Hargrave

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EFFECTS OF CHANGES IN EFFECTIVE RAIL HEIGHT ON BARRIER PERFORMANCE

Volume 1: Research Report

April 1987

Final Report

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16. Abstract

The objective of this project was to determine the critical rail mounting heights to prevent underride and override for traffic barriers. W-beam guardrails, which are the most commonly specified barrier in the U.S., were used to develop criteria for both this element and the thrie beam.

The scope of the project included both computer simulation and full-scale crash tests. The test barriers were installed on level and sloping terrains. Most of the testing was accomplished using 4500-lb (2000-kg) and 1800-lb (800-kg) vehicles. One test was conducted using a low front profile car impacting a cable guardrail system.

This volume is the first in a series. The others in the series are:

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METRIC (SI*) CONVERSION FACTORS

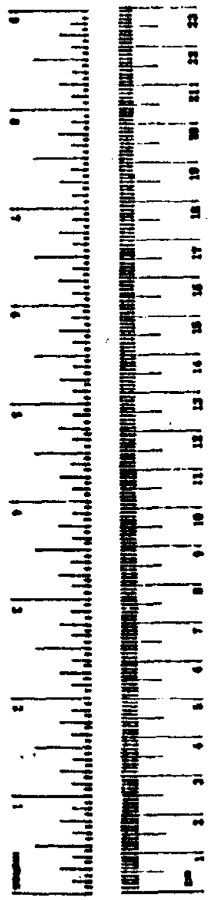
APPROXIMATE CONVERSIONS TO SI UNITS

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.

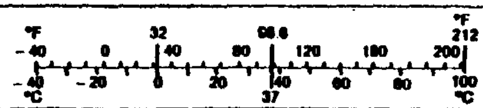
Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 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.

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I. INTRODUCTION AND RESEARCH APPROACH

A. Statement of the Problem

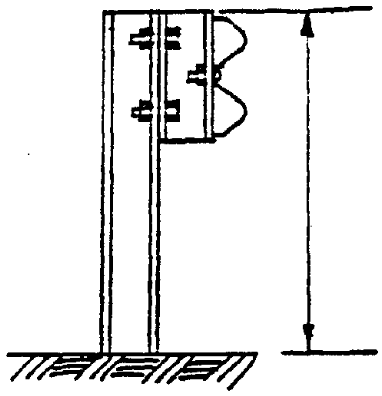
Prior to the initiation of this and similar other projects, roadside barriers had been tested on flat and level terrain in order to permit relative assessments of their safety. On subsequent real world installations, the barriers were sometimes installed on slopes or at railing heights differing from the system designs. Over a period of time, the barrier heights were further changed by site variations caused by resurfacing, settlement, erosion, soil and grass buildup adjacent to the barriers, etc. Thus, a need existed to determine the degree to which barrier performance was degraded by these railing height variations.

The performance of guardrails had been shown in numerous full-scale tests to be sensitive to minor changes in installation details. The performance both on level terrain and on side slopes might be improved by making such design changes as (a) removing the washers from the button head bolts and (b) increasing the size or changing the geometry of the blockouts. Several States had developed adjustable blockouts for raising or lowering W-beam rails. Evaluations were needed to verify the strength and performance of such changes.

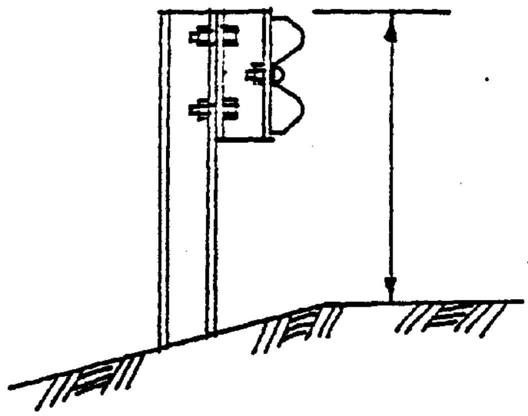
The three problem areas of interest in this study are illustrated in figure 1. View (a) shows a guardrail that is on flat and level terrain but is at a height that is either lower or higher than the design standard. View (b) shows a system on a slope. Finally, view (c) illustrates systems with coupled rails, uncoupled rails with standard blockout, and uncoupled rails with variable blockouts.

