)	13.4 (5.28)	13.1 (5.16)	9.3 (3.66)	7.6 (2.99)	7.3 (2.87)	8.6 (3.39)	10.1 (3.98)

In 1983, Jeyapalan et al. (9) of the Texas Transportation Institute (TTI) conducted a limited study of the post-soil interaction to determine the relationship between laterally applied loads and the rotational displacements of steel and wooden guardrail posts in dry soils. Because the Texas State Department of Highways and Public Transportation at the time required steel posts to be placed in concrete footings that were not required for wooden posts, steel post guardrail systems were not considered to be as economical as the wooden post guardrail systems.

The load-displacement relationship was idealized as elastic-plastic with complete failure occurring at a post deflection of 50.8 cm (20 in.). Series of both static and dynamic tests were conducted to verify the performance capabilities of the posts.

The Jeyapalan tests indicated that the steel guardrail post, embedded without the concrete footing that was required by specifications at the time, performed similarly to the wooden post for cohesive soil. The results of the dynamic testing program are presented in Table 3.

Table 3. Jeyapalan Post Test Results.

Test No.	Post Material	Soil Conditions	Impact Velocity m/s (fps)	Maximum Force kN (kips)	Force at 18 in. Movement kN (kips)	Total Energy Absorbed kJ (ft-kips)
C1	Wooden	Non-cohesive	8.1 (26.6)	59.2 (13.3)	N/A	1.76 (1.3)
C2	Steel	Non-cohesive	8.0 (26.1)	99.6 (22.4)	99.6 (22.4)	39.59 (29.2)
C3	Wooden	Cohesive	6.9 (22.7)	72.5 (16.3)	85.4 (19.2)	36.88 (27.2)
C4	Steel	Cohesive	7.3 (24.1)	76.1 (17.1)	76.1 (17.1)	40.54 (29.9)

In 1984, Eggers et al. (10) studied the effects of soil and concrete as backfill for wooden guardrail posts embedded in rock. When located in rocky terrain, the Texas State Department of Highways and Public Transportation required wooden posts to be placed in drilled holes in the rock and backfilled with soil or concrete as required by the engineer. If concrete was required, the guardrail system became more expensive. Static load tests were performed on posts to determine the effects of the backfill material on load-deflection and energy absorption characteristics of the post. The study found that wooden guardrail posts using soil for the backfill material absorb more energy than if concrete is used for the fill material, however, the maximum lateral load capacity is much higher using concrete as the fill material.

Eggers also found that, overall, the posts behaved satisfactorily whether backfilled with clay, sand, weathered limestone, or concrete. Non-cohesive materials were recommended as backfill materials due to the ease of placing and compaction.

In 1985, Bedewi (11) conducted a series of pendulum tests to verify a simplified elastic-viscoplastic lumped parameter model for the analysis of guardrail posts in soil subjected to three-dimensional applied loads. Results from the post tests compared favorably with the results of the computer program developed.

TTI conducted static load post tests (12) in 1986 to study the effect of embedment depth, soil properties, and post type on the load-deformation characteristics of guardrail posts. The study found that a successful guardrail can be designed using more posts when full embedment is not possible. Posts with only 45.72 or 60.96-cm (18 or 24-in.) embedment could be used at 95.25 cm (37.5 in.) spacing and still produce the required strength.

In 1988 Bronstad, et al. (13) conducted twelve pendulum tests on wooden and steel posts. Bronstad's findings were different from the results of previous research conducted by Calcote (8). Bronstad concluded that the posts maintained significant reserve strength after the maximum load was reached when strong posts yield the soil. Bronstad used BARRIER VII computer simulations for guidance in selecting test conditions for the various transition configurations. For systems using larger posts, pendulum tests were conducted to determine post properties for BARRIER VII input. Results from testing indicated that the 45.7 x 61.0-cm (18 x 24-in.) soil paddle used on W150 x 23.3 (W6 x 15.5) posts apparently has little effect on the stiffness or maximum force, and a W150 x 23.3 (W6 x 15.5) post is only slightly less stiff than a 25.4 x 25.4-cm (10 x 10-in.) wood post but yield a greater maximum force. The results of the post testing study are summarized in Table 4

In 1988, Ataullah (14) utilized BARRIER VII for analyzing Nebraska's bridge rail to guardrail transition designs. From the simulations, Ataullah calculated the post properties of the transition and found that guardrail posts in wet soil are not as stiff as they are in dry soil. The deflections of guardrail posts in wet soil were found to be considerably higher than that of guardrail posts in dry soil. The wet and dry soil parameters were calculated by multiplying the experimentally collected data by a factor of 0.75 and 0.50, respectively. Although the parameters were not obtained directly and were altered in order to be used in the simulation, the effect of moisture content on the performance of a guardrail system was evident and found to be significant. It was also found that for smooth redirection of vehicles, the impact point needed to be farther downstream from the transition for the weaker wet soil.

In 1988, Stout et al. (15) conducted static and dynamic post tests, as well as full-scale tests for guardrail designs near foreslopes to determine the effects that embedment depth, slope, and distance to slope have on the guardrail behavior. It was found that 213-cm (7-ft) posts could develop full strength while 182.9-cm (6-ft) posts pushed away causing the soil to displace without the post bending. They concluded that on steeper slopes, 182.9-cm (6-ft) posts should be set farther in from the break point of the slope.

Table 4. Bronstad Post Test Results.

Post Material	Size cm (in.)	Axis	Maximum Force kN (kips)	Distance d_1 cm (in.)	Stiffness kN/m (kips/in.)	Distance d_2 cm (in.)	Remarks
Wood	30.5 x 30.5 (12 x 12)	N/A	99.20 (22.3)	16.61 (6.54)	597 (3.41)	43.56 (17.15)	Soil Yield
Wood	25.4 x 25.4 (10 x 10)	N/A	72.95 (16.4)	16.31 (6.42)	447 (2.55)	46.02 (18.12)	Soil Yield
Wood	20.3 x 20.3 (8 x 8)	N/A	55.16 (12.4)	18.90 (7.44)	292 (1.67)	50.98 (20.07)	Soil Yield
Wood	15.4 x 20.3 (6 x 8)	Weak	40.92 (9.2)	11.96 (4.71)	341 (1.95)	N/A	Post Fracture
Wood	15.4 x 20.3 (6 x 8)	Strong	36.48 (8.2)	13.36 (5.26)	273 (1.56)	39.29 (15.47)	Soil Yield
Steel	W150x23 (W6x15.5)	Strong with soil paddles	86.30 (19.4)	20.57 (8.10)	420 (2.40)	51.46 (20.26)	Soil Yield
Steel	W150x23 (W6x15.5)	Strong	81.40 (18.3)	20.42 (8.04)	399 (2.28)	54.86 (21.60)	Soil Yield
Steel	W150x23 (W6x15.5)	Weak	47.60 (10.7)	20.88 (8.22)	228 (1.30)	75.74 (29.82)	Post Yield
Steel	W150x12.6 (W6x8.5)	Weak	20.46 (4.6)	10.13 (3.99)	201 (1.15)	34.67 (13.65)	Post Yield
Steel	W150x12.6 (W6x8.5)	Strong	48.93 (11.0)	11.38 (4.48)	431 (2.46)	33.55 (13.21)	Soil Yield

In 1995, the effects of wood quality on W-beam guardrail performance were studied by Rohde et al (16). Due to inaccurate independent inspection, many of the guardrail posts installed by the Nebraska Department of Roads (NDOR) were below the DS-65 classification specified by the State. This specification provides a high factor of safety and is more stringent than required by Federal Guidelines. Researchers concluded that DS-65 posts were significantly stronger than lower graded posts. However, performance testing resulted in no significant difference in the strength or energy absorption between Grade 1 Southern Yellow Pine and Douglas Fir posts, the nationally recognized standard, and any of the lower grade posts that were currently installed in Nebraska at that time.

In 1996, Bierman et al. (1) validated the interpolation of stiffness and strength values from the force-deflection plots obtained from post tests. Twenty-one dynamic post tests were conducted with wooden and steel posts of 182.9-cm (6 ft) and 198.1-cm (6-½ ft) lengths.

3 SCOPE OF TESTING

3.1 Steel Post Test Matrix

The initial phase of the testing program gathered data for documenting the behavior of steel posts rotating in soil. Steel guardrail posts were embedded in soil material conforming to AASHTO M 147-65 Gradation "B" specifications (NCHRP Report 350 Strong Soil) and instrumented with strain gauges and string potentiometers. These posts were impacted with a bogie vehicle at 5.5, 8.9, and 13.4 m/s (12.3, 20, and 30 mph). The initial test matrix is shown in Table 5. The impacts were documented by accelerometers on the bogie vehicle and either high-speed photography or Super VHS video cameras.

Table 5. Initial Steel Post Frontal Impact Test Matrix.

Impact Velocity m/s (mph)	Post Type ASTM Designation	Soil Density kg/m^3 (pcf)	Embedment Depth m (in.)
5.5 (12.3)	W150x13.5 (W6x9)	2080 (130)	1.09 (43)
8.9 (20)	W150x13.5 (W6x9)	2080 (130)	1.09 (43)
13.4 (30)	W150x13.5 (W6x9)	2080 (130)	1.09 (43)

The impact type is that of the classical "head-on" or full frontal impact. The post is impacted 55 cm (21.6 in.) above the ground line perpendicular to the face of the post, as shown in Figure 1.

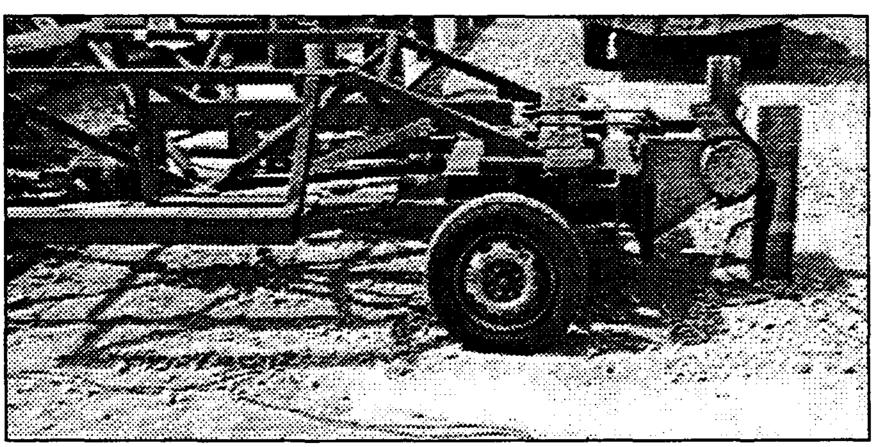


Figure 1. MwRSF Bogie Vehicle - Frontal Impact.

An offset impact was also performed using an angled bogie nose at 8.9 m/s (20 mph). The bogie head used to created the offset impact is shown in Figure 2.

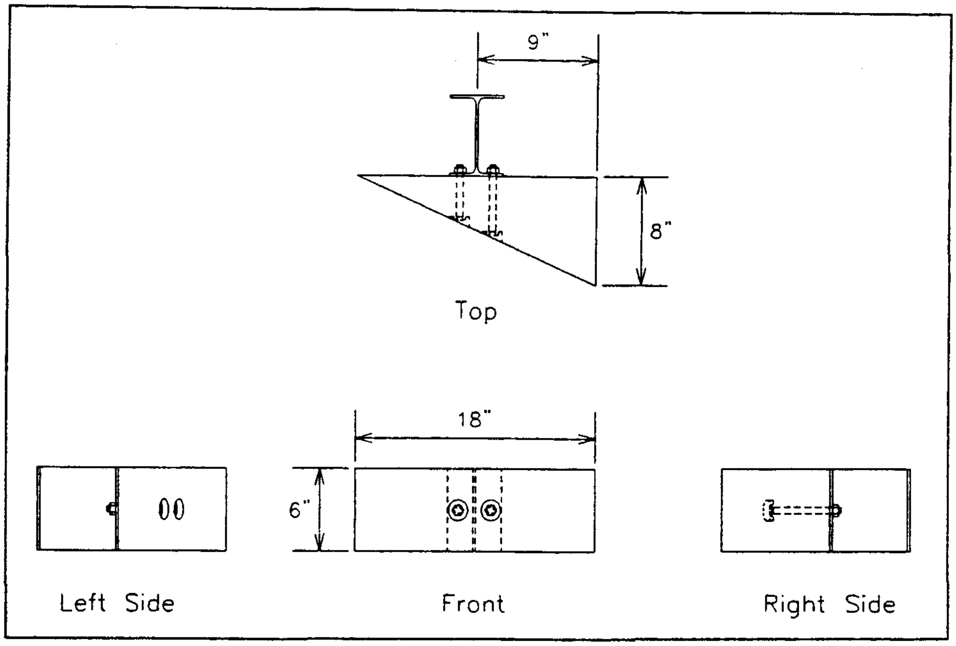


Figure 2. Offset Bogie Head

3.2 Wooden Post Test Matrix

The second phase of the testing program gathered data for documenting the behavior of wooden 150mm x 200 mm (6x8 in.) posts rotating in soil. Standard 150mm x 200 mm (6x8 in.) guardrail posts were embedded in soil material conforming to AASHTO M 147-65 Gradation "B" specifications (NCHRP Report 350 Strong Soil) and instrumented with strain gauges and string potentiometers. These posts were impacted with a bogie vehicle at 4.5, 8.9, and 13.4 m/s (10, 20, and 30 mph). The initial test matrix is shown in Table 6. The impacts were documented by accelerometers on the bogie vehicle and either high-speed photography or Super VHS video cameras.

Table 6. Initial Wooden Post Frontal Impact Test Matrix.

Impact Velocity m/s (mph)	Post Type ASTM Designation	Soil Density kg/m^3 (pcf)	Embedment Depth m (in.)
4.5 (10)	150x200mm (6x8 in.)	2080 (130)	1.09 (43)
8.9 (20)	150x200mm (6x8 in.)	2080 (130)	1.09 (43)
13.4 (30)	150x200mm (6x8 in.)	2080 (130)	1.09 (43)

3.3 Accelerometer Data Analysis and Processing

Accelerometer and initial velocity data were used to find the force, velocity, displacement, and energy absorbed by the post. Although an accelerometer measures the acceleration of the bogie at the bogie's center of gravity, the acceleration data was used to approximate the bogie/post forces at the impact location.

The raw accelerometer data was downloaded using "DynaMax 1.75" accelerometer software (17) and then loaded into the "DADiSP 4.0" data processing program (18). The data was filtered and the pertinent acceleration signal was extracted. The processed acceleration data was then multiplied by the mass of the bogie in order to find the impact force using Newton's Second Law (19). Next, the acceleration versus time curve was integrated to find the change in velocity. The initial velocity, which had been calculated using the data from the pressure tape switches data, was then used to determine the bogie velocity versus time. The calculated velocity versus time curve was then integrated to find the displacement versus time curve. Subsequently, using the previous results, the force versus deflection curve was plotted. Finally, the force versus deflection curve was integrated to find the energy versus deflection curve.

3.3.1 End of Test Determination

In cases where the bogie stopped and rebounded, the point where the bogie changed direction (velocity becomes zero) was considered the end of the test. For cases where the bogie overrode the post, however, the end of the test can not be the entire duration of the contact between the post and the bogie head. This is due to the fact that a portion of the bogie energy is consumed to lift the bogie in the vertical direction.

It is important to note that when the bogie head impacts the post, the total force exerted by the bogie is directed perpendicular to the face of the post. As the post begins to rotate, however, the bogie head is no longer perpendicular to the face of the post and begins to slide along the face of the post, as shown Figure 3. Additionally, the neoprene on the bogie head used to minimize stress concentrations increases the frictional forces acting along the surface of the post.

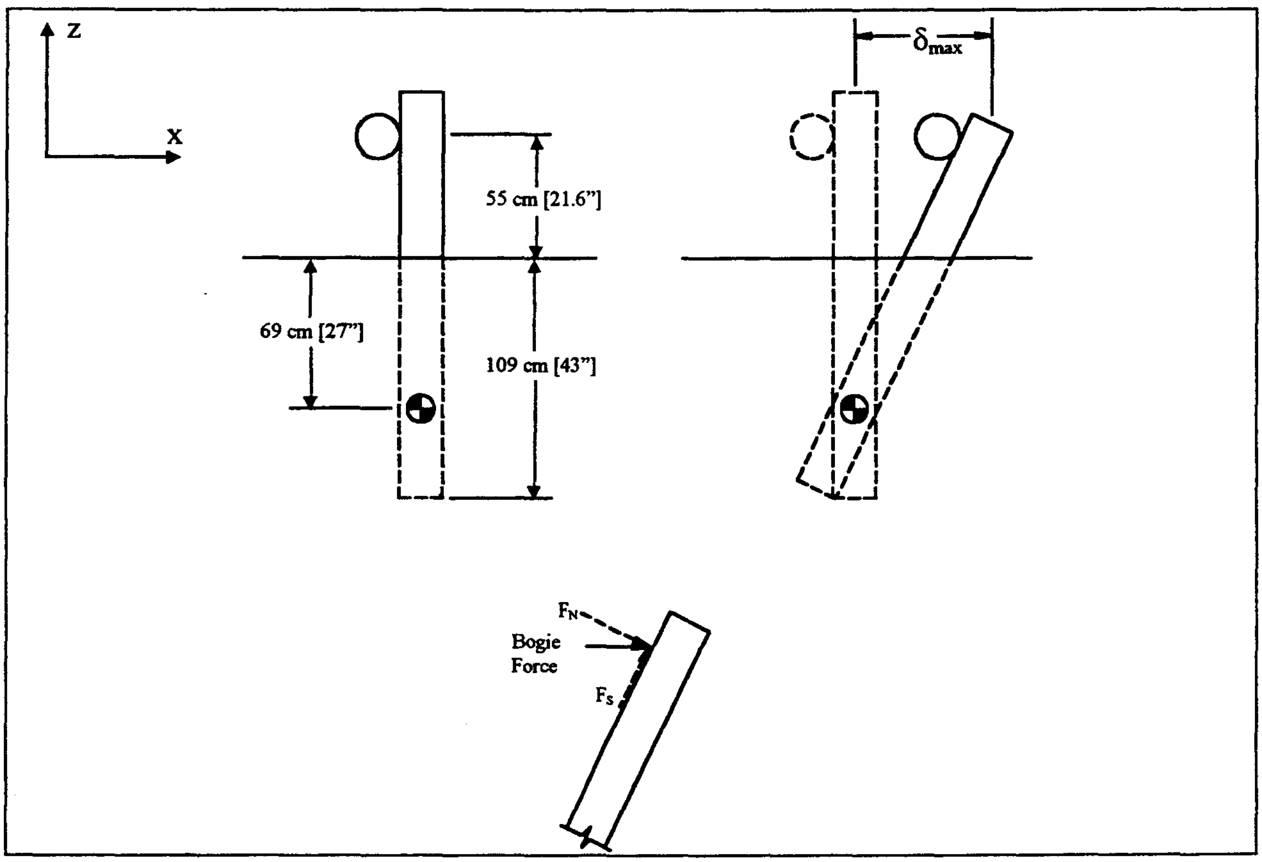


Figure 3. Discrepancy Between Bogie Force and Normal Force.

