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16. Abstract

The purpose of this study was to optimize the design of SDHPT metal beam guard fence GF(TD)-87, in terms of safety and cost. Parameters evaluated in the study included embedment depth of the post, post spacing, and the depth of the blockout. Extensive use of the BARRIER VII computer program was made in the evaluation of these parameters. As a result of the computer study, it was concluded that the present design could be optimized by increasing the post spacing from 6 ft-3 in. to 8 ft-4 in., thus eliminating 25 percent of the posts in a guard fence installation. All other details remain unchanged.

A series of full-scale vehicular crash tests was conducted to verify the computer results. Tests of the round wood post (no blockout) system and the steel post (with blockout) system were conducted with both systems having posts spaced at 8 ft-4 in. The tests were conducted and evaluated in accordance with nationally recognized guidelines. Although significant wheel snag was observed in some of the tests, the two optimized barrier systems satisfactorily met NCHRP Report 230 evaluation criteria.

It was concluded that the improved metal beam guard fence designs have safety performance comparable to standard designs and reduce costs by approximately 10-15 percent.

The study also addressed the length of need for guard fence and flare rates for the ends of guard fence. Recommended flare rates were developed and presented. Results of the study on guard fence length of need were inconclusive.

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OPTIMIZATION OF STRONG POST W-BEAM GUARDRAIL

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Research Report 1147-1F

on

Research Study No. 2-8-88-1147
Optimization of Guard Fence Design and Use

Sponsored by

Texas State Department of Highways and Public Transportation

in cooperation with

The U. S. Department of Transportation
Federal Highway Administration

November 1988

Texas Transportation Institute
Texas A&M University
College Station, Texas

METRIC (SI*) CONVERSION FACTORS

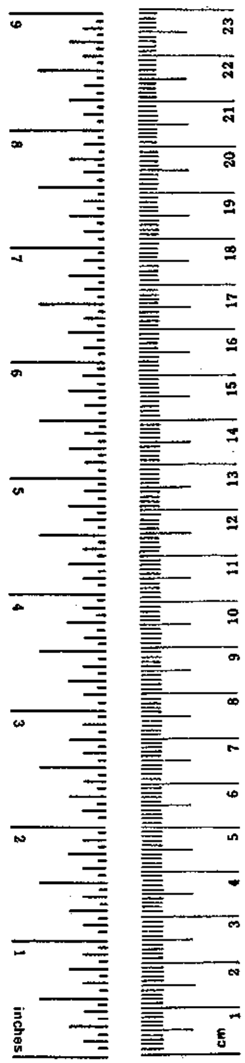
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

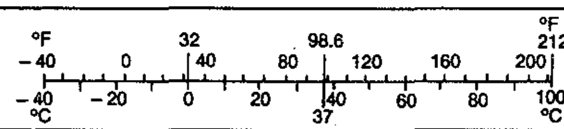
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

DISCLAIMER

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

KEY WORDS

Guardrail, Computer Simulation, Full Scale Crash Test, Benefit/Cost Analysis

ACKNOWLEDGMENTS

This research study was conducted under a cooperative program between the Texas Transportation Institute (TTI), the Texas State Department of Highways and Public Transportation (SDHPT), and the Federal Highway Administration (FHWA). Mark Marek and Harold Cooner of the SDHPT worked closely with the researchers, and their comments and suggestions are appreciated.

IMPLEMENTATION STATEMENT

Optimized guard fence designs developed in this study are recommended for immediate incorporation into the SDHPT standard specifications. Field performance of the new designs should be monitored to identify any potential problems with the optimized designs.

ABSTRACT

The purpose of this study was to optimize the design of SDHPT metal beam guard fence, GF(TD)-87, in terms of safety and cost. Parameters evaluated in the study included embedment depth of the post, post spacing, and the depth of the blockout. Extensive use of the BARRIER VII computer program was made in the evaluation of these parameters. As a result of the computer study, it was concluded that the present design could be optimized by increasing the post spacing from 6 ft-3 in. to 8 ft-4 in., thus eliminating 25 percent of the posts in a guard fence installation. All other details remain unchanged.

A series of full-scale vehicular crash tests was conducted to verify the computer results. Tests of the round wood post (no blockout) system and the steel post (with blockout) system were conducted with both systems having posts spaced at 8 ft-4 in. The tests were conducted and evaluated in accordance with nationally recognized guidelines. Although significant wheel snag was observed in some of the tests, the two optimized barrier systems satisfactorily met NCHRP Report 230 evaluation criteria.

It was concluded that the improved metal beam guard fence designs have safety performance comparable to standard designs and reduce costs by approximately 10-15 percent.

The study also addressed the length of need for guard fence and flare rates for the ends of guard fence. Recommended flare rates were developed and presented. Results of the study on guard fence length of need were inconclusive.

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INTRODUCTION

Standards for guard fence design and use have not changed significantly during the last two decades. Much research conducted during this period has indicidated that current guardrail design and placement criteria can be optimized to reduce costs associated with guard fence use. A recent study of the structural performance of strong post W-beam guardrails indicated that post spacings for standard guard fence could be significantly increased without affecting the barrier's safety performance (1). Increasing guard fence post spacing was shown to reduce construction costs by as much as 10 percent. Since the Texas State Department of Highways and Public Transportation (TSDHPT) installs over 750,000 ft of guardrail each year, reducing construction costs as little as 10 percent would result in an annual savings of over half a million dollars.

Guard fence placement criteria can also be improved to reduce construction and repair costs. Although Texas' guard fence design standards include both wood and steel post systems, little guidance is given regarding the proper applications of each system. Historically, due to the low cost of the wood post design, most highway districts have used this system almost exclusively. However, problems associated with wood post rotting have recently caused concern regarding the appropriate policy associated with guard fence post selection. Evaluation of the extent of wood post rotting problems should reduce guardrail maintenance costs arising from post rotting as well as reducing construction costs by eliminating the improper use of steel posts.

Another area where guard fence placement criteria can be improved is in determination of length of barrier need. Current procedures for calculating length of need are based on a somewhat subjective evaluation of roadside accidents. A more objective procedure for determining appropriate barrier runout lengths involves incorporating sophisticated benefit cost analysis procedures to determine optimum length of barrier need (2). Optimization of barrier runout lengths should lead to a better allocation of safety dollars by assuring that guard fence construction funds are used in a cost beneficial manner.

Therefore, a study was undertaken in an effort to conduct a thorough economic evaluation of guard fence design and use. The primary objectives of this study were to 1) optimize the structural design of W-beam guard fence in an effort to reduce costs without adversely affecting impact performance, 2.) use an economic evaluation of steel and wood post guard fence designs to determine where each is most cost beneficial, and 3.) conduct a benefit cost analysis of barrier length of need to determine optimum guard fence runout lengths.

DESIGN OPTIMIZATION

The overall goal of a structural optimization procedure is to reduce the labor and materials required to build a particular structure without sacrificing performance. The basic concept behind structural optimization is that, since a structure is only as strong as its weakest link, all other members in the structure are overdesigned. Thus, the size of noncritical members can be reduced, thereby reducing construction costs without affecting performance of the design. When a structure is completely optimized, every element in the design becomes a weakest link or critical member under some design load condition.

A structural optimization procedure consists of four basic phases, 1) selection of load conditions, 2) identification of design parameters to be included in the optimization study, 3) analysis of the performance of alternative designs, and 4) selection of the most cost beneficial design. The application of each of these phases to optimization of the design for W-beam guard fence is presented below.

Selection of Load Conditions

Longitudinal barrier performance is measured in terms of the range of vehicular impact conditions for which the barrier can safely redirect errant vehicles. Nationally recognized performance standards, established by NCHRP Report 230 (3), require that roadside barriers must be capable of redirecting full-size automobiles weighing 4,500 lb, impacting at 60 mph and an angle of 25 degrees and mini-size vehicles weighing 1800 lb impacting at 60 mph and an angle of 15 degrees. An optimized barrier must demonstrate this minimum level of performance. However, recent accident analysis studies have indicated that the frequency of barrier accidents involving impact angles above 15 degrees may be higher than that indicated by prior research. As a result, most longitudinal barriers are now expected to perform for impacts 60 mph and 20 degrees with mini-size vehicles. Therefore, it was decided to select 4,500 lb/60 mph/25 deg. and 1,800 lb/60 mph/20 deg. as the two design loading conditions for the optimized guard fence design.

Design Parameter Selection

Economic considerations prohibit the complete optimization of most structural designs. For example, there are only a limited number of structural steel shapes that are available for use in a steel structure. As a result of the high cost associated with the use of nonstandard structural shapes, any optimization procedure must be limited to commonly available members. Similarly, a W-beam guard fence optimization study is limited to the use of W-beam as a rail element. Remaining design parameters can then be optimized include post spacing, post size and embedment depth, blockout size, and rail height.

A recent analytical study of W-beam optimization investigated all of these W-beam design parameters (1). Results of this study showed that the rail height of 27 in. used in current guard fence designs is very near the optimal height. The appropriateness of the 27 in. rail height is further demonstrated by comparing the midheight of standard guard fence to the center of gravity heights of modern automobiles. Ideally, the center of the guardrail element should be as close as possible to the center of gravity of impacting vehicles. As shown in Table 1, the 21 in. guardrail midheight is very near the center of gravity heights of most classes of automobiles. Therefore, guardrail height was excluded from the design parameters to be included in the optimization study.

Remaining guardrail design parameters and the associated variations included in the optimization study are presented in Table 2. Note that alternate post spacings investigated were limited to two and three posts per 25 ft section of guardrail. Additional findings from reference 1 indicate that the primary effect of blockout depth is to move guardrail posts away from an impacting vehicle's tire path. Thus, blockout size required to reduce or prevent wheel snag can be determined from the results of the evaluation study and need not be included directly in the analysis.

Barrier Performance Analysis

The high cost of testing precludes evaluation of potential barrier design alternatives through full scale crash tests. The best remaining alternative is to use computer simulation programs to analyze barrier performance. Barrier VII, HVOSM, and GUARD are the only sophisticated computer programs that have been successfully used to analyze guard fence impact performance. Barrier VII is a two dimensional vehicle/barrier simulation model that has been shown to be capable of accurately predicting vehicle trajectory, barrier deflection, and wheel snagging (4,5). HVOSM and GUARD are three dimensional simulation models that are commonly used when vehicle underride and override are a primary concern. However, as presented in reference 1, these phenomenon were not predicted by the GUARD program for the types of barriers under consideration. Therefore, the added level of complexity associated with the 3-D models was not considered to be warranted for this study and Barrier VII was chosen for analyzing performance of guard fence design alternatives.

Although Barrier VII has been successfully used to simulate impacts with a variety of flexible barriers, its use in studying the performance of guard fence mounted on round wood posts has been somewhat limited. Therefore, the first step in analyzing the

TABLE 1. TYPICAL CENTER OF GRAVITY HEIGHTS FOR VARIOUS SIZED VEHICLES

	Vehicle C.G. Height (in.)
Full-Size Sedan	21–24
Mid-Size Sedan	20–23
Mini-Size Sedan	19–22

TABLE 2. OPTIMIZATION DESIGN PARAMETERS

	Variations in W-beam Design Parameters		
Post Spacing (ft.)	6.25	8.33	12.50
Blockout Depth (in.)	0.0	6.0	12.0
Post Embedment (in.)	38.0	48.0	

performance of alternate guard fence designs was to conduct a limited validation of Barrier VII for simulation of impacts with Texas standard guard fence. Two full scale crash tests of Texas standard guard fence incorporating 7 in. round wood posts were selected from reference 6 for use in the validation effort. These tests involved angular impacts with the guard fence near a new end treatment. As a result, posts in the impact region were weakened with 2 7/8 in. diameter holes drilled at the ground line and 18 in. below ground line. Post properties used in the Barrier VII simulations are shown in Table 3. Note that one of the referenced crash tests involved movement of the end anchor. For purposes of simulating this crash test, a longitudinal anchor stiffness of 12,000 lb/in. was used in the Barrier VII analysis.

The first validation test involved a 1,780 lb vehicle striking the guard fence 6.25 ft from the end at a speed of 59.1 mph and 15.6 deg. The test vehicle was smoothly redirected with only minor wheel snagging. The simulation program was able to accurately predict barrier deformations, vehicle trajectory, and the degree of wheel snagging for this test. Table 4 summarizes the correlation between the Barrier VII simulation and test results. Figure 1 shows simulated and measured vehicle trajectories for this test.

The second test selected for use in the validation effort involved a 4,410 lb vehicle impacting the guardrail 12.5 ft. from the end at a speed of 58.9 mph and an angle of 24.9 deg. The guardrail end anchor was displaced approximately 3 in. during this test and, as a result, barrier deflection and wheel snagging was somewhat more significant than expected. However, by incorporating a flexible anchorage system, the Barrier VII simulation program was able to accurately predict vehicle trajectory, barrier deformations, and the extent of wheel snagging. Table 5 summarizes the results of this simulation and Figure 2 shows measured and predicted vehicle trajectories for this test.

Based on the findings of this limited simulation effort and the extensive validation efforts reported elsewhere (4,5), the Barrier VII program was considered to be sufficiently accurate for analyzing the performance of alternate guard fence designs. The next phase of the simulation effort involved determination of impact locations to maximize the potential for wheel snag on a guard fence post. This study involved using Barrier VII to simulate a large number of impact locations for each of the post spacings and embedments to be considered in the optimization study. Results of this effort indicated that the critical impact location was primarily influenced by post spacing. Table 6 shows the critical impact locations used for the remainder of the simulation effort. Note that for full-size vehicle

TABLE 3. POST PARAMETERS FOR BARRIER VII SIMULATION

(Effective Rail Height = 21")

MATERIAL	WOOD	STEEL
SIZE	7" Diam.	W6 X 8.5
k_A (k/in.)	2.9	1.15
k_B (k/in.)	2.9	2.46
M_A (in-k)	256.	256.2
M_B (in-k)	256.	107.1
F_A (k)	12.2	5.1
F_B (k)	12.2	12.2
Δ_A (in.)	18.	13.6
Δ_B (in.)	18.	13.2

A – Denotes Longitudinal or Major Axis

B – Denotes Transverse or Minor Axis

k – Stiffness of Post For Elastic Horizontal Deflections

M – Base Moment At Which Post Yields

F – Shear Force Causing Failure of Post

Δ – Deflection Causing Failure of Post

TABLE 4. BARRIER VII VALIDATION RESULTS FOR TEST 9429-1 (6)
Impact Conditions: 1780 lb/59.1 mph/15.6 deg

TEST PARAMETERS	MEASURED	SIMULATED
MAXIMUM RAIL DEFLECTION (ft)	1.2	1.3
LENGTH OF RAIL DEFORMATION (ft)	16.8	15.6
EXIT SPEED (mph)	52.3	47.1
EXIT ANGLE (deg)	7.7	9.7
LONGITUDINAL ACCELERATION (g)*	3.8	3.1
LATERAL ACCELERATION (g)*	7.2	5.1

* MAX. 50 msec AVG.

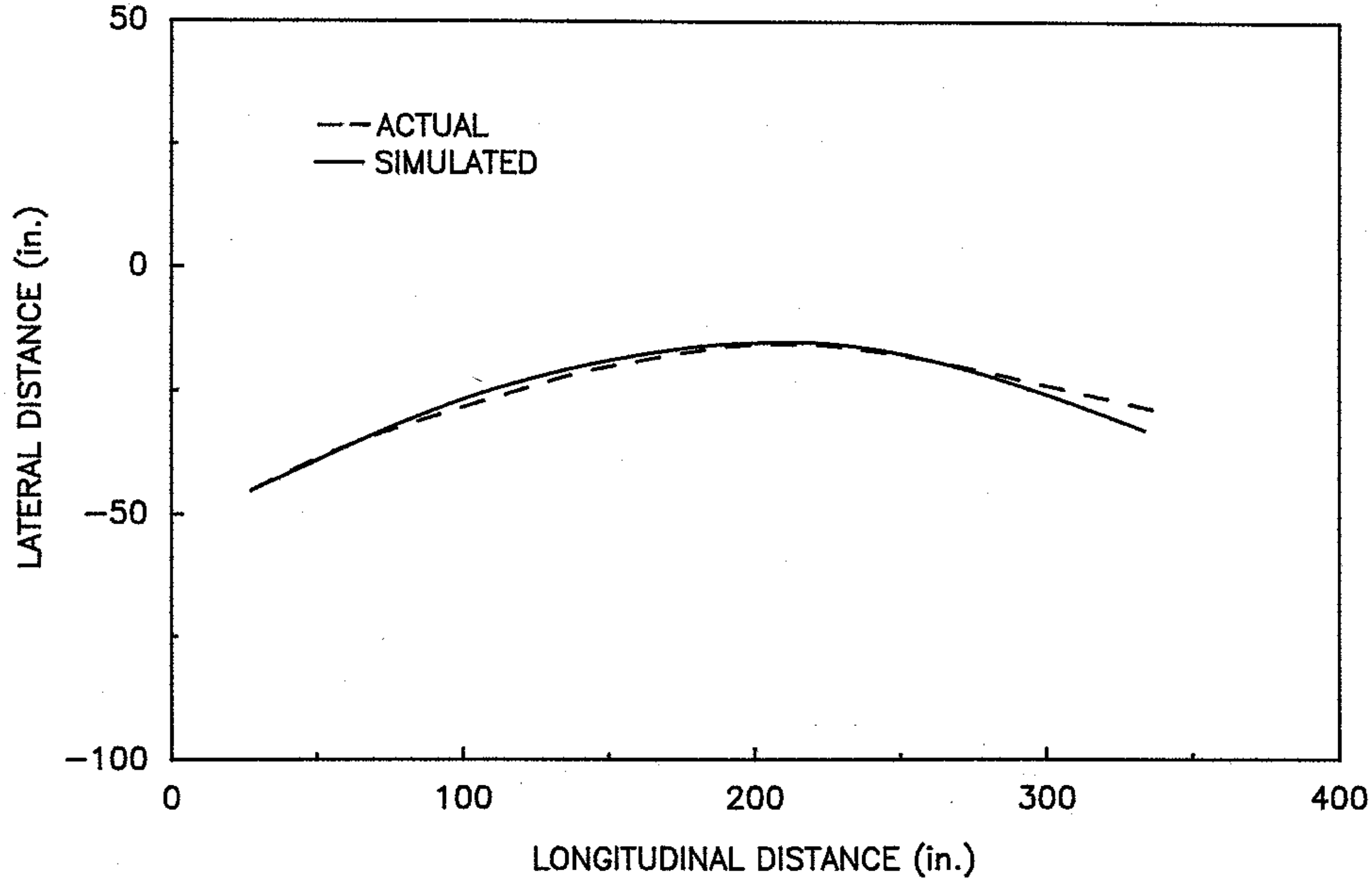


FIGURE 1. COMPARISON OF VEHICLE TRAJECTORY WITH BARRIER VII SIMULATION FOR TEST 9429-1 (6)

TABLE 5. BARRIER VII VALIDATION RESULTS FOR TEST 9429-2 (6)
Impact Conditions: 4410 lb/58.9 mph/24.9 deg

TEST PARAMETERS	MEASURED	SIMULATED
MAXIMUM RAIL DEFLECTION (ft)	3.6	3.4
LENGTH OF RAIL DEFORMATION (ft)	40.6	39.4
EXIT SPEED (mph)	38.1	35.8
EXIT ANGLE (deg)	5.3	9.5
LONGITUDINAL ACCELERATION (g)*	4.9	4.6
LATERAL ACCELERATION (g)*	6.4	5.0

* MAX. 50 msec AVG.

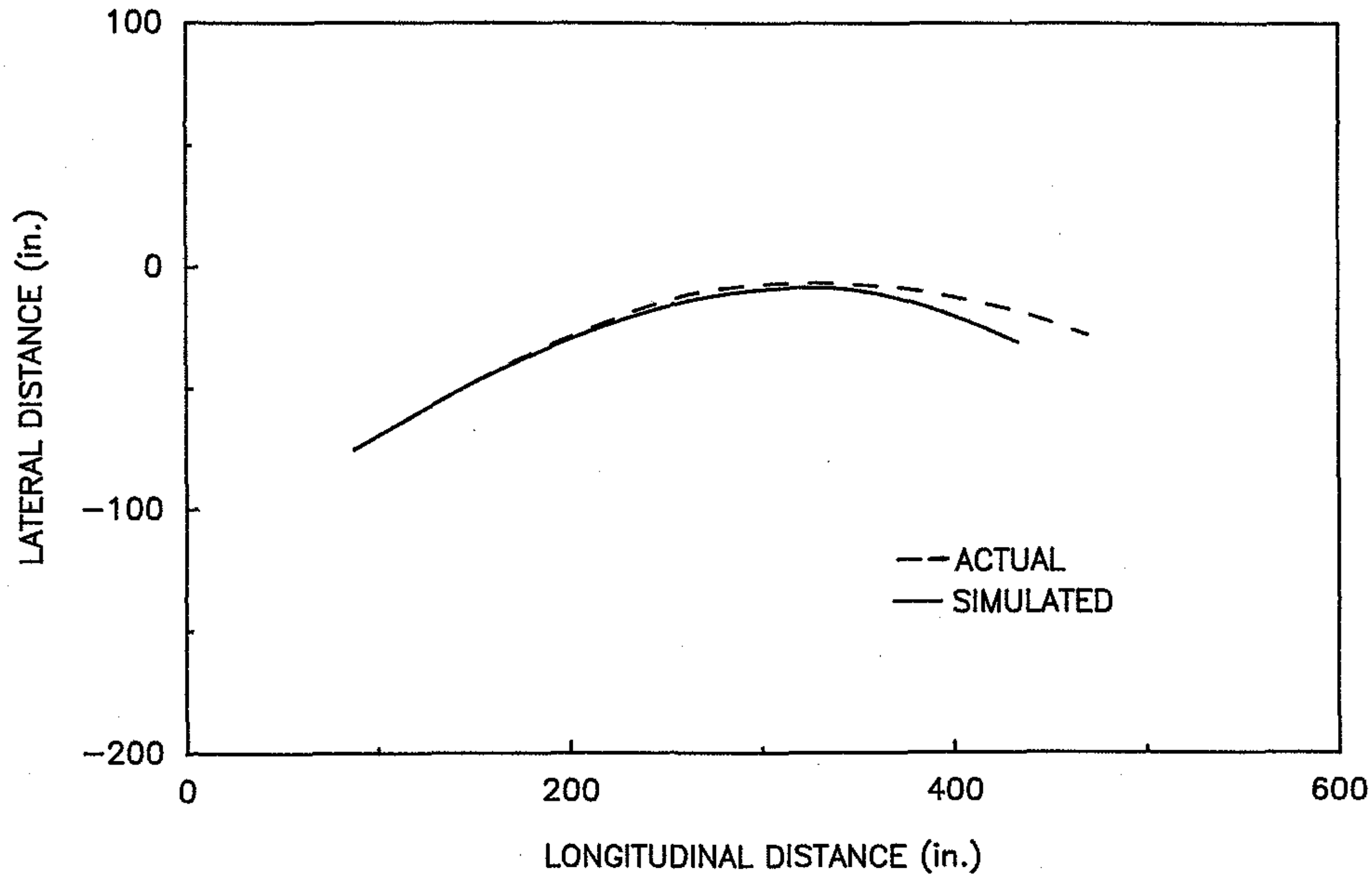


FIGURE 2. COMPARISON OF VEHICLE TRAJECTORY WITH BARRIER VII SIMULATION FOR TEST 9429−2 (6)

TABLE 6. CRITICAL IMPACT LOCATIONS DETERMINED FROM BARRIER VII SIMULATION

Post Spacing	Critical Impact Location (in. upstream from post)	
	Mini Size Vehicle	Full Size Vehicle
6'–3"	75	120
8'–4"	84	144
12'–6"	108	192

impacts, wheel snag is most likely to occur on the second post encountered. Thus, critical impact locations shown in Table 6 are greater than the post spacing.

A preliminary evaluation of optimized guard fence designs was then undertaken to identify the effects of various design parameter changes. These simulations revealed that increasing post embedment tended to increase predicted wheel snag without positive effects on barrier performance. Therefore, the 48 in. embedment option was abandoned and remaining design alternatives, shown in Table 2, were simulated for both design impact conditions. Typical input for the Barrier VII simulations is presented in Appendix A.

Optimized Barrier Selection

The simulation program predicted barrier deflections in excess of 6 ft for impacts involving 4,500 lb vehicles striking barrier systems with 12.5 ft post spacing. Experience with the Barrier VII program indicates that barriers do not perform well when deflections of this magnitude are predicted. Therefore, all design alternatives involving a 12.5 ft post spacing were abandoned. As discussed above, increased post embedment did not have significant positive effects on guardrail performance, and the standard 38 in. embedment depth was chosen as the best alternative.

Comparison of the 8.33 ft and 6.25 ft design alternatives revealed that the wider spacing allowed only a 10 percent increase in predicted barrier deflection and had little effect on predicted wheel snag or exit angle. Further, the 8.33 ft post spacing alternatives were predicted to reduce maximum accelerations imparted to impacting vehicles. Thus, the impact performance of a guard fence incorporating an 8.33 ft post spacing was determined to be comparable to that of standard designs. Based on the reduced cost of this system and its comparable safety performance, the 8.33 ft post spacing was selected for use in the optimized design. Tables 7 and 8 compare the predicted performance of the optimized and standard designs for the two design impact conditions.

The Barrier VII program predicted significant wheel snag for all of the nonblocked-out systems evaluated. Figure 3 demonstrates the degree of wheel snagging predicted for Texas standard guard fence when impacted by an 1,800 lb vehicle at a speed of 60 mph and an angle of 20 deg. Table 9 compares the extent of wheel snagging predicted for the standard and optimized guard fence designs when blockouts are not incorporated. Note that although significant interference between the guardrail post and vehicle tires was observed for the first validation test discussed previously, the vehicles tires were able to slide off of the round post without generating significant snagging forces. Further, although severe snagging has been observed in many guardrail tests involving 1,800 lb

TABLE 7. SIMULATED PERFORMANCE COMPARISON FOR 1800 LB/60 MPH/20 DEG IMPACT

	STANDARD	OPTIMIZED
Post Spacing (ft)	6.25	8.33
Max. Barrier Defl. (in.)	14.4	16.7
Blockouts (y/n)	N	N
Wheel Snag (y/n)	Y	Y
Max. 50 msec Avg. Accel.		
- Lateral (g's)	8.2	7.1
- Longitudinal (g's)	7.4	7.0
Vehicle Exit Angle (deg)	6.5	7.3
Vehicle Exit Speed (mph)	42.8	42.0

TABLE 8. SIMULATED PERFORMANCE COMPARISON FOR 4500 LB/60 MPH/25 DEG IMPACT

	STANDARD	OPTIMIZED
Post Spacing (ft)	6.25	8.33
Max. Barrier Defl. (in.)	33.3	37.1
Blockouts (y/n)	N	N
Wheel Snag (y/n)	Y	Y
Max. 50 msec Avg. Accel.		
- Lateral (g's)	4.7	5.3
- Longitudinal (g's)	5.5	5.0
Vehicle Exit Angle (deg)	9.3	9.7
Vehicle Exit Speed (mph)	38.6	37.8

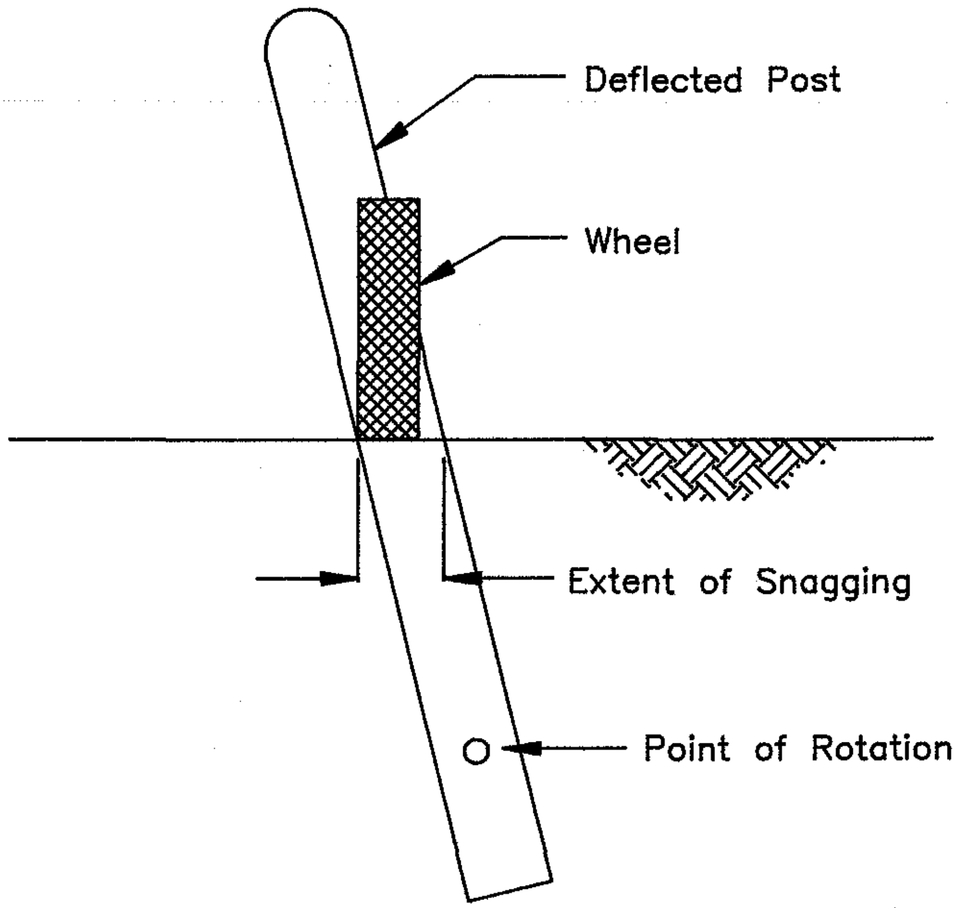


FIGURE 3. WHEEL SNAGGING PREDICTED BY BARRIER VII FOR STANDARD GUARD FENCE IMPACTED AT 1800 LB/60 MPH/20 DEG

TABLE 9. WHEEL SNAGGING PREDICTED BY BARRIER VII FOR STANDARD AND OPTIMIZED DESIGNS

Vehicle Weight (lb)	Impact Condition (mph/deg)	Post Spacing (ft)	Extent of Snagging (in)
1800	60/15	6.25	5.4
1800	60/15	8.33	5.8
1800	60/20	6.25	7.1
1800	60/20	8.33	7.5
4500	60/25	6.25	8.9
4500	60/25	8.33	9.3

vehicles impacting at 60 mph and 20 deg., vehicle decelerations have generally been found to be within recommended limits set by NCHRP Report 230 (3). Finally, as discussed previously, the primary effect of blockouts on wheel snagging is to move guard fence posts out of a vehicle's tire path. Thus, the blockout size required to prevent wheel snagging can be determined from films of crash tests involving nonblocked-out systems. Therefore, a nonblocked-out guard fence mounted on 7 in. round wood posts embedded 38 in. and spaced 8.33 ft was selected for use in the compliance testing phase of this study.

A limited simulation effort was then conducted to investigate the feasibility of extending these findings to steel post guardrails as reported in reference 1. Results of these simulations indicated that an optimized W-beam guard fence system incorporating 6 in. blockouts and mounted on W6X9 steel posts spaced 8.33 ft apart and embedded 38 in. would be very similar to that of a G4(1S) barrier. Further, Barrier VII again predicted significant wheel snagging for both the standard and optimized barriers. Note that although such wheel snagging was observed in a full scale crash tests of a G4(1S) system, measured decelerations were within limits recommended by NCHRP Report 230 (3). Therefore, an optimized steel post system incorporating 8.33 ft post spacings, 6 in. blockouts, and 38 in. post embedment was selected for compliance testing.

COMPLIANCE TESTING

NCHRP Report 230 (3) recommends two full scale crash tests, tests 10 and 12, for evaluation of the impact performance of longitudinal barriers. Test 10 involves a full-size vehicle impacting at 60 mph and 25 deg. while test 12 involves a mini-size vehicle impacting at 60 mph and 15 deg. As mentioned previously, some researchers have recommended raising the impact angle for the mini-size vehicle to 20 degrees (7) and many research organizations are now testing under this condition. Therefore, test 10 and a supplemental test S13, involving a mini-size vehicle impacting at 60 mph and 20 deg. were selected for evaluation of the impact performance of the optimized W-beam guard fence designs (3). The testing program involved evaluation of two optimized guardrails, one mounted on wood posts and the other mounted on steel posts. Accelerometer traces from the tests are shown in Appendix B, sequential photos are shown in Appendix C and rate gyro data is presented in Appendix D.