B. Objectives and Scope

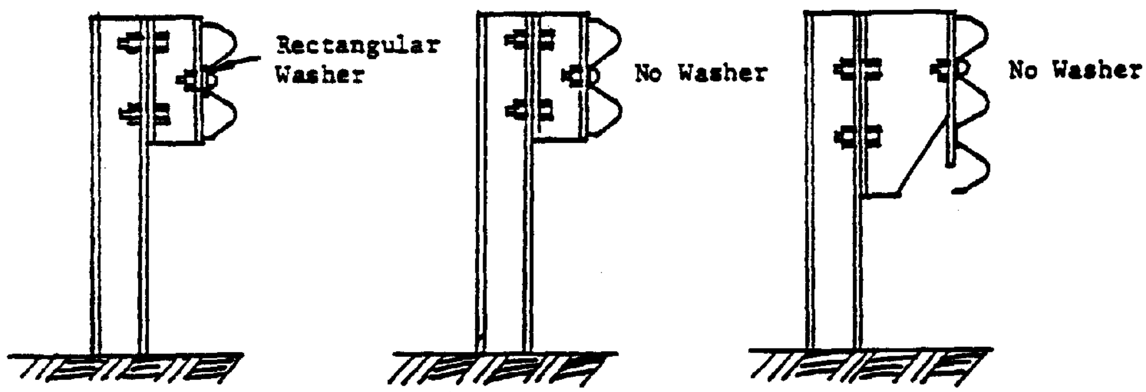
As delineated in the Statement of Work, the objectives of this study were (1) to determine the degree to which barrier performance is degraded



(a) Guardrails with Non-Standard Height



(b) Guardrails on Slopes



Coupled Beam

Uncoupled Beam w/Standard Blockout

Uncoupled Beam w/Variable Blockout (Ref. 1)

(c) Systems with Various Couplings

VEHICLE PROBLEM AREAS (ALL CASES):

1. Wheel Snagging
2. Vaulting
3. Rollover

Figure 1. Study areas.

by rail mounting height variations such as initial height differing from design standards, resurfacing, installations on slopes, soil and turf buildup, and (2) to improve the performance of guardrails on level terrain and on side slopes.

The stated scope of work was as follows:

> This requirement shall consist of using computer simulation and other analytical tools in combination with full-scale tests with passenger cars, vans, and pickup trucks to assess the performance of various traffic barriers on irregular roadsides and on slopes. Static tests and pendulum tests will be conducted on barrier components. Computer simulation and other analytical methods will be used to assess modified barrier designs before detailed drawings are prepared and the barriers are evaluated through full-scale tests.

The emphasis in this project was on W-beam guardrail systems which are the most commonly specified systems in the country. Findings from the W-beam investigations regarding barrier underride/override are also considered to be appropriate for thrie beam systems due to the geometrical similarity between the two beam elements.

II. REVIEW OF LITERATURE

A. Available Literature

A manual review of on-hand documentation and computer on-line searches of available literature were made early in this study. For the most part, these searches indicated a general lack of information concerning the performance of barriers with varying railing heights. However, three reports were found that were concerned with barrier railing height. These were from the States of Virginia[1] and New York[2] and from an FHWA study at Texas Transportation Institute (TTI)[3]. The reports were reviewed, and brief synopses and assessments are contained in table 1. More complete assessments of these and other related documentation are included in appendix B; an interim report was submitted on completion of task A.

The Virginia report did not contain definitive information about the relationship between railing height and barrier performance. However, both the New York and TTI reports did contain information that would be of value in selecting barrier systems and establishing trial railing height guidelines. The consensus was that the override/underride vehicle heights established in the New York study might be better than the bumper mid-heights of the TTI study. However, this was not conclusive and would be a subsequent determination of this study.