In cases where the bogie passed completely over the top of the post, a maximum deflection of 59.7 cm (23.5 in.) was allowed. This deflection corresponds to a 10% discrepancy between the normal force exerted against the post and the force measured by the accelerometer. The results from the accelerometer data are presented in Section 6. A methodology relating strain gauge data and accelerometer data is being developed to better verify this discrepancy.

3.4 Strain Gauge Data

Strain gauges were used to find the strain distribution and therefore the distribution of the moment about the y-axis in the posts. The strain gauge multiplication factors for each gauge were found by calibrating the post in a simply supported configuration and loading the post with known loads, as shown in Figure 4. This method was repeated at several points along the post in order to accurately calibrate each strain gauge. The dynamic moment distribution was then found by using the multiplication factors and the strain gauge output from the Vishay signal amplifier.

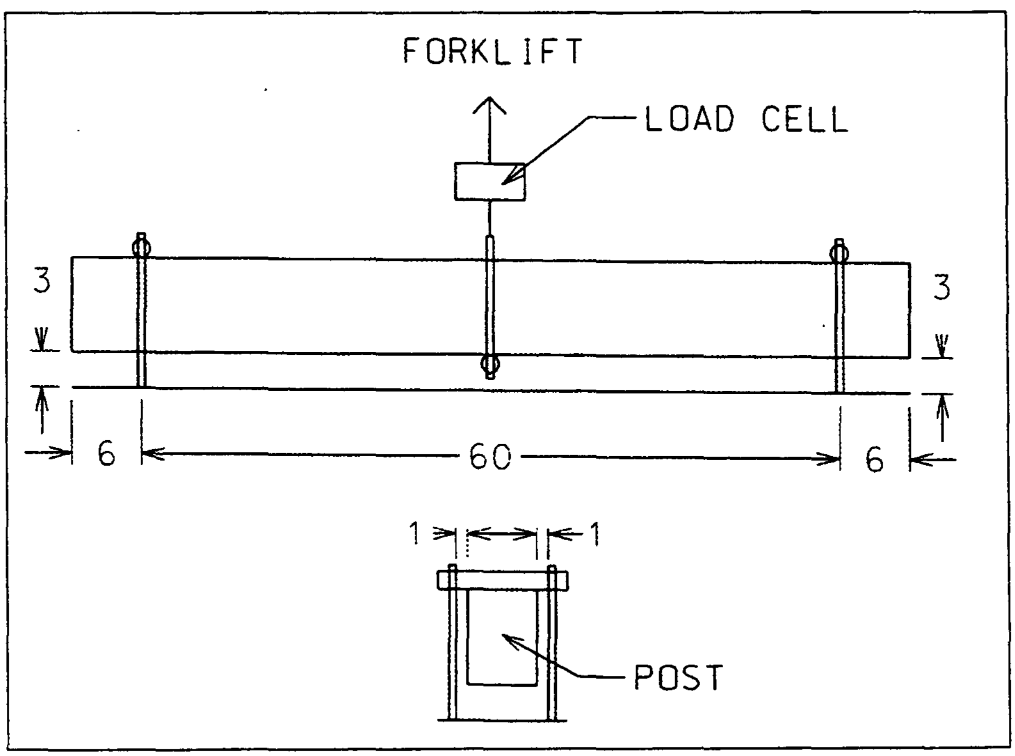


Figure 4. Three Point Loading Used To Calibrate Posts.

3.5 String Potentiometer Data

String potentiometers were used to measure post displacement at the groundline and twelve inches above the groundline. An attempt to obtain the location of the post's rotation point about the x-axis from the string potentiometer data was also attempted. Because the post not only moves laterally upon impact but also rises up out of the ground, two measured displacements on the post are not sufficient to determine the post's exact location. Since the post's exact location cannot be determined, the rotation point can not be obtained using only two string potentiometers.

Future research is needed to develop a methodology to determine the post's rotation point. Using strain gauge instrumentation to estimate post loadings and string potentiometers to determine post displacement, post behavior through rotation can be better determined.

4 POST INSTRUMENTATION

4.1 Steel Post Instrumentation

Initial testing consisted of two 183-cm (72-in.) long W150x13.5 (W6x9) steel guardrail posts impacted at approximately 5.5 m/s (12.3 mph). The posts were instrumented with twenty strain gauges spaced at 5.715-cm (2¼-in.) intervals evenly spaced beginning at the bottom of the post. The application of these strain gauges required that bare metal be exposed. Therefore, the galvanization on the inner flange of the guardrail posts was ground away using an angle grinder.

After the two initial tests, it was decided that fewer strain gauges could be used in order to simplify the data acquisition and instrumentation required. This new configuration consisted of a 12.7-cm (5-in.) spacing beginning 25.4 cm (10 in.) from the bottom of the post using ten weldable strain gauges. Figure 5 shows this strain gauge configuration.

After test nos. 3 and 4 were performed, a slight deformation in the flanges of the posts were observed; as show in Figure 7. It was believed that further testing of W150x13.5 (W6x9) posts would have been futile, since significant deformations would occur at higher speeds and undermine the load resisting characteristics of the soil, as shown in Figure 8. Therefore, to eliminate this deformation, the W150x13.5 (W6x9) steel posts were replaced with W150x23.5 (W6x16) steel posts for the higher speed impacts.

W150x13.5 (W6x9) and W150x23.5 (W6x16) posts have the same flange width and thus sweep out the same soil deformation pattern. The W150x23.5 (W6x16) post weighs more and is stiffer, which prevents deformation during testing. Strain gauge instrumentation for these posts is shown in Figure 6.

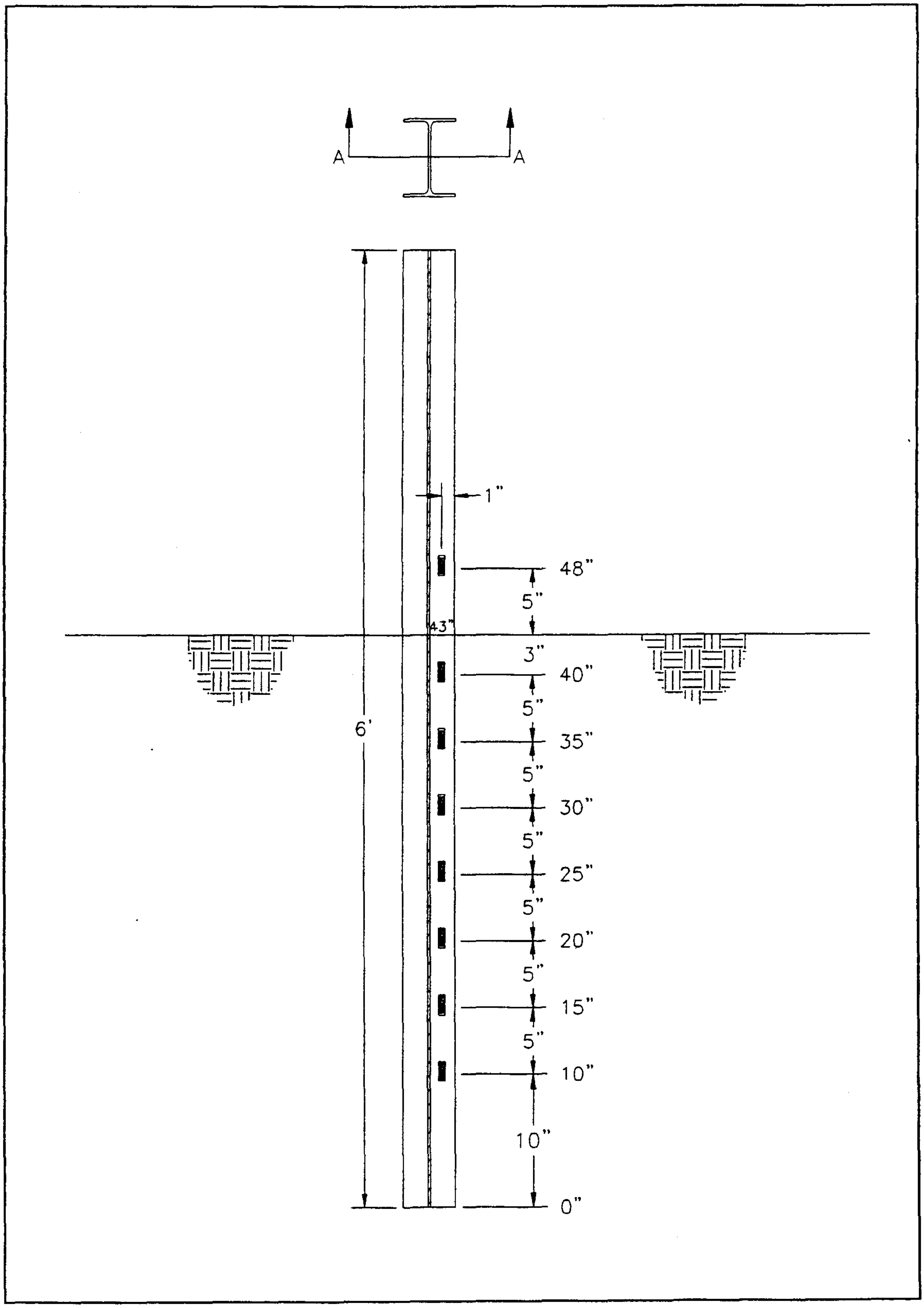


Figure 5. Strain Gauge Configuration for Test Nos. 3 and 4.

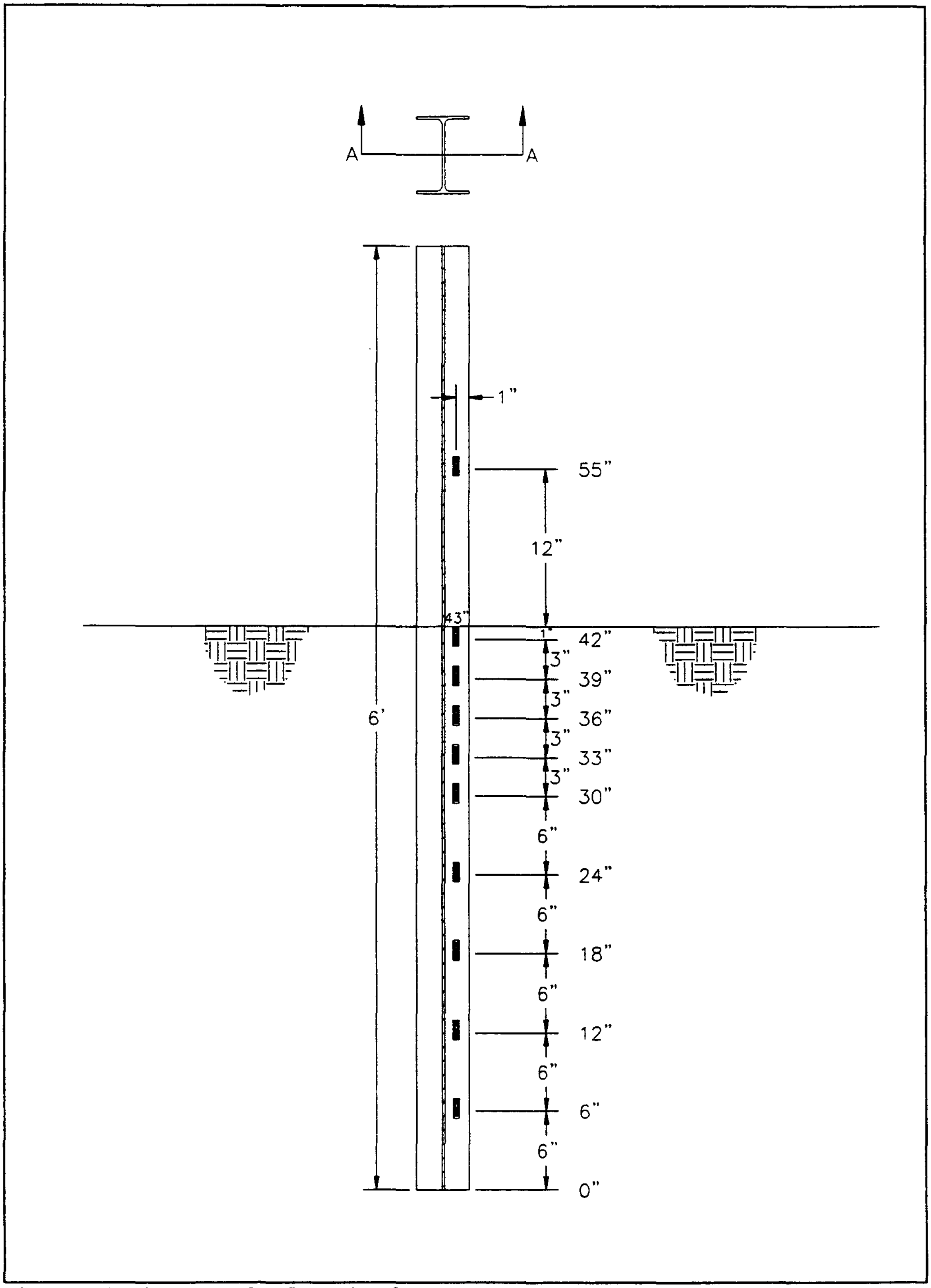


Figure 6. Strain Gauge Configuration for Test Nos. 5, 6, 10, and 11.

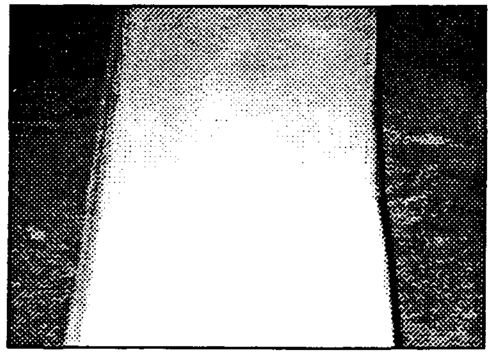


Figure 7. Slightly Deformed Flange of W150x13.5 (W6x9) (Test No. 3).

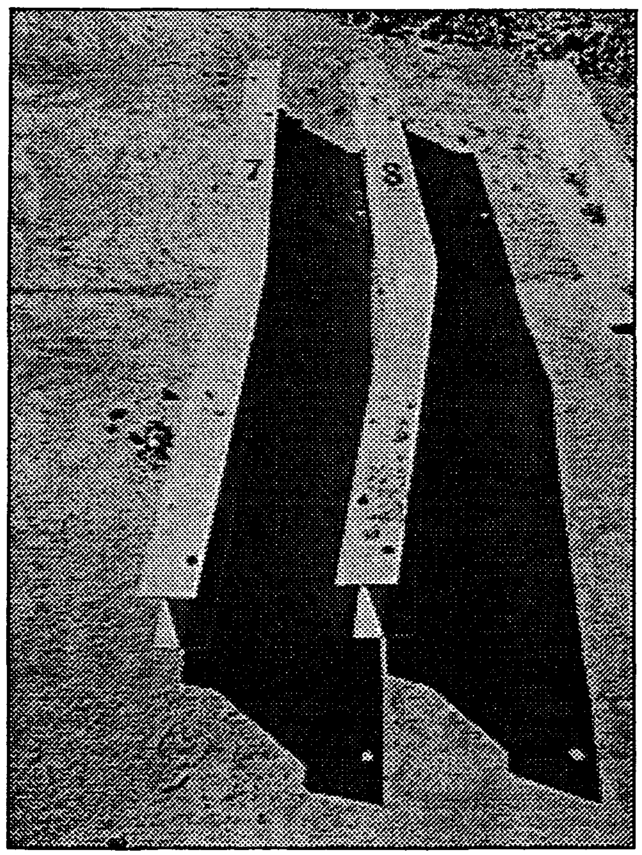


Figure 8. Structurally Compromised W150x13.5 (W6x9) Posts from Previous Post Testing

4.2 WOODEN POST INSTRUMENTATION

Direct instrumentation of wooden posts could not be achieved with strain gauges mounted directly on the surface of the posts as had been performed in the steel post testing since the strain gauges would be severely damaged during impact. As a result, it was necessary to develop a method to instrument the wooden posts. Since externally mounted gauges on the wood surface would be subject to abrasion and damage, the gauges were mounted on the inside of a post, as shown in Figure 9.

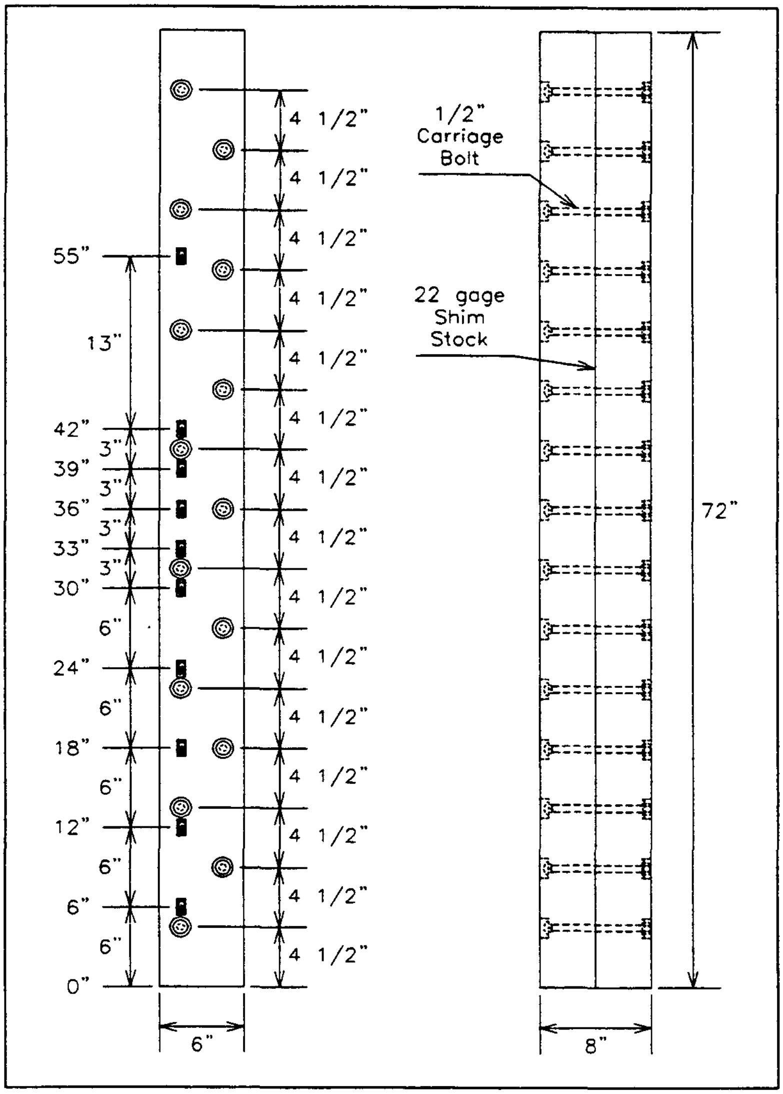


Figure 9. Initial strain gauge instrumentation design

Initially, two 150x200 (6x8 in.) posts were cut in half longitudinally through the 8 in. depth. A piece of 0.1016-mm (0.004-in.) thick steel shim stock was instrumented with strain gauges and placed between the two halves of each post. The post was then reassembled using Scotch-Weld epoxy, a structural adhesive specifically designed for load bearing in structures subjected to dynamic loading. The post was then bolted back together with carriage bolts and allowed to dry for one week. The reassembled post is shown in Figure 10.