The critical impact locations identified during the simulation effort were used in all of the crash tests. It should be noted that these critical impact locations maximize the potential for wheel snag and that NCHRP Report 230 does not require impacting the guardrail at the critical location. Impacting the guardrail at its critical location instead of midspan as recommended by NCHRP Report 230 (3) increases the degree of snagging for mini-size vehicle impacts predicted by BARRIER VII from 5.2 in. to 7.5 in. Thus testing the optimized guardrails at critical impact locations can be expected to increase the degree of snagging by as much as 50% compared to using impact locations recommended by NCHRP Report 230 (3).

Test 1147-1

The first full-scale crash test involved evaluation of the performance of the wood post optimized design during impacts with mini-size vehicles. The guard fence installation, shown in Figure 4, incorporated 7 in. round wood posts embedded 38 in. and spaced 8.33 ft. Note that the W-beam was not blocked out from the round wood posts. The test vehicle impacted the guard fence at 61.7 mph. and 20.7 deg. at a point 84 in. upstream of a post. The vehicle was redirected with significant wheel snag and some minor deformation of the passenger compartment at the back of the front wheel well, as shown in Figure 5. All measures of occupant risk were within recommended limits established by NCHRP Report 230 (3) and the vehicle stayed within 10 ft of the guardrail until it came to rest. Thus, although significant wheel snagging was observed, the test successfully met all evaluation criteria for test 12 as described in NCHRP Report 230 (3) and was considered a success. Test 1147-1 is summarized in Figure 6.

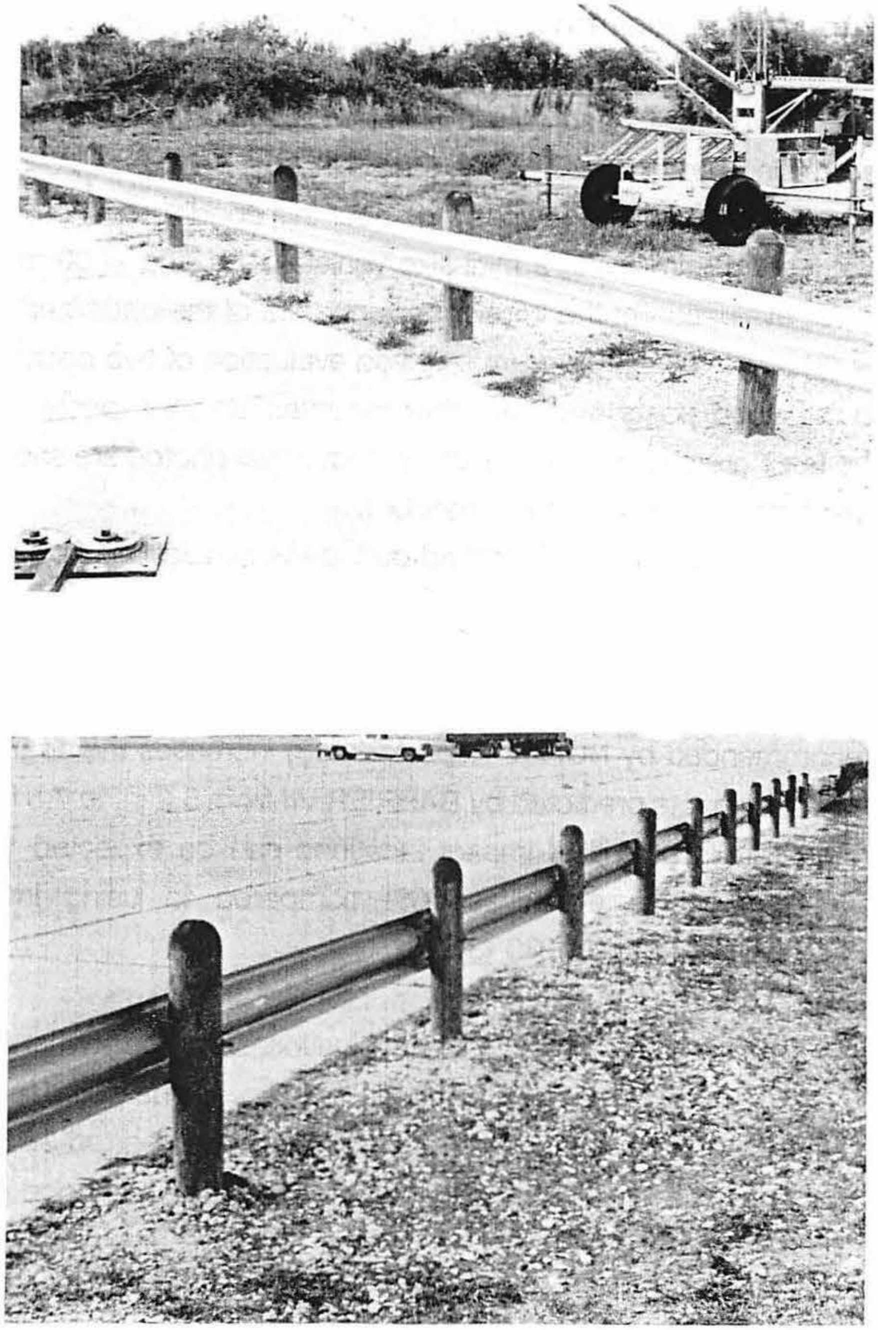


FIGURE 4. OPTIMIZED GUARD FENCE DESIGN WITH 7" ROUND WOOD POSTS

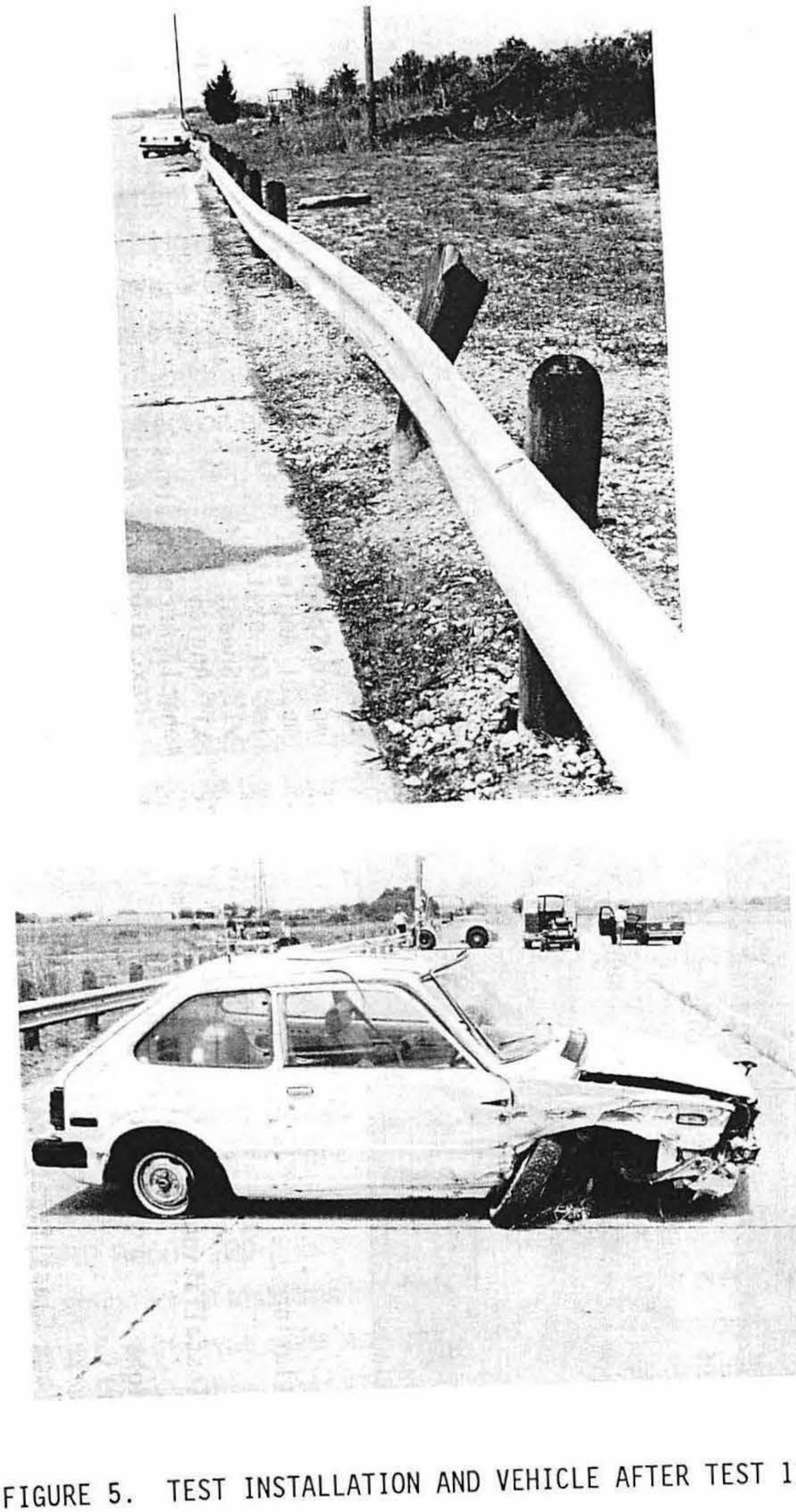
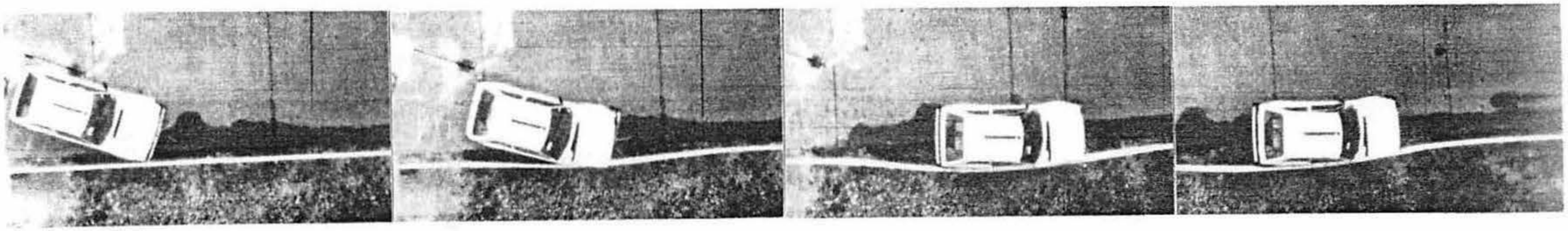
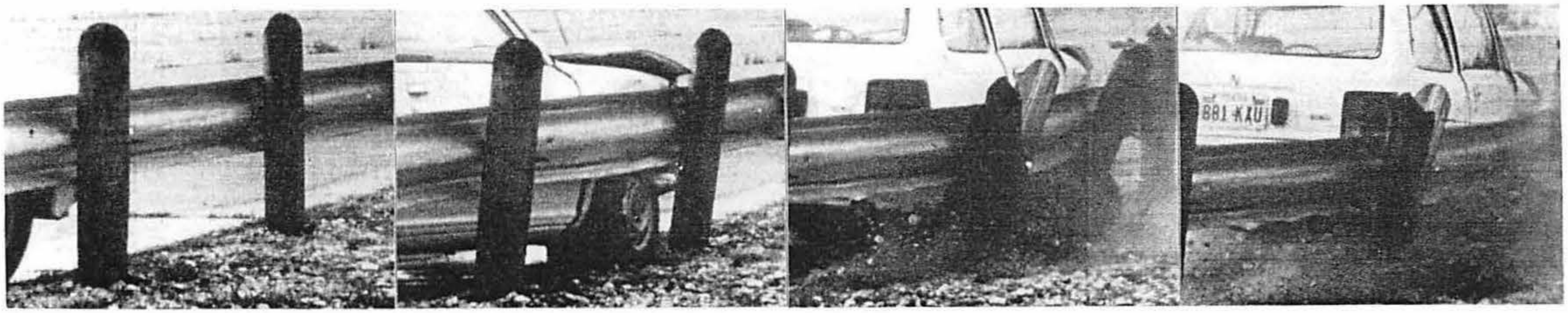


FIGURE 5. TEST INSTALLATION AND VEHICLE AFTER TEST 1147-1



0.000 s   0.065 s   0.194 s   0.258 s



Test No	1147-1
Date	05/10/88
Test Installation	Standard Texas guardfence with wood posts @ 8'4"
Length of Installation . . .	150 ft (45.7 m)
Vehicle	1980 Honda Civic
Vehicle Weight	
Test Inertia.	1,800 lb (817 kg)
Gross Static.	1,967 lb (893 kg)
Vehicle Damage Classification	
TAD	01RFQ4
CDC	01RFEW3
Maximum Vehicle Crush	12.0 in (30.5 cm)
Max. Dyn. Rail Deflection . .	16.0 in (40.6 cm)
Max. Perm. Rail Deformation .	8.0 in (20.3 cm)

Impact Speed.	61.7 mi/h (99.3 km/h)
Impact Angle.	20.7 deg
Time of exit.	0.395 sec
Exit Speed.	41.5 mi/h (66.8 km/h)
Exit Angle.	5.8 deg
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal.	-7.6 g
Lateral	7.4 g
Occupant Impact Velocity	
Longitudinal.	22.1 ft/s (6.7 m/s)
Lateral	17.9 ft/s (5.5 m/s)
Occupant Ridedown Accelerations	
Longitudinal.	-10.8 g
Lateral	8.4 g

FIGURE 6. SUMMARY OF RESULTS FOR TEST 1147-1

Note that although the commentary section of NCHRP Report 230 states that longitudinal barriers should redirect vehicles without exhibiting a tendency to snag on posts, the evaluation criteria contained in the guidelines do not contain such a provision. The authors of NCHRP Report 230 believed the high accelerations, that had been associated with severe wheel snag, would cause tests involving snagging to flunk flail space evaluation criteria. However, mini-size vehicles have proven to have very weak wheel and suspension assemblies. As a result, tests of these vehicles with widely used roadside barriers, such as the G4(1S), have shown that even severe wheel snag does not cause excessive vehicle decelerations. In fact crash test results indicate that wheel snag tends to have a positive effect on barrier performance during mini-size vehicle impacts by keeping the car close to the barrier and reducing its exit speed, thereby reducing the possibility of impacts with other vehicles in the traffic stream and improving overall vehicle stability. Therefore, although mini-size vehicles have exhibited a tendency for wheel snag on the optimized barrier design, the overall safety performance of this system is considered to be very good.

Another evaluation criteria contained in NCHRP Report 230 requires that if the test vehicle is judged to be redirected into adjacent traffic lanes, the velocity change during contact with the barrier should be less than 15 mph. As discussed previously the test vehicle was redirected at a very flat angle and steered quickly back into the barrier. No point on the vehicle was more than 10 ft from the barrier after impact and the car came to rest against the guardrail. Thus, although the velocity change during this test was somewhat higher than the recommended limit, the vehicle was judged to have stayed out of adjacent traffic lanes. Further, the link between low exit speed and occupant injury has never been well established. Many widely used guardrail systems, including the G4(1S), have failed to pass exit speed criteria from NCHRP Report 230 (6,3). In summary, although significant wheel snagging and minor occupant compartment deformations were observed, the test vehicle was safely redirected and this test passed evaluation criteria required by NCHRP Report 230 (3).

Careful examination of test films indicated that Barrier VII's prediction of the degree of wheel snagging (7.5 in.) was quite accurate. Since, as shown on Table 9, Barrier VII predicted only slightly less wheel snag (7.1 in.) for a 6.25 ft post spacing, it was concluded that the safety performance of the standard guard fence would be only slightly better than that of the optimized guard fence for this extremely severe impact condition. For less severe impacts, the optimized barrier would impart lower accelerations to an impacting vehicle and thus its performance would be considered slightly better than that of standard guard fence. Therefore, based on the results of this test, the accuracy of Barrier VII predictions, and the simulation effort described previously, it was concluded that the safety performance of the optimized guard fence for mini-size vehicles should be considered comparable to that of Texas standard guard fence.

Test 1147-2

The second test involved evaluation of the performance of the wood post optimized design during impacts with full-size vehicles. The test vehicle impacted the guard fence at a speed of 61.8 mph and an angle of 25 deg. The vehicle contacted the guard fence 144 in. upstream from a post and although there was significant contact between the vehicle's tires and a guardrail post, no large decelerations resulted. The vehicle was smoothly redirected and was only moderately damaged for a test of this severity as shown in Figure 7. All measures of occupant risk were below recommended limits established by NCHRP Report 230 (3). Although the exit speed was again slightly below the recommended value, the test vehicle again stayed within 15 ft. of the guardrail and would not have encroached significantly onto adjacent traffic lanes. Therefore this test was considered very successful. Figure 8 summarizes the results of this test.

Test 1147-3

An optimized guard fence incorporating steel posts was then constructed with an 8.33 ft post spacing and 6 in. blockouts. Note that standard G4(1S) posts were inadvertently installed and, therefore, the post embedment was 44 in. instead of the expected 38 in. Further, backup plates were not installed at nonsplice posts as called for in the G4(1S) design. Figure 9 shows the optimized steel post guard fence as it was constructed for tests 1147-3 and 1147-4. The third test involved a mini-size vehicle impacting the barrier 84 in. upstream from a post at a speed of 61.5 mph and an angle of 20.5 deg. The test vehicle was redirected with significant wheel snag on a steel post. Wheel snag again produced an exit speed slightly below the recommended limit of 46.5 mph (3). However, tire damage on the impact side kept the vehicle within 8 ft of the guard fence where it would not pose a hazard to adjacent traffic lanes. All measures of occupant risk were again within recommended limits. Results of this test are comparable to results of a similar test on a G4(1S) guardrail. Based on these findings, test 1147-3 was considered a success and the safety performance of the optimized guard fence for mini-vehicle impacts was considered to be comparable to that of the standard G4(1S). Figure 10 summarizes test 1147-3, and the test vehicle and barrier after the test are shown in Figure 11.

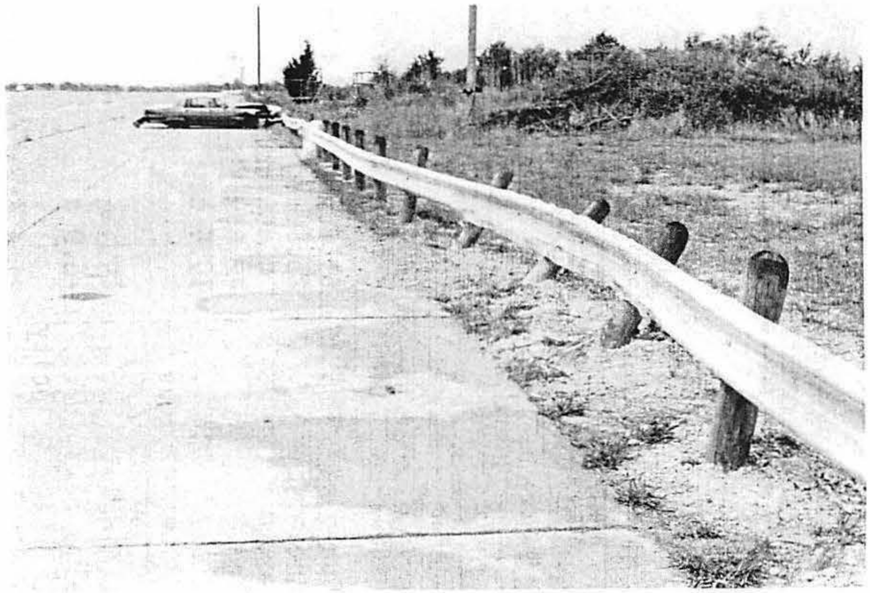
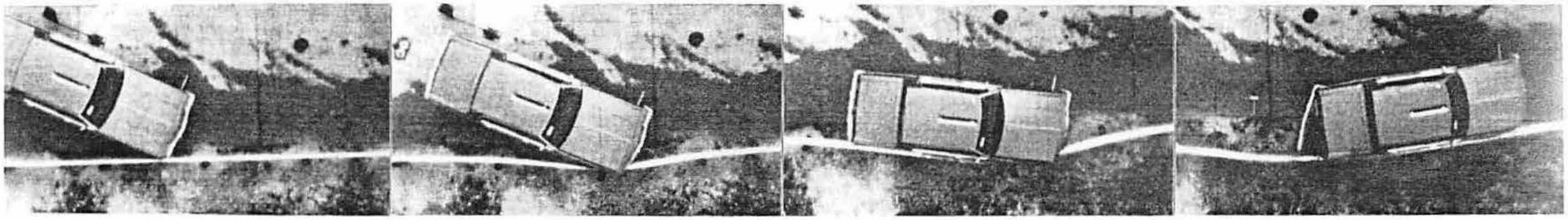


FIGURE 7. TEST INSTALLATION AND VEHICLE AFTER TEST 1147-2



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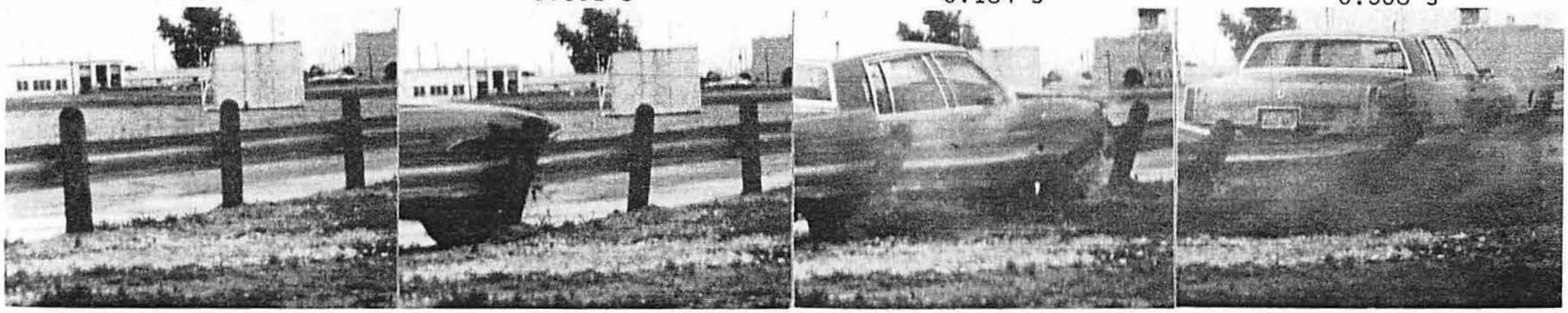


Test No	1147-2
Date	05/16/88
Test Installation	Standard Texas guardfence with wood posts @ 8′4″
Length of Installation. . . .	150 ft (45.7 m)
Vehicle	1980 Oldsmobile 98
Vehicle Weight	
Test Inertia.	4,530 lb (2,057 kg)
Vehicle Damage Classification	
TAD	01RFQ4
CDC	01RFEW3
Maximum Vehicle Crush	15.0 in (38.1 cm)
Max. Dyn. Rail Deflection . .	33.6 in (85.3 cm)
Max. Perm. Rail Deflection. .	27.0 in (68.6 cm)

Impact Speed.	61.8 mi/h (99.4 km/h)
Impact Angle.	25.6 deg
Time of exit.	0.466 sec
Exit Speed.	42.5 mi/h (68.4 km/h)
Exit Angle.	10.6 deg
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal.	-5.3 g
Lateral	5.9 g
Occupant Impact Velocity	
Longitudinal.	21.8 ft/s (6.6 m/s)
Lateral	18.5 ft/s (5.6 m/s)
Occupant Ridedown Accelerations	
Longitudinal.	-8.1 g
Lateral	9.4 g

FIGURE 8. SUMMARY OF RESULTS FOR TEST 1147-2

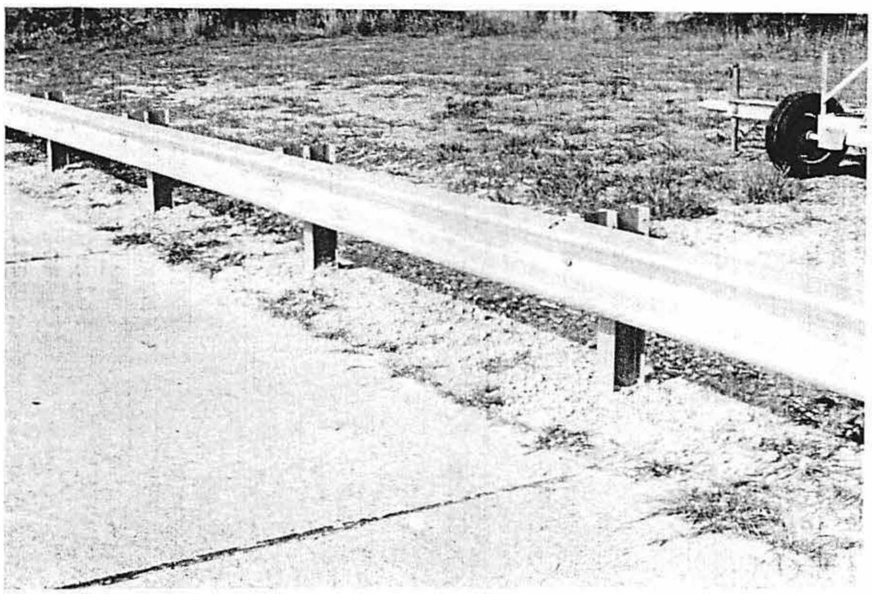
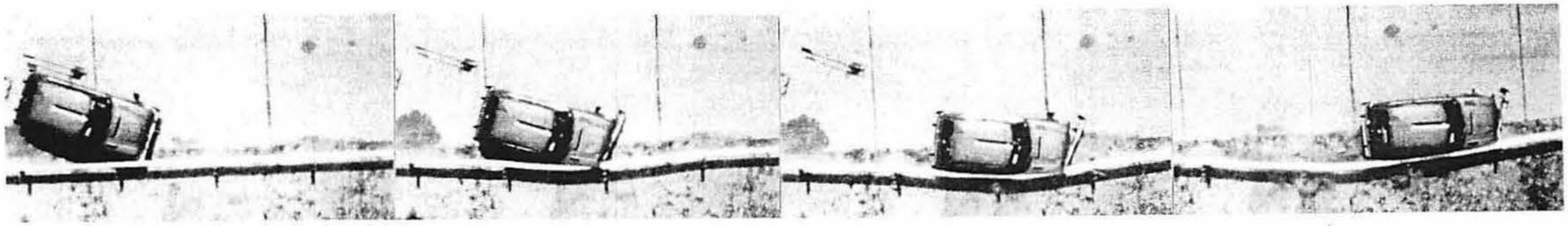


FIGURE 9. OPTIMIZED GUARD FENCE DESIGN WITH W6X9 STEEL POSTS.



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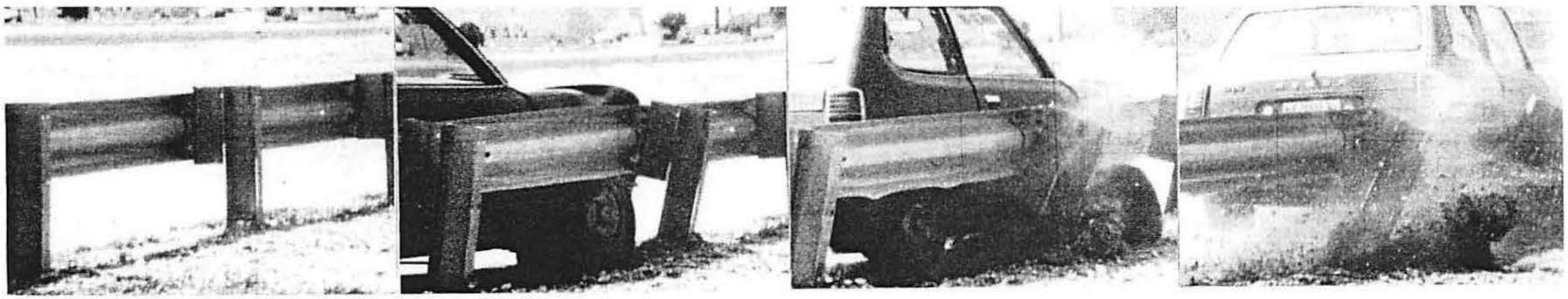


Test No	1147-3
Date	06/07/88
Test Installation	G4(1S) Barrier w/posts @ 8'4"
Length of Installation.	150 ft (45.7 m)
Vehicle	1979 Honda Civic
Vehicle Weight	
Test Inertia	1,800 lb (817 kg)
Gross Static	1,968 lb (893 kg)
Vehicle Damage Classification	
TAD	01FR4 & 01RFQ4
CDC	01FREK2 & 01RYEW3
Maximum Vehicle Crush	4.0 in (10.2 cm)
Max. Dyn. Rail Deflection . . .	2.0 ft (0.6 m)
Max. Perm Rail Deformation . .	1.4 ft (0.4 m)

Impact Speed	61.5 mi/h (99.0 km/h)
Impact Angle	20.5 degrees
Time of Exit	0.502 seconds
Exit Speed	43.4 mi/h (69.8 km/h)
Exit Angle	6.5 degrees
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal	-5.1 g
Lateral	6.5 g
Occupant Impact Velocity	
Longitudinal	21.7 ft/s (6.6 m/s)
Lateral	15.8 ft/s (4.8 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-4.7 g
Lateral	11.8 g

FIGURE 10. SUMMARY OF RESULTS OF TEST 1147-3

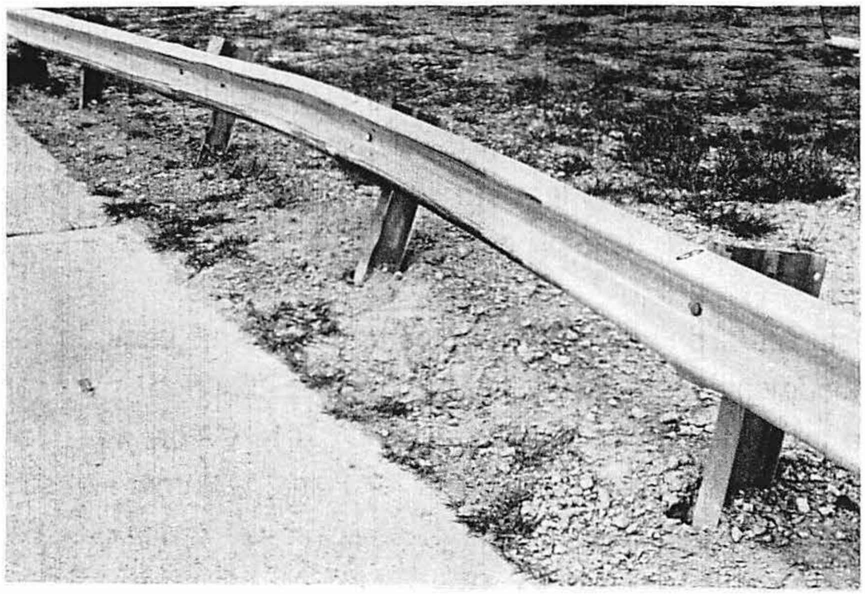


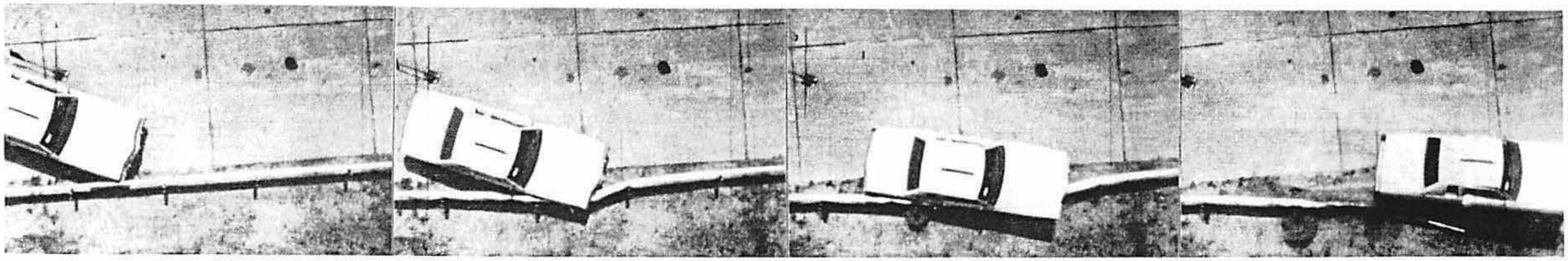
FIGURE 11. TEST INSTALLATION AND VEHICLE AFTER TEST 1147-3

Test 1147-4

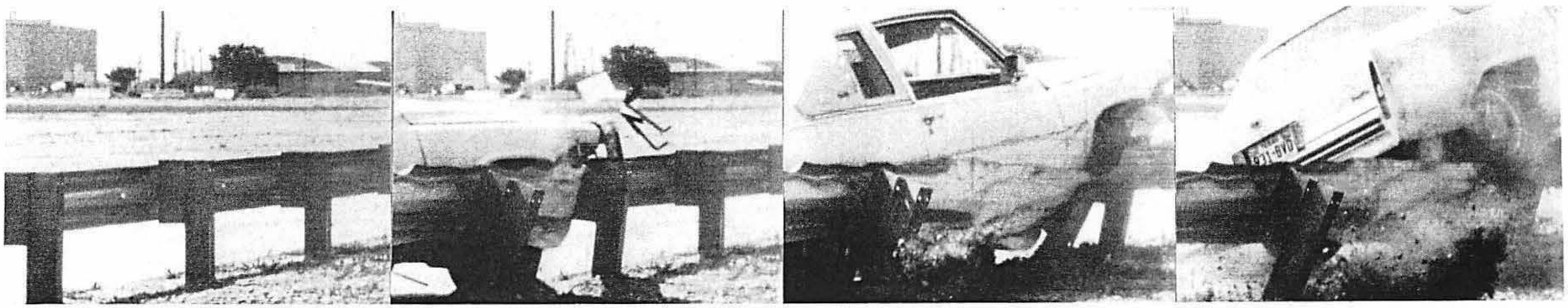
Test 1147-4 involved a full-size automobile impacting the same installation used in test 1147-3 at a speed of 60 mph and an angle of 25 deg. As mentioned previously, back-up plates were inadvertently omitted from the guard fence. As a result, the W-beam pocketed around a post and allowed the test vehicle to ramp over the barrier. The results of this test demonstrate the importance of using back-up plates at nonsplice posts in steel post guard fence systems. The test is summarized in Figure 12.