The TTI report was of particular interest in this study. In establishing the barrier placement guidelines shown in table 1, the TTI investigators had conducted 156 computer simulations using the HVOSM code[5] to estimate bumper mid-heights for various combinations of roadside geometries, vehicle types, and encroachment angles. Included were the 26 roadway/roadside geometric parameters shown in table 2, two vehicle types [4500-lb (2000-kg) and 1800-lb (800-kg)], and three encroachment angles (7.5°, 15°, and 25°). If critical override/underride heights could be determined and the mid-height curves adjusted accordingly, the range of barrier heights could be established therefrom. Thus, the HVOSM data were

Table 1. Synopses of directly related reports.

SYNOPSIS - VIRGINIA STUDY

Reference:

B. T. Hargroves and J. S. Tyler, "Identification, Analysis, and Remedial Treatment of Low Guardrail in Virginia," Virginia Highway and Transportation Research Council Report No. VHTRC 82-R15, September 1981.

Abstract:

Guardrails that are too low may fail to safely redirect errant vehicles; instead, the vehicles may vault the guardrails, resulting in severe accidents. An analysis of data on a small sample of guardrails throughout Virginia showed that over 80 percent of the guardrails were lower than the current standard height of 27 in.

The causes of low guardrail were identified as installation of old standards that were lower than current standards, faulty installation, and inadequate maintenance. Methods for locating low guardrails were identified and six remedial treatments were developed ranging from removal of the guardrail to complete reinstallation.

A numerical scoring system was developed whereby correction of low guardrails may be prioritized according to the degree of hazard presented by the low guardrail. The scoring system employs an equation based on the guardrail performance variables considered to be most important; namely, guardrail height, vehicle speed, and expected number of encroachments. Additional factors that can affect the degree of hazard but were not included in the equation are guardrail type, consequences of vaulting, and soil type. Provisions were made for increasing total scores for situations in which these variables are important.

Assessment:

Report might be used to show typical extent of the problem of non-standard railing heights. Assumptions used for establishing height and speed indexes in scoring system are subjective and might be checked with results of this study. However, no definitive relationship between railing height and barrier performance is given.

Table 1. Synopses of directly related reports (continued).

SYNOPSIS - NEW YORK STUDY

Reference:

J. E. Bryden, "Development of Proposed Height Standards and Tolerances for Light-Post Traffic Barriers," Transportation Research Record 970, 1984.

Procedure:

1. Vehicle geometric characterics were measured for virtually all 1983 model passenger vehicles, light trucks, vans, and utility vehicles. Characteristics of primary concern were:

   a. Bumper override point - height to a point on the bumper which can lead to vaulting if that point reaches the top of a barrier.

   b. Hood underride point - height to a point on the hood which can result in underriding if this point gets below the bottom of the rail.

2. Assumed vehicle suspension range of ±3 inches on selected design vehicle and established desired heights to prevent underride (submarining) or override (vaulting). Top of rail heights for both conditions were:

   Cable - 27 in
   Box-beam - 27 in
   W-beam - 30 in

3. Supported results of item 2 from previous New York and TTI full-scale tests (no vaulting or submarining implies support). Also supported results from re-examination of previous New York accident study.

4. Mounting height tolerances of ±3 inches were found to be satisfactory for most of the vehicle profiles.

Assessment:

Procedure is satisfactory. However, the study is limited to the weak post systems that are predominant in New York but not used much in other States.

Table 1. Synopses of directly related reports (continued).

SYNOPSIS - TII STUDY

References:

1. H. E. Ross, Jr. and D. L. Sicking, "Guidelines for Placement of Longitudinal Traffic Barriers on Roadside Slopes," Contract No. DOT-FH-11-9343, TTI Research Report 3659-1, December 1982.