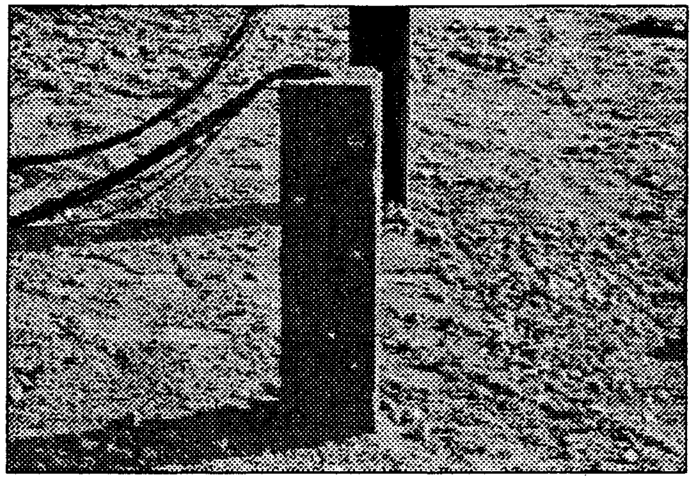


Figure 10. Longitudinally Cut Instrumented Post

Initial calibrations, static tests, and 4.5 m/s (10 mph) impacts caused no detectable damage to the post. When impacted at 8.9 m/s (20 mph), however, the posts fractured due to stress concentrations induced by the bolt holes used to reassemble the posts.

To minimize the stress concentrations of the post caused by post instrumentation, a small notch was routered out of the post rather than cutting the post the entire length. Steel shim stock was again used as the mounting surface for the strain gauges. This method of instrumentation is shown in Figure 11.

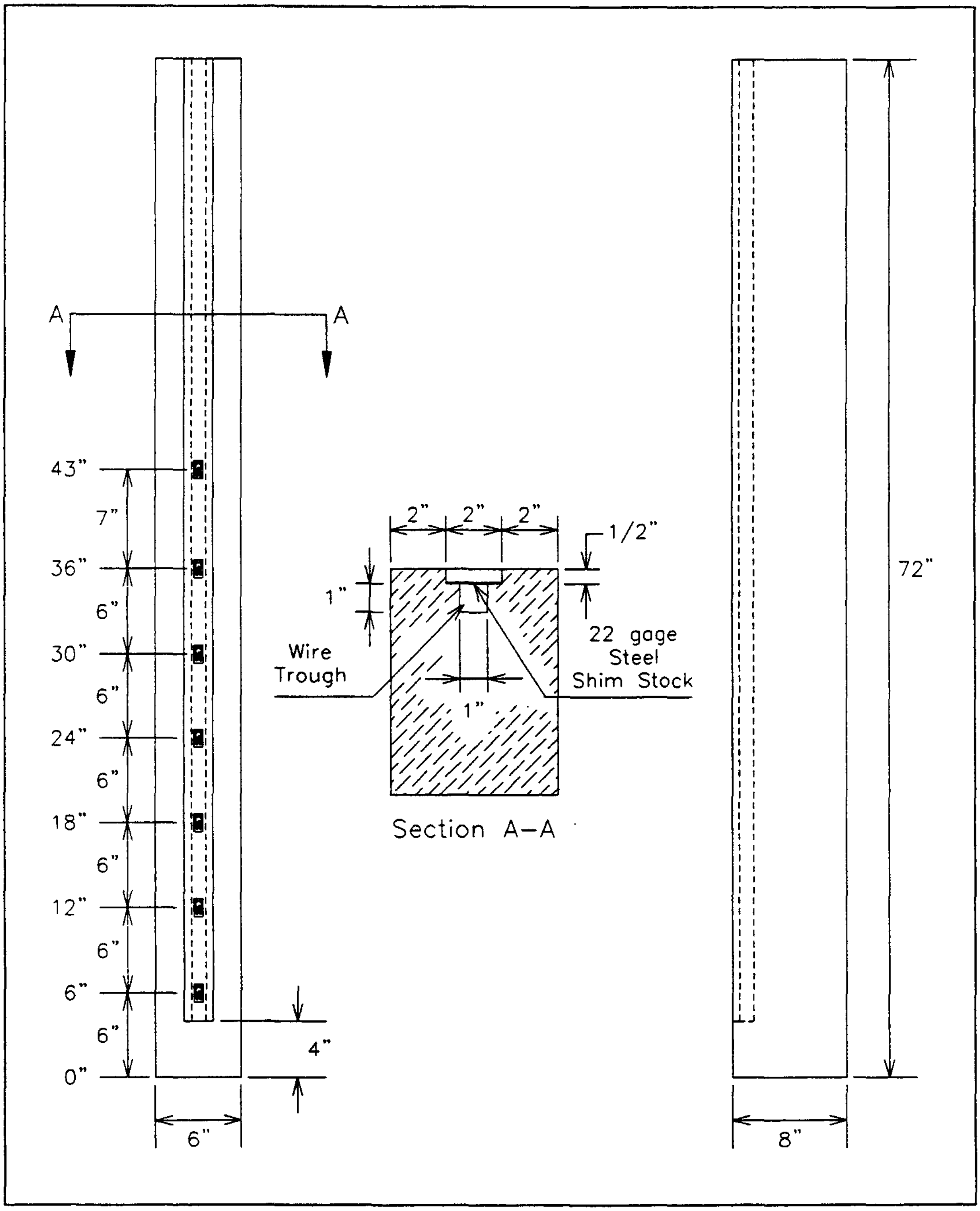


Figure 11. Notched design for strain gauge instrumentation.

Since the notches where the strain gauge wires exit the posts were not along the neutral axis, the moment of inertia, I, would be lessened due to the removal of the wood. Additionally, the insertion of the steel shim stock would increase the moment of inertia. Since a change the rigidity of the posts, EI, due to the instrumentation was not desired, the rigidity change (ΔEI) caused by the insertion of the steel shim stock was calculated to balance the rigidity change caused by the wood removed for the strain gauge wires. A post during the assembly process is shown in Figure 12.

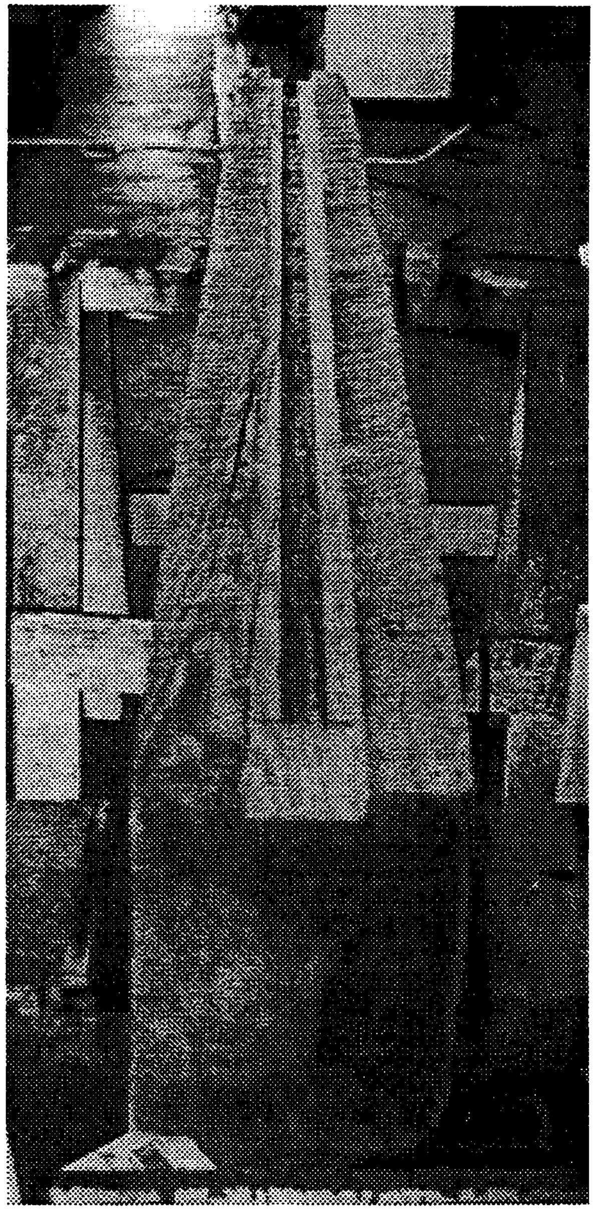


Figure 12. Slotted Wooden Instrumented Post.

5 TEST CONDITIONS

5.1 Test Facility

The post tests were conducted at the Midwest Roadside Safety Facility's outdoor test site located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport. The testing site is located on the east side of the facility where an area was cut in the 30.96-cm (2-ft) concrete tarmac. A native Nebraska soil occupies the majority of the pit, which is 6.1 m x 61 m (20 ft x200 ft).

5.1.1 Bogie tow and guidance system

A rigid frame bogie, constructed from FHWA specifications (20), was used to impact the posts. The bogie was modified with a rigid cylinder impactor. Computer simulation results indicate that the bogie duplicates actual vehicle impact and post-impact performance up to 6.7 meters (22 feet) following impact and realistically simulates runout trajectory up to 45.7 meters (150 feet) beyond impact (21).

The 8.9 and 13.4 m/s (20 and 30 mph) tests were conducted using a steel corrugated beam guardrail to guide the tire of the bogie. A pickup truck was used to push the bogie to the required impact velocity, at which point the pickup truck released, allowing the bogie to become a free projectile as it came off the guide track. The bogie vehicle positioned in the guide track configuration is shown in Figure 13.

For the 13.4 m/s (30 mph) tests, a cable and guide rail system was used to pull the bogie up to impact velocity where the cable released just prior to impact. This allowed the bogie, traveling at the prescribed speed, to be free of all external restraints at impact.

In all tests, the wheels of the bogie were aligned for caster and toe-in values of zero so that the bogie would track properly along the guidance system. A remote braking system was installed on the bogie to allow the bogie to be brought safely to a stop after the test. Accelerometers, located at the bogie's center of gravity recorded lateral, horizontal, and vertical accelerations.

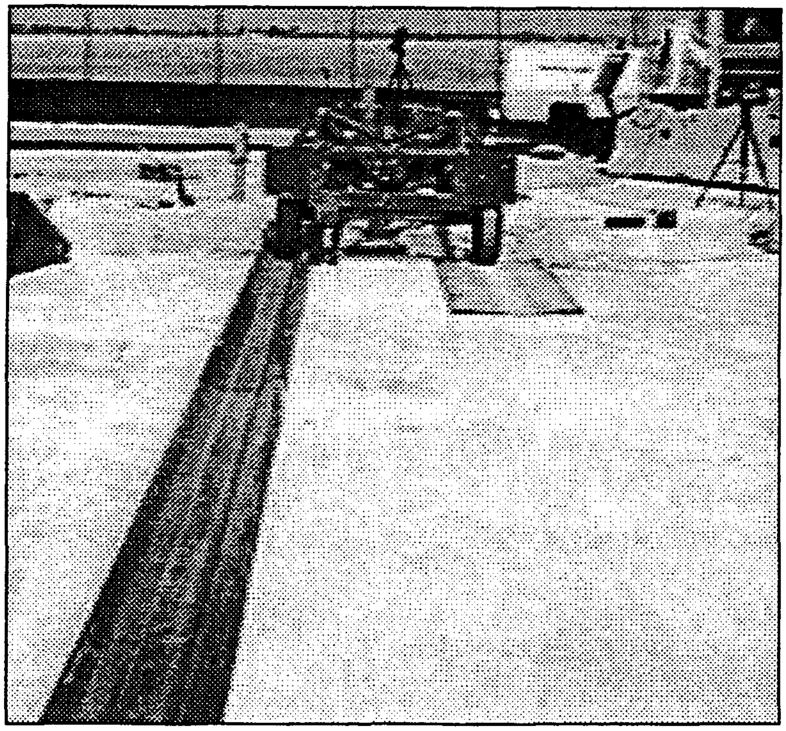


Figure 13. Bogie Positioned in Guide Track Configuration

5.1.2 Post Installation Procedure

A plan view of the test setup and post test pit is shown in Figure 14. The test pits were located at a sufficient distance from the edge of the concrete apron so as not to interfere with the soil response during impact.

Embedment of the posts consisted of excavating a 91.44-cm by 182.88-cm (3-ft by 6-ft) area to a depth of approximately 1.5 meters (5 ft). AASHTO M 147-65 specification soil was then compacted with a pneumatic hand tamper in 15-cm (6-in.) lifts. Soil density measurements were taken using the sand replacement method (standard sand cone).

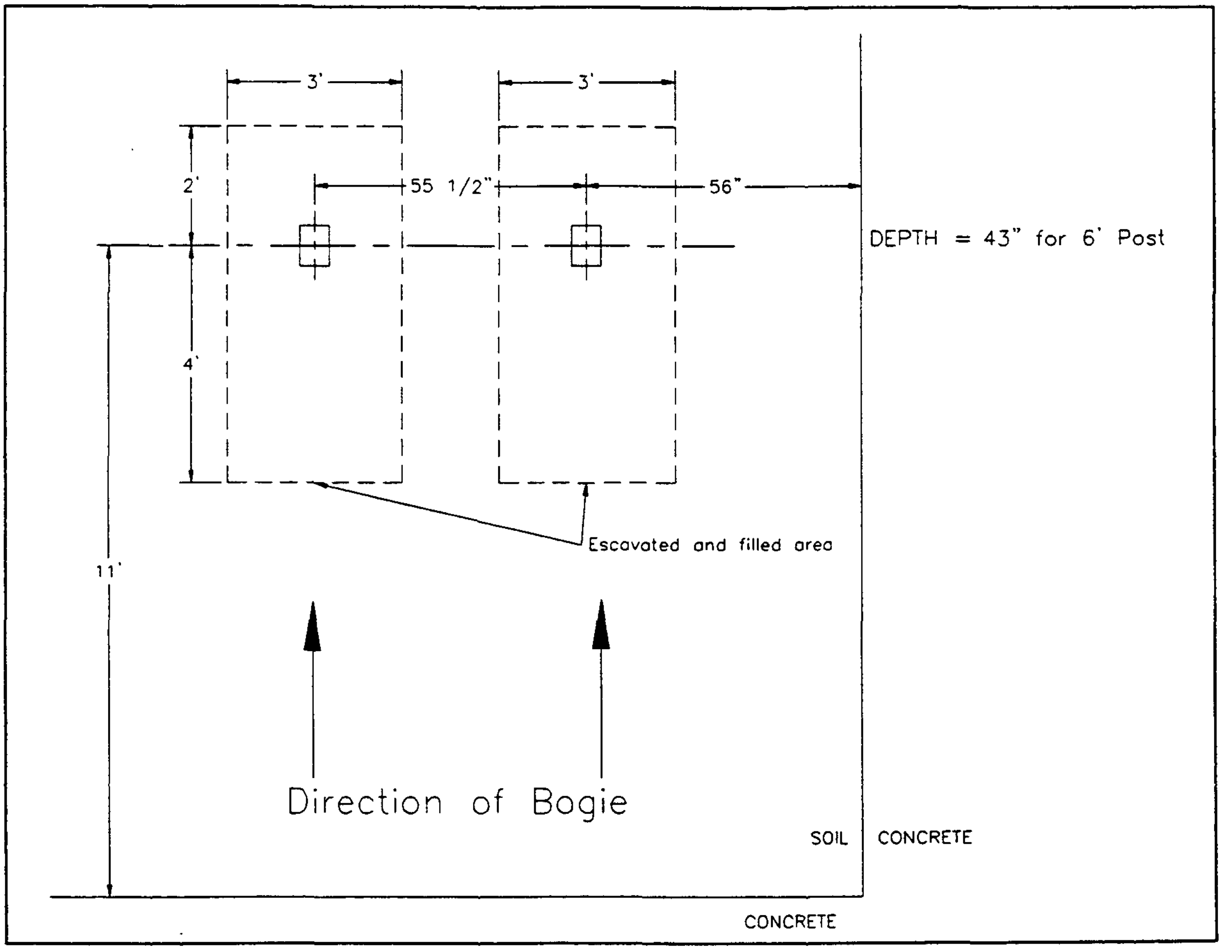


Figure 14. Plan View of Excavated Area

5.1.3 Steel Post Material Properties

In the first four tests, standard galvanized W150x13.5 (W6x9) posts were used. After slight deformations were observed in the low speed testing, it was determined to use stronger W150x23.5 (W6x16) steel posts in order to ensure soil failure rather than post failure. The W150x23.5 (W6x16) posts were not galvanized. The steel posts were manufactured using ASTM A36 steel. The cross-sections conformed to their respective dimensions as defined in ASTM A6M. The posts and their material properties are shown in Table 7.

Table 7. Steel Post Material Properties

ASTM Designation	Area, A, mm^2 (in^2)	Flange Width, b_f, mm (in)	Moment of Inertia, I_x mm^4 (in^4)	Section Modulus, S_x, mm^3 (in^3)	Plastic Section Modulus, Z_x, mm^3 (in^3)
W150x13.5 (W6x9)	1700 (2.68)	100.08 (3.940)	$6.84x10^6$ (16.4)	91,112 (5.56)	102,091 (6.23)
W150x23.5 (W6x16)	3007 (4.74)	102.36 (4.030)	$13.0x10^6$ (32.1)	167,148 (10.2)	191,728 (11.7)

5.1.4 Wooden Post Material Properties

Wooden posts were DS-65 structural grade Southern Yellow Pine (22). The posts and their material properties are shown in Table 7.

Table 8. Wooden Post Material Properties

ASTM Designation	Wood Species	Area, A, mm^2 (in^2)	Moment of Inertia, I_x mm^4 (in^4)	Section Modulus, S_x, mm^3 (in^3)
150x200 mm (6x8 in.)	Southern Yellow Pine	30000 (48)	$100.0x10^6$ (240)	1000000 (61.0)

5.1.5 Soil Material Properties

A crusher run coarse aggregate material consisting of gravel and crushed limestone was used for filling the excavated pit area. The soil conformed to AASHTO standard specifications for "Materials for Aggregate and Soil Aggregate Subbase, Base, and Surface Courses," designation M 147-65 (1990), grading B. The moisture content was relatively dry (3% to 7%), which was considerably below the optimum moisture content of 17%. Due to the gradation of the material, additional moisture content would have greatly increased the *in situ* density.

5.2 Data Acquisition System

5.2.1 Accelerometer

A triaxial piezoresistive accelerometer system with a range of ±200 G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions. The environmental shock and vibrations sensor/recorder system, Model EDR-3, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 kb of RAM and was set to sample data at 3,200 Hertz using a 1,120 Hertz low-pass filter (anti-aliasing with 3-db cutoff). Computer software programs "DynaMax 1.75" and "DADiSP 4.0" were used to digitize, analyze, and plot the accelerometer data.