Test 1147-5

The test installation was then modified to incorporate back-up plates and reduce the post embedment depth to 38 in. as originally planned. Figure 13 shows the reconstructed guard fence used in test 1147-5. Test 1147-4 was then repeated with dramatically improved results. The test vehicle struck the barrier at a speed of 62.0 mph and an angle of 25.1 deg. The impact point was again selected to maximize the possibility of wheel snag as described previously. The test vehicle was smoothly redirected with only minimal damage as shown in Figure 14. Although the vehicles tires contacted several guard fence posts, snagging forces were not large and all measures of occupant risk were within recommended limits (3). The vehicle exit speed was again slightly below limits recommended by NCHRP Report 230 (3) but the test vehicle remained within 10 ft. of the guard fence installation and would not have posed a hazard to adjacent traffic lanes. Thus this test met all evaluation criteria set forth in NCHRP Report 230 and was considered to be very successful. Figure 15 summarizes results of this test.

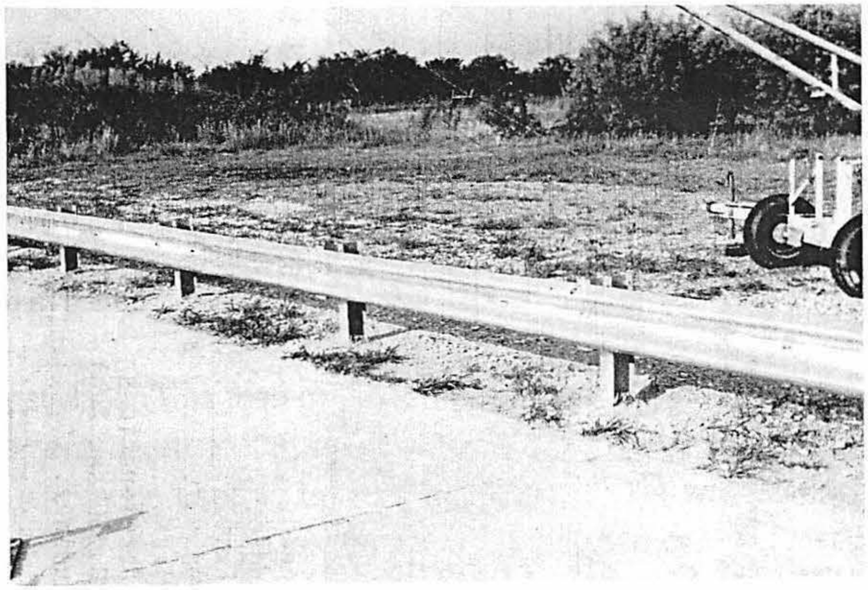


0.000 s 0.099 s 0.199 s 0.372 s



Test No.	1147-4	Impact Speed.	61.7 mi/h (99.3 km/h)
Date	06/09/88	Impact Angle.	24.5 degrees
Test Installation.	G4(1S) Barrier w/posts @ 8'4"	Time of Exit.	N/A
		Exit Speed.	N/A
Length of Installation	150 ft (45.7 m)	Exit Angle.	N/A
Vehicle.	1979 Cadillac	Vehicle Accelerations (Max. 0.050-sec Avg)	
Vehicle Weight			
Test Inertia	4,490 lb (2,038 kg)	Longitudinal.	-4.9 g
Gross Static	4,490 lb (2,038 kg)	Lateral	4.4 g
Max. Dyn. Rail Deflection. . .	2.7 ft (0.8 m)	Occupant Impact Velocity	
Max. Perm Rail Deformation . .	1.7 ft (0.5 m)	Longitudinal.	19.8 ft/s (6.0 m/s)
		Lateral	14.2 ft/s (4.3 m/s)
		Occupant Ridedown Accelerations	
		Longitudinal.	-7.4 g
		Lateral	6.8 g

FIGURE 12. SUMMARY OF RESULTS OF TEST 1147-4



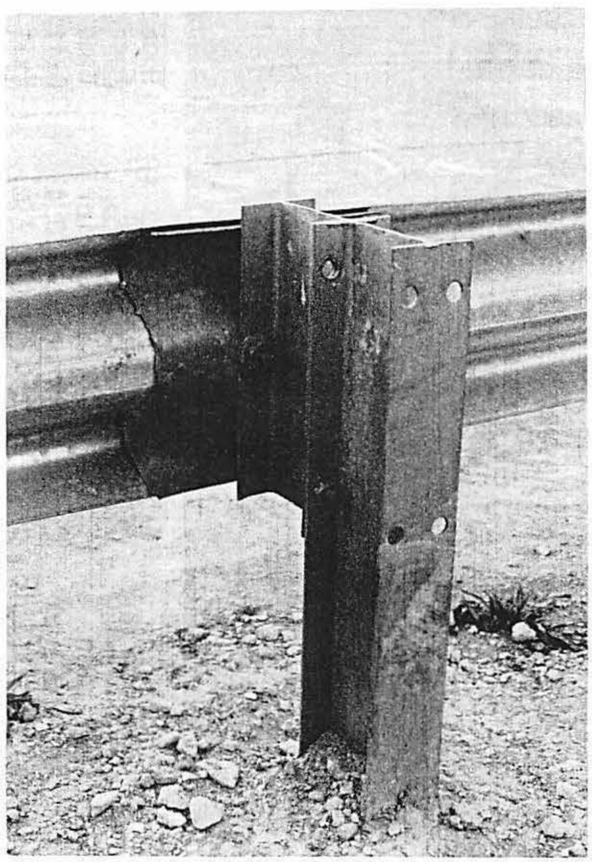


FIGURE 13. OPTIMIZED STEEL POST GUARD FENCE DESIGN WITH BACK UP PLATES

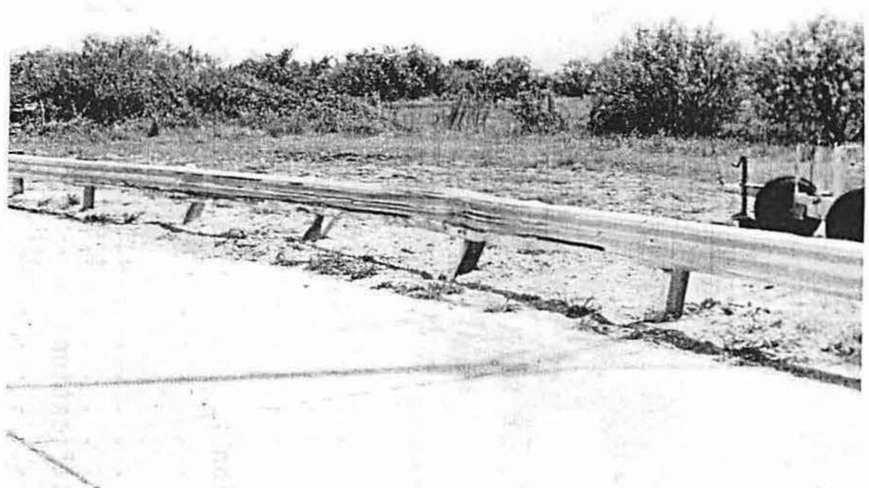
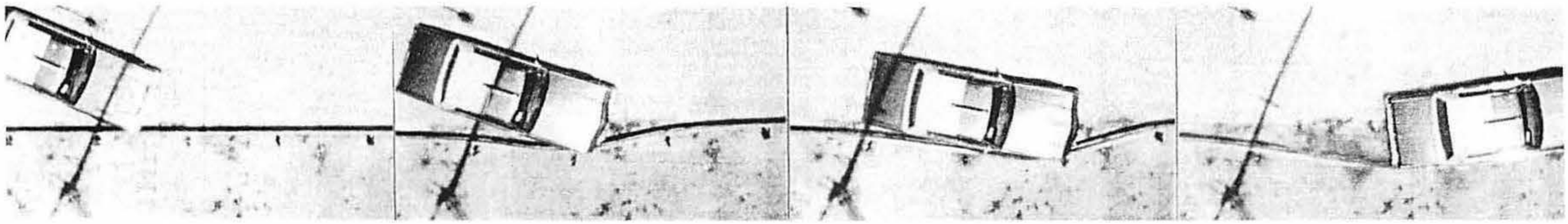
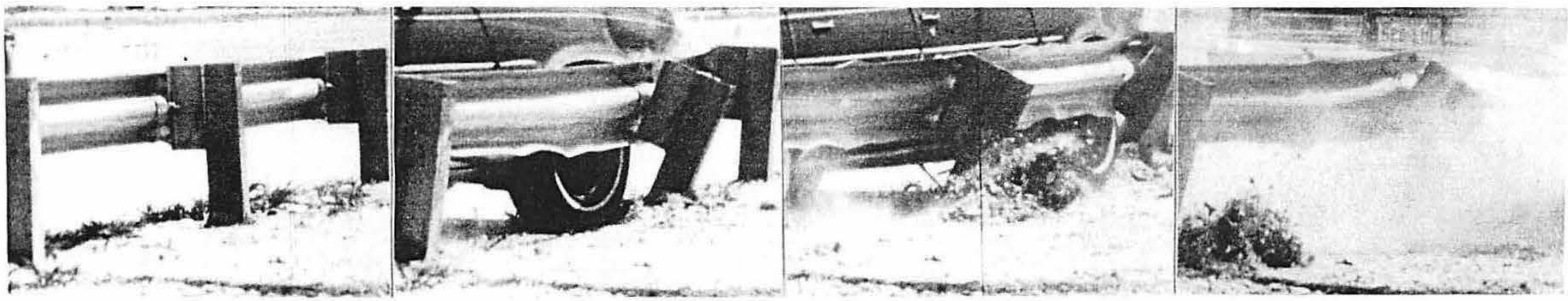


FIGURE 14. TEST INSTALLATION AND VEHICLE AFTER TEST 1147-5



0.000 s 0.077 s 0.155 s 0.310 s



Test No	1147-5
Date	07/14/88
Test Installation	G4(1S) Barrier w/posts @ 8'4"
Length of Installation.	150 ft (45.7 m)
Vehicle	1979 Oldsmobile 98
Vehicle Weight	
Test Inertia	4,500 lb (2,043 kg)
Gross Static	4,500 lb (2,043 kg)
Vehicle Damage Classification	
TAD	01FR4 & 01RFQ4
CDC	01FREK2 & 01RFEW3
Maximum Vehicle Crush	6.0 in (15.2 cm)
Max. Dyn. Rail Deflection . . .	3.0 ft (0.9 m)
Max. Perm Rail Deformation . .	1.9 ft (0.6 m)

Impact Speed	62.0 mi/h (99.8 km/h)
Impact Angle	25.1 degrees
Time of Exit	0.632 seconds
Exit Speed	42.5 mi/h (68.4 km/h)
Exit Angle	11.0 degrees
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal	-4.1 g
Lateral	5.3 g
Occupant Impact Velocity	
Longitudinal	18.8 ft/s (5.7 m/s)
Lateral	15.4 ft/s (4.7 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-6.4 g
Lateral	8.0 g

FIGURE 15. SUMMARY OF RESULTS OF TEST 1147-5

OPTIMIZED GUARD FENCE COSTS

Findings from the crash test program demonstrate that the safety performance of the optimized guard fence is comparable to that of standard Texas guard fence designs. Therefore, the optimized design is recommended as a direct substitute for the standard guard fence designs at any site. A survey of SDHPT district maintenance and construction engineers was undertaken in an effort to quantify construction cost reductions associated with the two optimized designs. Results of this survey are shown in Table 10. Costs figures shown in this table were taken from bid sheets for guardrail construction and repair. Average construction costs for the standard and optimized barriers were then estimated from the unit cost figures shown in Table 10. As shown in Table 11, the optimized wood post design can be constructed for approximately $6.76 per foot compared to $7.65 for the current SDHPT standard design. This represents a savings of approximately 11.6 percent and could translate into a total cost reduction of over $660,000 for the 750,000 ft of guard fence constructed by the TSDHPT each year. Cost reductions for steel post guard fence are even more dramatic, thereby further enhancing the potential benefits of incorporating the optimized guard fence designs.

TABLE 10. GUARDRAIL UNIT COSTS

	Cost ($)
W–beam Guardrail	2.17 per foot
7" Round Wood Post	11.49 ea.
W6X9 Steel Post	20.39 ea.
6" Steel Blockout	5.59 ea.
W–beam Backup Plate	2.49 ea.
9" Post Bolt with Nut	0.63 ea.
Splice Bolt with Nut	0.21 ea.
Labor – Post Installation	9.92 ea.
– Guardrail Assembly	1.88 per foot

TABLE 11. GUARDRAIL CONSTRUCTION COSTS

	WOOD			STEEL		
	Stand.	Optimized	% Reduction	Stand.	Optimized	% Reduction
Material ($/ft)	4.18	3.69	11.7	6.89	5.73	16.8
Labor ($/ft)	3.47	3.07	11.5	3.47	3.07	11.5
Total	7.65	6.76	11.6	10.36	8.80	15.1

GUARD FENCE POST SELECTION

As shown in Table 11, wood post guard fence designs are significantly less costly than are steel post designs. Not surprisingly, wood post systems have comprised the vast majority of guard fence installations constructed around Texas. However, several districts have recently reported rotting problems with treated wood posts. Therefore, a survey of district maintenance engineers from all areas of Texas was undertaken in an effort to determine the extent of problems associated with rotting of wood guard fence posts. This survey revealed that post rotting problems were restricted to coastal districts. Each coastal district was then contacted in an effort to quantify useful life of wood guard fence posts installed near the costs. Not surprisingly, estimates of the useful life of these posts varied widely. However, for those districts that had investigated the problem, there seemed to be a consensus that wood posts installed within 20 miles of the coast could not be expected to last for more than five to eight years before rotting begins to significantly reduce their strength. Further, several districts reported that wood guard fence posts installed within 40 miles of the coast began to show significant signs of rotting within 10 to 15 years. All of the engineers contacted indicated that guard fence posts installed more than 50 miles from the coast could be expected to perform adequately for a normal 20 year life. Thus, the expected life of wood post guard fence was identified in terms of three geographic zones. In the first zone extending 20 miles inland from the coast, wood posts can be expected to last at least five years. The second zone includes a region from 20 to 50 miles from the coast where a wood guard fence post can be expected to have a useful life of at least 10 years. The third region includes the rest of the state where guard fence posts can be expected to have a full 20 year life.

The most cost beneficial post for each of the three zones was then determined through a simple economic evaluation based on a lowest present cost analysis with a four percent discount rate. Barrier cost data was taken from Table 10 and the normal useful life of a guard fence installation was assumed to be 20 years. Further, the labor associated with replacing wood posts at the end of their useful life was assumed to be 30 percent greater than the cost of placing the post originally. This simple economic analysis indicated that wood post systems are more cost beneficial than steel post systems in zones 2 and 3, while steel post systems are more cost beneficial in zone 1.

GUARD FENCE PLACEMENT GUIDELINES

Procedures for determining appropriate lengths of guardrail contained in the AASHTO Guide for Designing, Selecting, and Locating Traffic Barriers (8) have been widely accepted across the country. These procedures are based on a rather limited study of roadside encroachments on Illinois and California freeways during the early 1960's (9). All of this data was collected on highways with a 70 mph speed limit, and a large portion of it was collected during winter months when tracks in ice and snow could be easily detected. Data collected in this study indicated that approximately 95 percent of all errant vehicles travel less than 400 ft along the highway before either returning to the roadway or coming to a stop. This 95th percentile encroachment distance was then used to develop runout length recommendations for high speed roadways.

Findings from a more comprehensive study of encroachments along roadways with 60 mph speed limits, conducted during summer months when ice and snow are not a consideration, indicated that the 95th percentile encroachment length is closer to 200 ft (10). When this data is used to develop runout length guidelines, significantly less barrier is recommended than when the procedures found in the '77 Barrier Guide (8) are implemented.

Both of the aforementioned approaches for determining guardrail runout lengths are based on the concept that guardrails should be positioned to redirect 95 percent of all vehicles that might reach the hazard behind the guardrail. This type of approach is very conservative and results in the placement of long sections of guardrail, even on relatively low volume roadways where encroachments are very infrequent. A more consistent procedure for determining appropriate runout lengths involves incorporating a benefit/cost analysis. Recently developed benefit/cost analysis techniques have the versatility to study the effectiveness of guardrail placement details and can be used to obtain some insight into this difficult problem (2). Therefore, a benefit cost analysis of guardrail runout lengths was undertaken in an effort to develop better guardrail placement guidelines.

Guardrail runout lengths can be defined by two parameters, the flare rate and the angle between the back of the hazard and the end of the guardrail. The guardrail flare rate is the rate at which guardrail is tapered away from the traveled way. The angle between the back of a roadside hazard and the end of the approach guardrail, unshielded path angle for purposes of this report, is the maximum encroachment angle at which a vehicle can leave the traveled way and follow a straight line to impact the hazard. As shown in Figure 16, guardrail runout length can be defined in terms of flare rate and unshielded path angle.

Flare Rate

Flaring a guard fence away from the traveled way reduces the number of impacts with the barrier and provides a better shield between traffic and the hazard. However, flaring the barrier also increases the effective impact angle for vehicles striking the flared region. Thus, there must be an optimum flare rate that provides for a reduction in the number accidents without unduly increasing the severity of the remaining barrier accidents. The first phase of the benefit cost analysis was devoted to determination of this optimum flare rate.

The benefit cost program described in reference 2 was used to study the effectiveness of various flare rates. Guardrail construction costs used in the analysis were based on optimized wood post guard fence costs shown in Table 11. Impact severities and barrier repair costs associated with the guard fence are shown in Figures 17 and 18. For purposes of this analysis, traffic delay resulting from accidents and barrier repair activities was assumed to be inconsequential. Other input parameters used in the analysis are presented in the sample data sets shown in Appendix E.

The flare rate B/C analysis involved comparing benefits and costs of seven guardrail installations having the same unshielded path angle and incorporating seven different flare rates. The benefit cost analysis program indicated that for most traffic volumes, barrier offset distances, and unshielded path angles, a flare rate of 10:1 was the most cost beneficial alternative. Although 8:1 and 12:1 flare rates were more cost beneficial for some roadway classifications, the 10:1 flare rate was very nearly the most cost beneficial alternative in every case. It should be noted that this analysis suggests that flare rate recommendations found in reference 8 are somewhat conservative, but generally within an acceptable range. Further, note that although flaring a guardrail away from the traveled way generally makes the barrier use more cost beneficial, guard fence safety performance deteriorates significantly when installed on a roadside slope. Therefore, flaring the barrier end is generally not recommended when the flare would cause the guardrail to be placed on a slope. Specific recommendations regarding the use of guardrails on roadside slopes are presented in references 11 and 12.

Finally, it should be noted that the optimum flare rate analysis is controlled by the relationship between accident severity and impact angle. The relationships used in this analysis, shown in Figure 18, were developed from full scale crash test results and formulas for estimating injury probabilities from vehicular accelerations (13). Detailed

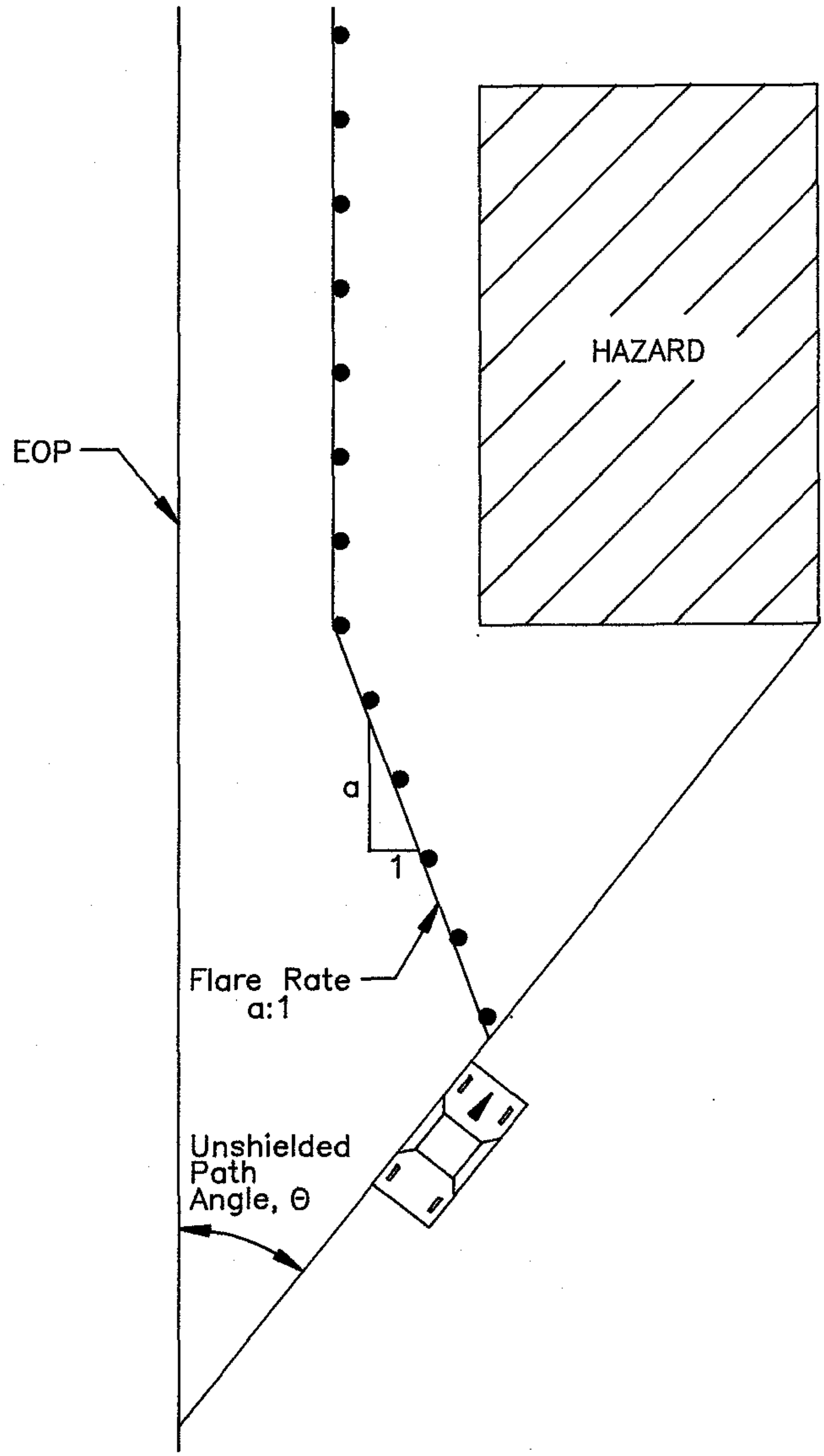


FIGURE 16. FLARE RATE AND UNSHIELDED PATH ANGLE DEFINITIONS

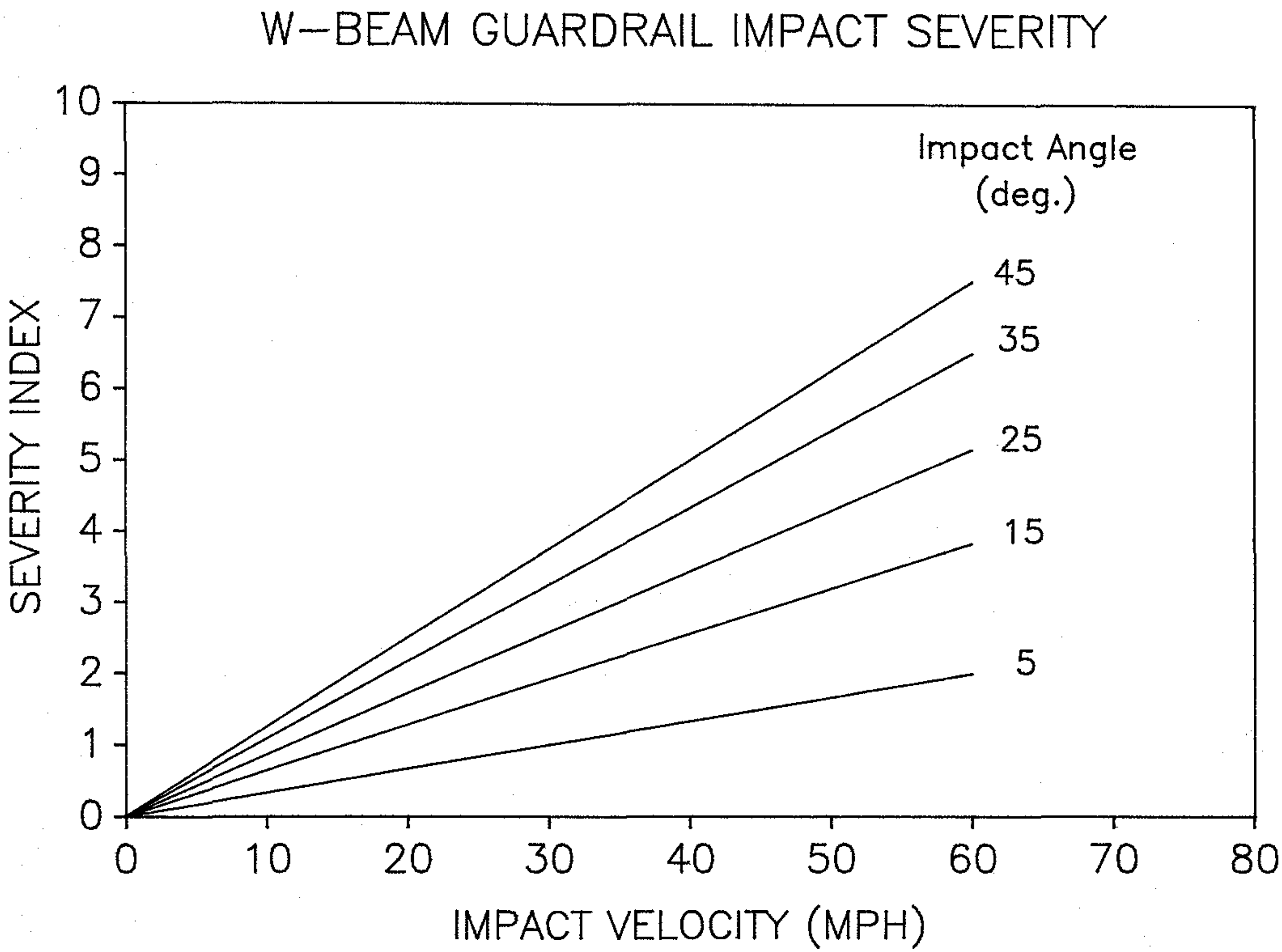


FIGURE 17. GUARDRAIL IMPACT SEVERITIES

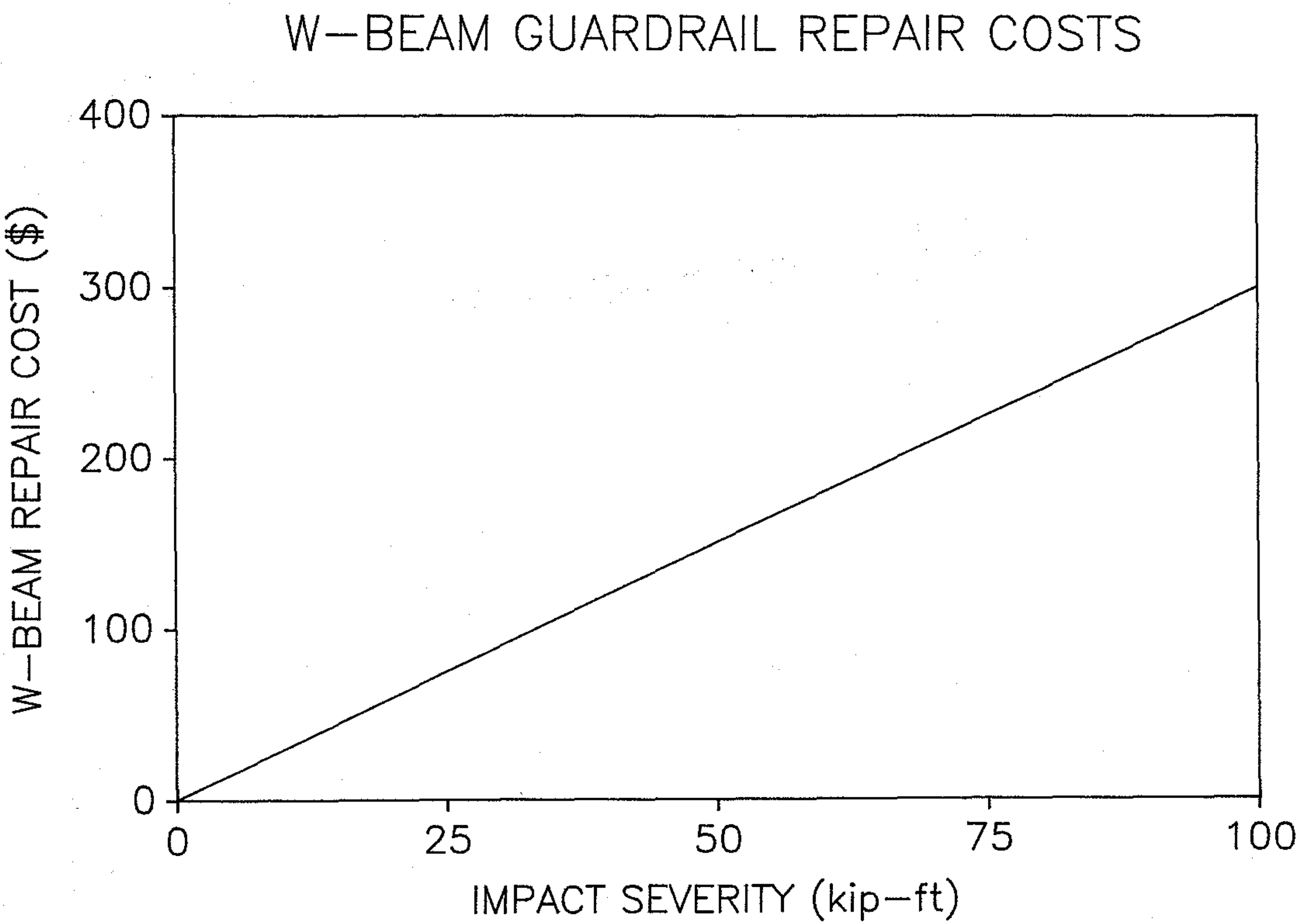


FIGURE 18. GUARDRAIL REPAIR COSTS

descriptions of the procedures used to develop guardrail impact severities as a function of impact angle can be found in references 2 and 14.