5.2.2 High Speed Photography

A Red Lake Locam with a wide-angle lens was placed perpendicular to the side of guardrail post to record the impact event. High speed photography at 500 frames/second was obtained for steel post test no. 10 and test nos. 3 -6 of the wooden post tests.

5.2.3 Pressure Tape Switches

Three pressure tape switches spaced at 1-m (3.38-ft) intervals were used to determine the speed of the bogie before impact. As the front tire of the bogie passed over each tape switch, a strobe light was fired which sent an electronic timing signal to the computerized data acquisition system. Test speeds were determined by knowing the time between these signals from the data acquisition system and the distance between switches.

5.2.4 Strain Gauges

Strain gauges were installed to measure bending moment on the tensile side of the posts. Where epoxyable strain gauges were adhered, strain gauges model CEA-06-125UN-120, manufactured by the Micro-Measurements Division of the Measurements Group, Incorporated in Raleigh, North Carolina, were used. The epoxyable gauges had a nominal resistance of 120±1.56 Ohms and a gauge factor of 2.065. Where weldable strain gauges were used, strain gauges model LWK-06-W250B-350 were employed. The nominal resistance of these strain gauges was 350.0±1.4 Ohms and a gauge factor of 2.065.

A Measurements Group Vishay Model 2310 signal conditioning amplifier was used to power, condition, and amplify the low-level signals to high-level signals for acquisition by a Keithley Metrabyte DAS-1802HC data acquisition board. The computer program "Test Point 4.0" was then used to record and permanently store the data. All strain gauge data was recorded at 3,200 samples per second (3,200 Hz.) for a duration of 6 sec.

5.2.5 String Potentiometers

Two UniMeasure PA-20-70120 string potentiometers (linear position transducers) were installed on the post at 5.08 cm (2 in.) and 30.48 cm (12 in.) above the ground line in order to measure deflection and rotation of the post. The PA-20 potentiometers have a range of 508 mm (20 in.) and a sensitivity of 1.909 mV/V/mm (48.48 mV/V/inch).

A specially designed catcher was used to prevent hyperextension and abrupt retraction of the string potentiometers. The string potentiometer and string catcher positions are shown in Figure 15.

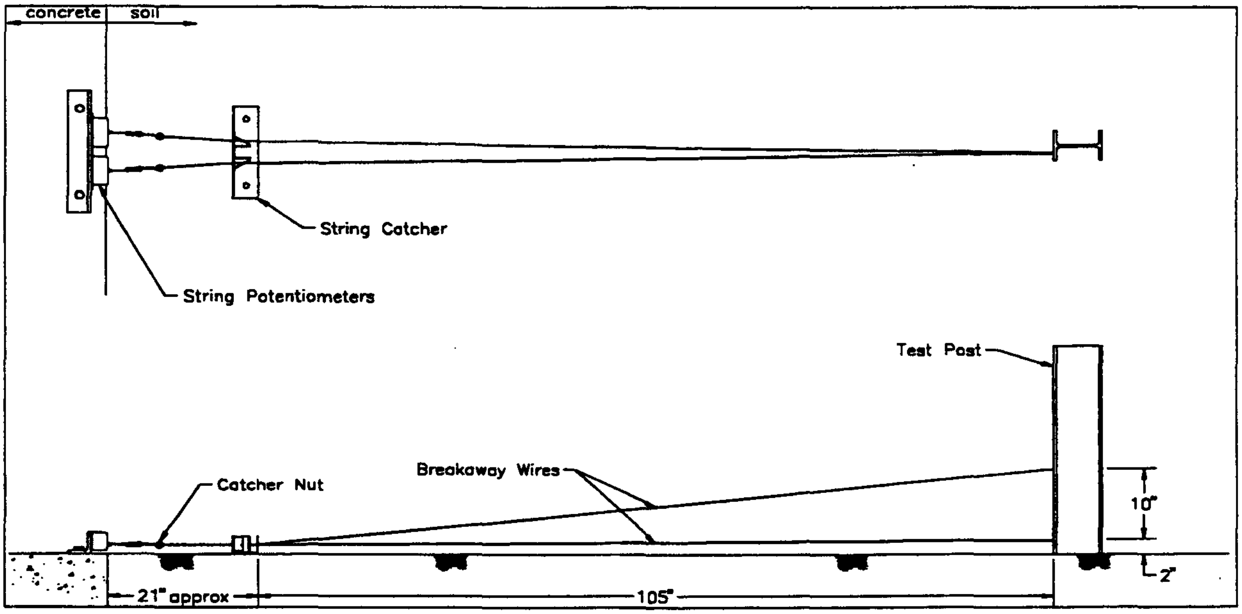


Figure 15. String Potentiomenter Configuration

During the tests, the output voltage signals from the string potentiometers were sent to the Keithley Metrabyte DAS-1802HC data acquisition board, acquired by the "Test Point" software, and then permanently stored on the computer. The sample rate for the string potentiometers was 3,200 Hertz and the duration was 6 seconds.

6 TEST RESULTS

6.1 Steel Post Impacts

The test matrix performed for frontal impact analysis on steel posts consisted of four impacts at 5.5 m/s (12.3 mph), two impacts at 8.9 m/s (20 mph), and two impacts at 13.4 m/s (30 mph). The soil densities and velocities, along with post types, can be found in Table 9. The posts were impacted 550 mm (21.6 in.) above the ground line with the rigid bogie.

Table 9. Steel Post Test Matrix

Test Number	Post Type ASTM Designation	Soil Density kg/m^3 (pcf)	Impact Velocity m/s (mph)	Strain Gauge Spacing mm (in)
1	W150x13.5 (W6x9)	1980 (124)	4.6 (10.4)	4.41 (2)
2	W150x13.5 (W6x9)	2018 (126)	6.0 (13.4)	4.41 (2)
3	W150x13.5 (W6x9)	2110 (132)	5.4 (12.1)	11.03 (5)
4	W150x13.5 (W6x9)	2240 (140)	5.9 (13.1)	11.03 (5)
5	W150x23.5 (W6x16)	2080 (130)	8.9 (19.9)	6.62 and 13.23 (3 and 6)
6	W150x23.5 (W6x16)	2110 (132)	8.9 (20.0)	6.62 and 13.23 (3 and 6)
7	Static Test			
8*	W150x23.5 (W6x16)	2110 (132)	8.9 (20.0)	None
9	Not Used			
10	W150x23.5 (W6x16)	2150 (134)	14.1 (31.5)	6.62 and 13.23 (3 and 6)
11	W150x23.5 (W6x16)	2130 (133)	12.7 (28.4)	6.62 and 13.23 (3 and 6)

*Offset impact

For all of the bogie impacts, soil failure was the primary mode of failure. The posts successfully rotated in the soil, with slight deformation of the flanges of test nos. 3 and 4. However, in the two cases where there was slight deformation of the posts, the accelerometer data closely matched the tests where post deformation had not occurred. A summary of test results is shown in Table 10.

Table 10. Dynamic Steel Test Results Summary

Test No.	Post Type ASTM Designation	Impact Velocity m/s (mph)	Peak Force kN (kips)	Maximum Deflection cm (in.)	Energy Absorbed Joules (kip*in)	Resulting Bogie Condition
1	W150x13.5 (W6x9)	4.6 (10.4)	64.0 (14.4)	23.4 (9.2)	10.2 (89.9)	Stopped
2	W150x13.5 (W6x9)	6.0 (13.4)	32.3 (7.3)	59.7 (23.5)**	14.1 (124.8)	Stopped
3	W150x13.5 (W6x9)	5.4 (12.1)	66.9 (15.0)	31.4 (12.4)	14.2 (125.9)	Stopped
4	W150x13.5 (W6x9)	5.9 (13.1)	67.0 (15.1)	34.8 (13.7)	15.8 (139.6)	Stopped
5	W150x23.5 (W6x16)	8.9 (19.9)	104.7 (23.5)	59.7 (23.5)**	28.9 (256.4)	Ride Over
6	W150x23.5 (W6x16)	8.9 (20.0)	86.3 (19.4)	59.7 (23.5)**	23.2 (205.4)	Ride Over
7	Static Test					
8*	W150x23.5 (W6x16)	8.9 (20.0)	63.8 (14.3)	59.7 (23.5)**	26.2 (231.9)	Ride Over
9	Not Used					
10	W150x23.5 (W6x16)	14.1 (31.5)	122.2 (27.5)	59.7 (23.5)**	29.1 (257.1)	Ride Over
11	W150x23.5 (W6x16)	12.7 (28.4)	89.6 (20.2)	59.7 (23.5)**	19.8 (174.8)	Ride Over

*Offset impact
**Test terminated at D_{max} = 59.7 cm (23.5 in.), see section 3.1.1

The relationship between impact velocity and peak force is shown in Figure 16 and the relationship between impact velocity and energy absorbed is shown in Figure 17. In both cases, the correlation coefficient for a linear relationship is significantly less than 1 (0.588 and 0.569, respectively).

Figure 16. Velocity-Force Relationship for Steel Post Tests.

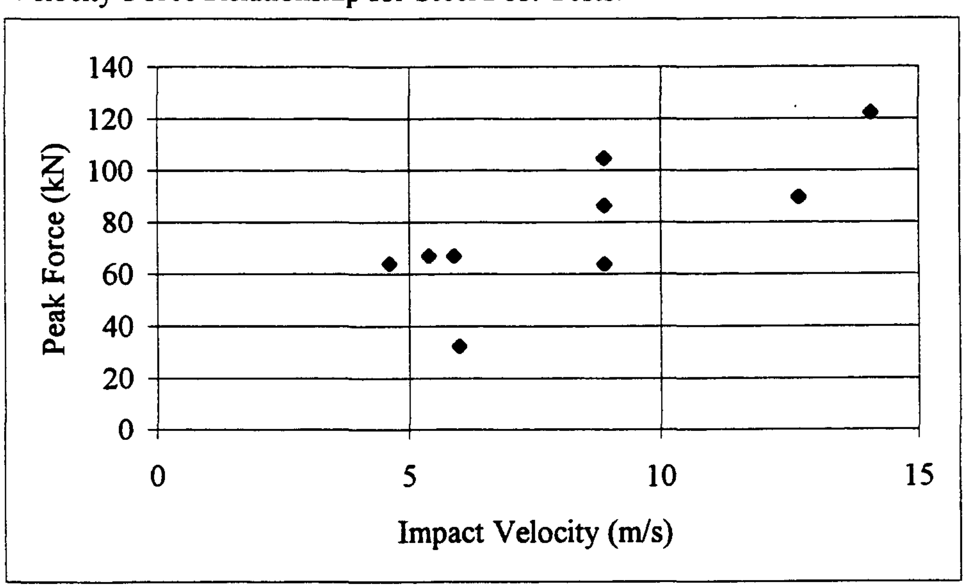
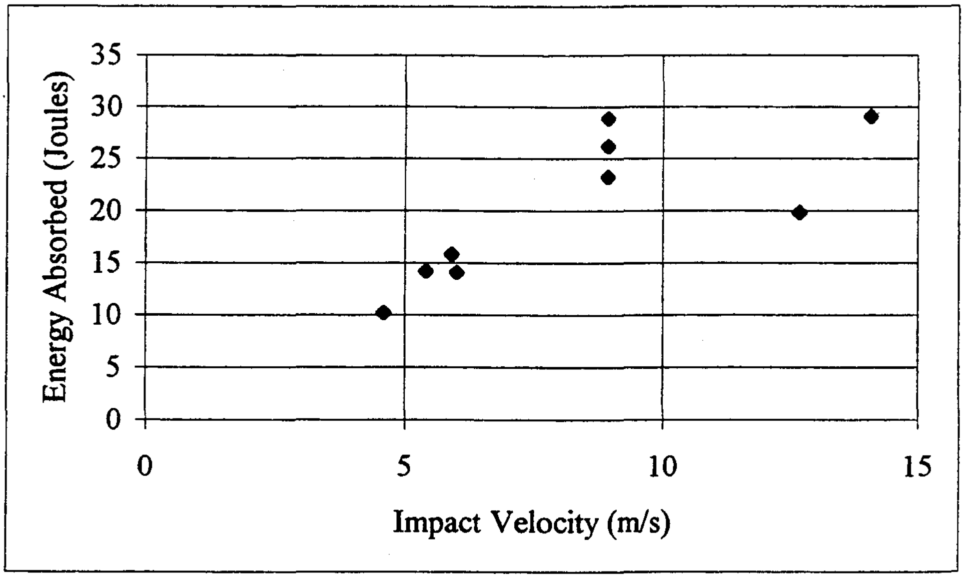


Figure 17. Velocity-Energy Relationship For Steel Post Tests.



6.1.1 Low speed steel post tests

Tests using the W150x13.5 (W6x9) posts were all very similar in nature. In each of the cases, moderate rotation of the posts occurred. After impacting the posts, the bogie vehicle reversed its direction of travel and moved away from the posts. Typical post damage after impact is shown in Figure 18.

Figure 18. Typical Low-speed Bogie Impact (Test Nos. 1 and 2)

6.1.2 High speed steel post tests

Tests using the W150x23.5 (W6x16) posts all resulted with the posts completely rotating in the soil. The bogie, in each case, continued to travel forward after post rotation, and after clearing the post, the bogie continued along its path and was stopped when it impacted a backstop of wooden posts. Typical post damage after impact is shown in Figure 19.

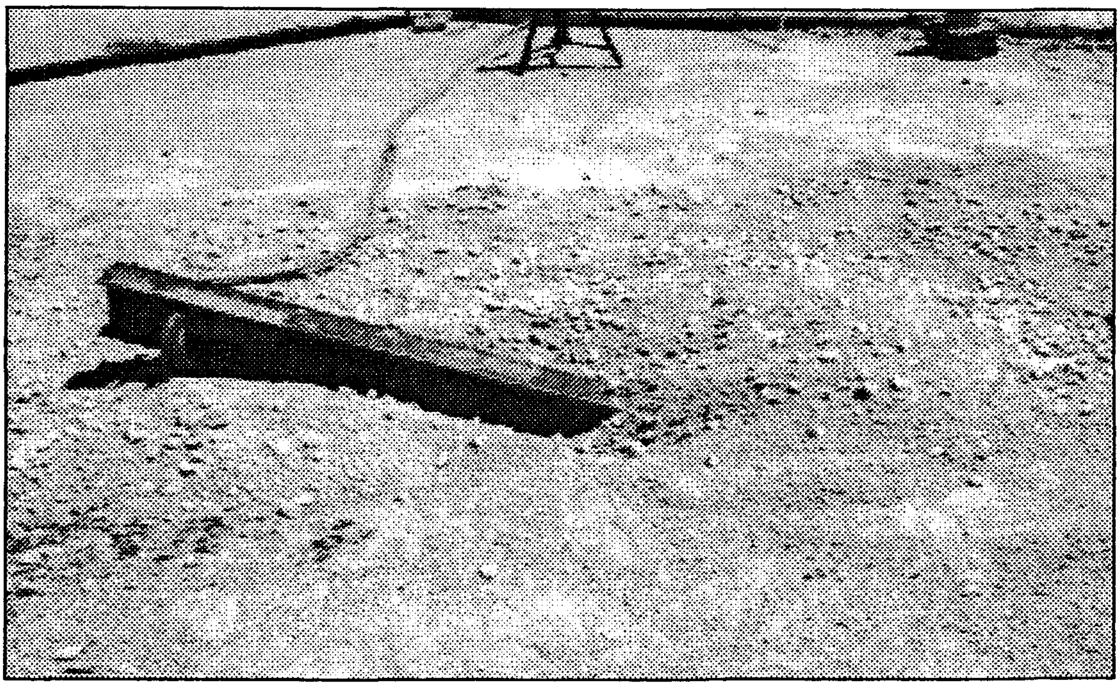


Figure 19. Typical High-speed Bogie Impact (Test No. 5)

6.1.3 Offset Steel Post Impacts

The offset steel post impact performed at 8.9 m/s (20 mph) showed significantly lower peak forces than full frontal impacts, as shown in Table 10, for similar velocity impacts. The energy absorbed, however, was not significantly different.

6.2 Wooden Post Impacts

The test matrix performed for frontal impact analysis of wooden posts consisted of four impacts at 4.9 m/s (10 mph) and two impacts at 8.9 m/s (20 mph). The soil densities and velocities, along with post types, can be found in Table 11. The posts were impacted 550 mm (21.6 in.) above the ground line with the rigid bogie.

Table 11. Wooden Post Test Matrix

Test Name	Post Type ASTM Designation	Date	Soil Density (pcf)	Soil Density (kg/m^3)	Velocity		
					m/s	fps	mph
Wood-1	150x200mm (6x8 in.)	11/13/98	134.0	2146	Static Test		
Wood-2	150x200mm (6x8 in.)	11/13/98	132.4	2121	Static Test		
Wood-3	150x200mm (6x8 in.)	11/18/98	134.4	2152	4.9	16.2	11.0
Wood-4	150x200mm (6x8 in.)	11/18/98	127.6	2045	4.8	15.9	10.9
Wood-5	150x200mm (6x8 in.)	11/20/98	133.7	2141	9.6	31.6	21.5
Wood-6	150x200mm (6x8 in.)	11/20/98	128.6	2059	9.0	29.4	20.1
Wood-7	Not Used						
Wood-8	150x200mm (6x8 in.)	11/20/98	138.0	2211	6.0	19.6	13.4
Wood-9	150x200mm (6x8 in.)	11/20/98	138.0	2211	6.7	22.0	15.0

For the low-speed wooden post impacts (4.8 m/s (10 mph)), soil failure was the primary mode of failure. At higher speeds (8.9 m/s (20 mph)), the mode of failure was not consistant. This is due to primarily to three conditions: the stress concentrations induced by the instrumentation of the posts, as discussed earlier, variations in post quality due to the inherent nature of wood, and to the variations in gradations that are allowed within AASHTO M 147-65 (1990) grading "B" specifications. A summary of test results is shown in Table 12.

Table 12. Dynamic Wooden Test Results Summary

Test Name	Post Type ASTM Designation	Impact Velocity m/s (mph)	Peak Force kN (kips)	Maximum Deflection cm (in.)	Energy Absorbed Joules (kip*in)	Resulting Bogie Condition
Wood-01	Static Test					
Wood-02	Static Test					
Wood-03	150x200mm (6x8 in.)	4.9 (11.0)	36.3 (8.15)	44.4 (17.5)	11.2 (98.8)	Stopped
Wood-04	150x200mm (6x8 in.)	4.8 (10.9)	38.8 (7.82)	45.0 (17.7)	10.3 (90.8)	Stopped
Wood-05	150x200mm (6x8 in.)	9.6 (21.5)	77.8 (17.48)	59.7 (23.5)*	27.1 (240.0)	Stopped
Wood-06	150x200mm (6x8 in.)	9.0 (20.1)	64.2 (14.43)	14.5 (5.7)	5.4 (47.6)	Post Fracture
Wood-07	Not Used					
Wood-08	150x200mm (6x8 in.)	6.0 (13.4)	51.7 (11.62)	27.6 (10.9)	10.4 (91.6)	Post Fracture
Wood-09	150x200mm (6x8 in.)	6.7 (15.0)	55.0 (12.36)	18.2 (7.15)	5.3 (47.3)	Post Fracture

*Test terminated at D_{max} = 59.7 cm (23.5 in.), see section 3.1.1

The relationship between impact velocity and peak force is shown in Figure 20 and the relationship between impact velocity and energy absorbed is shown in Figure 21. There is a strong linear relationship between the peak force and the impact velocity (R^2=0.938), however, there is no linear relationship between energy and velocity (R^2=0.179).