Unshielded Path Angle

The benefit cost analysis was then extended to investigate the effects of guardrail length on barrier cost-effectiveness. This analysis involved investigating various unshielded path angles for both straight and flared barrier ends. The B/C program predicted that an unshielded path angle of 14 to 15 degrees represents the most cost beneficial guard fence configuration, even for high speed facilities such as rural interstate. These high unshielded path angles correspond to relatively low runout lengths. For example, a 15 deg unshielded path angle would correspond to a guardrail runout length of 200 ft for a rigid obstacle that extends to 50 ft from the roadway. The AASHTO Barrier Guide (8) would recommend a 480 ft runout length when such a situation is found along a rural interstate. Thus, the benefit cost analysis suggests that guardrail runout lengths found in reference 8 may be excessive.

Careful consideration of the assumptions behind the B/C analysis can shed some light on the large discrepancies between findings from this study and recommendations from reference 8. The B/C analysis is based on the assumption that errant vehicles encroaching onto the roadside follow a straight path. This assumption tends to increase the apparent effectiveness of a guardrail installation since it neglects vehicles which would encroach behind a barrier and then steer back toward the roadway and strike the hazard. As a result, the straight path assumption is conservative when used to evaluate whether or not a barrier should be used because it tends to increase the likelihood that the barrier will be found cost beneficial. However, when the analysis procedure is used to evaluate varying runout lengths, the effects of this assumption are less clear cut. Therefore, although the B/C analysis tends to indicate that current runout length standards are high, results of this study cannot be recommended at this time.

Methods for eliminating the effects of the straight path assumption were then evaluated. One procedure for eliminating the straight path assumption involves changing the basis of the accident prediction algorithm from a lateral encroachment distance to either a longitudinal encroachment distance or a combined probability formulation. Although such modifications could eliminate the aforementioned problems with the straight path assumption, it would significantly complicate the analysis. Budgetary and time constraints did not allow further investigation of these alternatives in this study. Additional research into these approaches for determining optimum runout lengths is recommended.

CONCLUSIONS AND RECOMMENDATIONS

Optimized guard fence designs incorporating 8.33 ft post spacings and 38 in. post embedment have been shown to exhibit safety performance comparable to that of standard guard fence for both wood and steel post systems. Although significant wheel snag was observed in some of the tests, the two optimized barrier systems satisfactorily met NCHRP Report 230 (3) evaluation criteria. Construction cost savings for the optimized barriers when compared to Texas' standard designs have been shown to be approximately 11.6 and 15.1 percent for wood and steel post systems respectively. These reductions should translate into an annual savings of over $660,000 in TSDHPT guard fence construction costs when optimized barrier designs replace current standard designs. Immediate implementation of the optimized guard fence designs is recommended.

The performance of the optimized barriers can be improved to be better than that of standard G4(1S) and G4(1W) designs by adding 8 in. blockouts to eliminate wheel snagging. Although these blockouts would raise the cost of the optimized barriers by approximately $0.60 per ft for the wood post systems and $0.14 per ft for steel systems, the optimized barriers could still be constructed at cost savings of approximately 4.0% and 13.7% respectively. Note that the use of these oversized blockouts is not considered to be warranted as described above.

A survey of guardrail post durability indicated that wood post rotting is significant only in coastal regions. Further, wood posts were found to perform adequately for at least five years when placed within 20 miles of the coast and at least 10 years when placed between 20 and 50 miles from the coast. A lowest present cost economic analysis of guardrail post usage indicated that the additional costs associated with steel post guard fence are warranted only within 20 miles of the coast. Wood post guardrail installations have the lowest present cost for all other regions of the state. Note that the economic analysis assumed that wood guardrail posts installed between 20 and 50 miles from the coast would need to be replaced after approximately ten years of service. Therefore, wood guardrail posts used in zone 2 should be inspected after ten years of service in order to assure adequate barrier performance.

A benefit cost analysis of barrier flare rates indicated that a guardrail flare rate of 10:1 is near the optimum flare rate for almost all traffic and roadside conditions. Although efforts to determine optimum runout lengths were not conclusive due to limitations of the benefit cost model, the analysis did indicate that current runout lengths may be excessive. Further research into evaluation of barrier length of need requirements is recommended.

REFERENCES

1. Sicking, D. L. and Ross, H. E. Jr., "Structural Optimization of Strong-Post W-Beam Guardrail," Transportation Research Record 1133, Transportation Research Board, Washington D. C., 1987.

2. Sicking, D. L. and Ross, H. E., Jr., "Benefit-Cost Analysis of Roadside Safety Alternatives," Transportation Research Record 1065, Transportation Research Board, Washington D. C., 1986.

3. Michie, J. D., "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, March 1981.

4. Calcote, L. R., "Development of a Cost-Effectiveness Model for Guardrail Selection," FHWA Report No. Federal Highway Administration Report No. FHWA-RD-78-75, January 1980.

5. Bligh, R. P., Sicking, D. L., and Ross, H. E. Jr., "Development of a Strong Beam Guardrail to Bridge Rail Transition Guardrail," Transportation Research Record, Transportation Research Board, Washington D. C., in publication.

6. Sicking, D. L., et al., "Development of New Guardrail End Treatments," Research Report 404-1F, Texas Transportation Institute, Texas A&M University System, June 1988.

7. Mak, K. K., Sicking, D. L., and Ross, H. E. Jr., "Real-World Impact Conditions for Run-Off-the-Road Accidents," Transportation Research Record 1065, Transportation Research Board, Washington D. C., 1986.

8. "Guide For Selecting, Locating, and Designing Traffic Barriers," American Association of State Highway and Transportation Officials, Washington, D. C., 1977.

9. Hutchinson, J. W., and Kennedy, T. W., "Medians of Divided Highways-Frequency and Nature of Vehicle Encroachments," Engineering Experiment Station Bulletin 487. University of Illinois, Champaign, Ill., June 1966.

10. Cooper, Peter, "Analysis of Roadside Encroachments-Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces," British Columbia, Canada, March 1980.

11. Ross, H. E., and Sicking, D. L., "Guidelines for Placement of Longitudinal Barriers on Slopes," Transportation Research Record 970, Transportation Research Board, Washington D. C., 1984.

12. Ross, H. E., and Sicking, D. L., "Guidelines for Placement of Longitudinal Barriers on Slopes," Research Report 3659-2, Texas A&M Research Foundation, Texas A&M University, College Station, Texas, 1982.

13. Olson, Robert M., et al., "Bridge Rail Design Factors, Trends, and Guidelines," NCHRP Report 149, Transportation Research Board, National Research Council, Washington, D. C., 1974.

14. Sicking, D. L., and Ross, H. E., "Benefit/Cost Analysis of Highway Safety Alternatives," Paper presented at ASCE Spring Convention, Denver Co., 1985.

APPENDIX A.

BARRIER VII INPUT DATA

```
1BARRIER VII  -  ANALYSIS OF AUTOMOBILE BARRIERS  -  U.C. BERKELEY,  1972

 ************************************************************************

0CONTROL INFORMATION

  NUMBER OF BARRIER NODES                =    79
  NUMBER OF CONTROL NODES                =    12
  NUMBER OF NODE GENERATIONS             =    11

  NUMBER OF INTERFACES                   =     1

  NUMBER OF MEMBERS                      =    93
  NUMBER OF MEMBER GENERATIONS           =    18
  NUMBER OF DIFFERENT MEMBER SERIES      =     2

  NUMBER  OF ADDITIONAL WEIGHT SETS      =     0

0BASIC TIME STEP (SEC)                   =    .00100
  LARGEST ALLOWABLE TIME STEP (SEC)      =    .00100
  MAXIMUM TIME SPECIFIED (SEC)           =    .35000
  MAX. NO. OF STEPS WITH NO CONTACT      =   100

  OVERSHOOT INDEX                        =     0
  ROTATIONAL DAMPING MULTIPLIER          =  1.00

  STEP-BY-STEP INTEGRATION TYPE          =     1



  OUTPUT FREQUENCIES

  AUTOMOBILE DATA       =  1
  BARRIER DEFLECTIONS   = 10
  BARRIER FORCES        =  0

  ENERGY BALANCE        =  0

  CONTACT INFORMATION   =  0

  PUNCHED JOINT DATA    =  0

  PUNCHED TRAJECTORY    =  0
1CONTROL NODE COORDINATES (IN)
 NODE           X-ORD          Y-ORD

    1             .00            .00
```

FIGURE A1. TYPICAL BARRIER VII INPUT

5	300.00	.00
7	375.00	.00
13	525.00	.00
17	600.00	.00
22	675.00	.00
58	1125.00	.00
63	1200.00	.00
67	1275.00	.00
73	1425.00	.00
75	1500.00	.00
79	1800.00	.00

COORDINATE GENERATION COMMANDS

FIRST NODE	LAST NODE	NO. OF NODES	NODE DIFF	DISTANCE
1	5	3	1	.00
5	7	1	1	.00
7	13	5	1	.00
13	17	3	1	.00
17	22	4	1	.00
22	58	35	1	.00
58	63	4	1	.00
63	67	3	1	.00
67	73	5	1	.00
73	75	1	1	.00
75	79	3	1	.00

1NODE COORDINATES (IN)

NODE	X-ORD	Y-ORD
1	.00	.00
2	75.00	.00
3	150.00	.00
4	225.00	.00
5	300.00	.00
6	337.50	.00
7	375.00	.00
8	400.00	.00
9	425.00	.00
10	450.00	.00
11	475.00	.00
12	500.00	.00
13	525.00	.00
14	543.75	.00
15	562.50	.00
16	581.25	.00
17	600.00	.00
18	615.00	.00

FIGURE A1. CONTINUED

19	630.00	.00
20	645.00	.00
21	660.00	.00
22	675.00	.00
23	687.50	.00
24	700.00	.00
25	712.50	.00
26	725.00	.00
27	737.50	.00
28	750.00	.00
29	762.50	.00
30	775.00	.00
31	787.50	.00
32	800.00	.00
33	812.50	.00
34	825.00	.00
35	837.50	.00
36	850.00	.00
37	862.50	.00
38	875.00	.00
39	887.50	.00
40	900.00	.00
41	912.50	.00
42	925.00	.00
43	937.50	.00
44	950.00	.00
45	962.50	.00
46	975.00	.00
47	987.50	.00
48	1000.00	.00
49	1012.50	.00
50	1025.00	.00
51	1037.50	.00
52	1050.00	.00
53	1062.50	.00
54	1075.00	.00
55	1087.50	.00
56	1100.00	.00
57	1112.50	.00
58	1125.00	.00
59	1140.00	.00
60	1155.00	.00
61	1170.00	.00
62	1185.00	.00
63	1200.00	.00
64	1218.75	.00
65	1237.50	.00
66	1256.25	.00
67	1275.00	.00
68	1300.00	.00
69	1325.00	.00
70	1350.00	.00

FIGURE A1. CONTINUED

```
  71        1375.00             .00
  72        1400.00             .00
  73        1425.00             .00
  74        1462.50             .00
  75        1500.00             .00
  76        1575.00             .00
  77        1650.00             .00
  78        1725.00             .00
  79        1800.00             .00
1CONTACT INTERFACES


 INTERFACE  1

 NO. OF NODES =  47,  FRICTION COEFF. =  .300

 LIST OF NODES
          63      62      61      60      59      58      57      56      55
   54
          53      52      51      50      49      48      47      46      45
   44
          43      42      41      40      39      38      37      36      35
   34
          33      32      31      30      29      28      27      26      25
   24
          23      22      21      20      19      18      17
 BEAM ELEMENTS, 100 SERIES

 TYPE NUMBER                   =          1          2          3          4
    5          6


 M. OF I. (IN4)                  =  2.330E+00  2.330E+00  2.330E+00  2.330E+00
2.330E+00  2.330E+00
 AREA (IN2)                      =  1.990E+00  1.990E+00  1.990E+00  1.990E+00
1.990E+00  1.990E+00
 LENGTH (IN)                     =  7.500E+01  3.750E+01  2.500E+01  1.875E+01
1.500E+01  1.250E+01
 YOUNGS MODULUS (KSI)            =  3.000E+04  3.000E+04  3.000E+04  3.000E+04
3.000E+04  3.000E+04
 WEIGHT (LB/FT)                  =  6.770E+00  6.770E+00  6.770E+00  6.770E+00
6.770E+00  6.770E+00
 YIELD FORCE (K)                 =  9.950E+01  9.950E+01  9.950E+01  9.950E+01
9.950E+01  9.950E+01
 YIELD MOMENT (K.IN)             =  6.850E+01  6.850E+01  6.850E+01  6.850E+01
6.850E+01  6.850E+01
 YIELD ACCURACY LIMIT            =  1.000E-01  1.000E-01  1.000E-01  1.000E-01
1.000E-01  1.000E-01
1POSTS, 300 SERIES
```

FIGURE A1. CONTINUED

TYPE NUMBER	=	1	2
HEIGHT OF NODE I (IN)	=	2.100E+01	2.100E+01
HEIGHT OF NODE J (IN)	=	.000E+00	.000E+00
A AXIS STIFFNESS (K/IN)	=	1.500E+01	2.900E+00
B AXIS STIFFNESS (K/IN)	=	2.900E+00	2.900E+00
EFFECTIVE WEIGHT (LB)	=	5.100E+01	5.100E+01
B AXIS YIELD MOMENT (K.IN)	=	1.000E+04	2.560E+02
A AXIS YIELD MOMENT (K.IN)	=	1.000E+04	2.560E+02
YIELD ACCURACY LIMIT	=	1.000E-01	1.000E-01
A SHEAR AT FAILURE (K)	=	1.000E+04	2.000E+01
B SHEAR AT FAILURE (K)	=	1.000E+04	2.000E+01
A DEFLN AT FAILURE (IN)	=	1.000E+04	1.800E+01
B DEFLN AT FAILURE (IN)	=	1.000E+04	1.800E+01

1MEMBER GENERATION COMMANDS

FIRST MEMBER	NODE I	NODE J	LAST MEMBER	NODE DIFF	TYPE NO.	PRESTRESS DATA 1	2	3	4	5
1	1	2	4	1	101	.000	.000	.000	.000	.000
5	5	6	6	1	102	.000	.000	.000	.000	.000
7	7	8	12	1	103	.000	.000	.000	.000	.000
13	13	14	16	1	104	.000	.000	.000	.000	.000
17	17	18	21	1	105	.000	.000	.000	.000	.000
22	22	23	57	1	106	.000	.000	.000	.000	.000
58	58	59	62	1	105	.000	.000	.000	.000	.000
63	63	64	66	1	104	.000	.000	.000	.000	.000
67	67	68	72	1	103	.000	.000	.000	.000	.000
73	73	74	74	1	102	.000	.000	.000	.000	.000
75	75	76	78	1	101	.000	.000	.000	.000	.000
79	1	0	0	0	301	.000	.000	.000	.000	.000
80	5	0	81	3	302	.000	.000	.000	.000	.000
82	12	0	83	5	302	.000	.000	.000	.000	.000
84	24	0	88	8	302	.000	.000	.000	.000	.000
89	63	0	90	5	302	.000	.000	.000	.000	.000

FIGURE A1. CONTINUED

```
   91        72         0        92          3       302                .000          .000
       .000         .000          .000
   93        79         0         0          0       301                .000          .000
       .000         .000          .000
1COMPLETE MEMBER DATA
```

BEAMS, 100 SERIES

MEMBER	NODE I	NODE J	TYPE	FORCE	I-MOMENT	J-MOMENT
1	1	2	101	.00	.00	.00
2	2	3	101	.00	.00	.00
3	3	4	101	.00	.00	.00
4	4	5	101	.00	.00	.00
5	5	6	102	.00	.00	.00
6	6	7	102	.00	.00	.00
7	7	8	103	.00	.00	.00
8	8	9	103	.00	.00	.00
9	9	10	103	.00	.00	.00
10	10	11	103	.00	.00	.00
11	11	12	103	.00	.00	.00
12	12	13	103	.00	.00	.00
13	13	14	104	.00	.00	.00
14	14	15	104	.00	.00	.00
15	15	16	104	.00	.00	.00
16	16	17	104	.00	.00	.00
17	17	18	105	.00	.00	.00
18	18	19	105	.00	.00	.00
19	19	20	105	.00	.00	.00
20	20	21	105	.00	.00	.00
21	21	22	105	.00	.00	.00
22	22	23	106	.00	.00	.00
23	23	24	106	.00	.00	.00
24	24	25	106	.00	.00	.00
25	25	26	106	.00	.00	.00
26	26	27	106	.00	.00	.00
27	27	28	106	.00	.00	.00
28	28	29	106	.00	.00	.00
29	29	30	106	.00	.00	.00
30	30	31	106	.00	.00	.00
31	31	32	106	.00	.00	.00
32	32	33	106	.00	.00	.00
33	33	34	106	.00	.00	.00
34	34	35	106	.00	.00	.00
35	35	36	106	.00	.00	.00
36	36	37	106	.00	.00	.00
37	37	38	106	.00	.00	.00
38	38	39	106	.00	.00	.00
39	39	40	106	.00	.00	.00
40	40	41	106	.00	.00	.00
41	41	42	106	.00	.00	.00

FIGURE A1. CONTINUED

42	42	43	106	.00	.00	.00
43	43	44	106	.00	.00	.00
44	44	45	106	.00	.00	.00
45	45	46	106	.00	.00	.00
46	46	47	106	.00	.00	.00
47	47	48	106	.00	.00	.00
48	48	49	106	.00	.00	.00
49	49	50	106	.00	.00	.00
50	50	51	106	.00	.00	.00
51	51	52	106	.00	.00	.00
52	52	53	106	.00	.00	.00
53	53	54	106	.00	.00	.00
54	54	55	106	.00	.00	.00
55	55	56	106	.00	.00	.00
56	56	57	106	.00	.00	.00
57	57	58	106	.00	.00	.00
58	58	59	105	.00	.00	.00
59	59	60	105	.00	.00	.00
60	60	61	105	.00	.00	.00
61	61	62	105	.00	.00	.00
62	62	63	105	.00	.00	.00
63	63	64	104	.00	.00	.00
64	64	65	104	.00	.00	.00
65	65	66	104	.00	.00	.00
66	66	67	104	.00	.00	.00
67	67	68	103	.00	.00	.00
68	68	69	103	.00	.00	.00
69	69	70	103	.00	.00	.00
70	70	71	103	.00	.00	.00
71	71	72	103	.00	.00	.00
72	72	73	103	.00	.00	.00
73	73	74	102	.00	.00	.00
74	74	75	102	.00	.00	.00
75	75	76	101	.00	.00	.00
76	76	77	101	.00	.00	.00
77	77	78	101	.00	.00	.00
78	78	79	101	.00	.00	.00

POSTS, 300 SERIES

MEMBER	NODE I	NODE J	TYPE	A-SHEAR	B-SHEAR	B-MOMENT	A-MOMENT	ANGLE
79	1	0	301	.00	.00	.00	.00	.00
80	5	0	302	.00	.00	.00	.00	.00
81	8	0	302	.00	.00	.00	.00	.00
82	12	0	302	.00	.00	.00	.00	.00

FIGURE A1. CONTINUED

83	17	0	302	.00	.00	.00	.00	.00
84	24	0	302	.00	.00	.00	.00	.00
85	32	0	302	.00	.00	.00	.00	.00
86	40	0	302	.00	.00	.00	.00	.00
87	48	0	302	.00	.00	.00	.00	.00
88	56	0	302	.00	.00	.00	.00	.00
89	63	0	302	.00	.00	.00	.00	.00
90	68	0	302	.00	.00	.00	.00	.00
91	72	0	302	.00	.00	.00	.00	.00
92	75	0	302	.00	.00	.00	.00	.00
93	79	0	301	.00	.00	.00	.00	.00

STIFFNESS MATRIX STORAGE

REQUIRED = 1422
ALLOCATED = 6000

1AUTOMOBILE PROPERTIES

WEIGHT (LB)	=	1800.0
MOMENT OF INERTIA (LB.IN.SEC2)	=	17000.0
NO. OF CONTACT POINTS	=	13
NO. OF UNIT STIFFNESSES	=	2
NO. OF WHEELS	=	4
BRAKE CODE (1=ON, 0=OFF)	=	0
NO. OF OUTPUT POINTS	=	3

UNIT STIFFNESSES (K/IN/IN)

NO.	BEFORE BOTTOMING	AFTER BOTTOMING	UNLOADING	BOTTOMING DISTANCE
1	.025	.150	.200	10.00
2	.900	5.500	7.150	1.00

FIGURE A1. CONTINUED

CONTACT POINT DATA

POINT CONTACTS	R COORD	S COORD	STIFFNESS NO.	TRIBUTARY LENGTH	INTERFACE			
1	35.00	24.00	2	1.00	0	0	0	0
2	35.00	-24.00	2	1.00	0	0	0	0
3	-83.00	30.00	1	40.00	1	0	0	0
4	-40.00	30.00	1	40.00	1	0	0	0
5	.00	30.00	1	20.00	1	0	0	0
6	20.00	30.00	1	20.00	1	0	0	0
7	40.00	30.00	1	20.00	1	0	0	0
8	61.00	30.00	1	20.00	1	0	0	0
9	61.00	15.00	1	15.00	1	0	0	0
10	61.00	.00	1	15.00	1	0	0	0
11	61.00	-15.00	1	15.00	1	0	0	0
12	61.00	-30.00	1	20.00	1	0	0	0
13	-83.00	-30.00	1	20.00	0	0	0	0

OWHEEL COORDINATES (IN), STEER ANGLES (DEG), AND DRAG FORCES (LB)

POINT	R-ORD	S-ORD	STEER ANGLE	DRAG FORCE
1	35.00	24.00	.00	400.00
2	35.00	-24.00	.00	400.00
3	-52.00	24.00	.00	300.00
4	-52.00	-24.00	.00	300.00

OOUTPUT POINT COORDINATES (IN)

POINT	R-ORD	S-ORD
1	.00	.00
2	61.00	.00
3	35.00	24.00

FIGURE A1. CONTINUED

1INITIAL POSITION AND VELOCITIES OF AUTO

SPECIFIED BOUNDARY POINT	=	8
X ORDINATE OF POINT	=	712.00
Y ORDINATE OF POINT	=	.00
ANGLE FROM X AXIS TO R AXIS (DEG)	=	20.00
VELOCITY IN R DIRECTION (M.P.H)	=	60.00
VELOCITY IN S DIRECTION (M.P.H)	=	.00
ANGULAR VELOCITY (RAD/SEC)	=	.000
MINIMUM RESULTANT VELOCITY (M.P.H)	=	.00
TRANSLATIONAL KINETIC ENERGY (K.IN)	=	2600.06
ROTATIONAL KINETIC ENERGY (K.IN)	=	.00
TOTAL INITIAL KINETIC ENERGY (K.IN)	=	2600.06

FIGURE A1. CONTINUED

APPENDIX B.

ACCELEROMETER TRACES

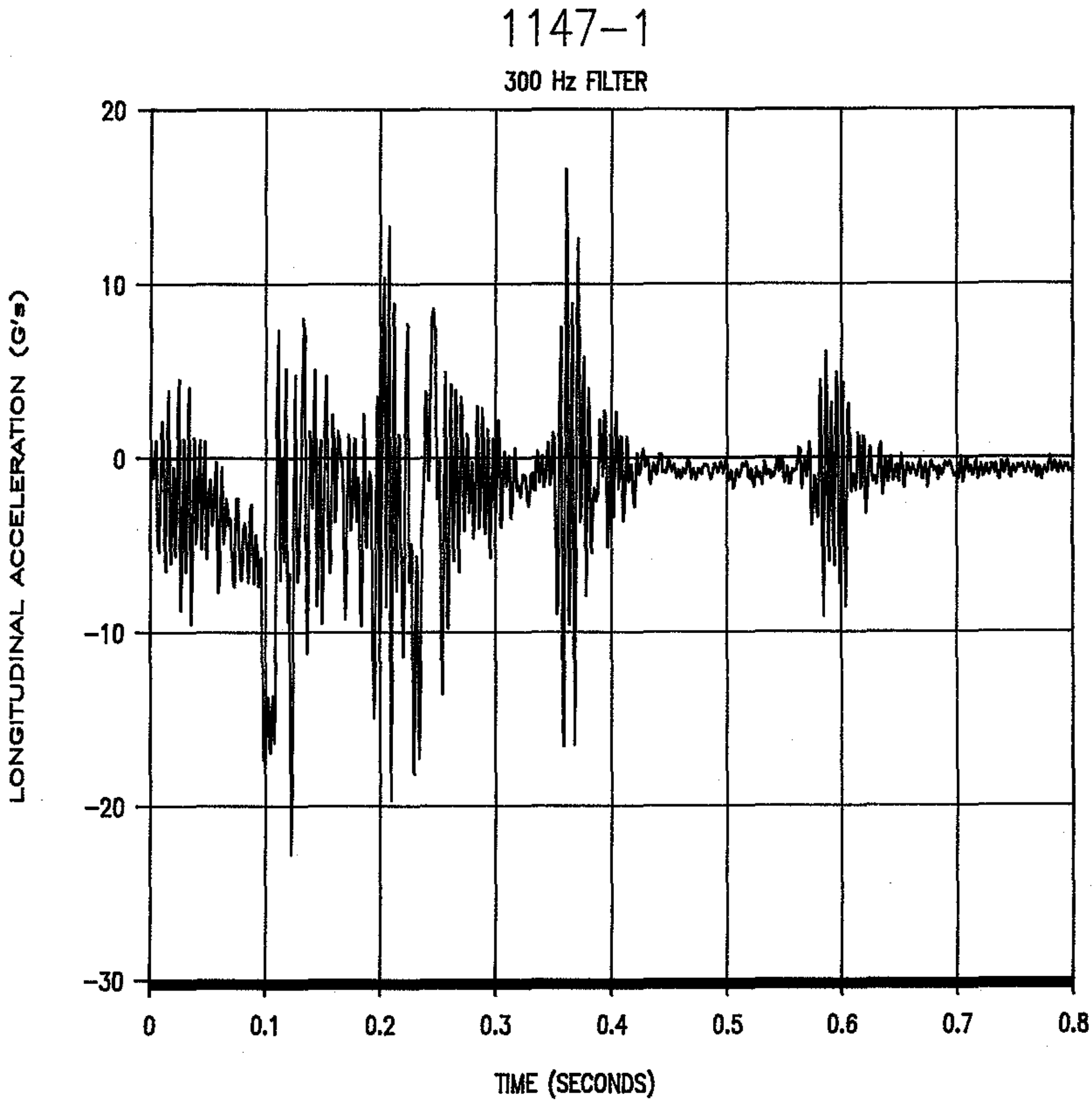


FIGURE B-1. LONGITUDINAL ACCELEROMETER TRACE FROM TEST 1147-1.

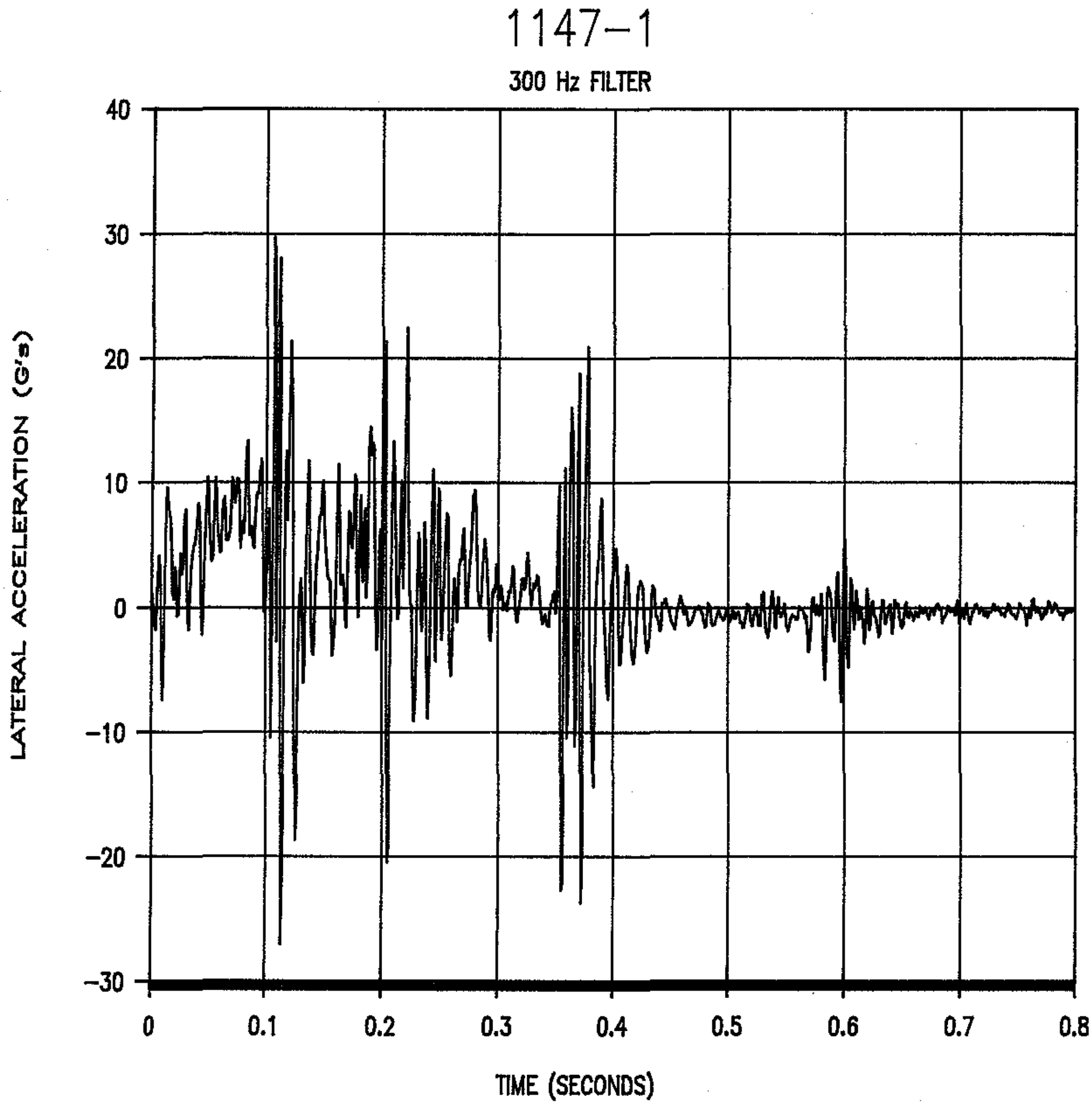


FIGURE B-2. LATERAL ACCELEROMETER TRACE FROM TEST 1147-1.

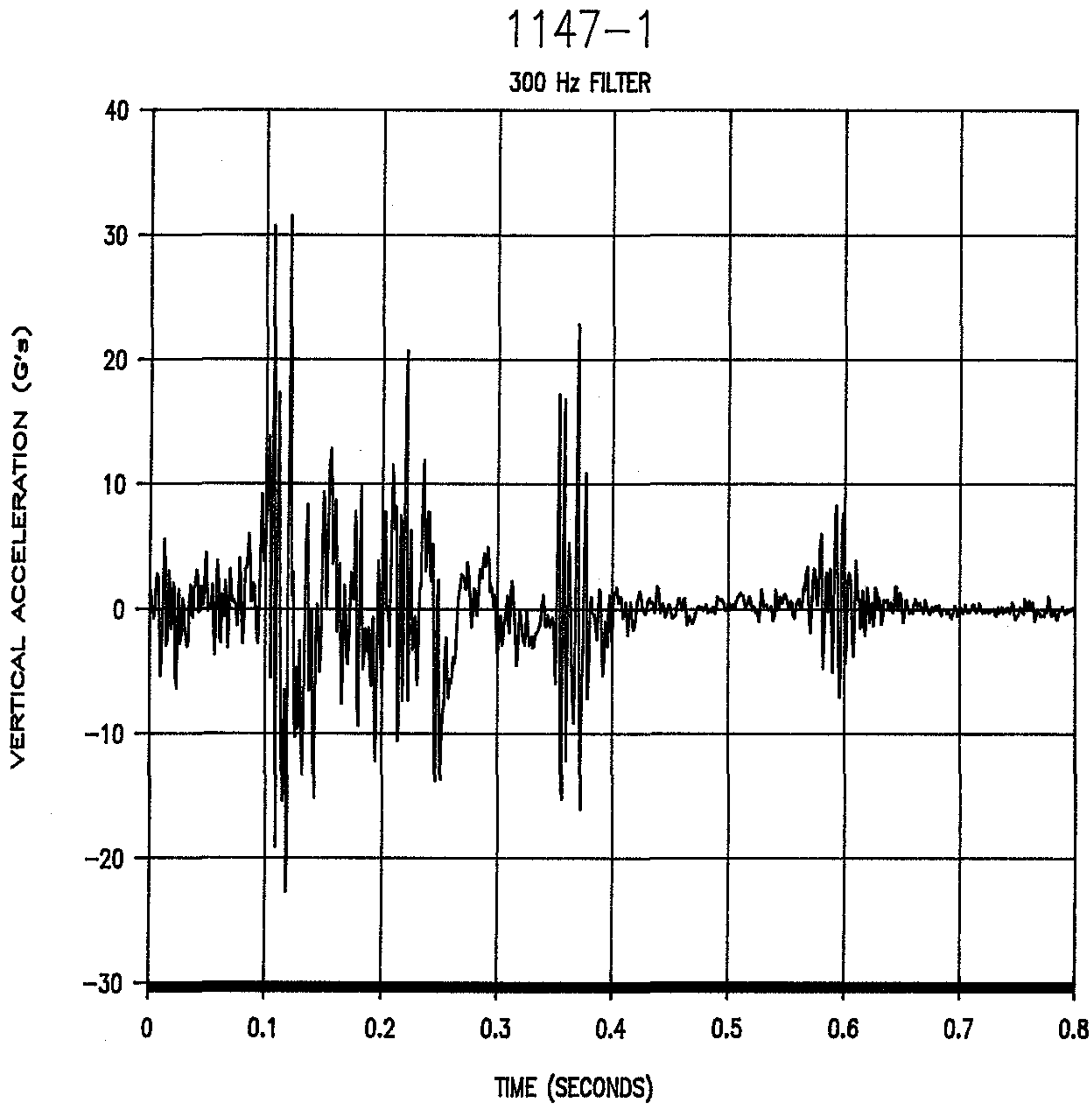


FIGURE B-3. VERTICAL ACCELEROMETER TRACE FROM TEST 1147-1

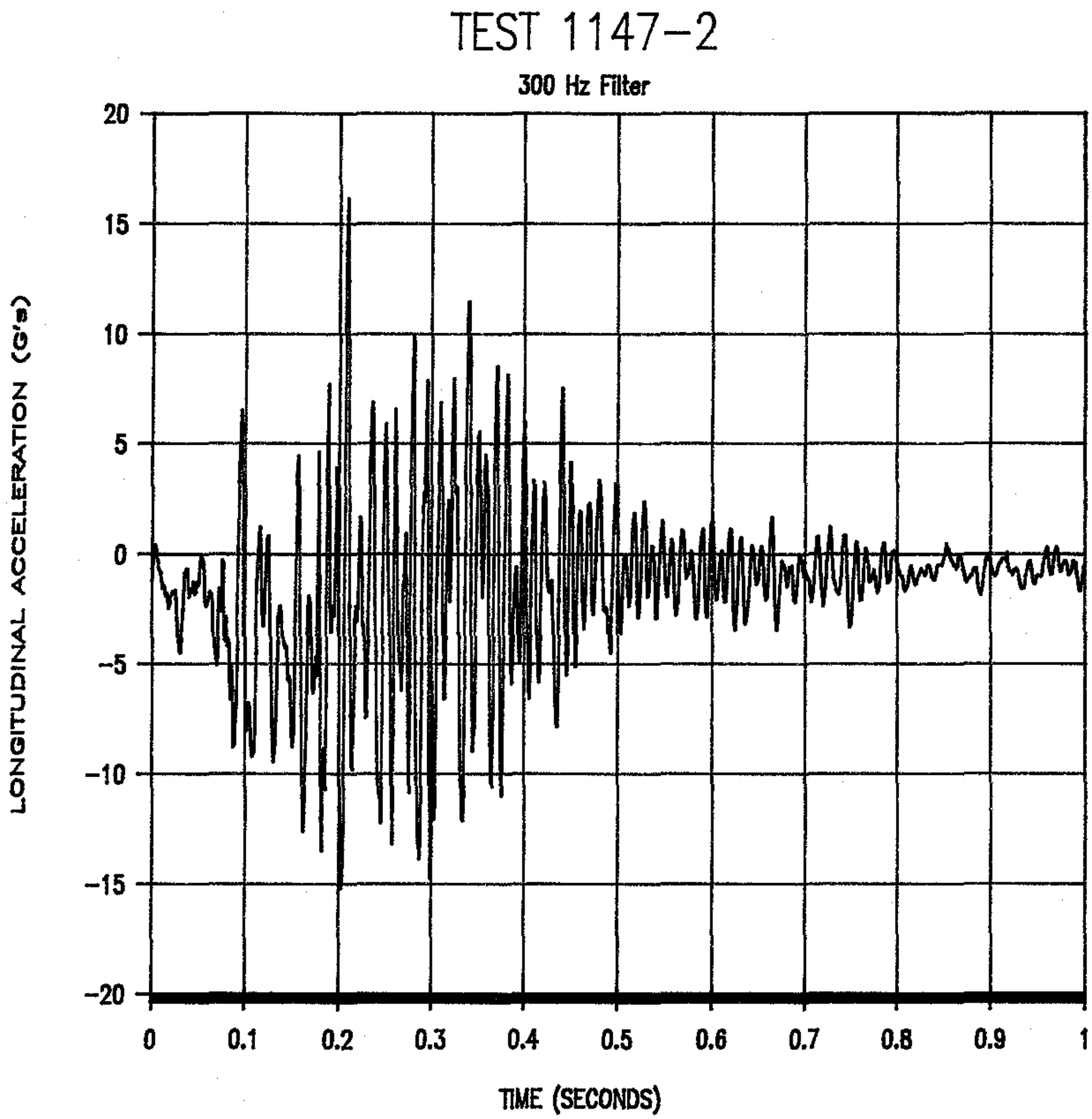


FIGURE B-4. LONGITUDINAL ACCELEROMETER TRACE FROM TEST 1147-2.

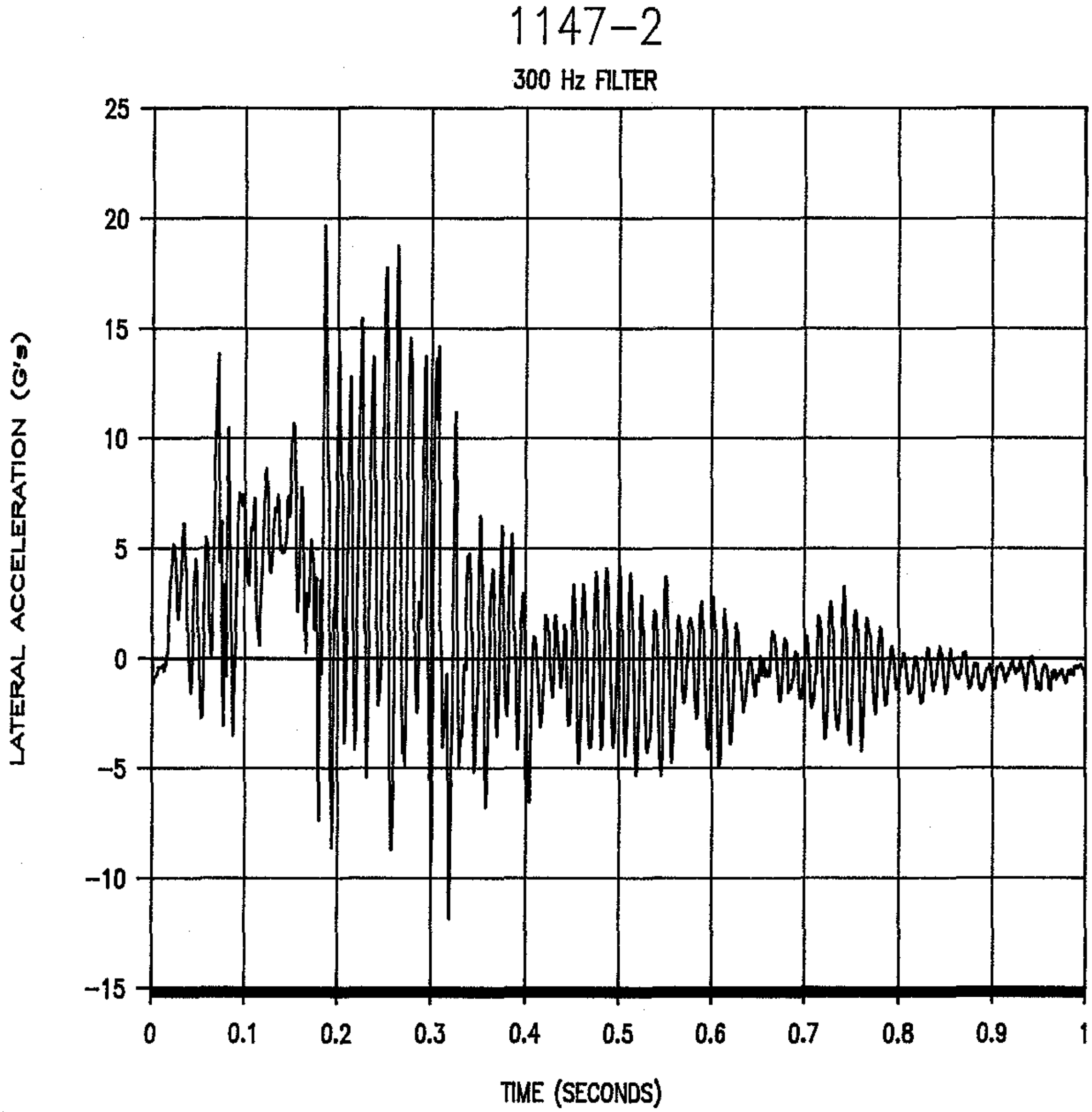


FIGURE B-5. LATERAL ACCELEROMETER TRACE FROM TEST 1147-2.

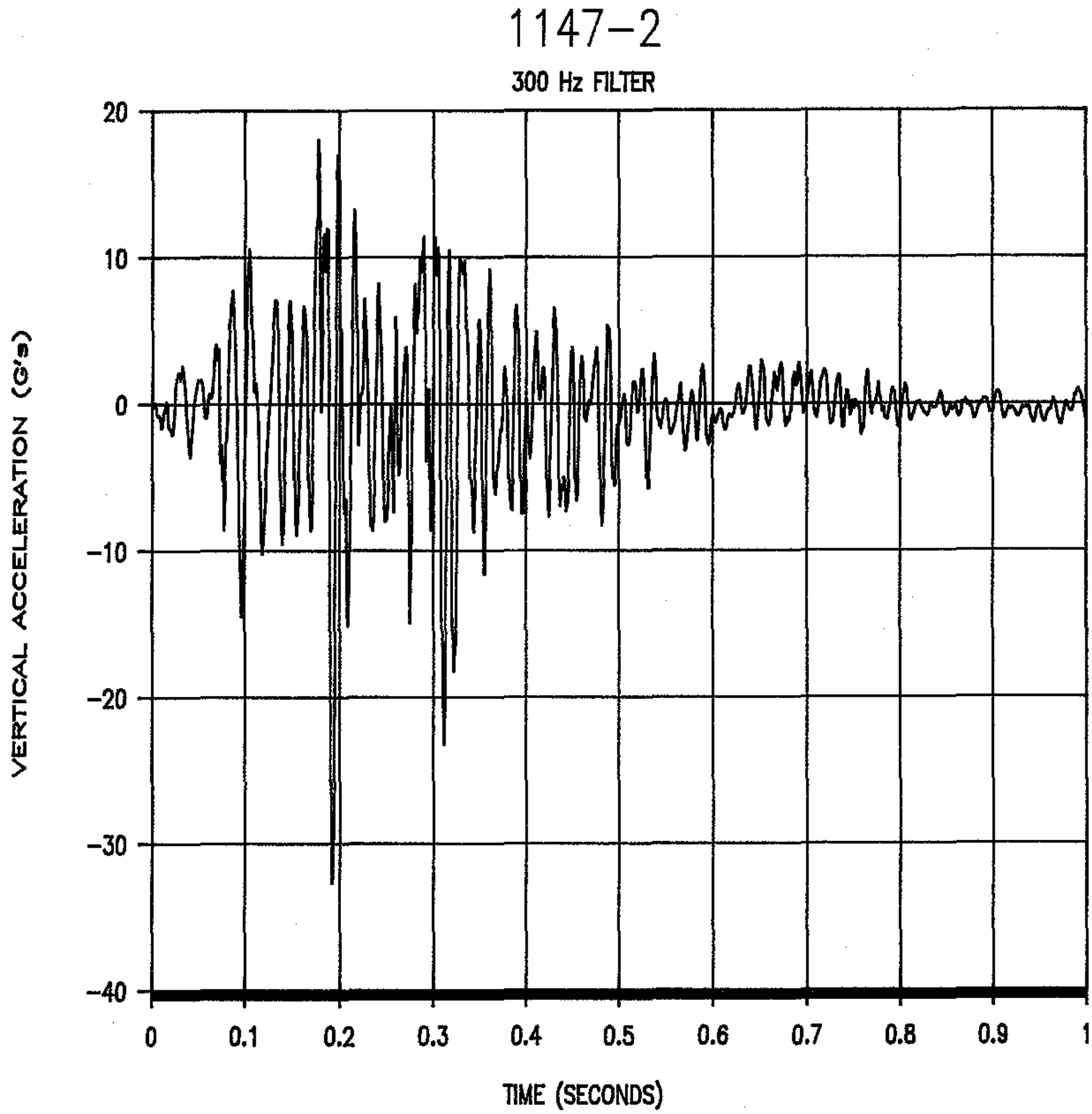


FIGURE B-6. VERTICAL ACCELEROMETER TRACE FROM TEST 1147-2.

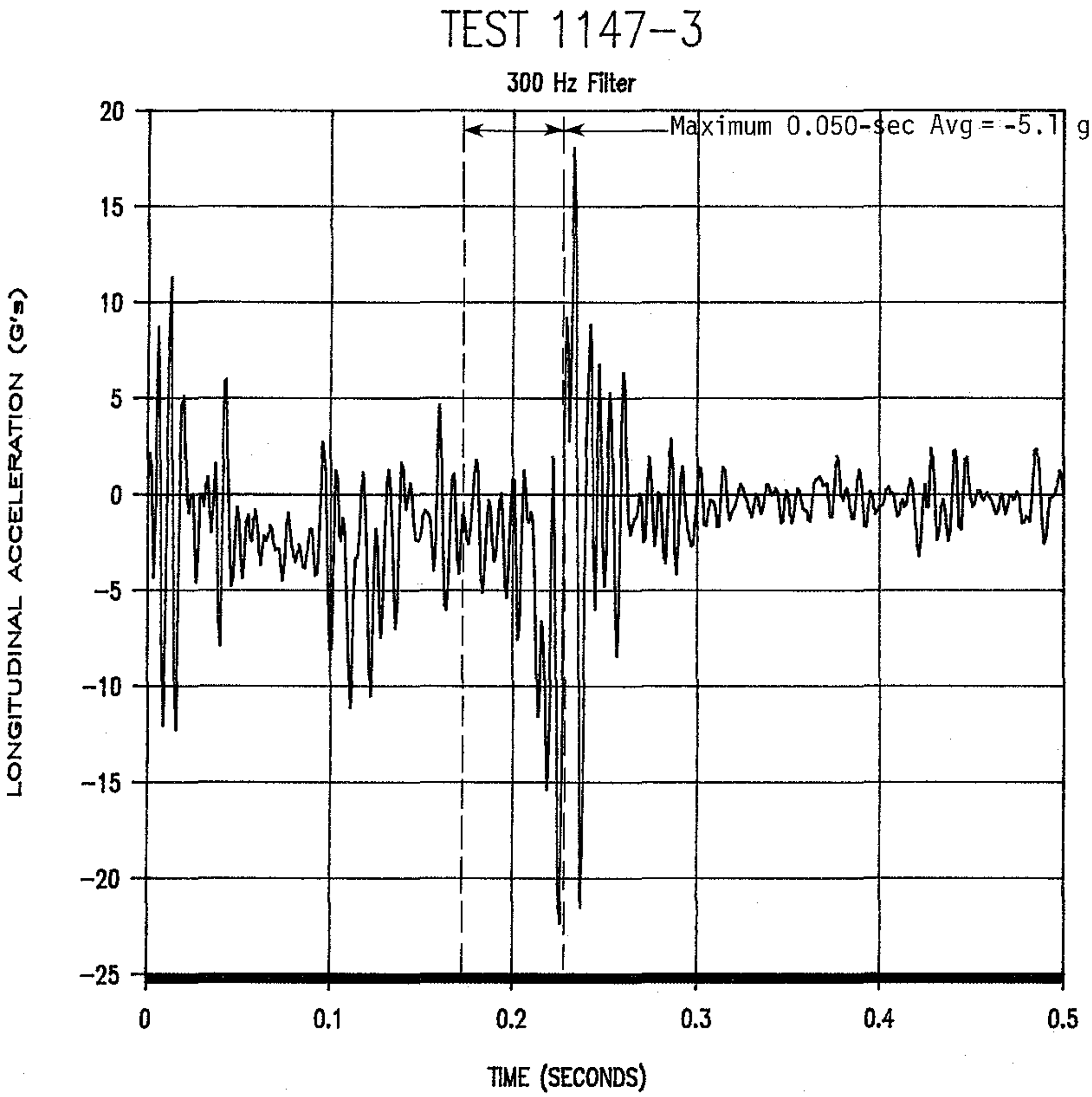


FIGURE B-7. LONGITUDINAL ACCELEROMETER TRACE FROM TEST 1147-3.

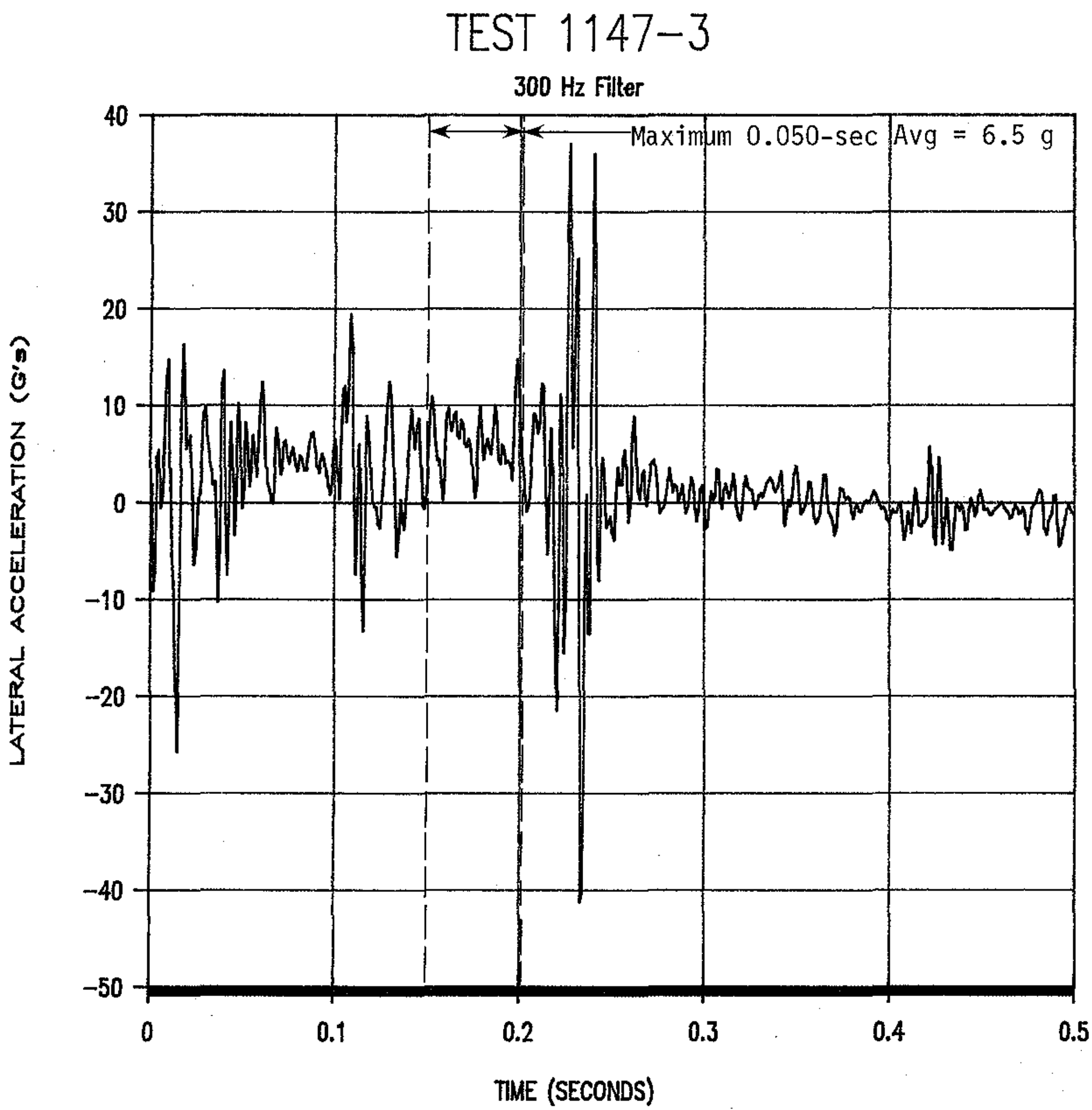


FIGURE B-8. LATERAL ACCELEROMETER TRACE FROM TEST 1147-3.

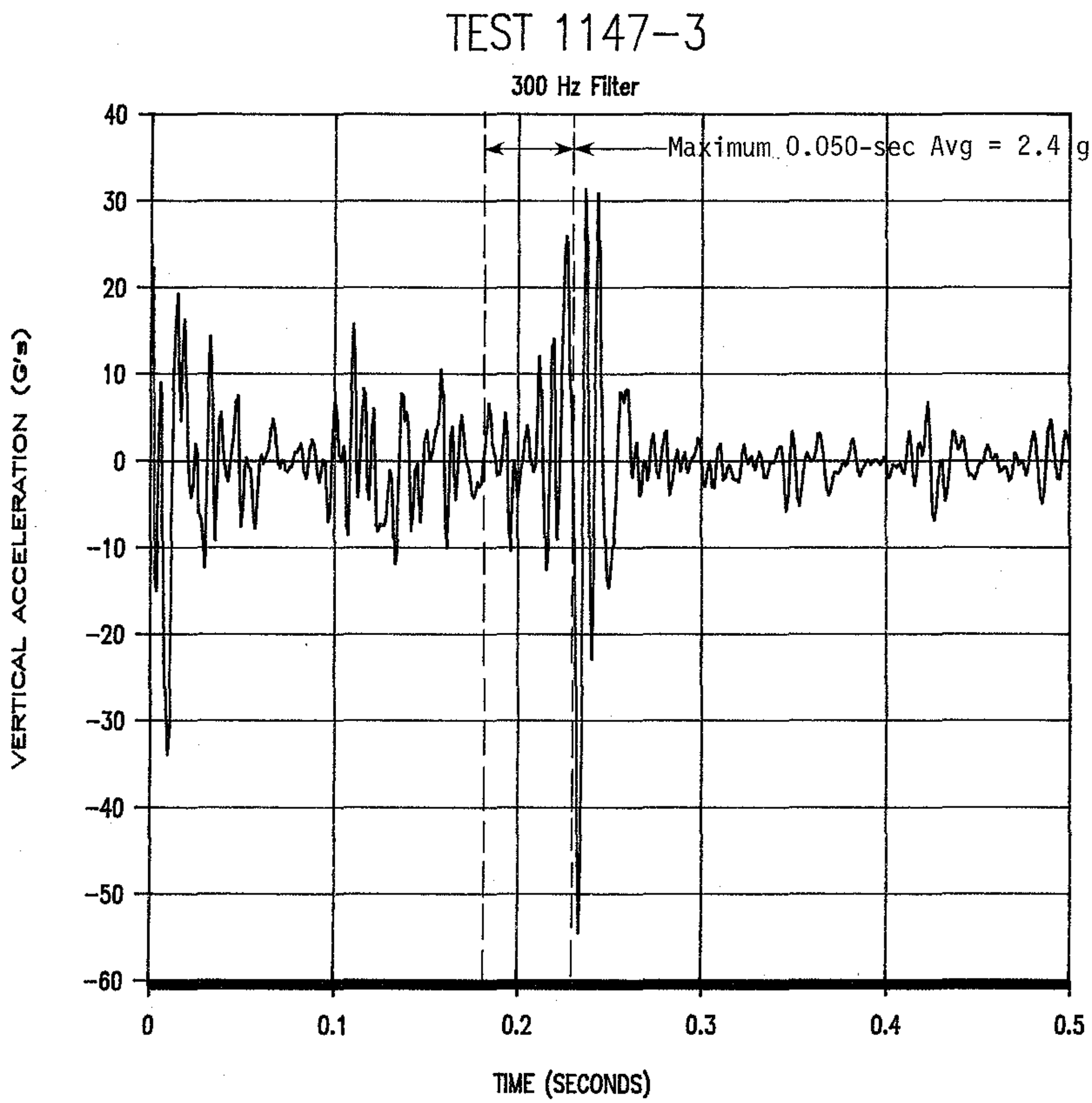


FIGURE B-9. VERTICAL ACCELEROMETER TRACE FROM TEST 1147-3.

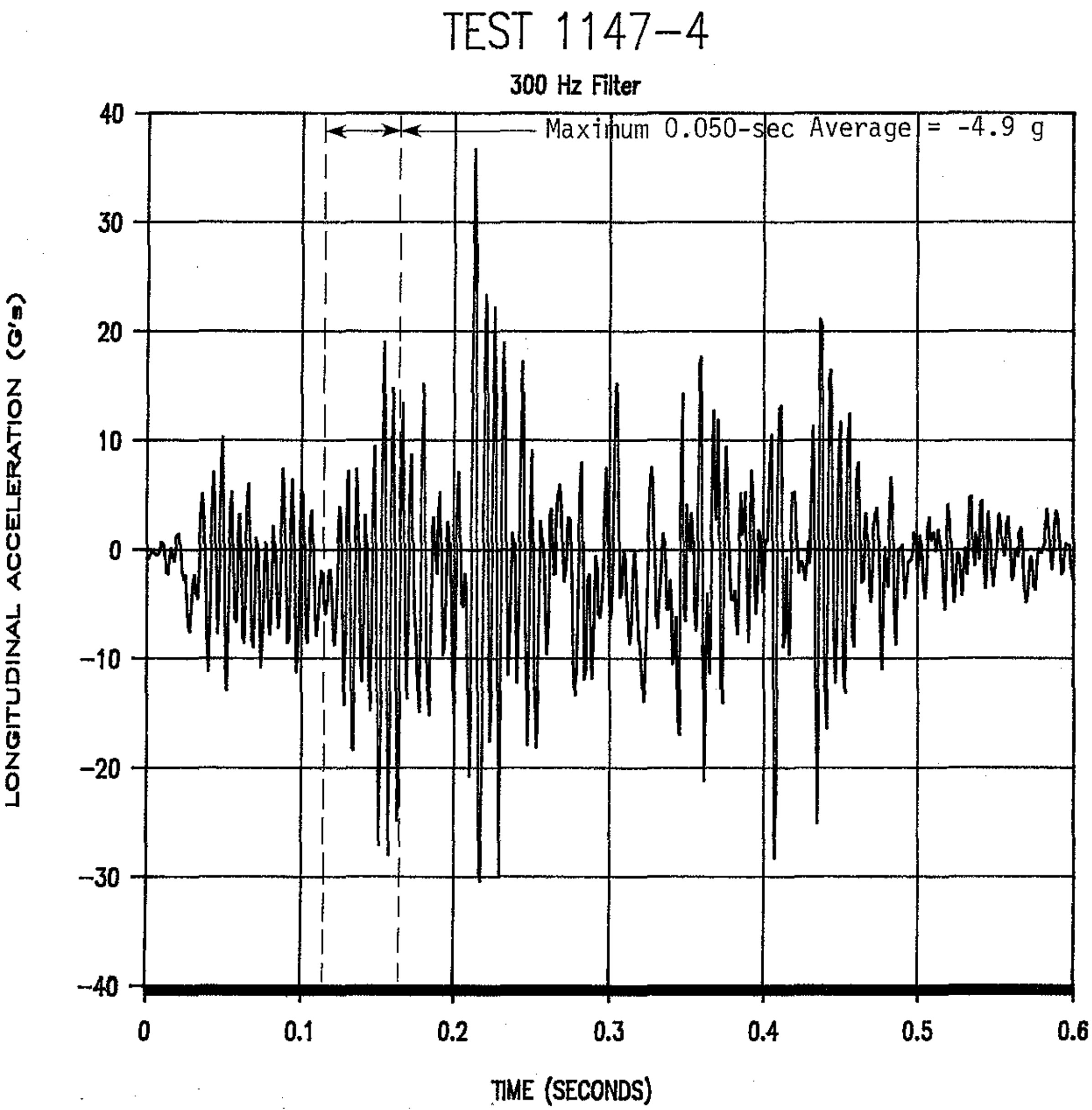


FIGURE B-10. LONGITUDINAL ACCELEROMETER TRACE FROM TEST 1147-4.

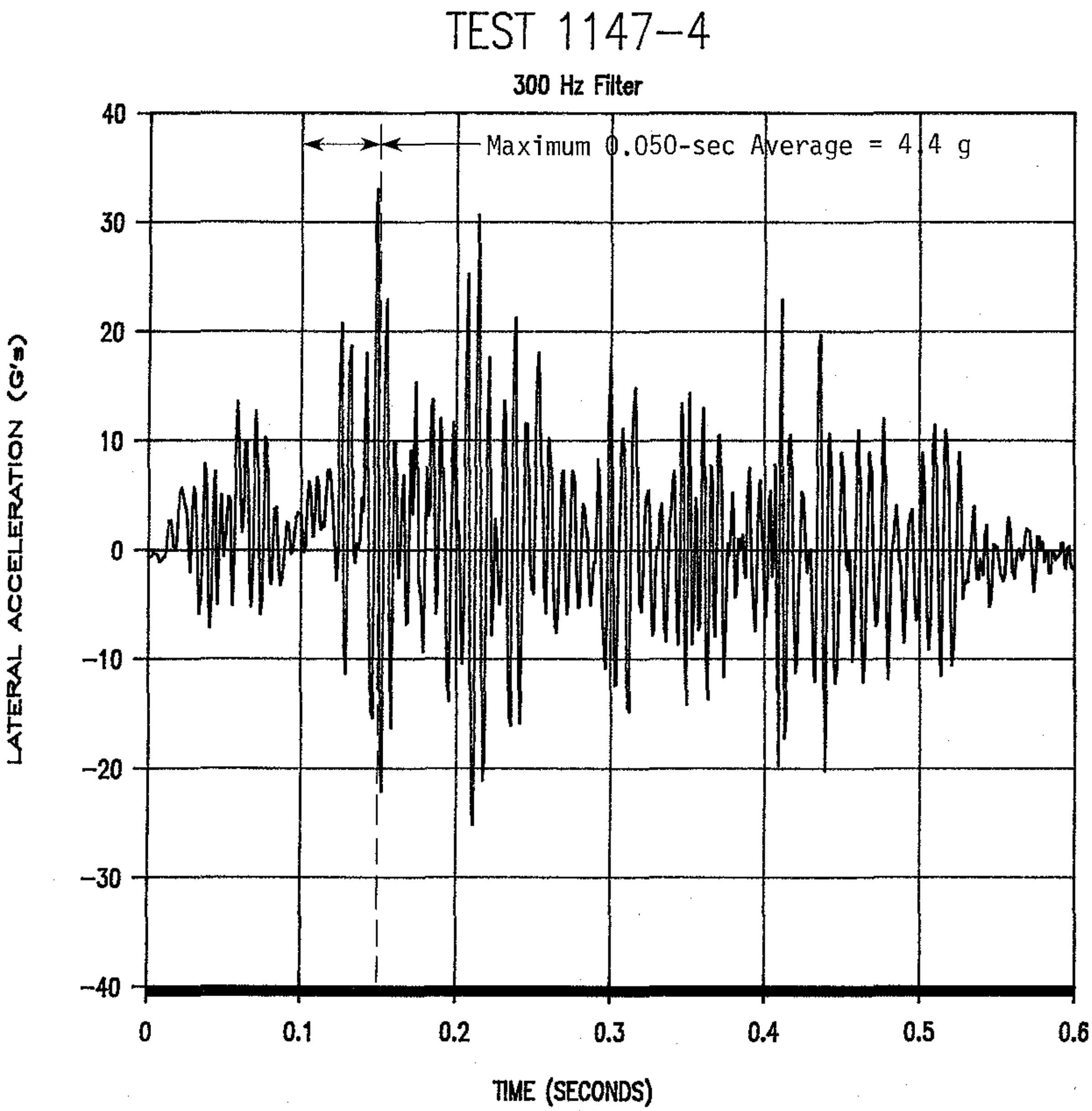


FIGURE B-11. LATERAL ACCELEROMETER TRACE FROM TEST 1147-4.