Figure 20. Velocity-Force Relationship for Wooden Post Tests.

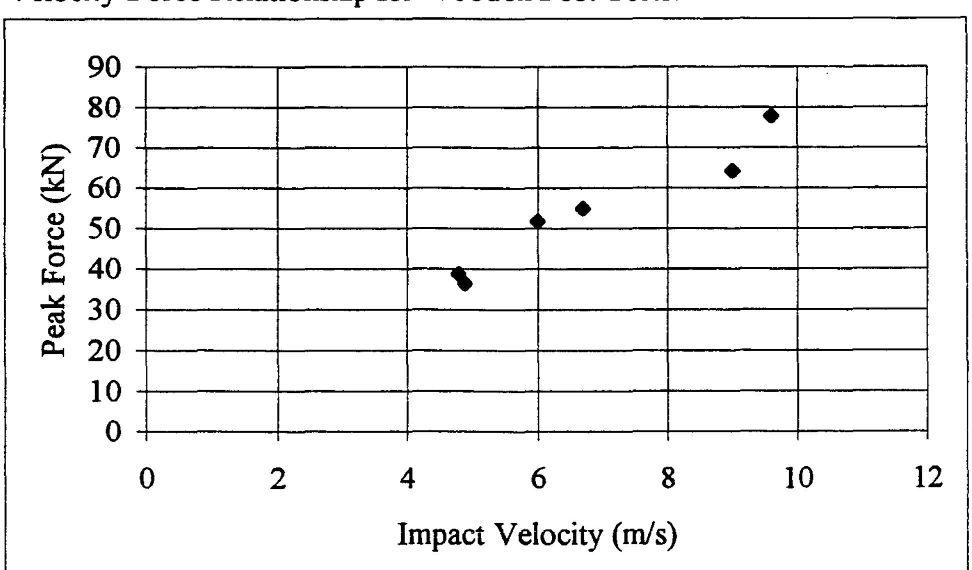
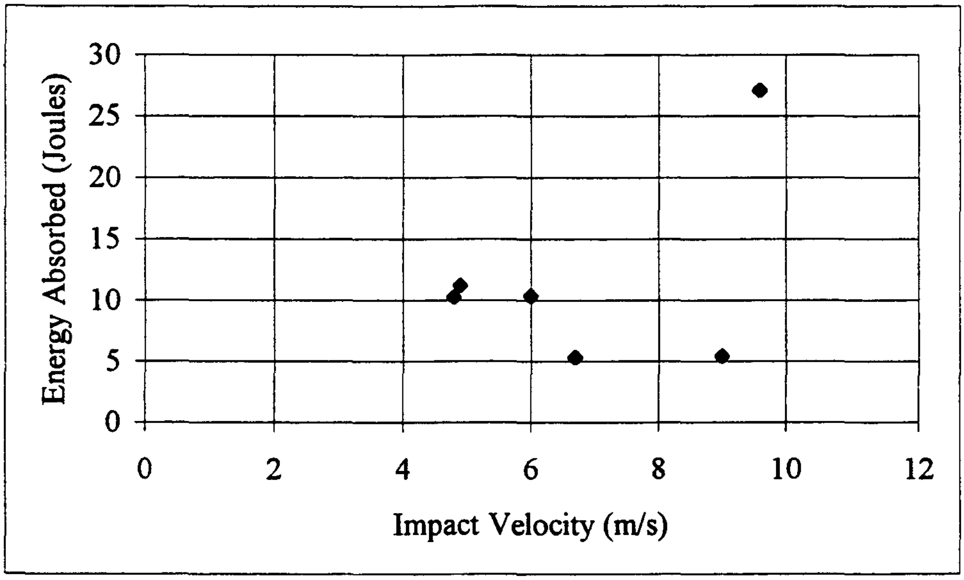


Figure 21. Velocity-Energy Relationship For Wooden Post Tests



6.3 Test Summary Information

A summary sheet for each test is provided in this section. Summary sheets include acceleration, velocity, and displacement versus time plots, and force and energy versus deflection plots.

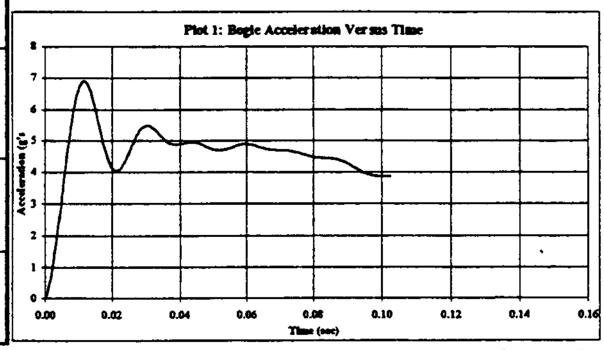
In test Wisc-02, soil moisture was considerably high, approaching 26% at the surface. This increased moisture content caused the post deflection to be much higher than normal and the peak force and energy absorbed to be much lower. An initial peak force is not observed in this test as a result of the high moisture content.

Table 13. Post Tests Performed.

Test Number	Post Type	Velocity (m/s)	Figure Number
Wisc-1	Steel	4.6	Figure 22
Wisc-2	Steel	6.0	Figure 23
Wisc-3	Steel	5.4	Figure 24
Wisc-4	Steel	5.9	Figure 25
Wisc-5	Steel	8.9	Figure 26
Wisc-6	Steel	8.9	Figure 27
Wisc-7	Steel	Static Test	Figure 28
Wisc-8	Steel	8.9	Figure 29
Wisc-9		Not Used	
Wisc-10	Steel	14.1	Figure 30
Wisc-11	Steel	12.7	Figure 31
Wood-01	Wood	Static Test	Figure 32
Wood-02	Wood	Static Test	Figure 33
Wood-03	Wood	4.9	Figure 34
Wood-04	Wood	4.8	Figure 35
Wood-05	Wood	9.6	Figure 36
Wood-06	Wood	9.0	Figure 37
Wood-07		Not Used	
Wood-08	Wood	6.0	Figure 38
Wood-09	Wood	6.7	Figure 39

Midwest Roadside Safety Facility

Bogie Test Summary		
Test Information		
Test Number:	Wisc-1	
Test Date:	19-May-98	
Failure Type:	Rotation in Soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x13.5 mm	(W6x9)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	1986 kg/m^3	(124 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	4.6 m/s	(10.3 mph) (15.1 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Rear and Side View, S-VHS		
String Potentiometer Data		



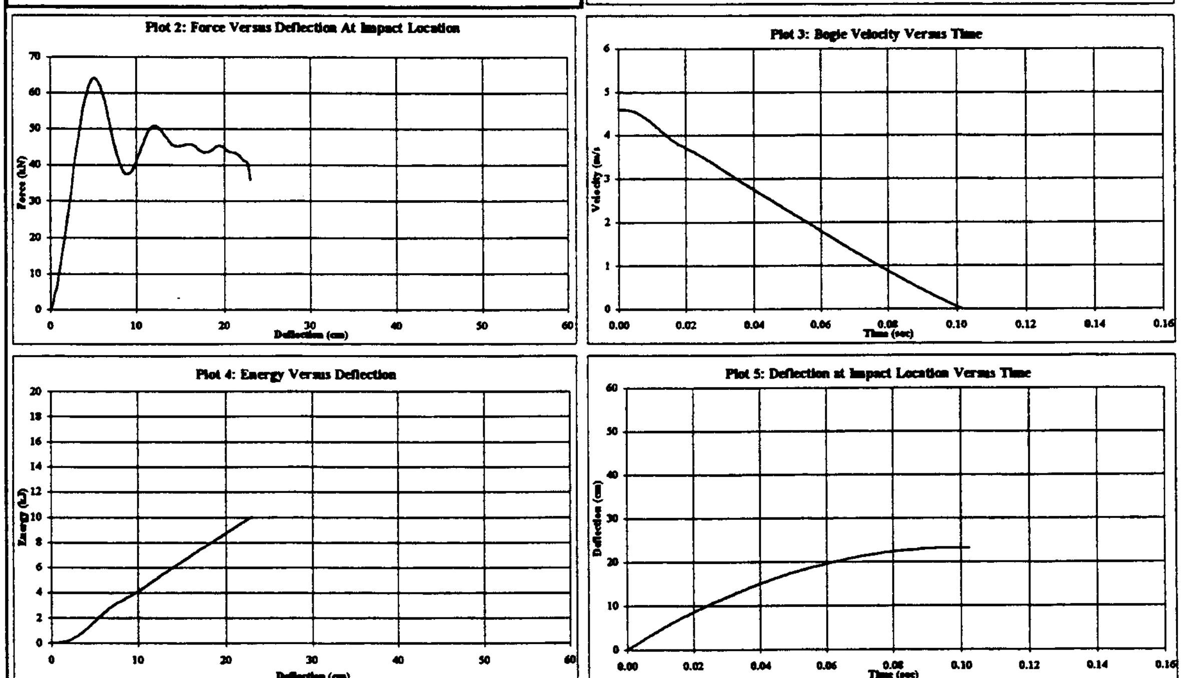
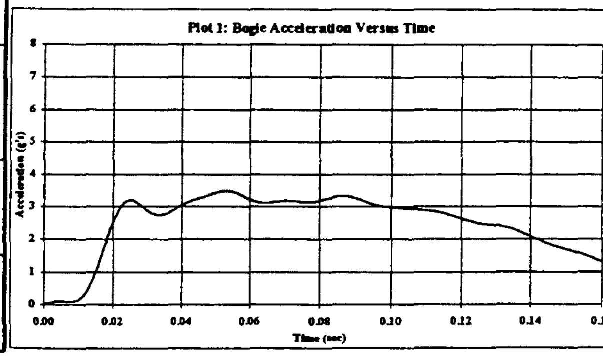


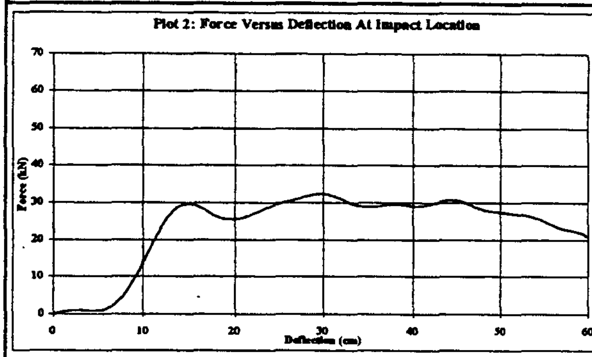
Figure 22. Results of Wisc-1.

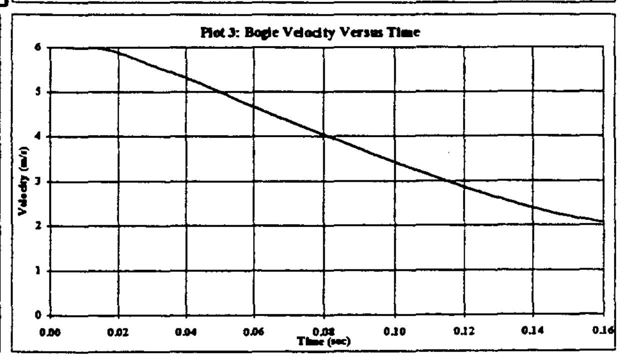
Midwest Roadside Safety Facility

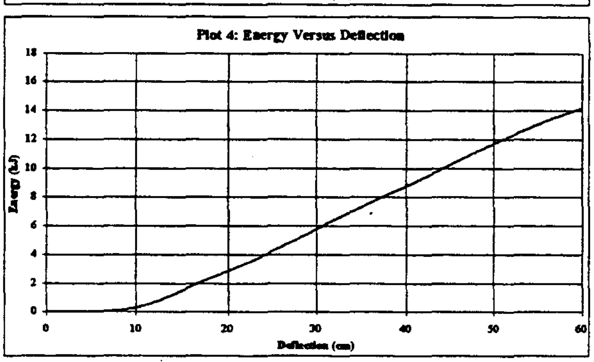
Bogie Test Summary

Test Information		
Test Number:	Wisc-2	
Test Date:	21-May-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x13.5 mm	(W6x9)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Wet (w=26%)	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2018 kg/m^3	(126 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	6.0 m/s	(13.4 mph) (19.7 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf)
Data Acquired		
Accelerometer Data		
Rear and Side View, S-VHS		









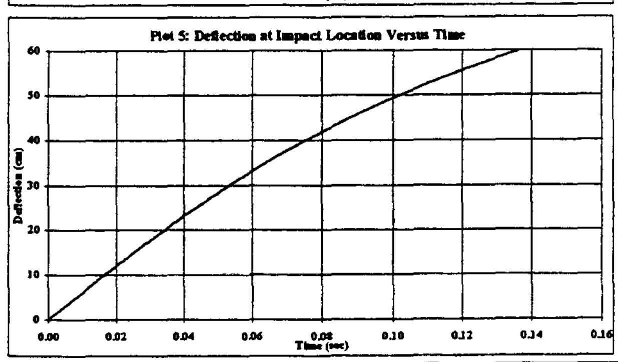


Figure 23. Results of Wisc-2.

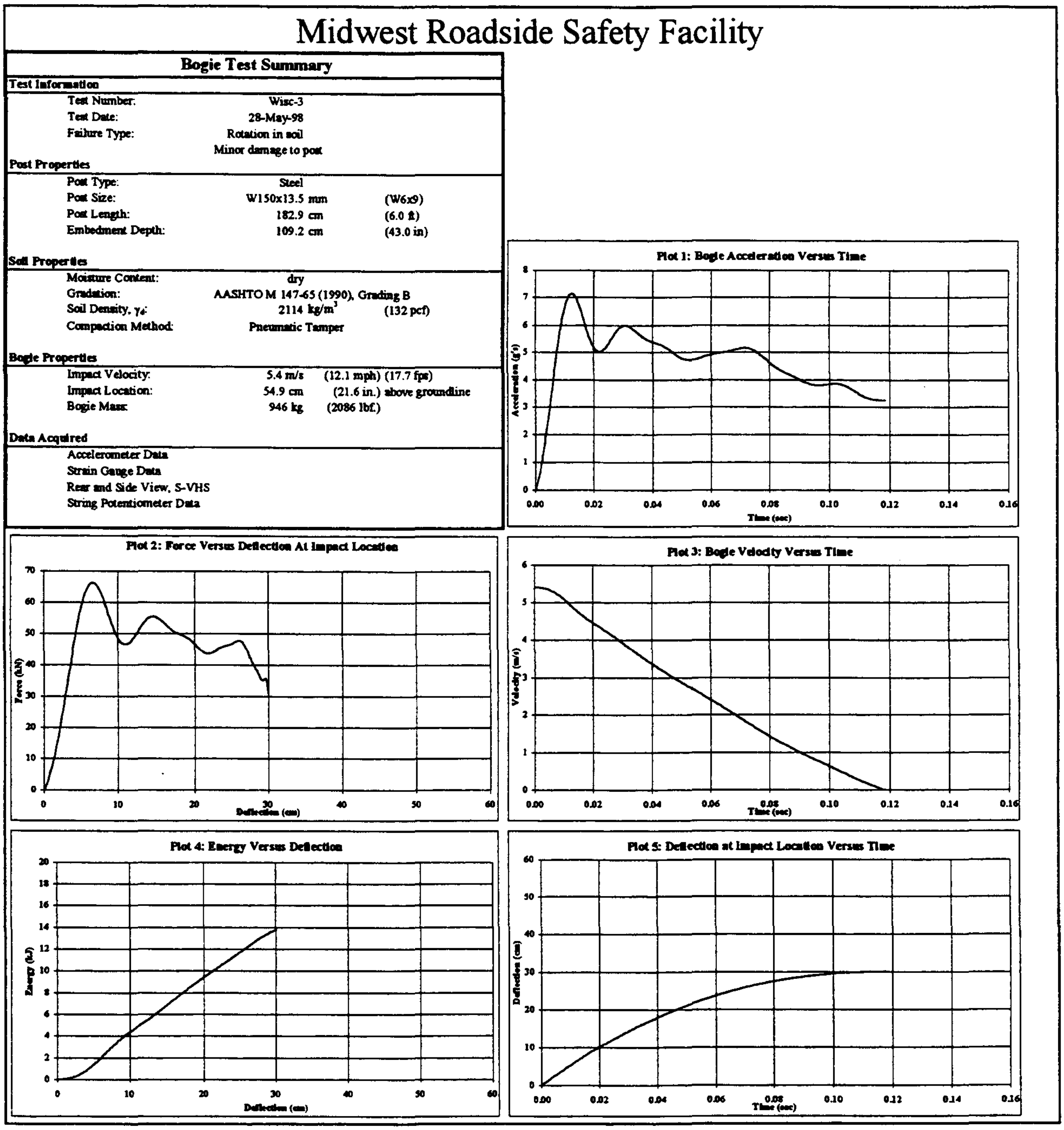
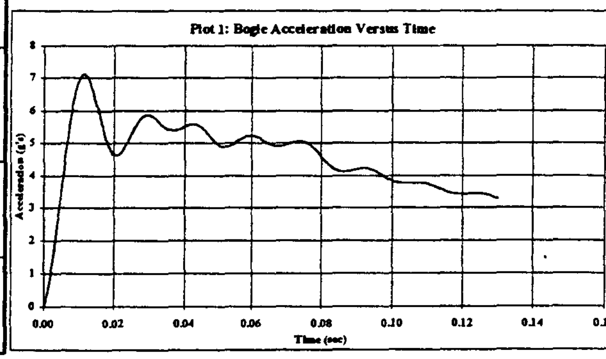


Figure 24. Results of Wisc-3.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information			
Test Number:	Wisc-4		
Test Date:	28-May-98		
Failure Type:	Rotation in soil		
	Minor damage to post		
Post Properties			
Post Type:	Steel		
Post Size:	W150x13.5 mm	(W6x9)	
Post Length:	182.9 cm	(6.0 ft)	
Embedment Depth:	109.2 cm	(43.0 in)	
Soil Properties			
Moisture Content:	dry		
Gradation:	AASHTO M 147-65 (1990), Grading B		
Soil Density, γ_d:	2243 kg/m^3	(140 pcf)	
Compaction Method:	Pneumatic Tamper		
Bogie Properties			
Impact Velocity:	5.9 m/s	(13.2 mph) (19.4 fps)	
Impact Location:	54.9 cm	(21.6 in.) above groundline	
Bogie Mass:	946 kg	(2086 lbf)	
Data Acquired			
Accelerometer Data			
Strain Gauge Data			
Rear and Side View, S-VHS			
String Potentiometer Data			