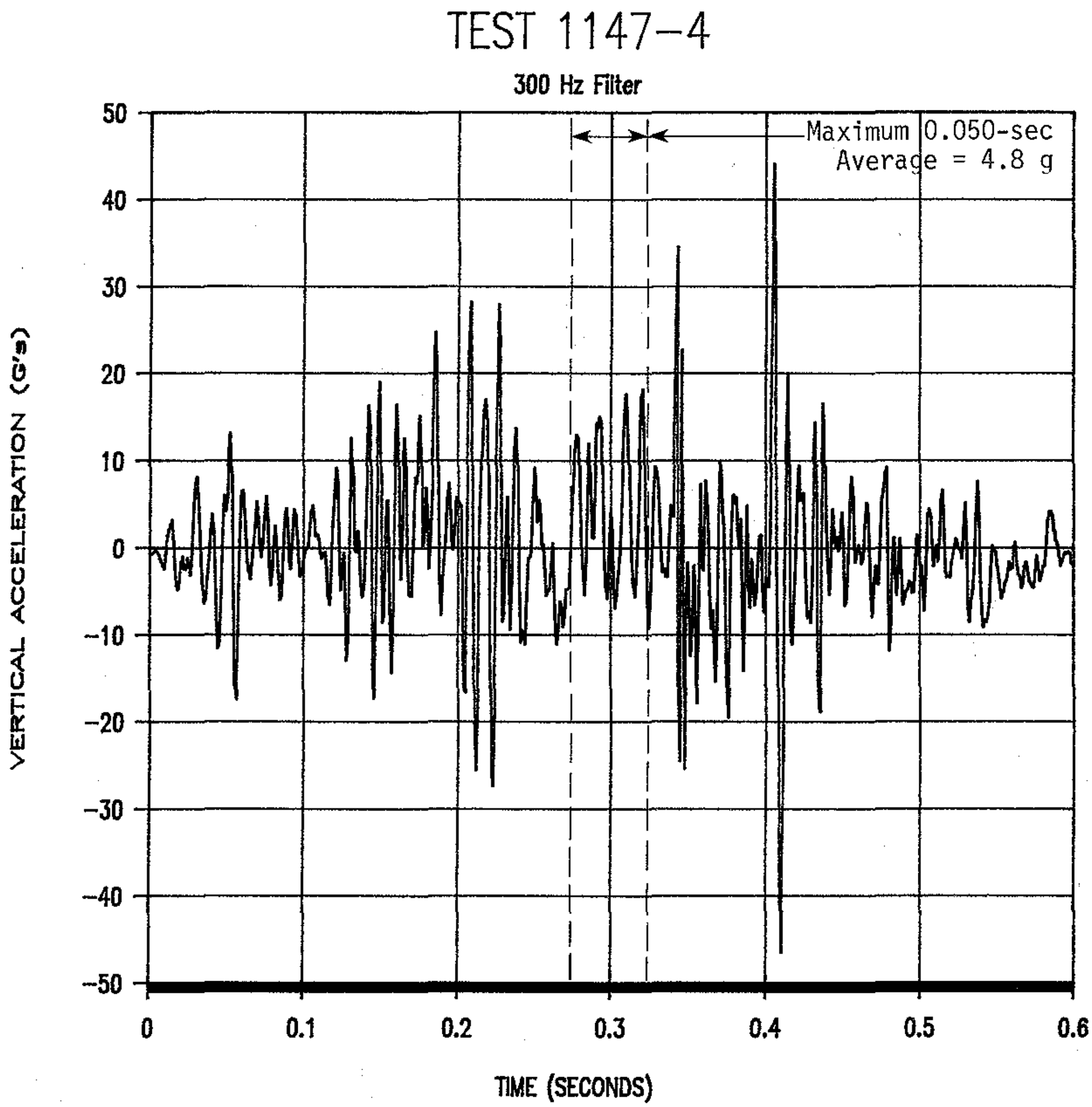


FIGURE B-12. VERTICAL ACCELEROMETER TRACE FROM TEST 1147-4.

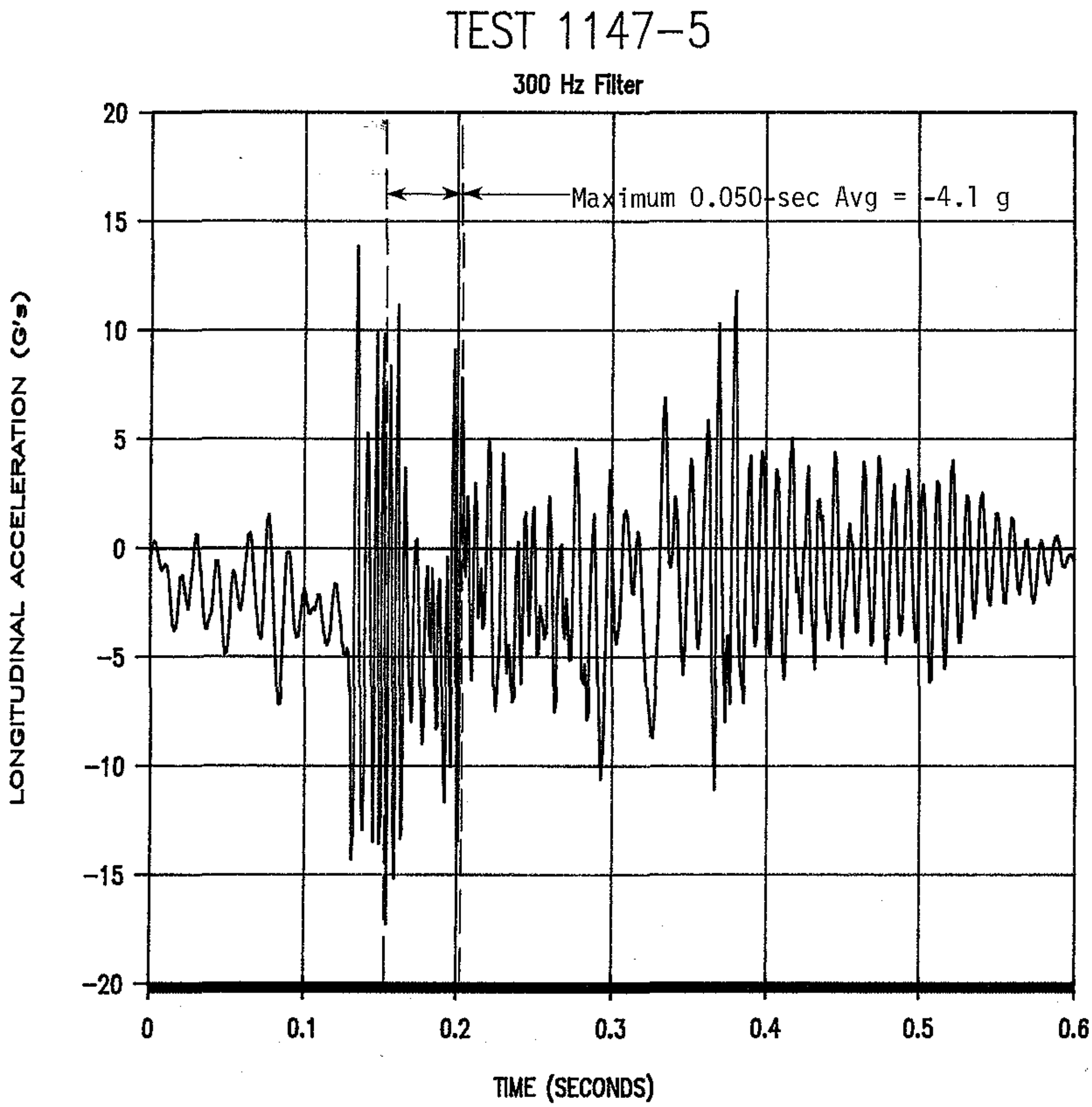


FIGURE B-13. LONGITUDINAL ACCELEROMETER TRACE FROM TEST 1147-5.

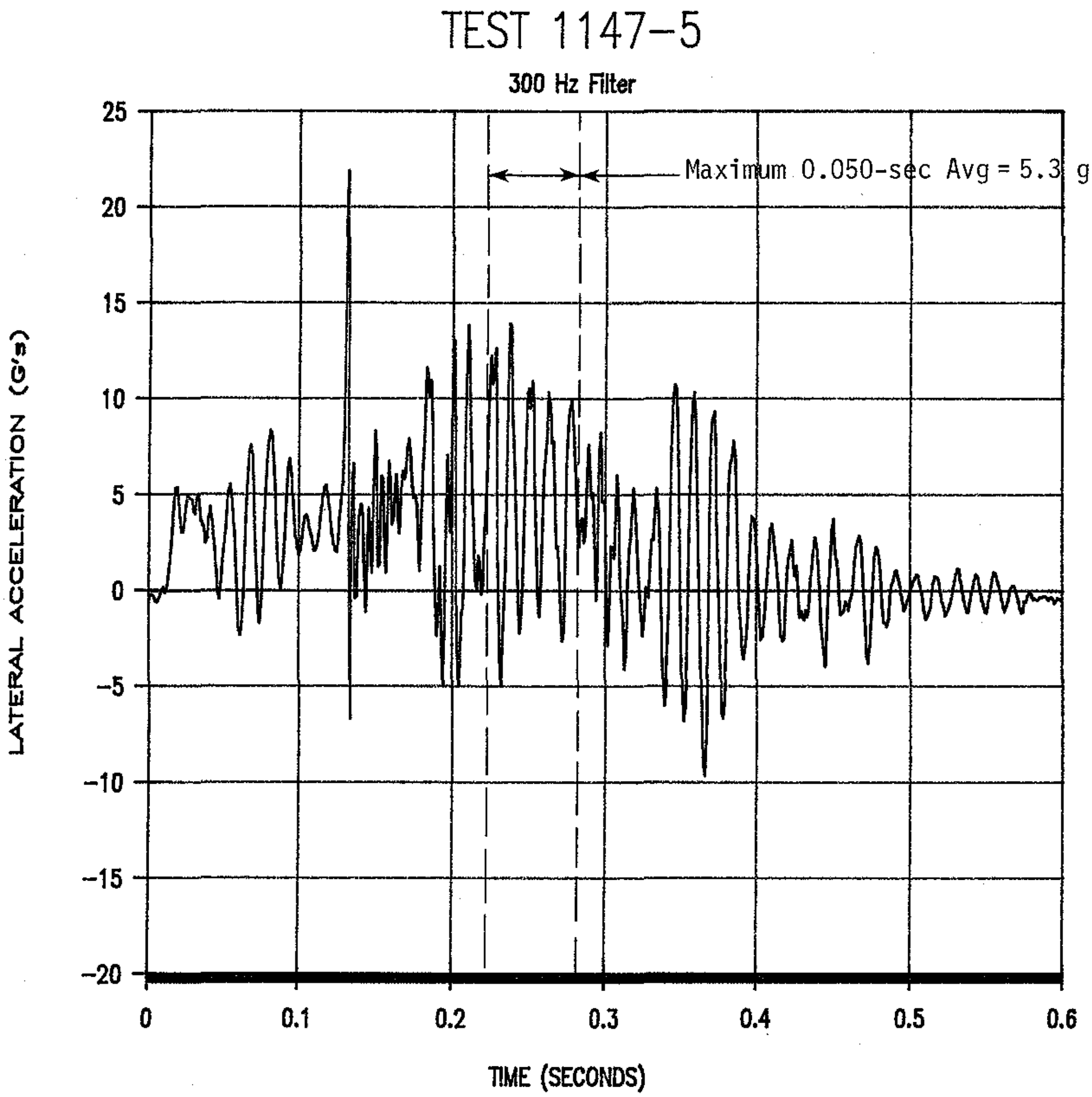


FIGURE B-14. LATERAL ACCELEROMETER TRACE FROM TEST 1147-5.

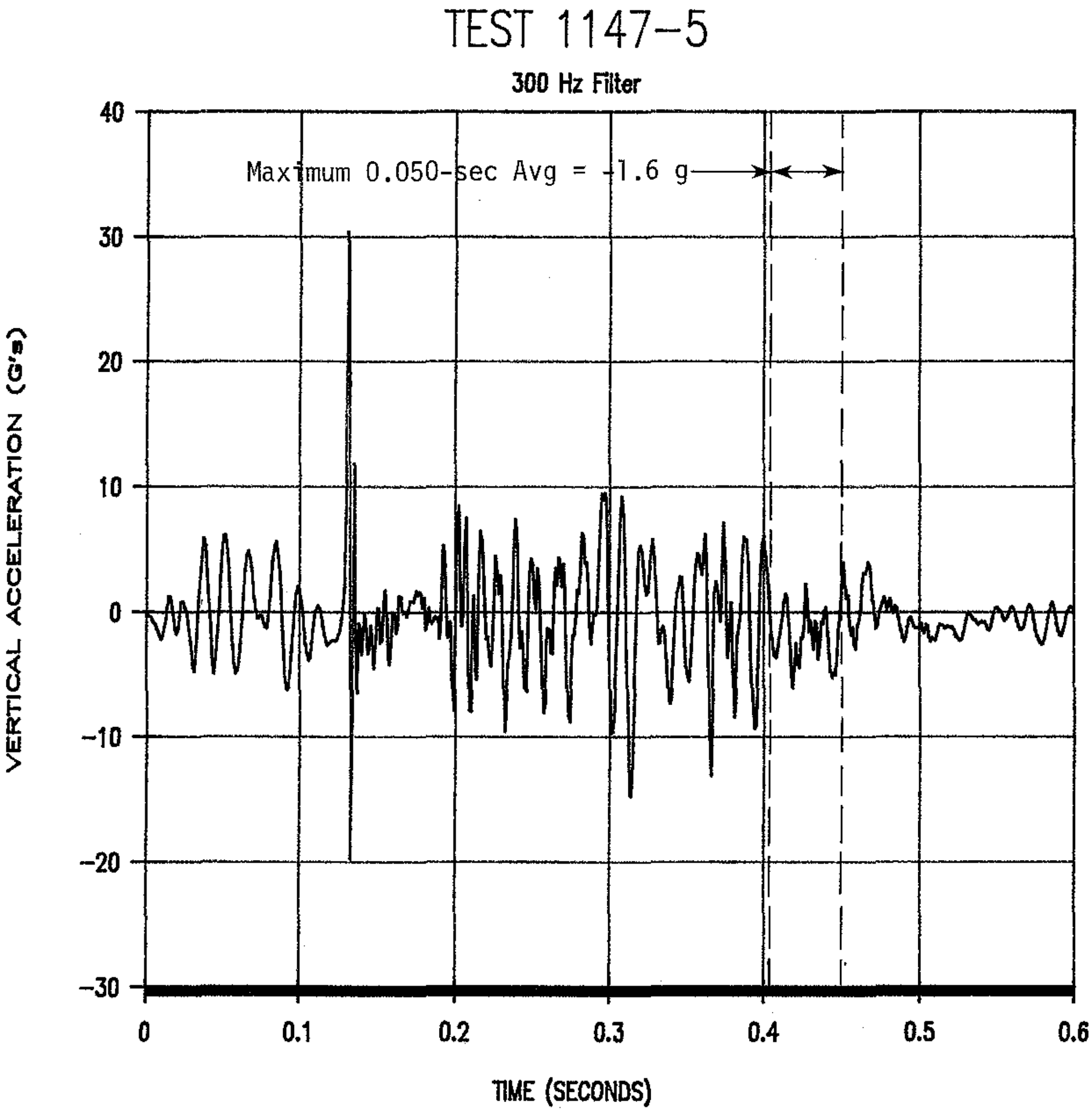
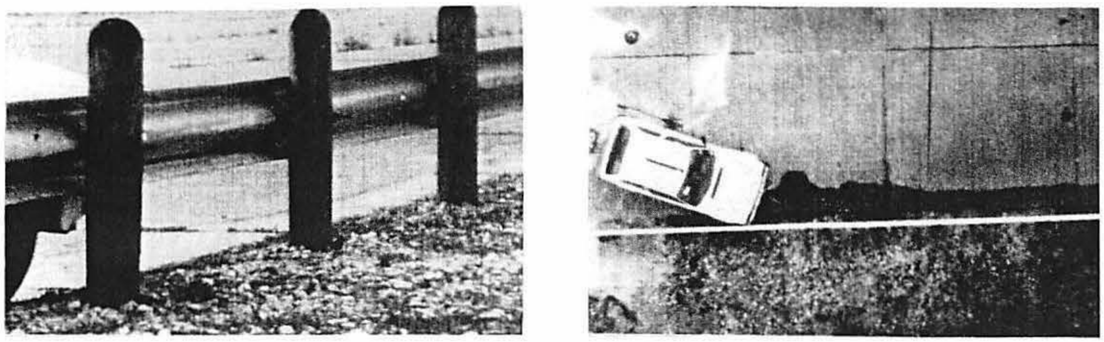


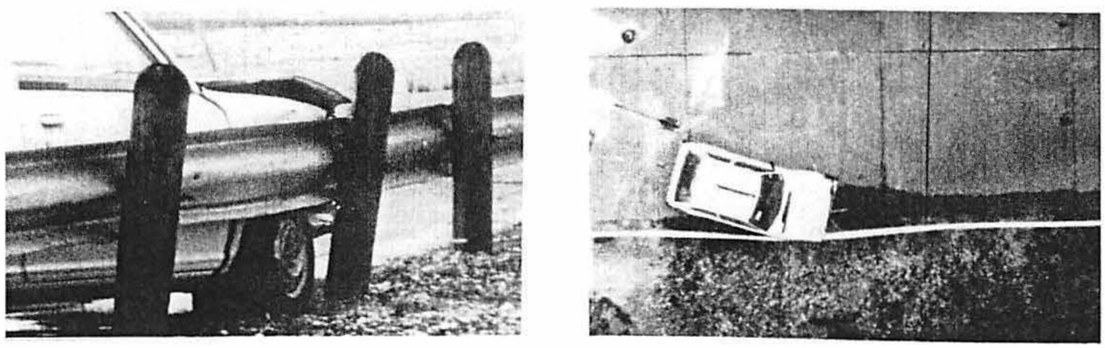
FIGURE B-15. VERTICAL ACCELEROMETER TRACE FROM TEST 1147-5.

APPENDIX C.

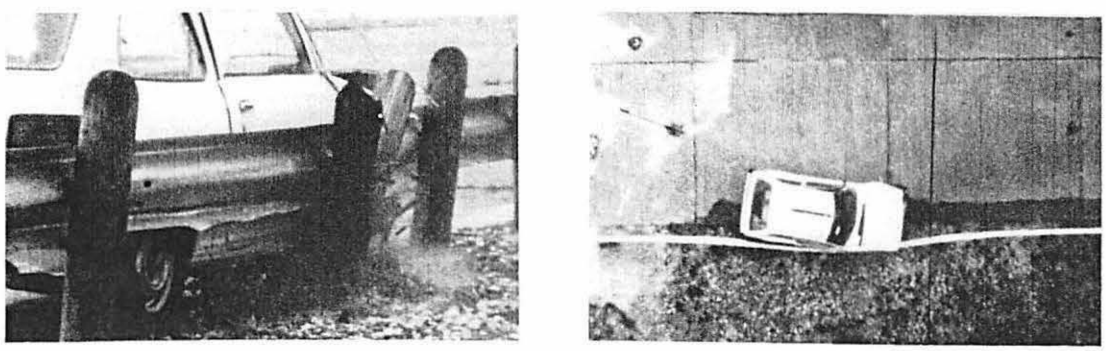
SEQUENTIAL PHOTOGRAPHS



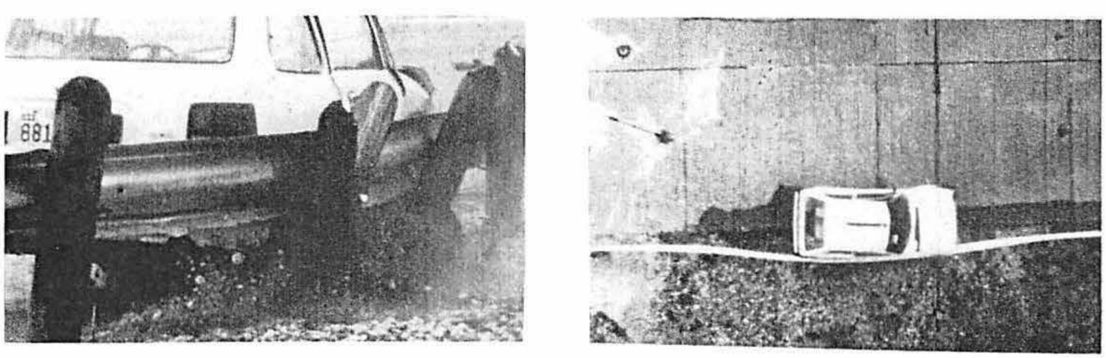
0.000 s



0.065 s

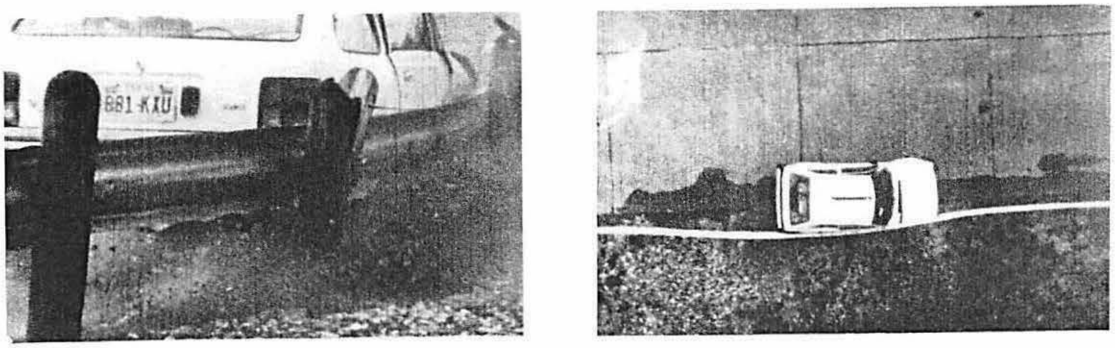


0.129 s

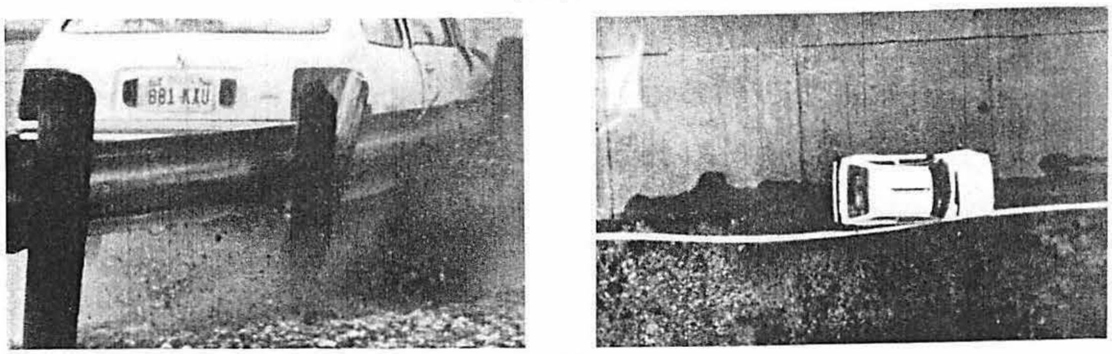


0.194 s

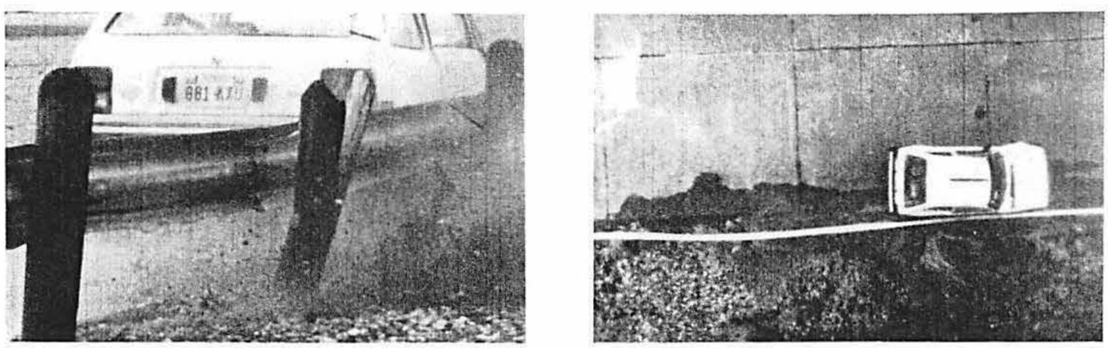
Figure C-1. Sequential photographs for test 1147-1.



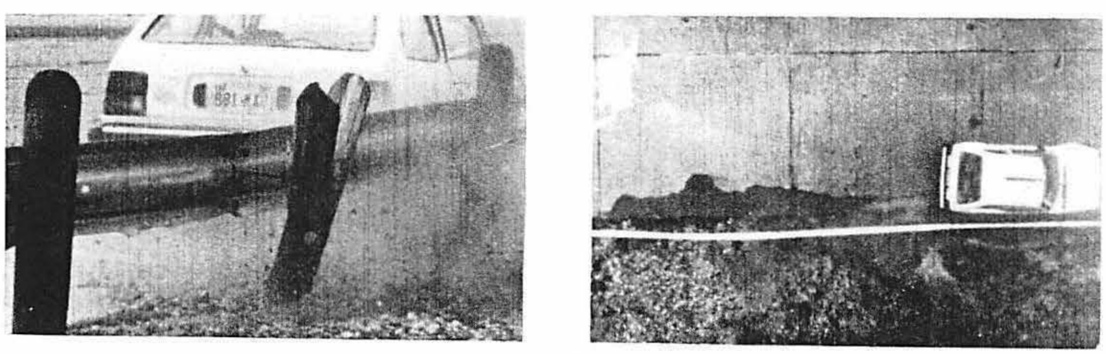
0.258 s



0.323 s

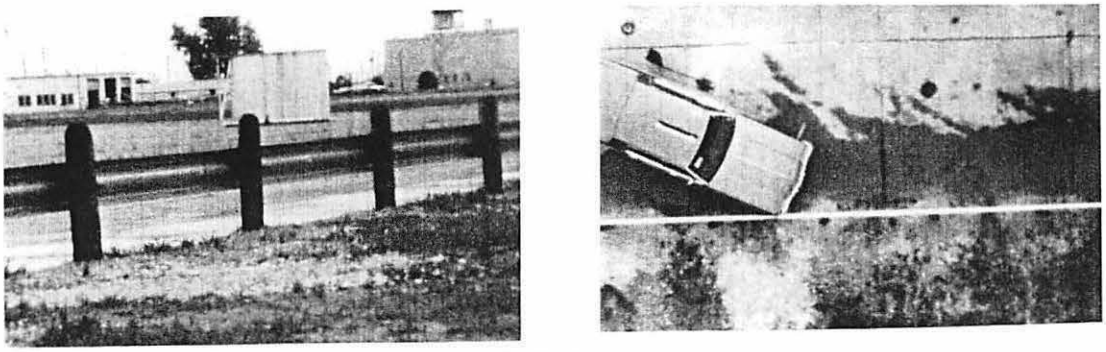


0.395 s

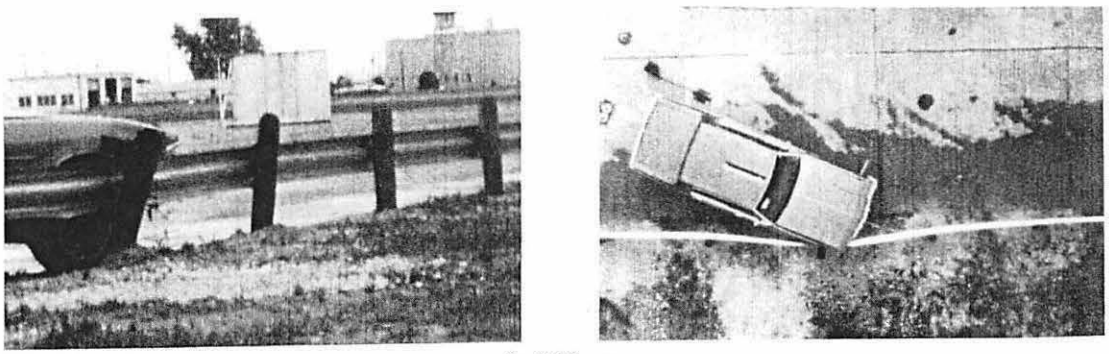


0.469 s

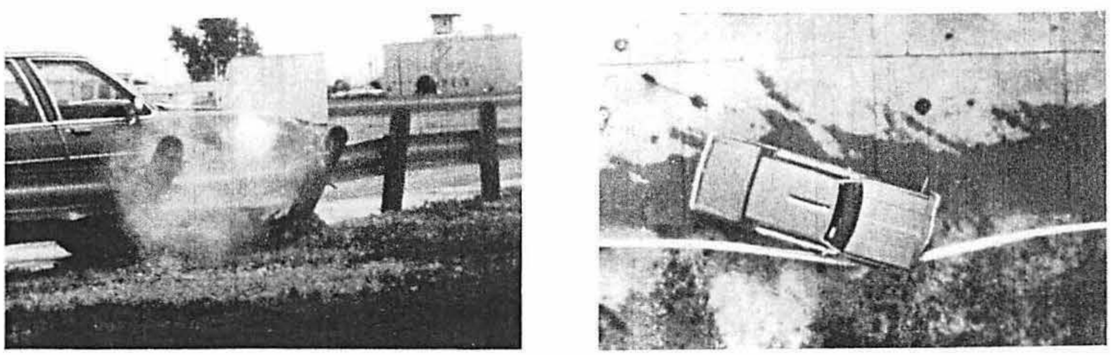
Figure C-1. Sequential photographs for test 1147-1. (Continued)



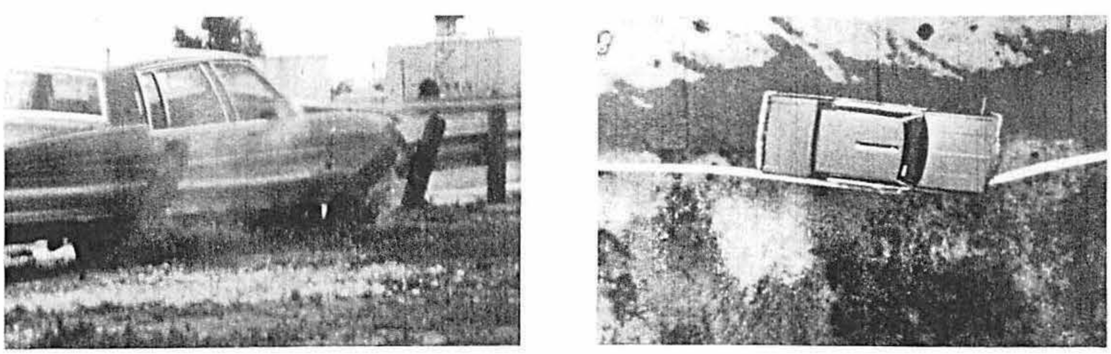
0.000 s



0.061 s

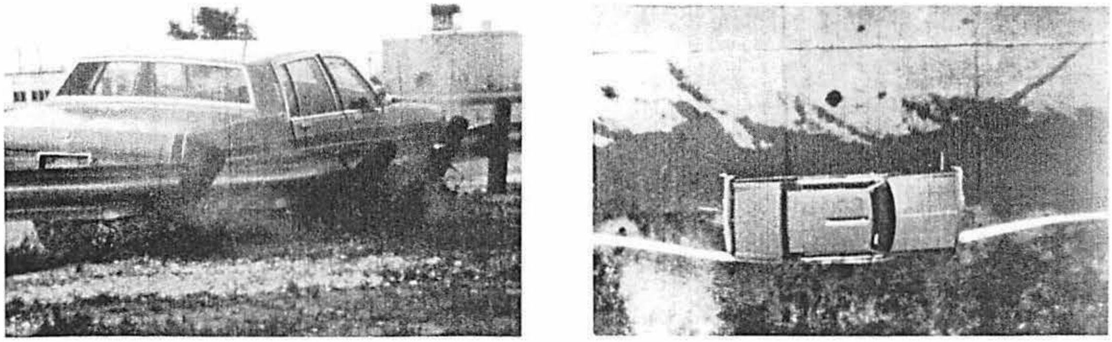


0.123 s

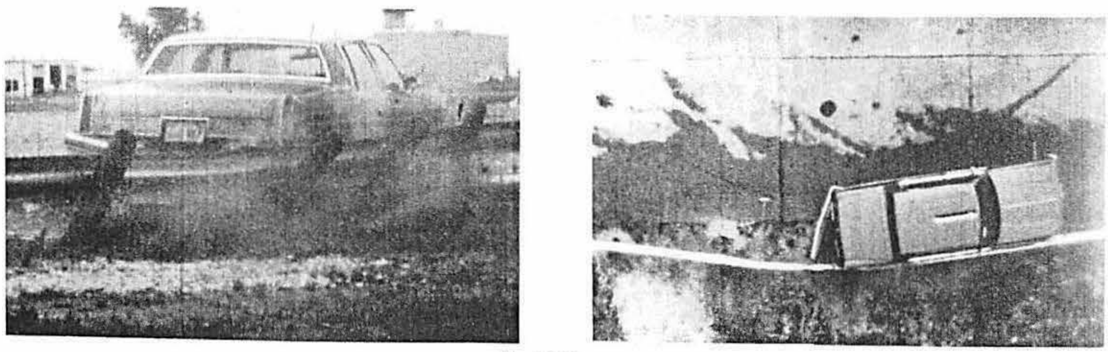


0.184 s

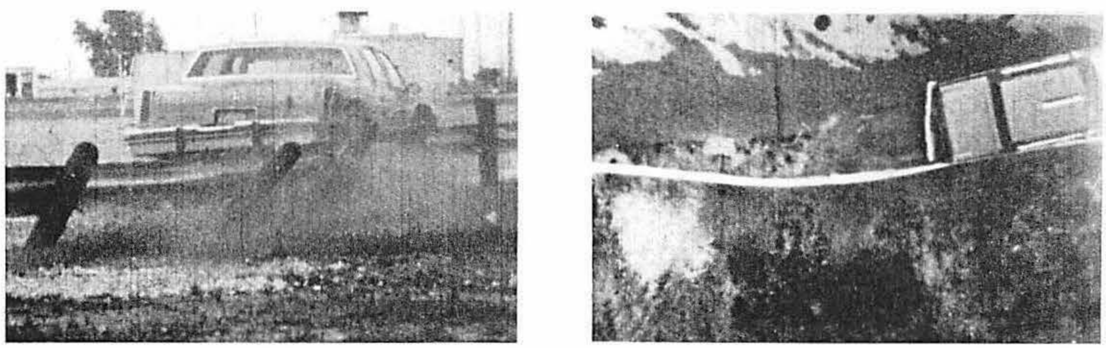
Figure C-2. Sequential photographs for test 1147-2.



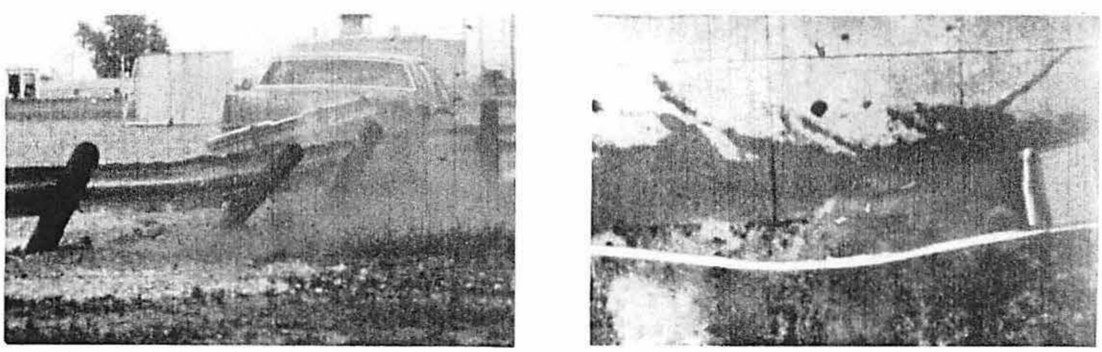
0.245 s



0.368 s

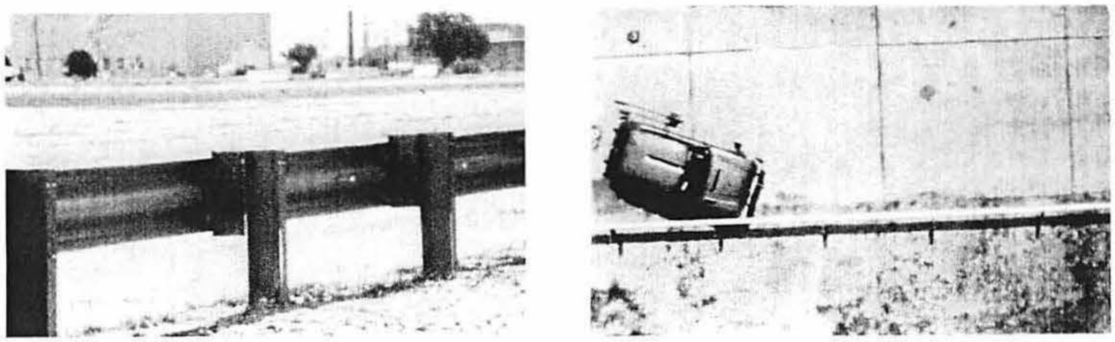


0.490 s

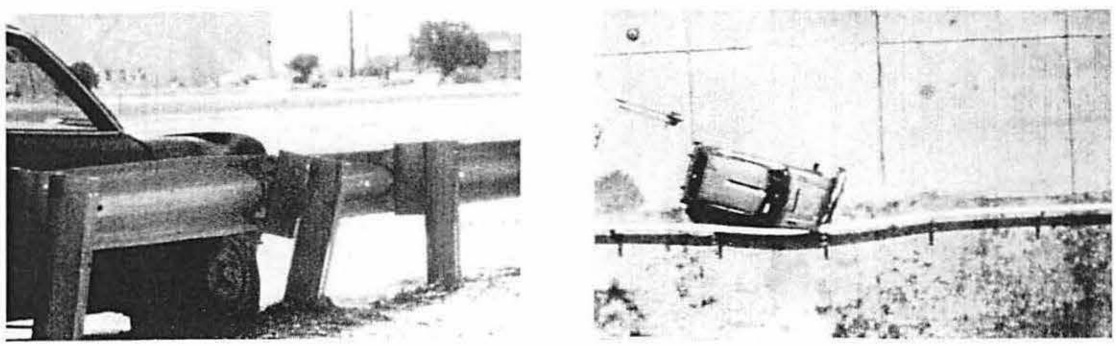


0.610 s

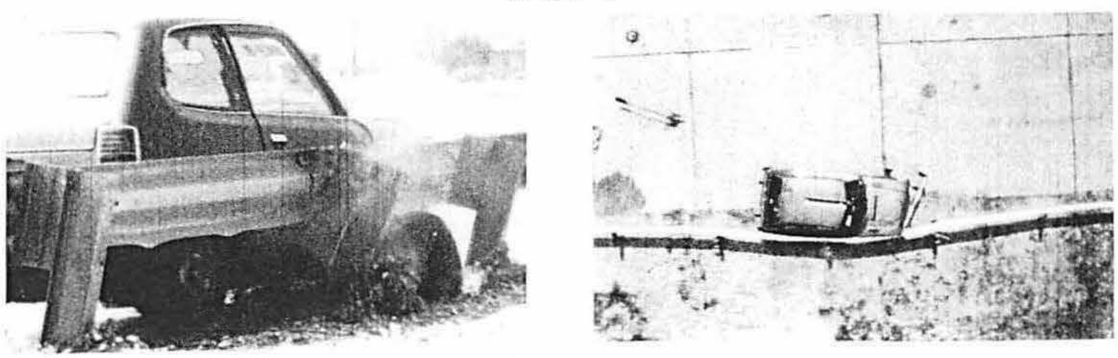
Figure C-2. Sequential photographs for test 1147-2. (Continued)



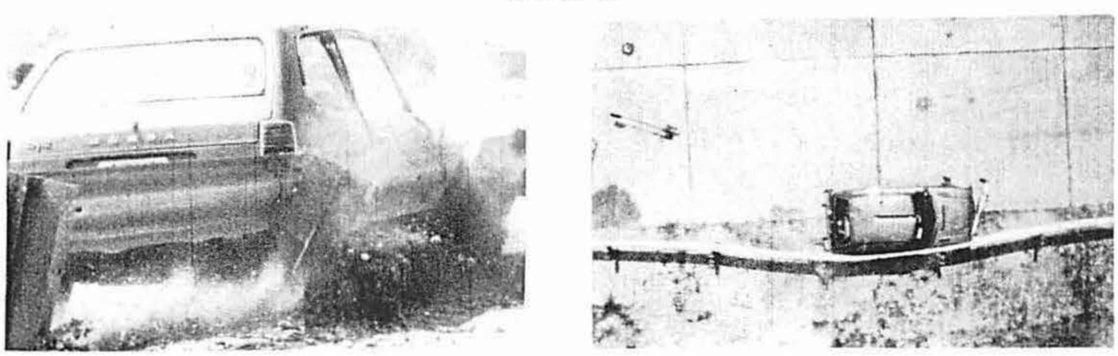
0.000 s



0.072 s

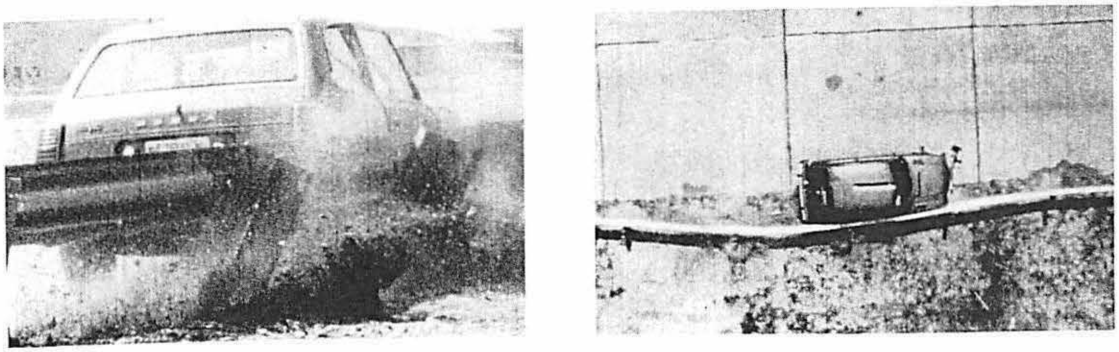


0.145 s

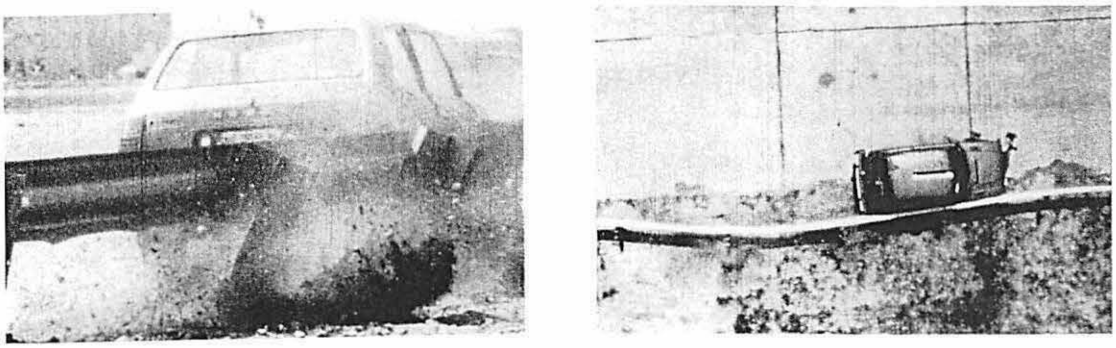


0.217 s

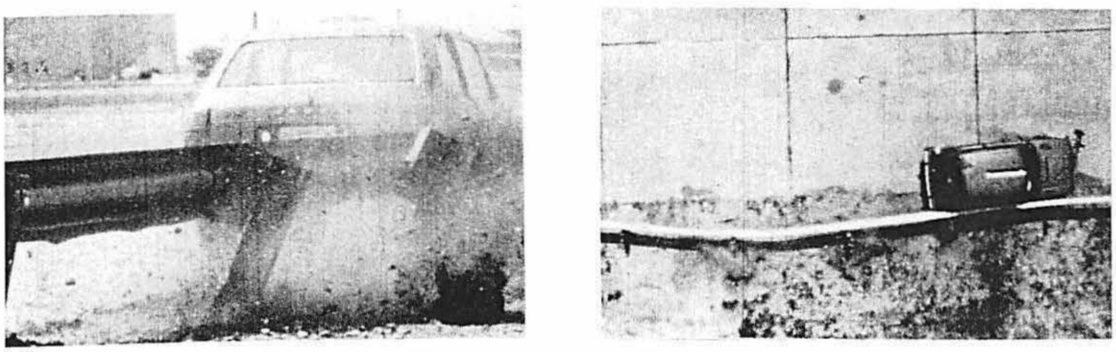
Figure C-3. Sequential photographs for test 1147-3.



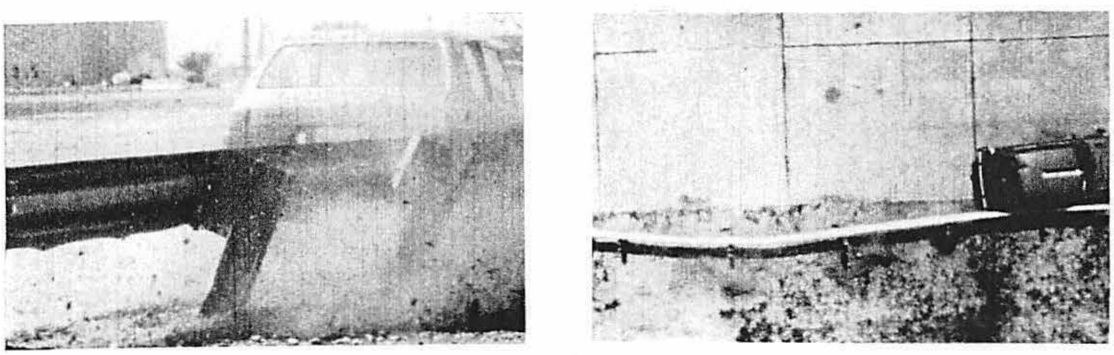
0.290 s



0.362 s

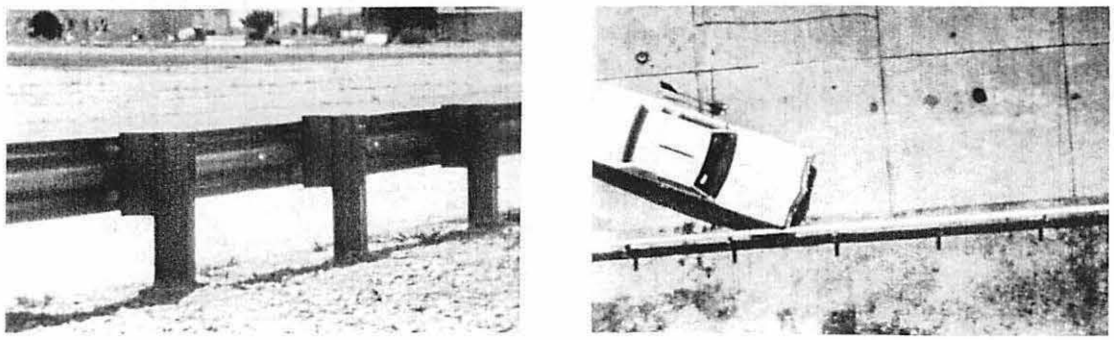


0.435 s

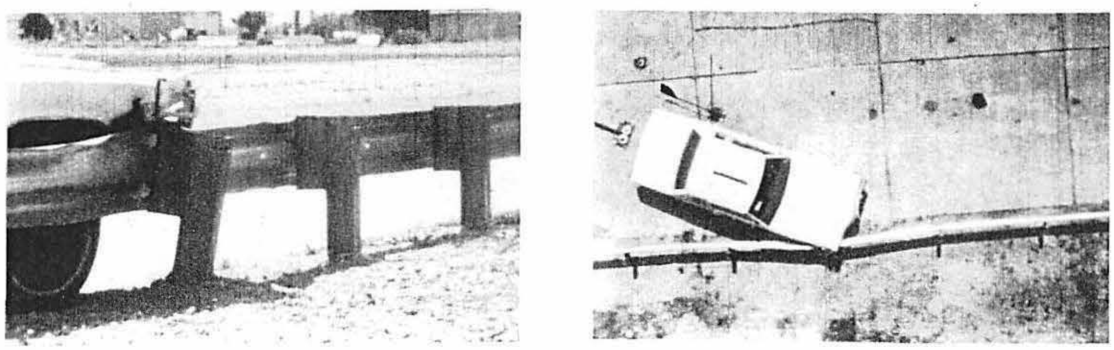


0.502 s

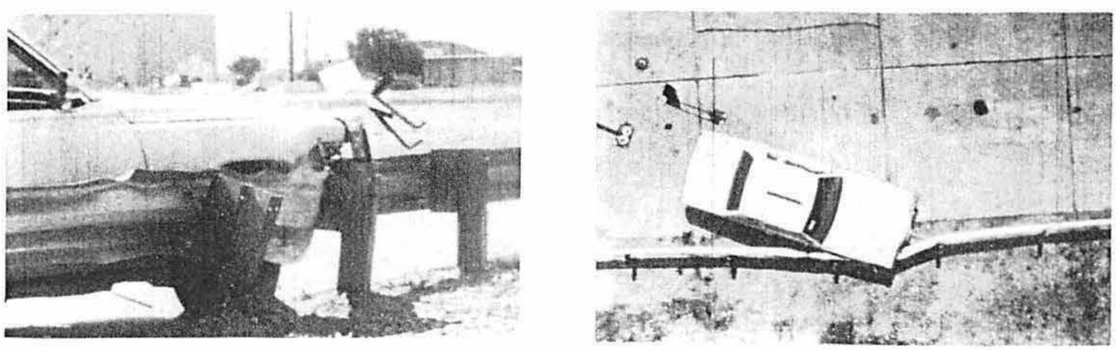
Figure C-3. Sequential photographs for test 1147-3.
(Continued)



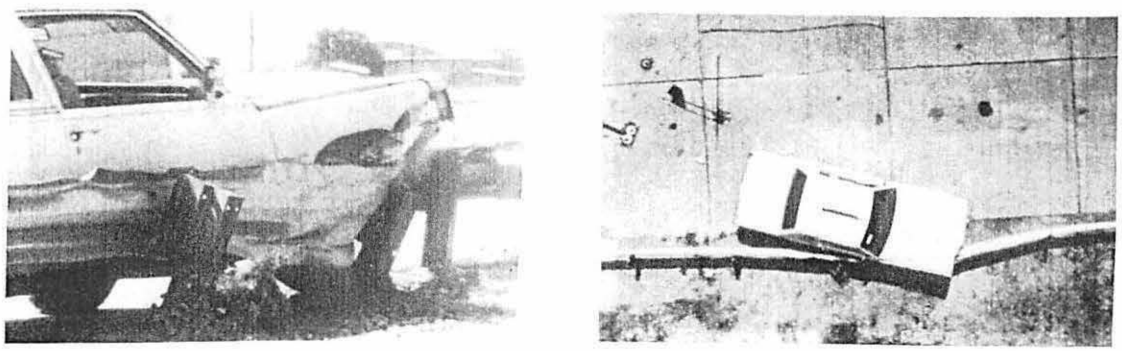
0.000 s



0.050 s

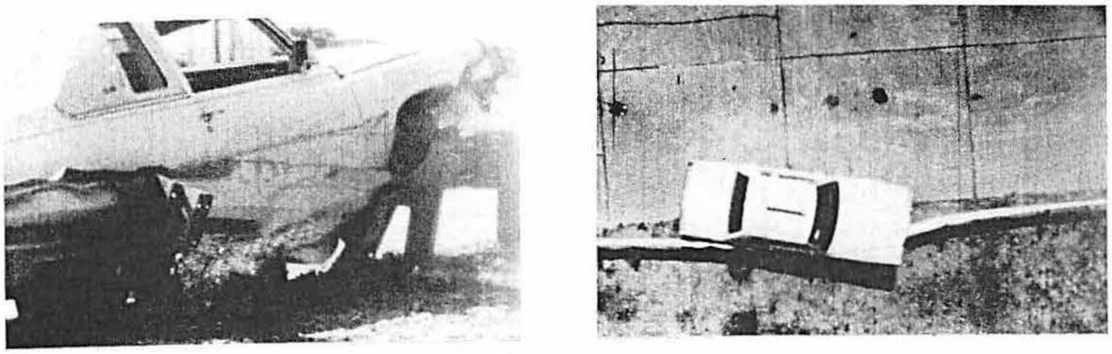


0.099 s

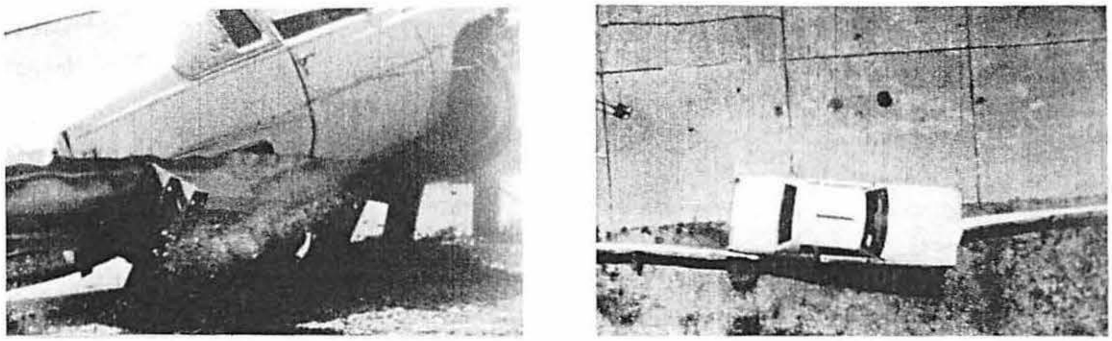


0.149 s

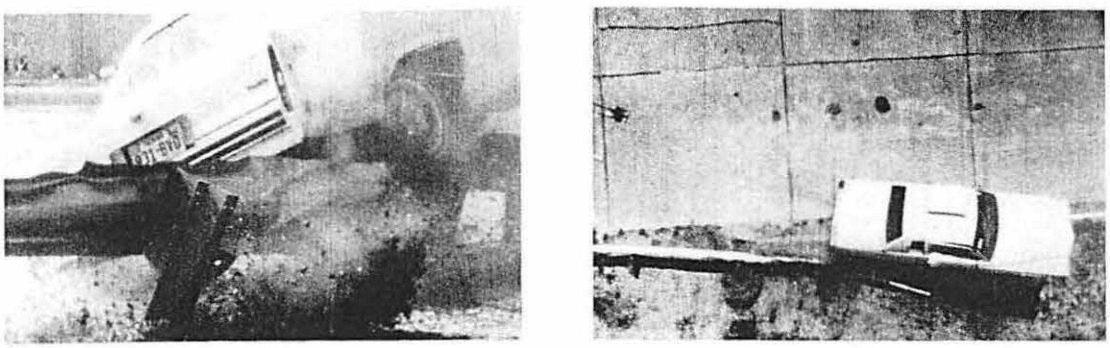
Figure C-4. Sequential photographs for test 1147-4.



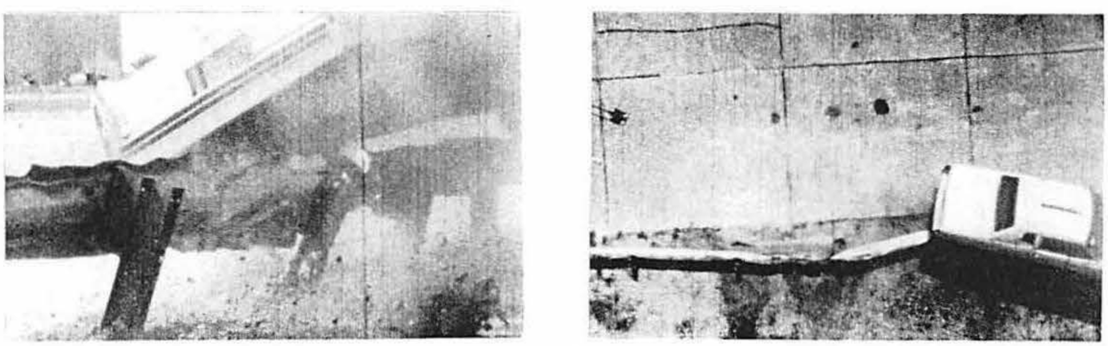
0.199 s



0.248 s

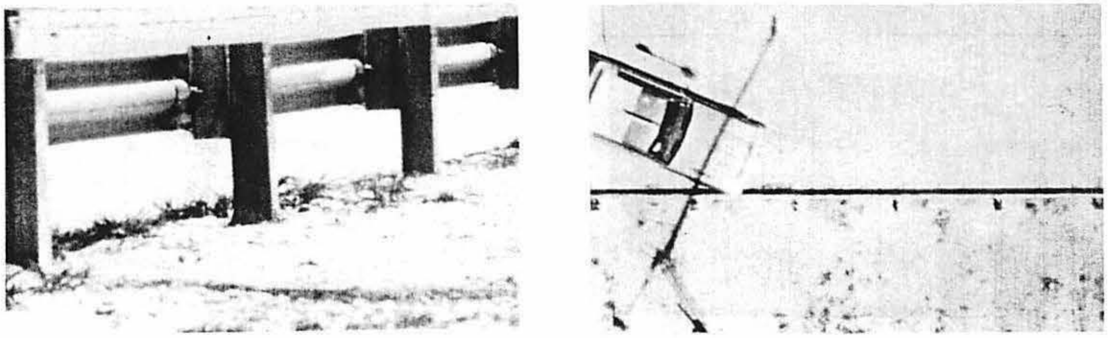


0.372 s

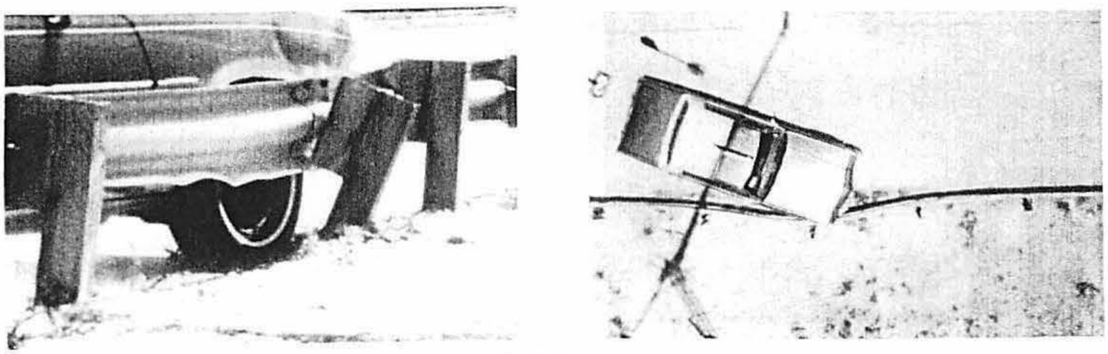


0.499 s

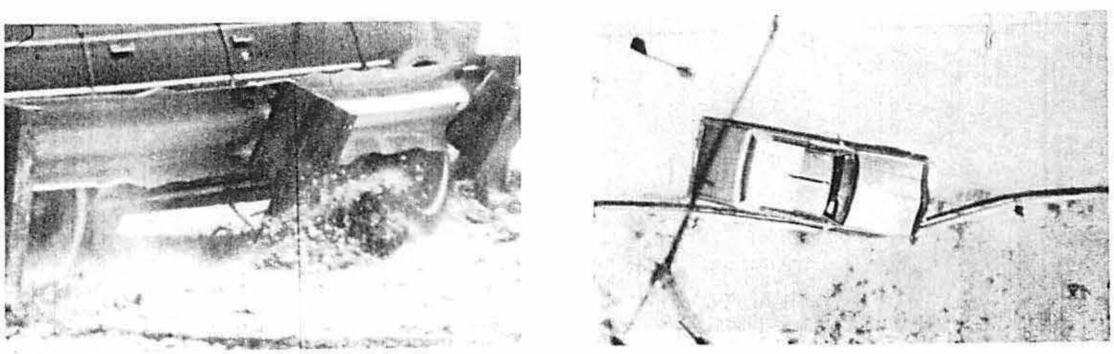
Figure C-4. Sequential photographs for test 1147-4.



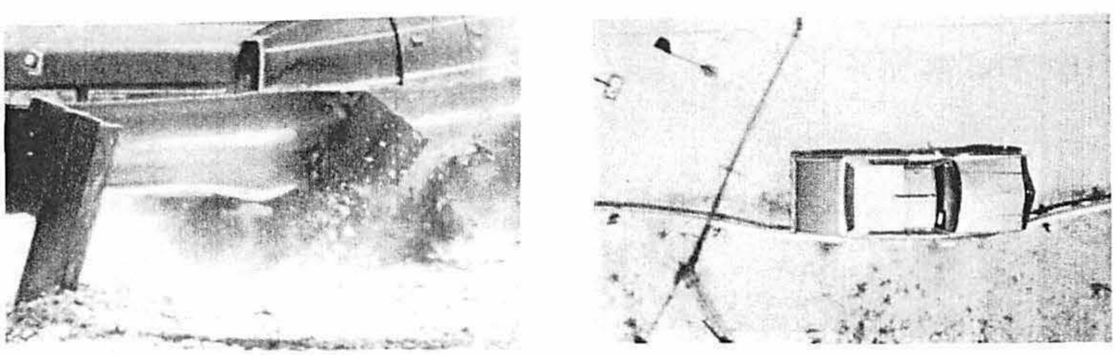
0.000 s



0.077 s

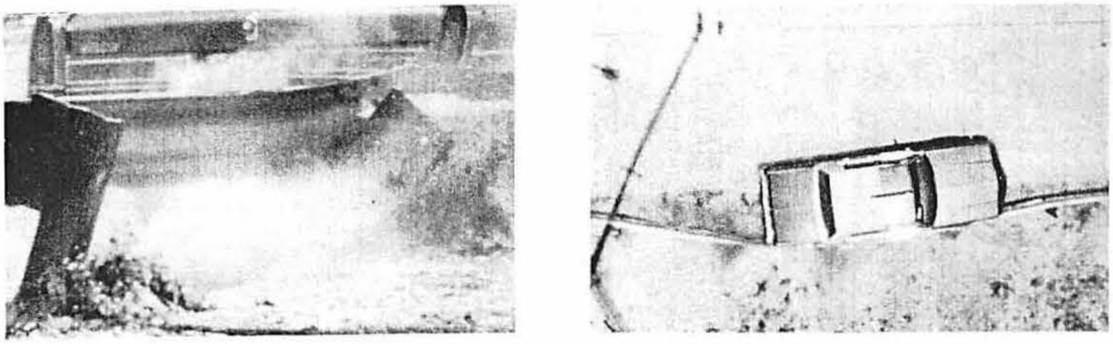


0.155 s

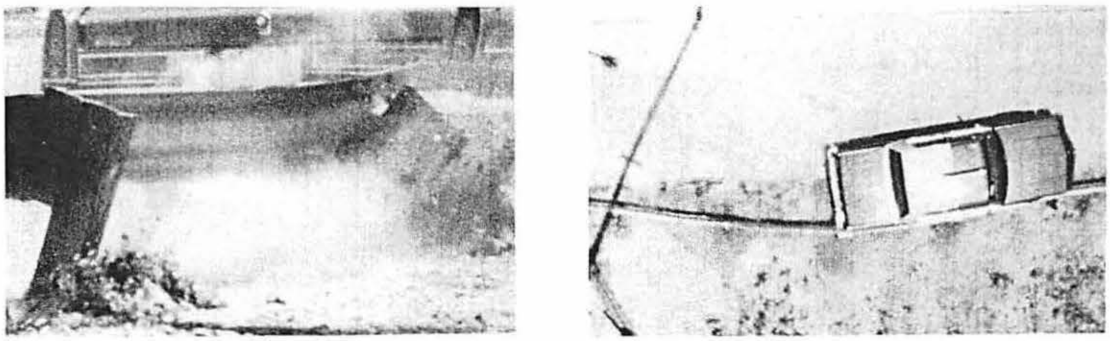


0.232 s

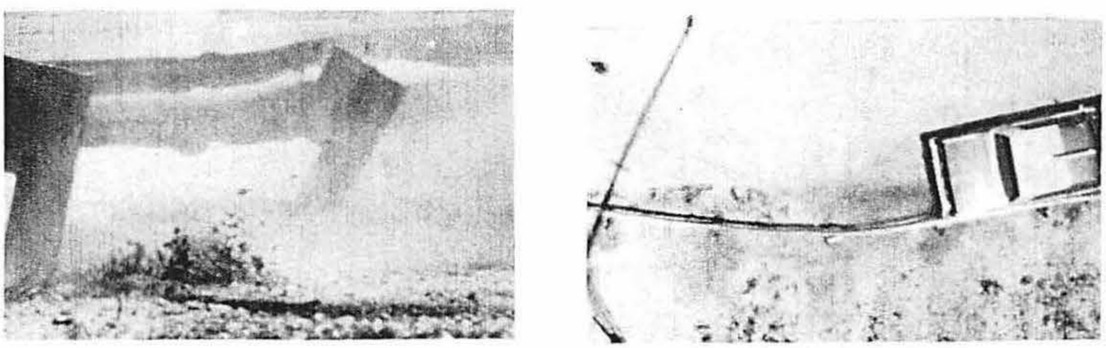
Figure C-5. Sequential photographs for test 1147-5.