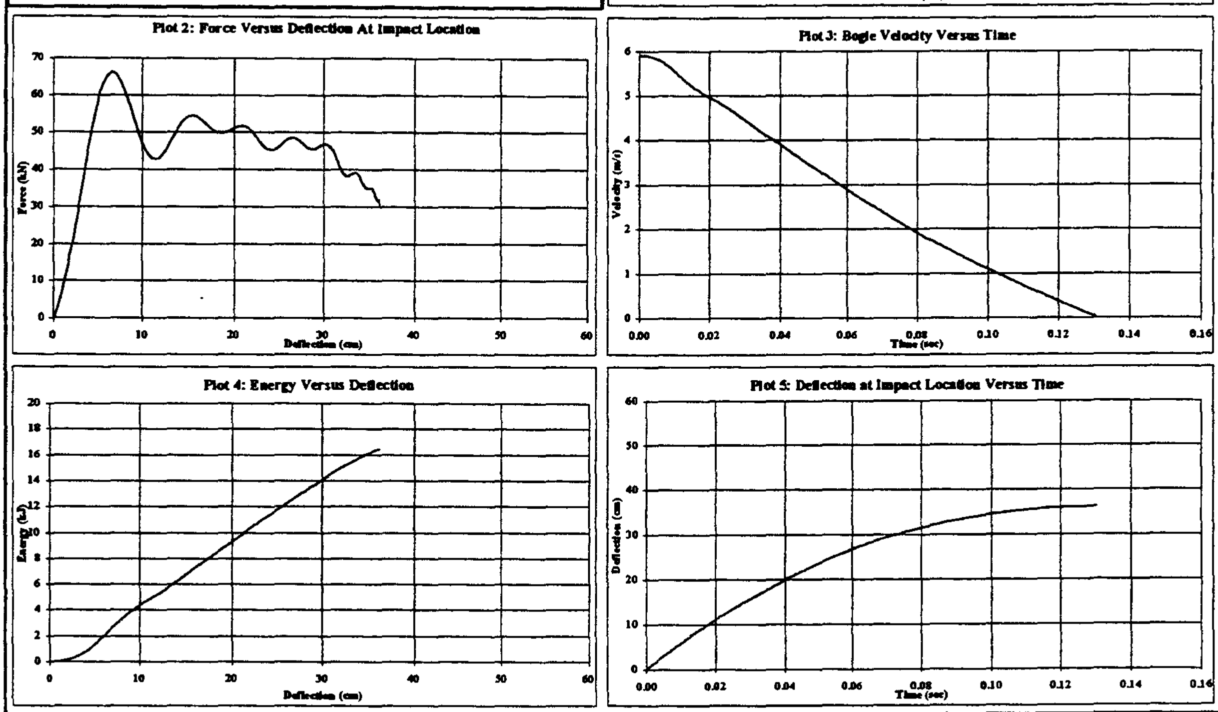
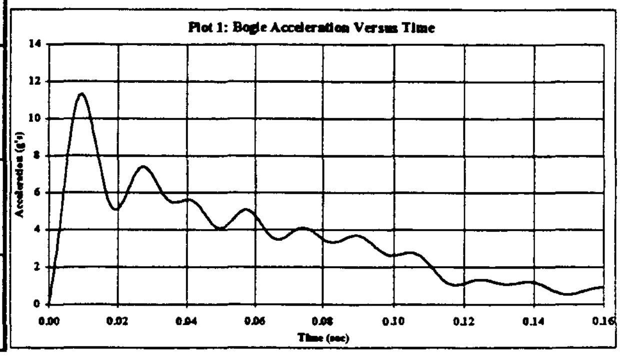


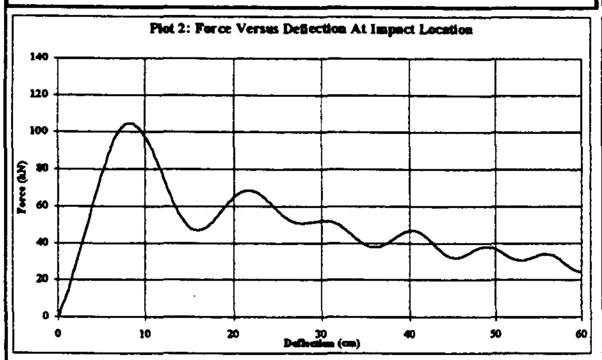
Figure 25. Results of Wisc-4.

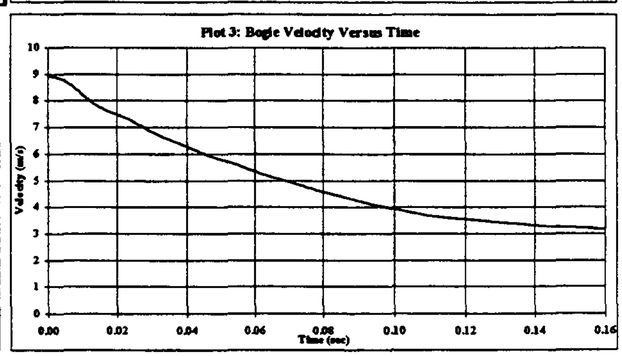
Midwest Roadside Safety Facility

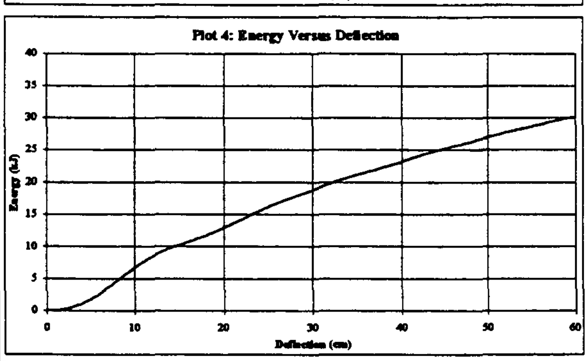
Bogie Test Summary

Test Information		
Test Number:	Wisc-5	
Test Date:	1-Jun-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x23.5 mm	(W6x16 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2082 kg/m^3	(130 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	8.9 m/s	(19.9 mph) (29.2 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Side View, S-VHS		
String Potentiometer Data		









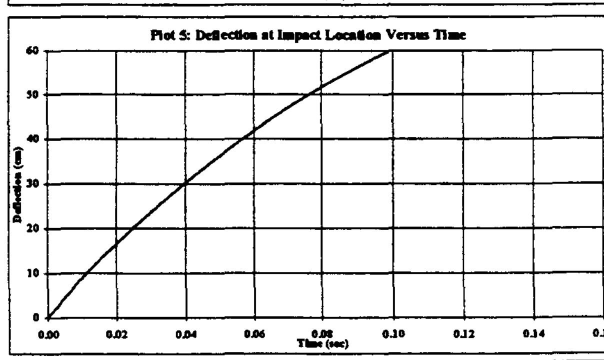
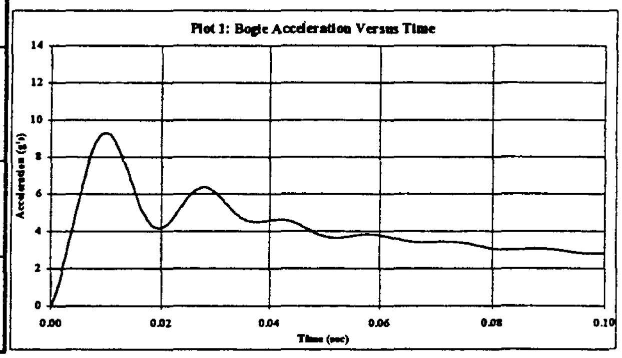


Figure 26. Results of Wisc-5.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wisc-6	
Test Date:	19-Jun-98	
Failure Type:	Rotation in Soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x23.5 mm	(W6x16)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2114 kg/m^3	(132 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	8.9 m/s	(19.9 mph) (29.2 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Side View, S-VHS		



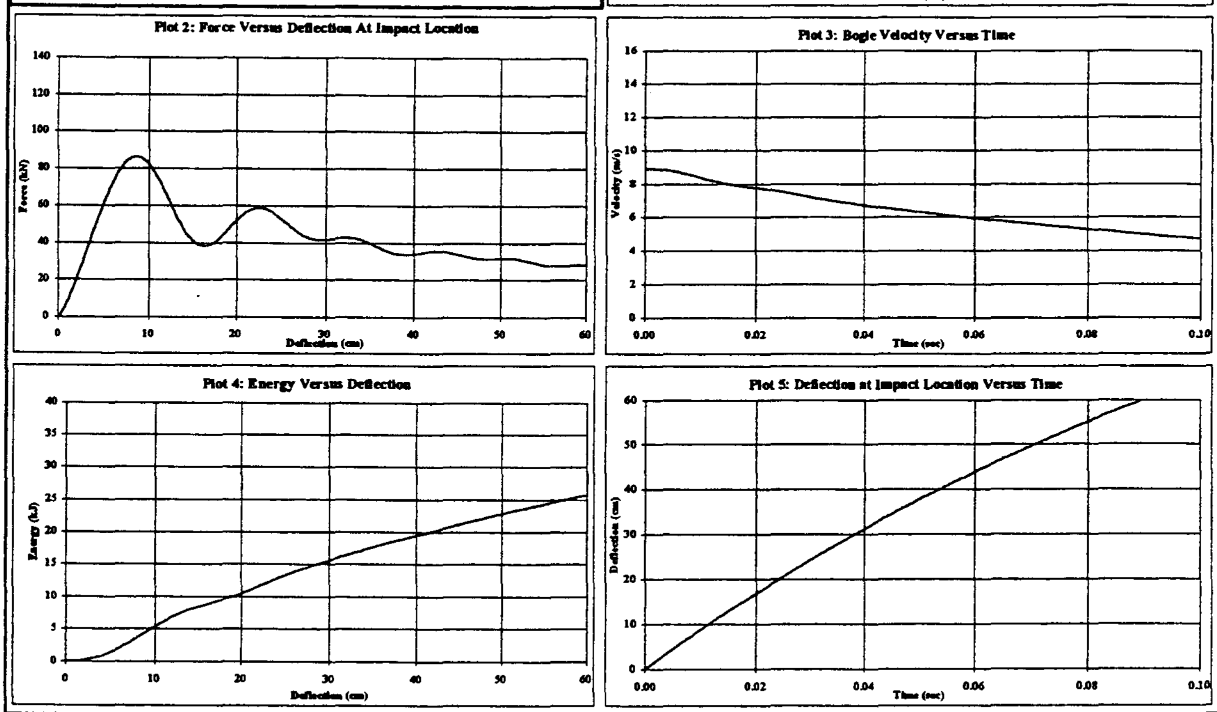


Figure 27. Results of Wisc-6.

Midwest Roadside Safety Facility

Bogie Test Summary		
Test Information		
Test Number:	Wisc-7	
Test Date:	19-Jun-98	
Failure Type:	Rotation in Soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x23.5 mm	(W6x16)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2114 kg/m^3	(132 pcf)
Compaction Method:	Pneumatic Tamper	
Data Acquired		
Side View, S-VHS		

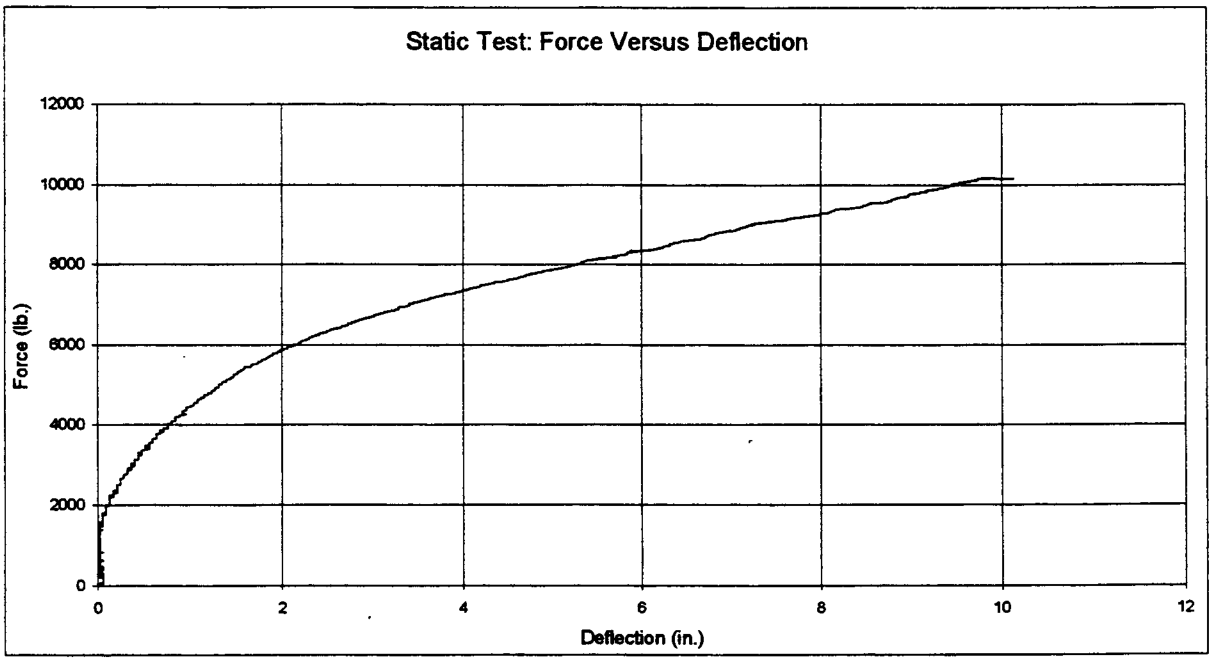


Figure 28. Results of Wisc-7.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information

Test Number:	Wisc-8	
Test Date:	8-Dec-98	
Failure Type:	Rotation in soil	

Post Properties

Post Type:	Steel - offset impact	
Post Size:	W150x23.5	(W6x16)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)

Soil Properties

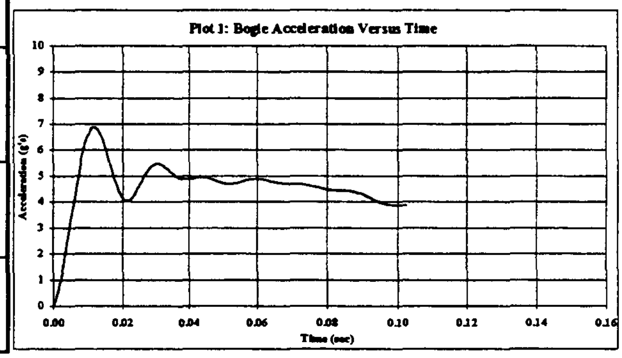
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	1986 kg/m^3	(124 pcf)
Compaction Method:	Pneumatic Tamper	

Bogie Properties

Impact Velocity:	8.9 m/s	(19.9 mph) (29.2 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)

Data Acquired

Accelerometer Data
Side View, S-VHS



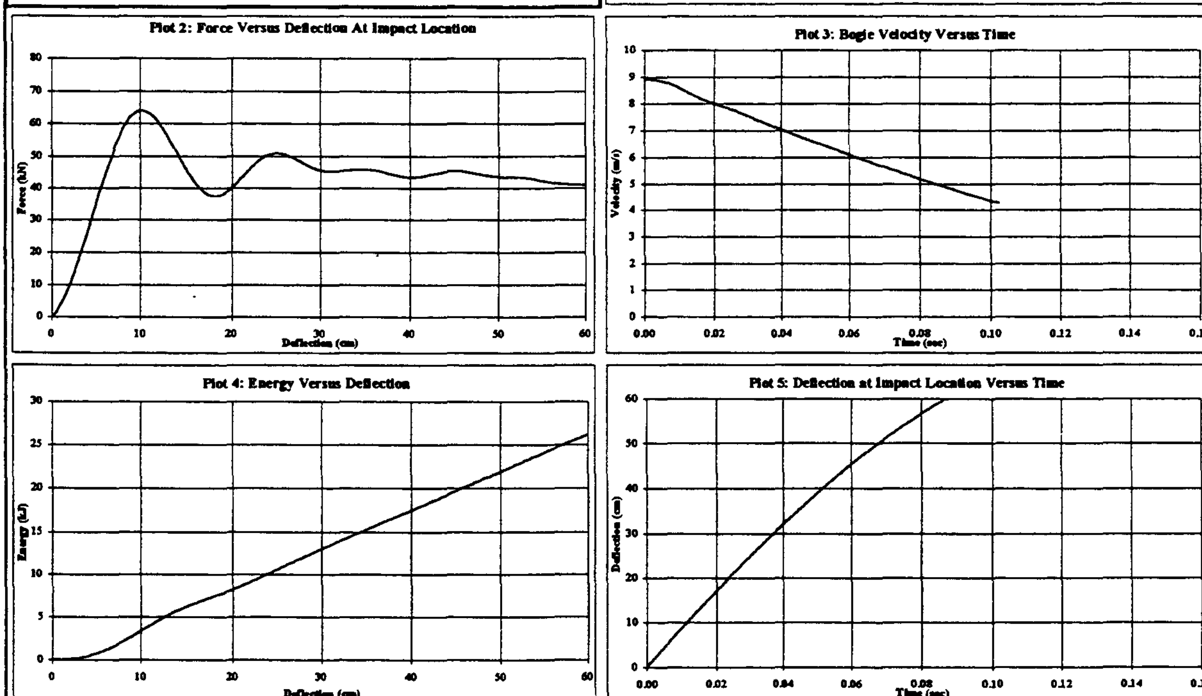
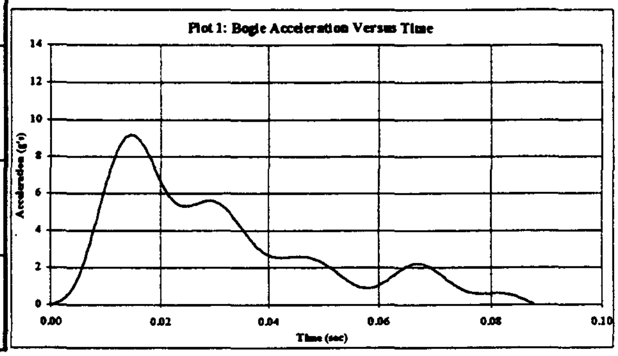


Figure 29. Results of Wisc-8.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wisc-10	
Test Date:	1-Jul-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Steel	
Post Size:	W150x23.5 mm	(W6x16)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2146 kg/m^3	(134 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	14.1 m/s	(31.5 mph) (46.3 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Side View, S-VHS and High Speed Video		
String Potentiometer Data		



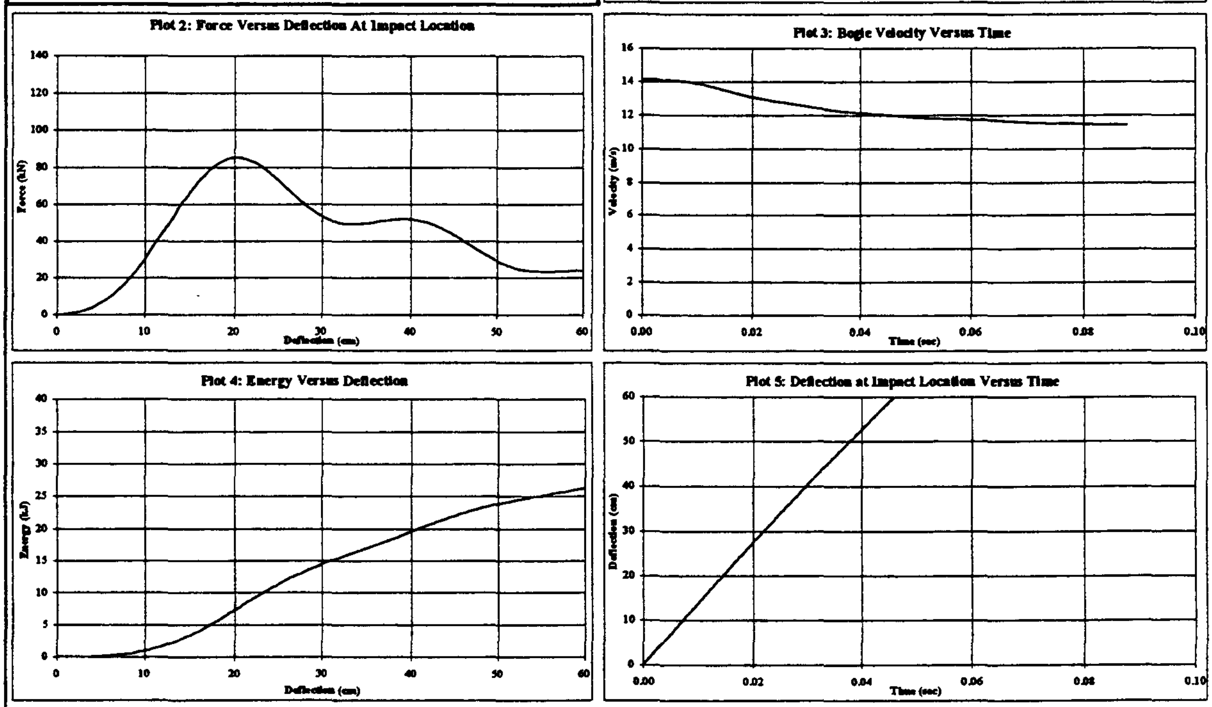
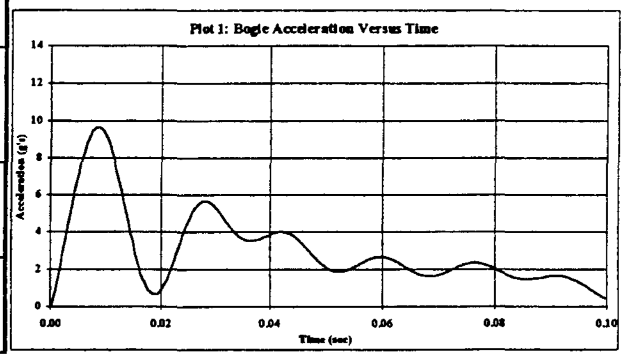


Figure 30. Results of Wisc-10.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wisc-11	
Test Date:	7-Jul-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Steel	
Post Size:	150x23.5 mm	(W6x16)
Post Length:	213.4 cm	(7.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2130 kg/m^3	(133 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	12.7 m/s	(28.4 mph) (41.7 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Side View, S-VHS		
String Potentiometer Data		



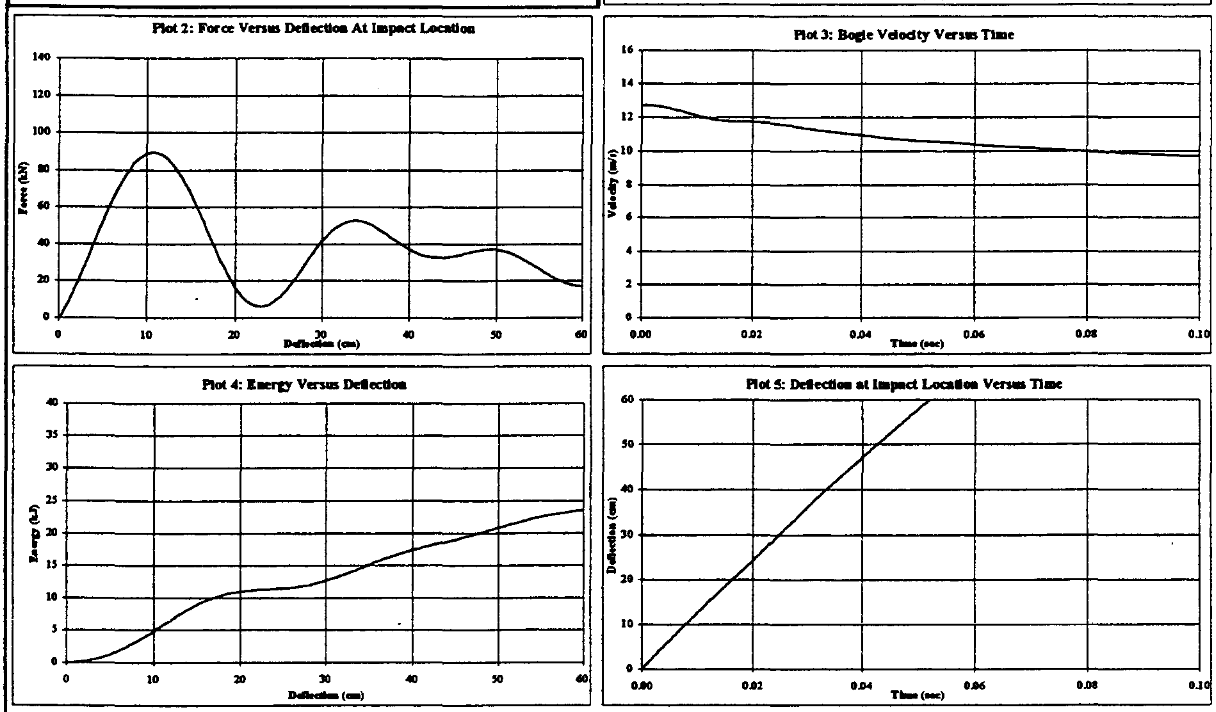


Figure 31. Results of Wisc-11.

Midwest Roadside Safety Facility

Bogie Test Summary		
Test Information		
Test Number:	Wood-1	
Test Date:	18-Nov-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Wood	
Post Size:	150x200 mm	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2146 kg/m^3	(134 pcf)
Compaction Method:	Pneumatic Tamper	
Data Acquired		
Strain Gauge Data		
Side View and S-VHS		

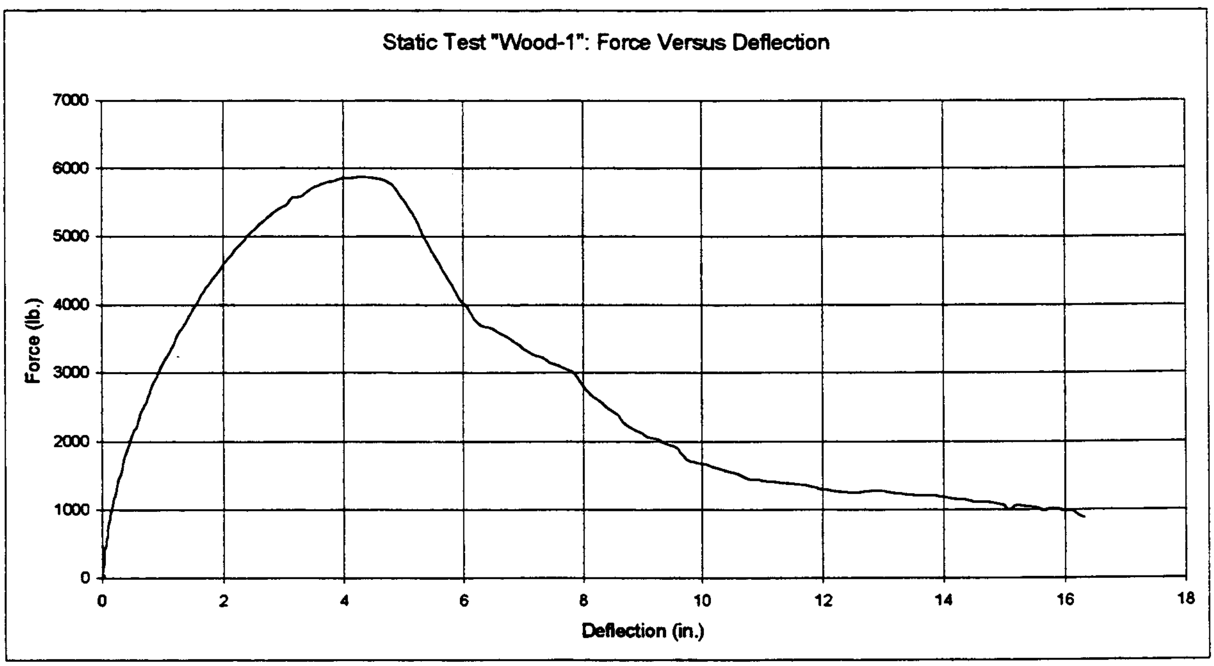


Figure 32. Results of Wood-1.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wood-2	
Test Date:	18-Nov-98	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Wood	
Post Size:	150x200 mm	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2114 kg/m^3	(132 pcf)
Compaction Method:	Pneumatic Tamper	
Data Acquired		
Side View and S-VHS		

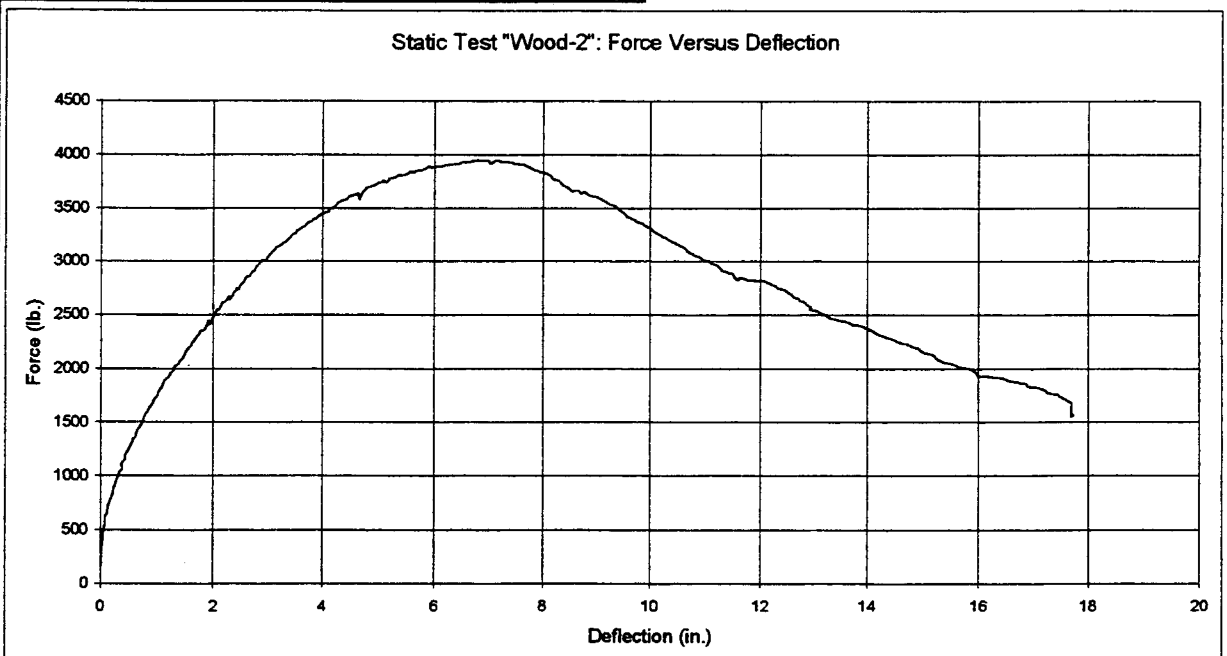


Figure 33. Results of Wood-2.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information

Test Number:	Wood-3	
Test Date:	18-Nov-98	
Failure Type:	Rotation in soil	

Post Properties

Post Type:	Wood	
Post Size:	150x200 mm	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)

Soil Properties

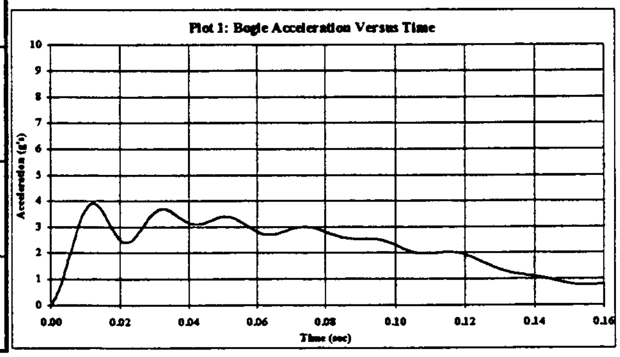
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2146 kg/m^3	(134 pcf)
Compaction Method:	Pneumatic Tamper	

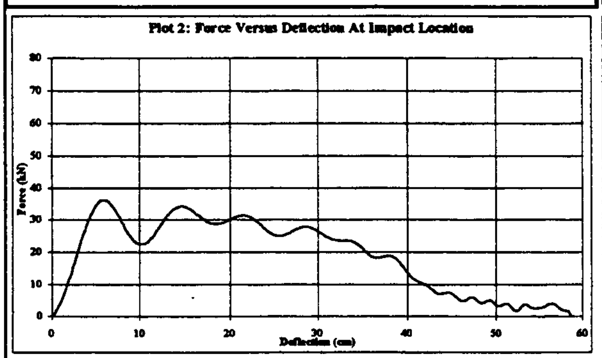
Bogie Properties

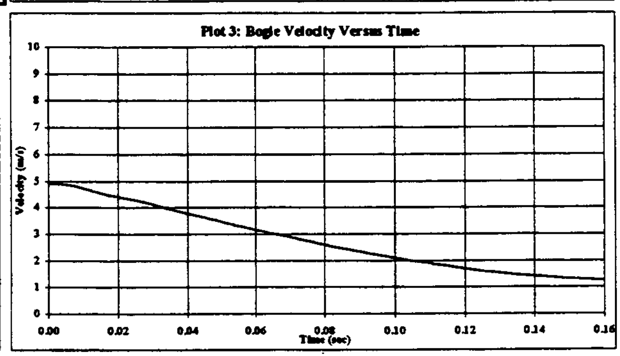
Impact Velocity:	4.9 m/s	(11.0 mph) (16.1 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)

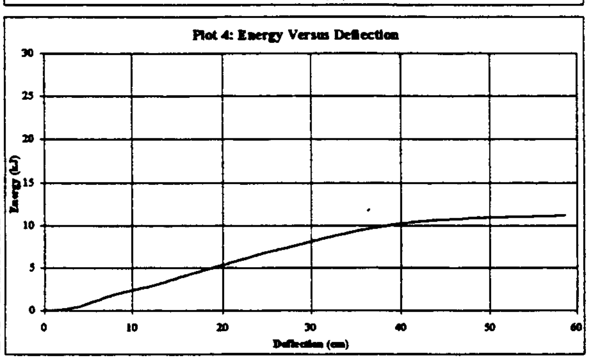
Data Acquired

Accelerometer Data
Strain Gauge Data
Side View, S-VHS and High Speed Video









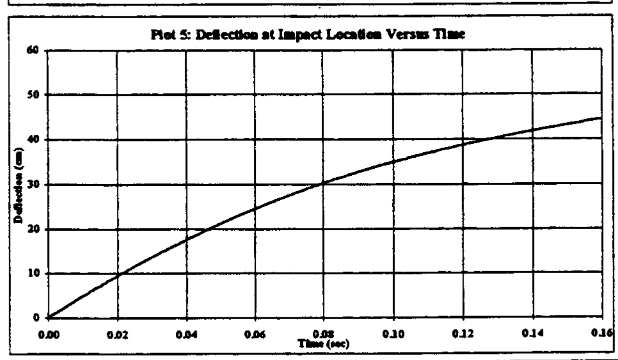
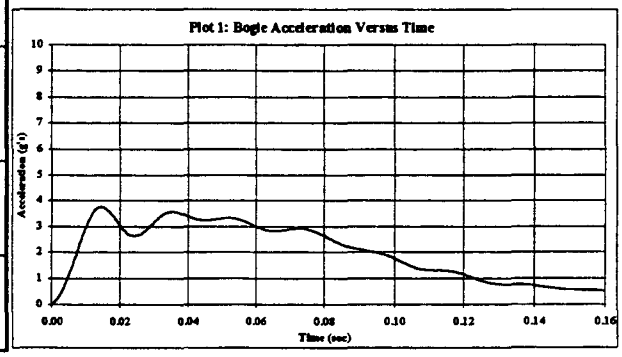


Figure 34. Results of Wood-3.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information			
Test Number:	Wood-4		
Test Date:	18-Nov-98		
Failure Type:	Rotation in soil		
Post Properties			
Post Type:	Wood		
Post Size:	150x200 mm	(6x8 in.)	
Post Length:	182.9 cm	(6.0 ft)	
Embedment Depth:	109.2 cm	(43.0 in)	
Soil Properties			
Moisture Content:	Dry		
Gradation:	AASHTO M 147-65 (1990), Grading B		
Soil Density, γ_d:	2050 kg/m^3	(128 pcf)	
Compaction Method:	Pneumatic Tamper		
Bogie Properties			
Impact Velocity:	4.8 m/s	(10.7 mph)	(15.7 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline	
Bogie Mass:	946 kg	(2086 lbf.)	
Data Acquired			
Accelerometer Data			
Strain Gauge Data			
Side View, S-VHS and High Speed Video			