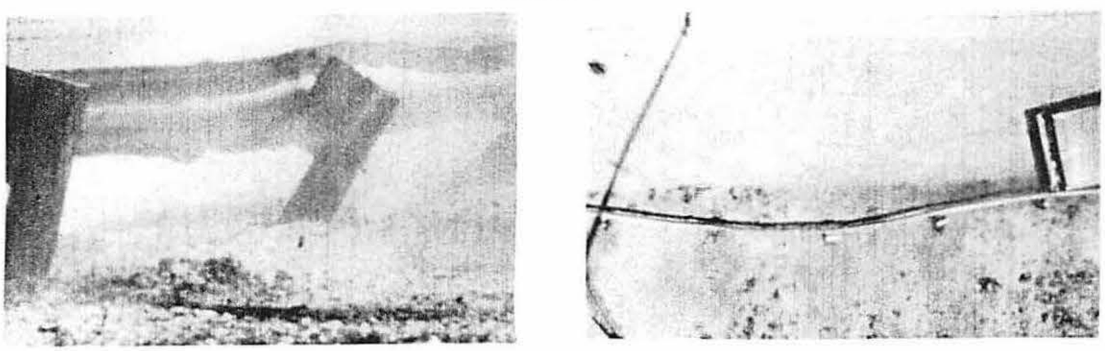
0.310 s



0.387 s



0.516 s

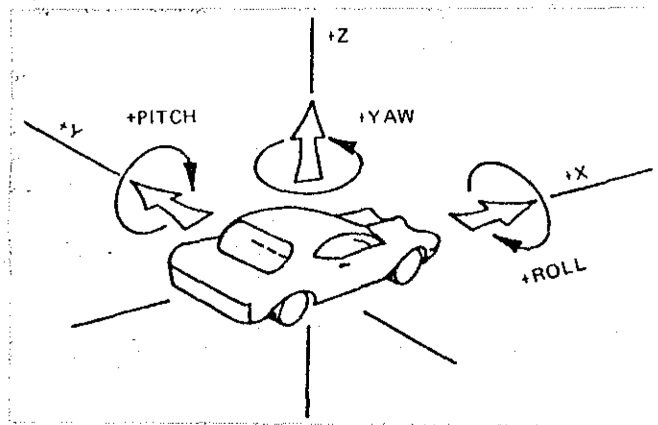


0.645 s

Figure C-5. Sequential photographs for test 1147-5. (Continued)

APPENDIX D.

RATE GYRO PLOTS



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

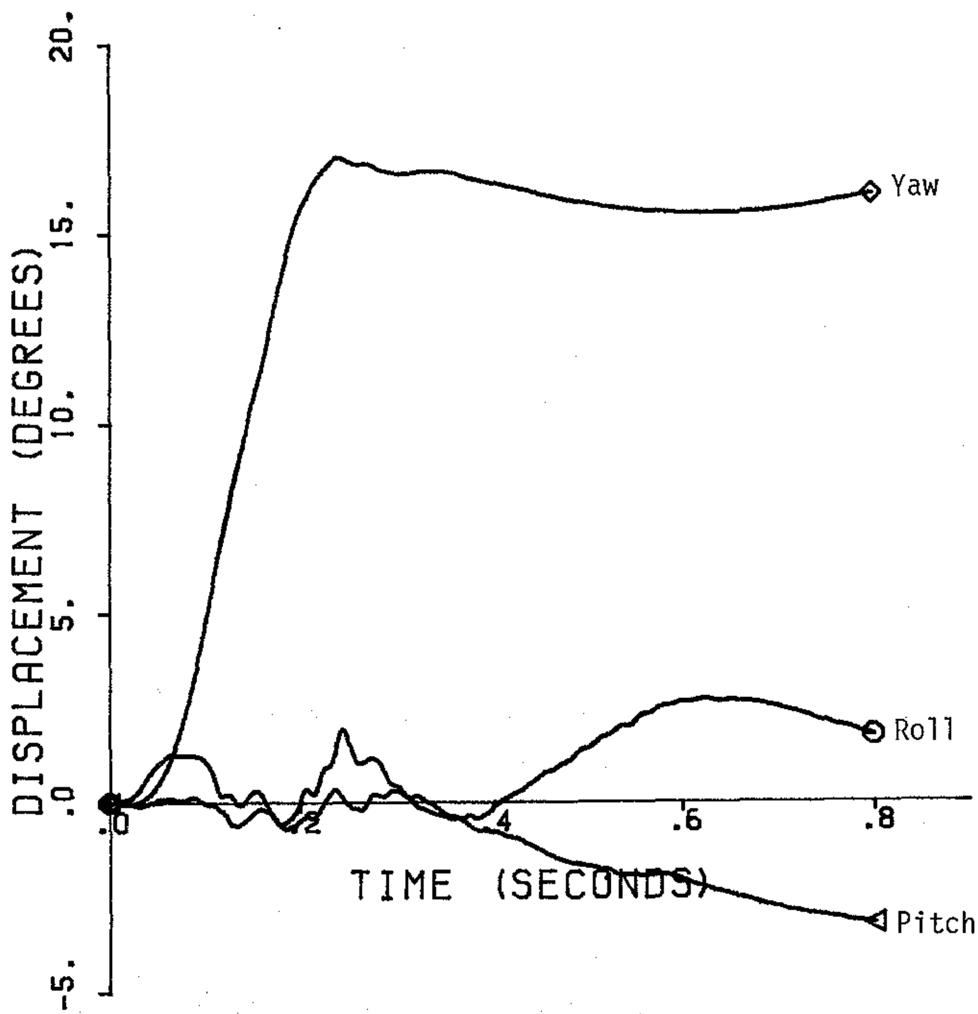
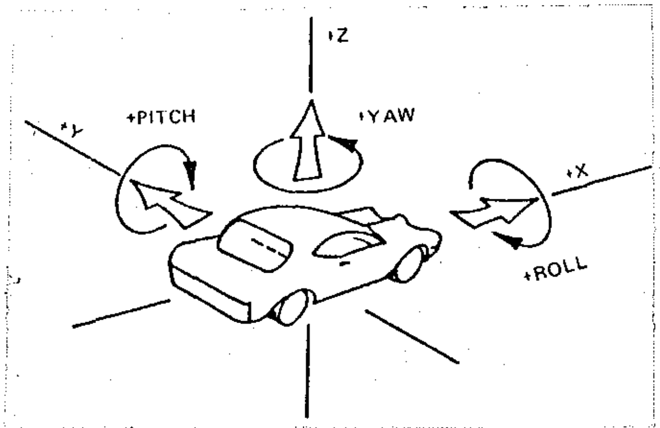


FIGURE D-1. VEHICLE ANGULAR DISPLACEMENTS FOR TEST 1147-1



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

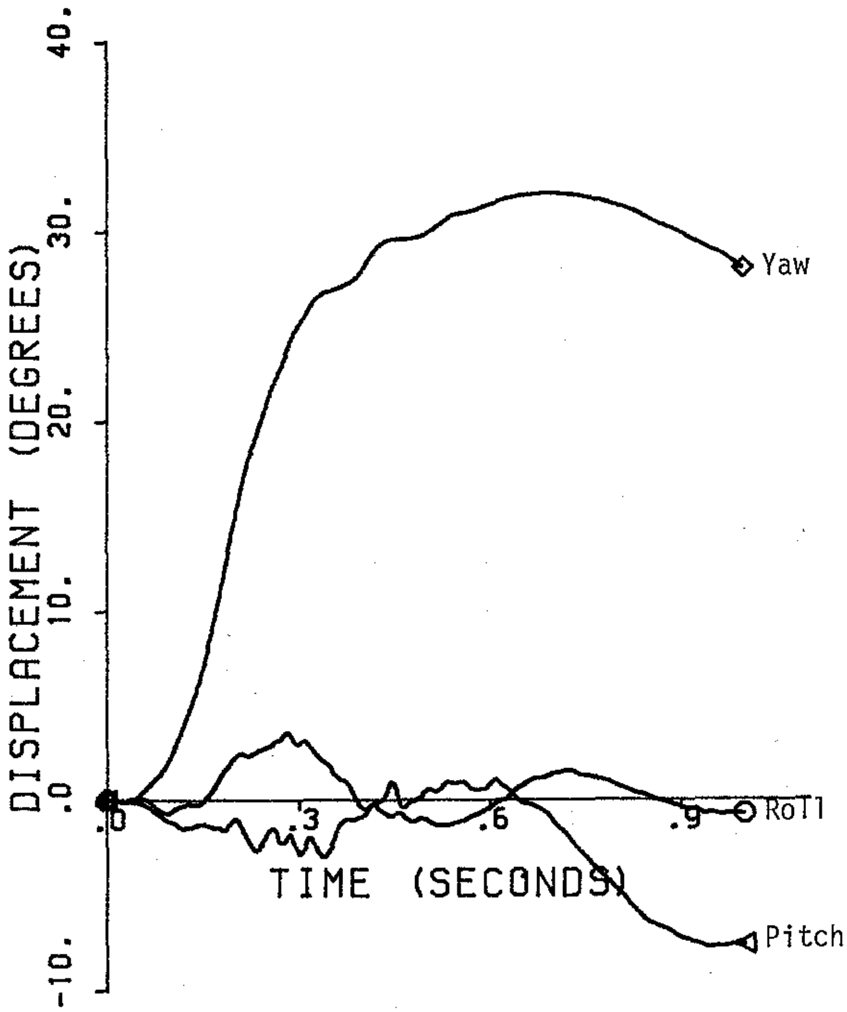


FIGURE D-2. VEHICLE ANGULAR DISPLACEMENTS FOR TEST 1147-2

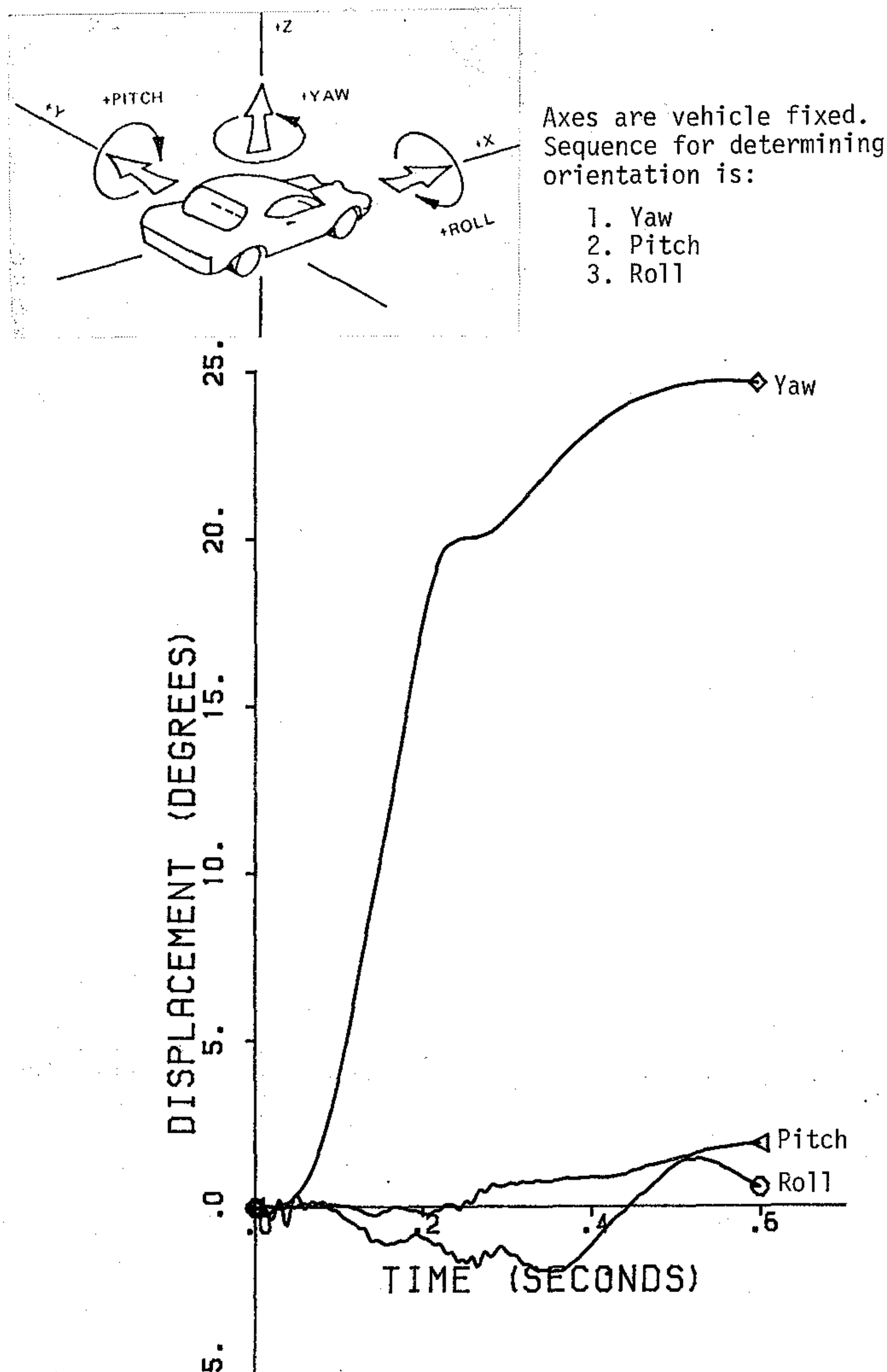


FIGURE D-3. VEHICLE ANGULAR DISPLACEMENTS FOR TEST 1147-3

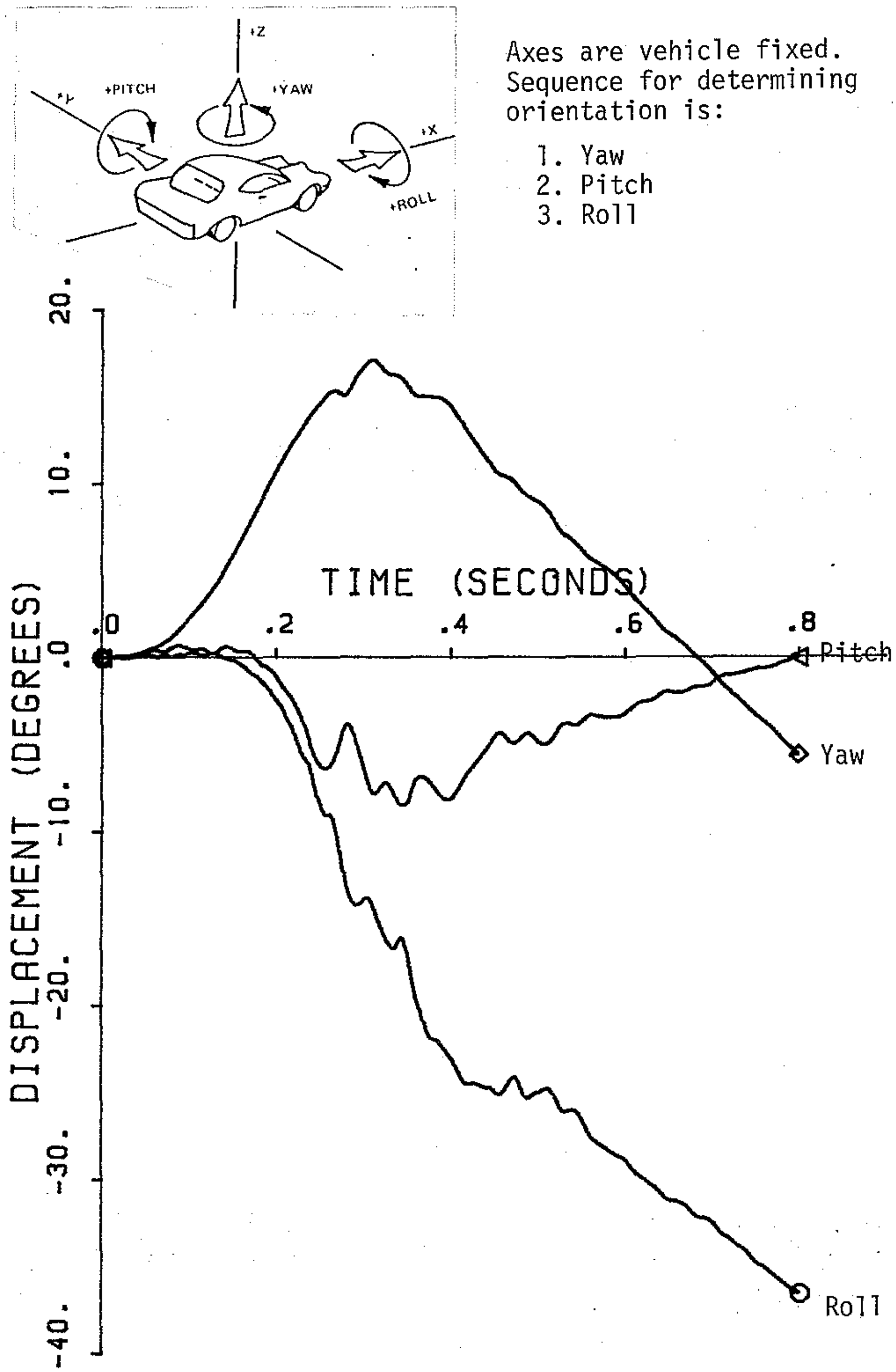
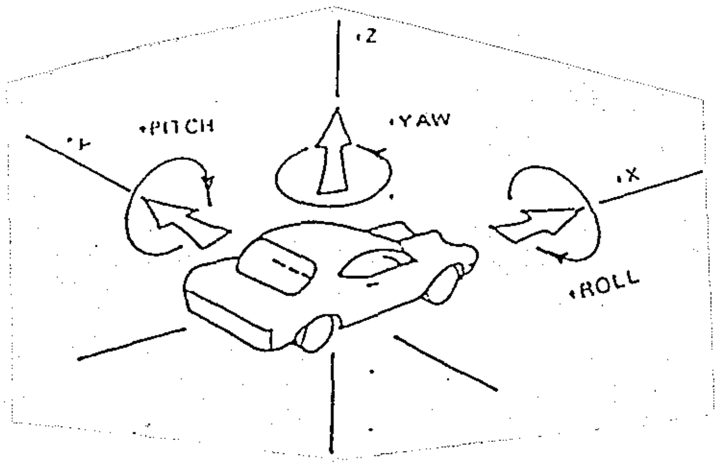


FIGURE D-4. VEHICLE ANGULAR DISPLACEMENTS FOR TEST 1147-4



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

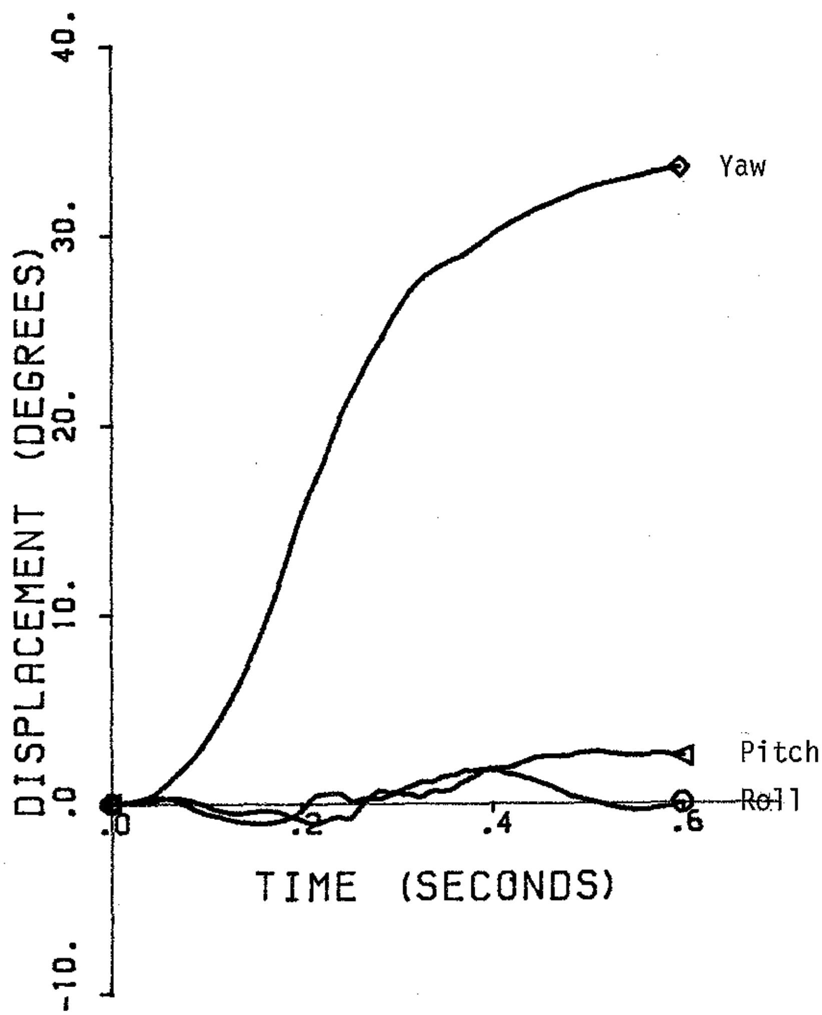


FIGURE D-5. VEHICLE ANGULAR DISPLACEMENTS FOR TEST 1147-5

APPENDIX E.

BENEFIT COST PROGRAM INPUT DATA

TTI BENEFIT COST ANALYSIS PROGRAM, VERSION 2.10

NUMBER OF ALTERNATIVES EVALUATED = 2 (NCASES)

PRINTED OUTPUT LEVEL = 3 (NPRINT)

ROADWAY PARAMETERS:

AVERAGE DAILY TRAFFIC	=	5000. VEH./DAY	(ADT)
ANNUAL CHANGE IN ADT	=	3. PERCENT/YEAR	(DELADT)
SPEED LIMIT	=	55. MPH.	(SPDLMT)
ROADWAY TYPE	=	4 LANE - DIVIDED	(NLANES,NHYTYP)
FUNCTIONAL CLASS	=	FREEWAY	(NCLASS)

ECONOMIC PARAMETERS:

ANNUAL INTEREST RATE = 4.00 PERCENT (RINT)

ESTIMATED LIFE OF ALTERNATIVE 1 = 20.0 YEARS (PROLIF)
ESTIMATED LIFE OF ALTERNATIVE 2 = 20.0 YEARS (PROLIF)

ROADWAY ALIGNEMENT (RAL)

PLACEMENT OF HAZARD WITH RESPECT TO CURVE	ROADWAY GRADE					
	GRADE < -2%			GRADE > -2%		
	CURVATURE (DEG)			CURVATURE (DEG)		
	0-3	3-6	>6	0-3	3-6	>6
INSIDE	---	.00	.00	---	.00	.00
OUTSIDE	---	.00	.00	---	.00	.00
NO EFFECT	.00	---	---	1.00	---	---

VEHICLE PARAMETERS:

VEHICLE CLASS	VEHICLE WIDTH FT. (VWIDTH)	VEHICLE LENGTH FT. (VLEN)	VEHICLE WEIGHT LBS. (VMASS)	FRACTION OF POPULATION (VDIST)	DELAY COST DOLLARS (DELCST)
1	5.82	14.47	2485.00	.34	5.00
2	6.42	17.61	4155.00	.46	5.00
3	7.39	33.65	18394.00	.12	5.00
4	8.00	55.00	62654.00	.08	5.00

FIGURE E-1. TYPICAL INPUT FOR BENEFIT COST ANALYSIS RUNS

ACCIDENT COSTS (SVCOST):

AASHTO SEVERITY INDEX	ACCIDENT COST (DOLLARS)
0	1960.00
1	4230.00
2	6750.00
3	9200.00
4	19400.00
5	52000.00
6	107800.00
7	203000.00
8	482000.00
9	629000.00
10	753000.00

ABBREVIATED INJURY SCALE (AIS)	ACCIDENT COST (DOLLARS)	POLICE INJURY CODE (PIC)	ACCIDENT COST (DOLLARS)
0	.00	O	.00
1,2	.00	A,B,C	.00
>=3	.00	K	.00

ENCROACHMENT FREQUENCY PER MILE = .9059 (EF)

ANGLE AND VELOCITY RANGE AVERAGES:

ANGLE AVERAGE DEGREES (ANGLE)	VELOCITY AVERAGE MPH (VEL)	VELOCITY FRACTIONAL PROPORTION (VELDST)
3	25.0	.0509
8	35.0	.1548
13	45.0	.2208
18	55.0	.2100
25	65.0	.1560
38	77.5	.2057

JOINT-PROBABILITY DISTRIBUTION OF VELOCITIES AND ANGLES (PRBVA):

VELOCITY (MPH)	ENCROACHMENT ANGLE IN DEGREES 0-5	6-10	11-15	16-20	21-30	>30
25.	.005	.012	.012	.009	.009	.004
35.	.015	.036	.036	.027	.028	.013
45.	.022	.052	.051	.038	.040	.018
55.	.021	.049	.049	.036	.038	.017
65.	.015	.037	.036	.027	.028	.013
78.	.020	.048	.048	.036	.037	.017

FIGURE E-1. CONTINUED

PROBABILITY OF LATERAL EXTENT OF ENCROACHMENT (PLENC):

LAT. DIST. (FT)	P(X>L)	LAT. DIST. (FT)	P(X>L)	LAT. DIST. (FT)	P(X>L)	LAT. DIST. (FT)	P(X>L)	LAT. DIST. (FT)	P(X>L
1	.9960	11	.6990	21	.3890	31	.2260	41	.1430
2	.9860	12	.6610	22	.3670	32	.2150	42	.1370
3	.9690	13	.6240	23	.3470	33	.2050	43	.1320
4	.9490	14	.5890	24	.3280	34	.1950	44	.1270
5	.9180	15	.5550	25	.3100	35	.1860	45	.1220
6	.8860	16	.5230	26	.2930	36	.1780	46	.1170
7	.8510	17	.4930	27	.2780	37	.1700	47	.1130
8	.8140	18	.4640	28	.2640	38	.1630	48	.1090
9	.7760	19	.4370	29	.2500	39	.1560	49	.1050
10	.7370	20	.4120	30	.2380	40	.1490	50	.1010

TTI BENEFIT COST ANALYSIS PROGRAM, VERSION 2.10

SAFETY ALTERNATIVE 1:

ALT #1 - GUARDRAIL WITH FLARE
THETA = 10 DEGREES FLARE ---> 10:1

NUMBER OF HAZARDS = 3 (LASTHZ)

ALTERNATIVE COSTS:

INSTALLATION COST	= $	510.14	(CSTINS)
ANNUAL MAINTENANCE COST	= $	.00	(CSTMAN)
SALVAGE VALUE	= $	.00	(CSTSLV)

ECONOMIC FACTORS:

SINKING FUND FACTOR	=	.0336	(SF)
CAPITAL RECOVERY FACTOR	=	.0736	(CRF)

HAZARD PARAMETERS (HZTYP, BRKAWY, SEVTYP, HZDATA):

HAZARD NO.	HAZARD TYPE	BREAKAWAY DEVICE	SEVERITY TYPE
1	2.	1.	1.
2	1.	0.	1.
3	2.	0.	1.

FIGURE E-1. CONTINUED

HAZARD NO.	UPSTREAM CORNER X (FT)	UPSTREAM CORNER Y (FT)	MAIN SECTION LENGTH (FT)	MAIN SECTION OFFSET (FT)	UPSTREAM TAPER LENGTH (FT)	UPSTREAM TAPER OFFSET (FT)	DOWNSTREAM TAPER LENGTH (FT)	DOWNSTREAM TAPER OFFSET (FT)
1	100.0	20.4	1.0	2.0	18.9	1.9	.0	.0
2	119.9	18.5	10.0	2.0	65.1	6.5	.0	.0
3	185.1	14.0	10.0	16.0	.0	.0	.0	.0

HAZARD NO.	SEVERITY OF FAILURE	HAZARD COLLISION INDEX (FT-LB) VEHICLE TYPE I	II	III	IV
1	1.0	1.	1.	1.	1.
2	7.0	53400.	100000.	100000.	100000.
3	9.0	0.	0.	0.	0.

SEVERITY LEVEL AND ACCIDENT COSTS
(DMGCST,SVINP)

	2485./60/25 ACCIDENT			2485./45/15 ACCIDENT		
HAZ NO.	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS
1	5.0	51348.00	100.00	3.7	16697.00	100.00
2	7.0	203000.00	160.20	2.6	8244.50	33.81
3	9.0	629000.00	.00	6.8	179200.00	.00

SEVERITY LEVEL AND ACCIDENT COSTS
(DMGCST,SVINP)

	4155./60/25 ACCIDENT			4155./45/15 ACCIDENT		
HAZ NO.	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS
1	5.0	51348.00	100.00	3.7	16697.00	100.00
2	4.8	45479.98	267.97	2.6	8244.50	56.53
3	9.0	629000.00	.00	6.8	179200.00	.00

FIGURE E-1. CONTINUED

SEVERITY LEVEL AND ACCIDENT COSTS
(DMGCST,SVINP)

	18394./60/25 ACCIDENT			18394./45/15 ACCIDENT		
HAZ NO.	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS
1	5.0	51348.00	100.00	3.7	16697.00	100.00
2	7.0	203000.00	300.00	2.6	8244.50	250.27
3	9.0	629000.00	.00	6.8	179200.00	.00

SEVERITY LEVEL AND ACCIDENT COSTS
(DMGCST,SVINP)

	62654./60/25 ACCIDENT			62654./45/15 ACCIDENT		
HAZ NO.	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS	AASHTO SEVERITY LEVEL	ACCIDENT COST DOLLARS	FACILITY DAMAGE DOLLARS
1	5.0	51348.00	100.00	3.7	16697.00	100.00
2	7.0	203000.00	300.00	7.0	203000.00	300.00
3	9.0	629000.00	.00	6.8	179200.00	.00

TRAFFIC DELAY PARAMETERS (DELY):

HAZARD NO.	INITIAL BLOCKAGE TIME (HOURS)	BLOCKAGE TIME FOR REPAIR (HOURS)	ACCIDENTS CAUSING DELAY (PERCENT)
1	.00	.00	.00
2	.00	.00	.00
3	.00	.00	.00

FIGURE E-1. CONTINUED