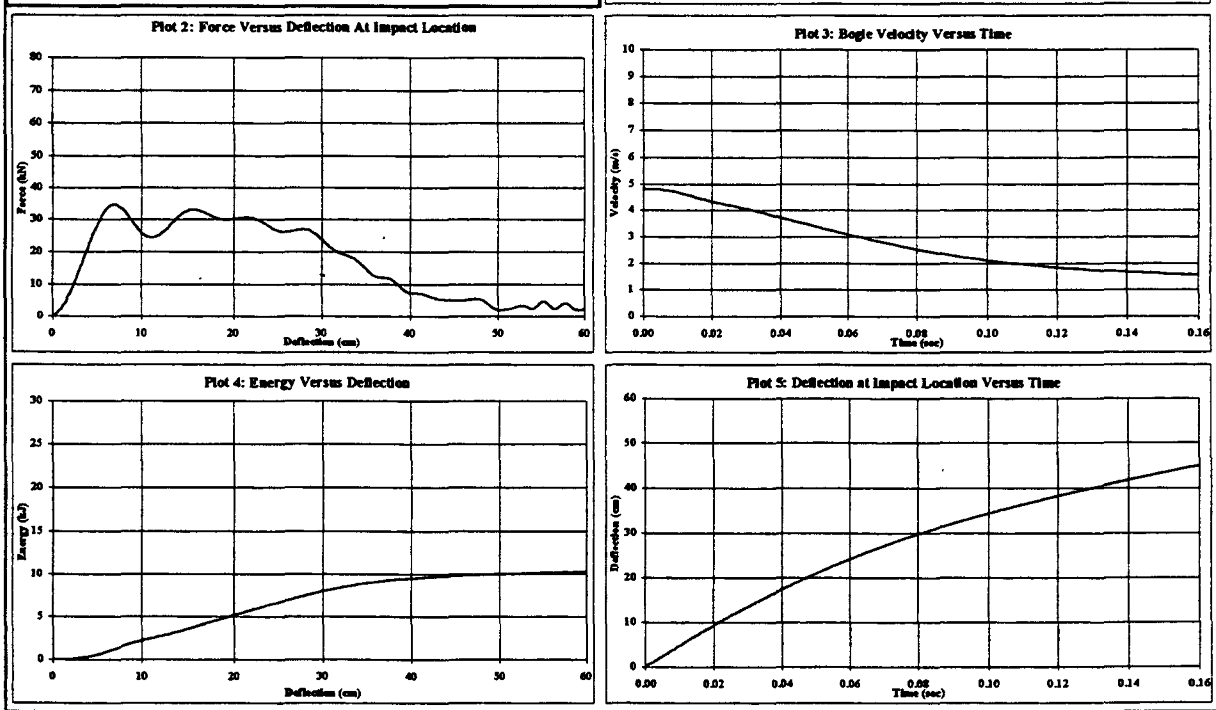
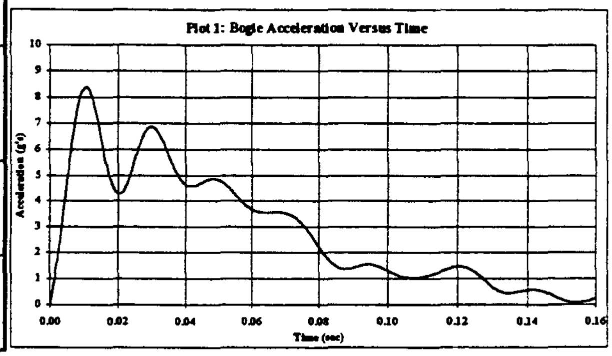


Figure 35. Results of Wood-4.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wood-5	
Test Date:	20-Nov-99	
Failure Type:	Rotation in soil	
Post Properties		
Post Type:	Wood	
Post Size:	150x200	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2146 kg/m^3	(134 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	9.6 m/s	(21.5 mph) (31.5 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Side View, S-VHS and High Speed Video		



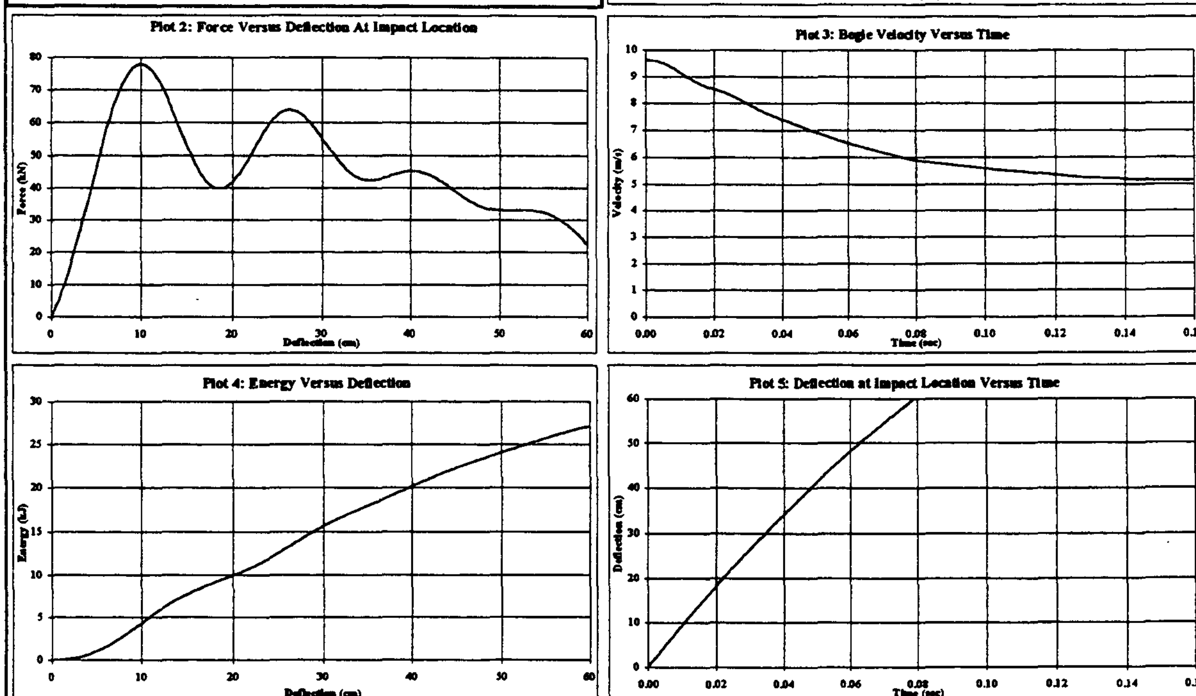
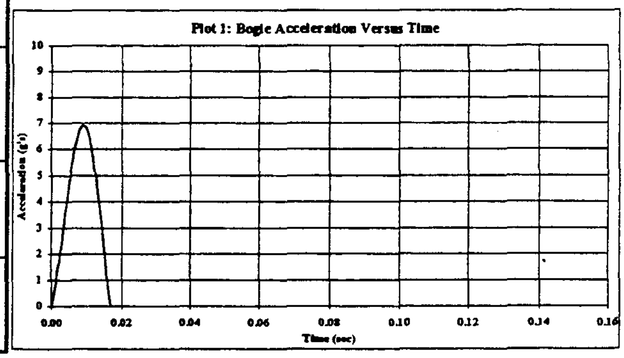


Figure 36. Results of Wood-5.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wood-6	
Test Date:	20-Nov-98	
Failure Type:	Post fracture	
Post Properties		
Post Type:	Wood	
Post Size:	150x200 mm	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2066 kg/m^3	(129 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	8.9 m/s	(19.9 mph) (29.2 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Strain Gauge Data		
Side View, S-VHS and High Speed Video		



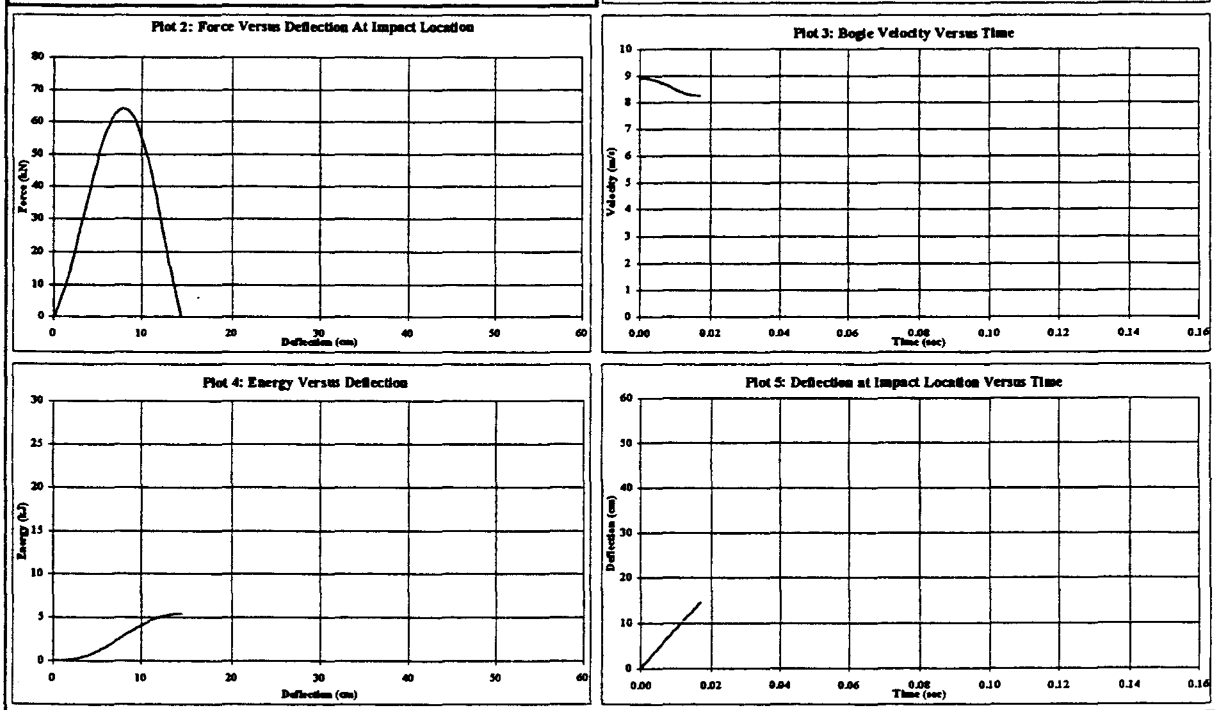
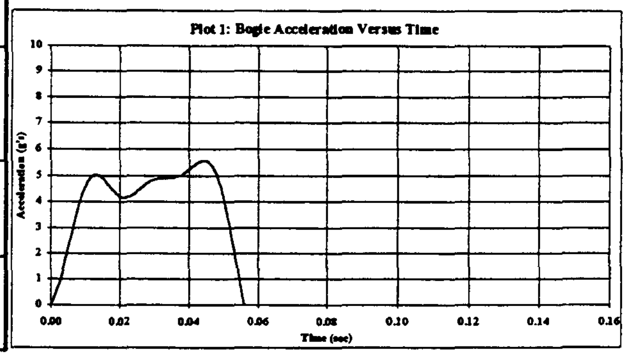


Figure 37. Results of Wood-6.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information		
Test Number:	Wood-8	
Test Date:	18-Nov-98	
Failure Type:	Post fracture	
Post Properties		
Post Type:	Wood	
Post Size:	150x200	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)
Soil Properties		
Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2211 kg/m^3	(138 pcf)
Compaction Method:	Pneumatic Tamper	
Bogie Properties		
Impact Velocity:	6.0 m/s	(13.4 mph) (19.7 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)
Data Acquired		
Accelerometer Data		
Side View, S-VHS		



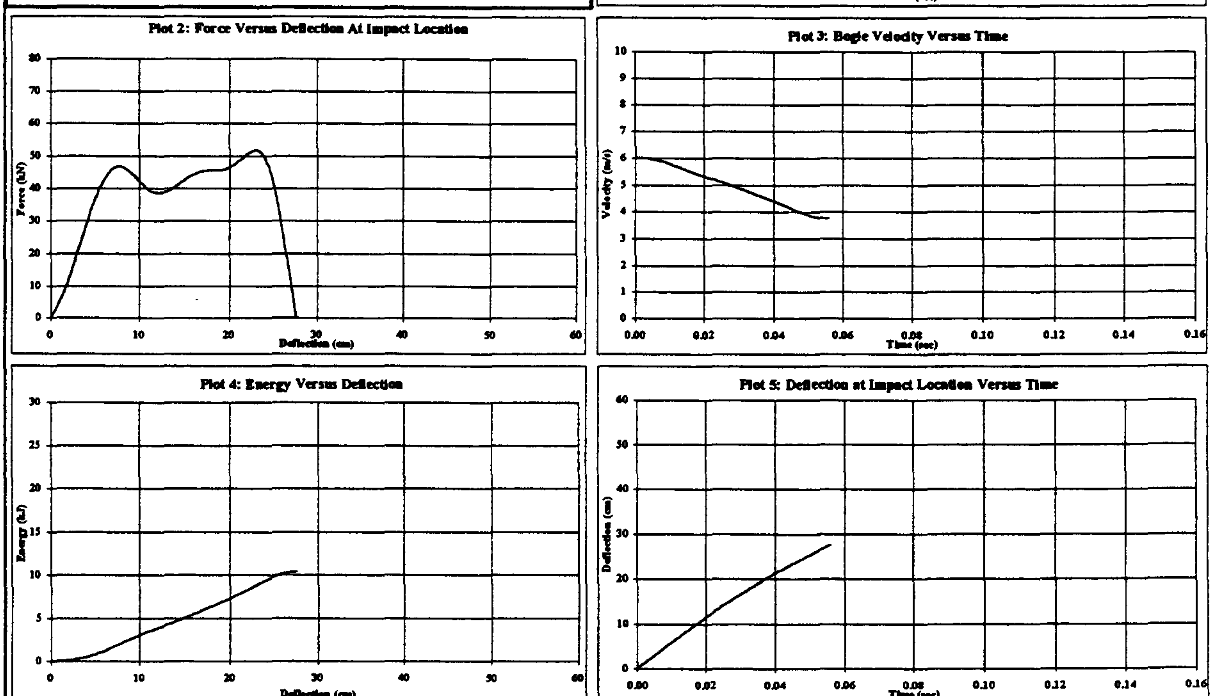


Figure 38. Results of Wood-8.

Midwest Roadside Safety Facility

Bogie Test Summary

Test Information

Test Number:	Wood-9	
Test Date:	18-Nov-98	
Failure Type:	Post Failure	

Post Properties

Post Type:	Wood	
Post Size:	150x200	(6x8 in.)
Post Length:	182.9 cm	(6.0 ft)
Embedment Depth:	109.2 cm	(43.0 in)

Soil Properties

Moisture Content:	Dry	
Gradation:	AASHTO M 147-65 (1990), Grading B	
Soil Density, γ_d:	2211 kg/m^3	(138 pcf)
Compaction Method:	Pneumatic Tamper	

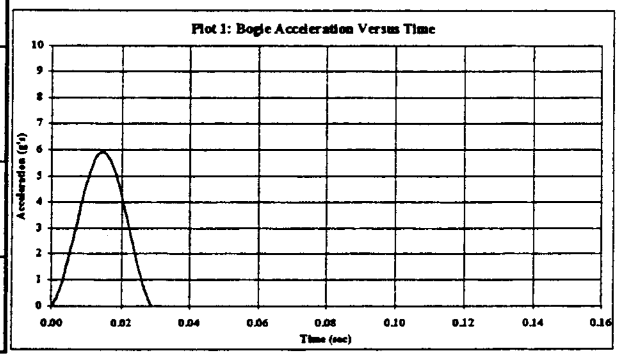
Bogie Properties

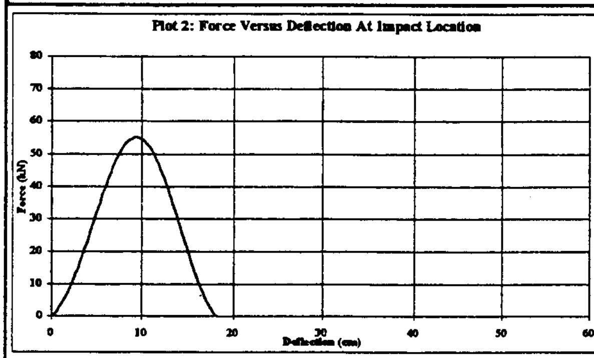
Impact Velocity:	6.7 m/s	(15.0 mph) (22.0 fps)
Impact Location:	54.9 cm	(21.6 in.) above groundline
Bogie Mass:	946 kg	(2086 lbf.)

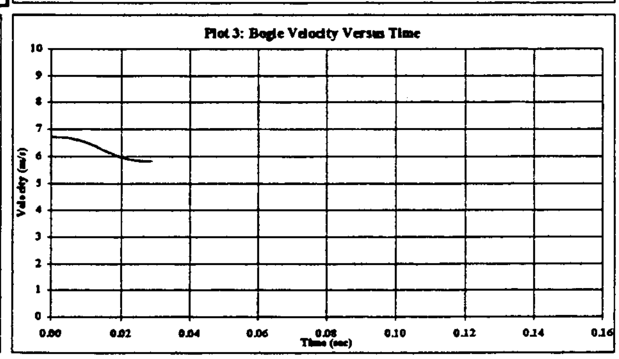
Data Acquired

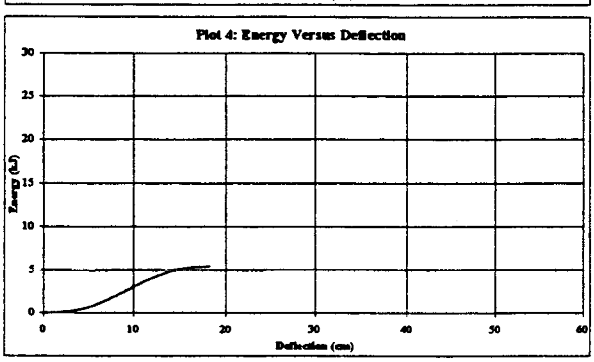
Accelerometer Data

Side View, S-VHS









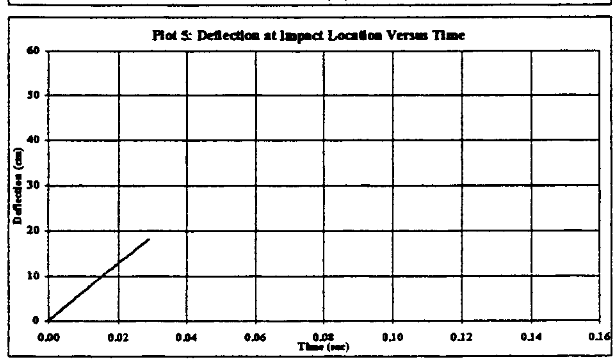


Figure 39. Results of Wood-9.

7 SUMMARY AND CONCLUSIONS

Nine wide-flange steel posts and six wooden posts were impacted in order to provide data about the post-soil interaction of guardrail posts rotating in soil. The posts were impacted in soil conforming to AASHTO M 147-65 Gradation "B" specifications.

In all nine steel post impacts, soil failure was the primary mode of failure. Differences in soil behavior were observed between test speeds of 5.5 and 8.9 m/s (12.3 and 20 mph). At higher speeds, the peak force and the amount of energy absorbed increased. However, no measurable differences in behavior were observed between test speeds of 8.9 and 13.4 m/s (12.3 and 30 mph).

In the wooden post impacts, soil failure only occurred in the 4.8, 4.9, and 9.6 m/s (10.7, 11.0, and 21.5 mph) impacts while post failure occurred in the 6.0, 6.7, and 8.9 m/s (13.4, 15.0, and 19.9 mph) impacts. Post failure is attributed primarily to stress concentrations induced by the instrumentation of the posts, inherent variations in wood quality, and gradation variations within AASHTO M 147-65 (1990) Gradation "B" specifications. It should be noted that the sampling size is too small to make a statistical analysis in either the wooden or steel post impacts.

8 RECOMMENDATIONS AND FUTURE WORK

The nine wide-flange steel posts and six wooden posts successfully impacted in this study provided data about the post-soil interaction of guardrail posts rotating in soil. It is suggested that the research herein be further expanded using the data collection methods utilized in order to provide further information about the nature of the post-soil interaction.

Identification of the rotation point of the post throughout impact, as well as correlation of the bogie accelerometer data with string potentiometer and strain gauge data, is required to further understand post-soil interaction. Further analysis of this data, as well as examining the effects of varying soil type and gradation, is also recommended.

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