2. H. E. Ross, Jr., D. G. Smith, D. L. Sicking, and P. R. Hall, "Tests of Longitudinal Barriers on Slopes," Contract No. DOT-FH-11-9343, TTI Research Report 3659-2, April 1979.

Procedure:

1. A limited crash test program (7 tests), supplemented by computer simulations (HVOSM), was used to evaluate performance of longitudinal barriers placed on sloping terrain.

2. From careful study of the crash test film, it was concluded that front bumper position relative to the barrier at impact was the critical factor with regard to vehicle containment and redirection. Barriers were categorized as shown in table 1.1, and containment criteria for the various barrier types are shown in figures 1.1, 1.2, 1.3, and 1.4.

3. From the criteria of item 2, HVOSM runs were made to develop placement guides (75 figures) for the barrier categories of table 1.1 and various combinations of travelway, shoulder, and embankment slopes (see figure 1.5 and table 1.2).

Assessment:

This report states that "it was concluded that HVOSM did not have sufficient capabilities to simulate vehicle/barrier impacts for nonlevel approach terrain. Instead, it was used to accurately determine vehicle kinematics upon impact with the barrier." While an entire appendix was included to show that GUARD was not a satisfactory program, no support for the accuracy of HVOSM, either by included documentation or by reference, could be found in the report.

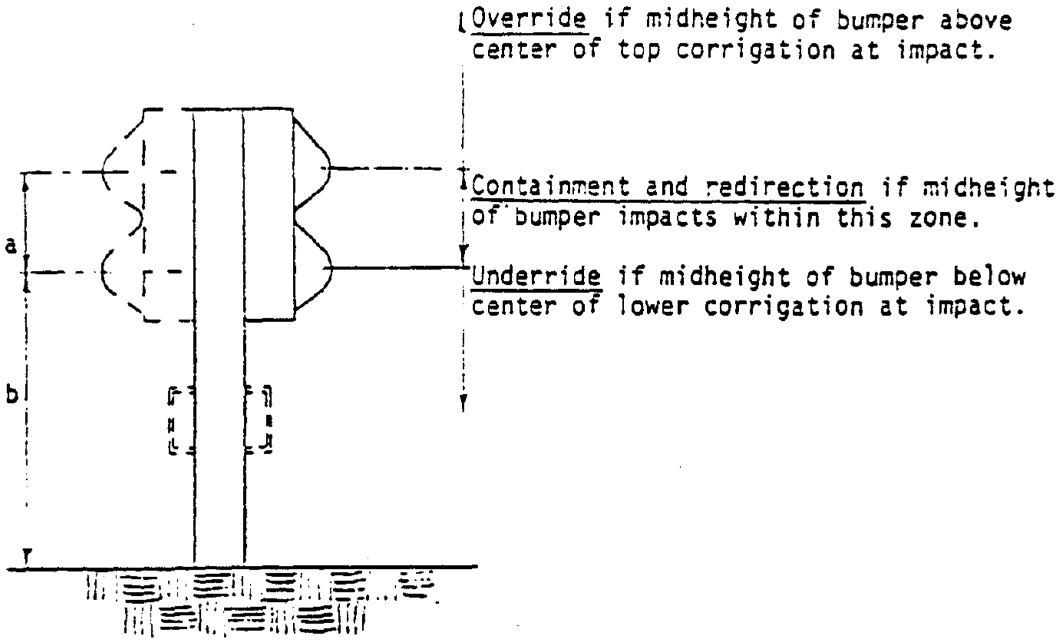
Barrier categories (table 1.1) should be useful in establishing the recommended guardrail systems. The containment criteria may or may not be applicable but should provide a good starting point for this study. A better indicator for underride might be the hood underride height of the New York study rather than this midheight of the bumper.

Table 1. Synopses of directly related reports (continued).

Table 1.1 Barrier Categories.

BARRIER CATEGORY	CORRESPONDING BARRIER TYPES
A	G1, MB3
B	G3
C	G4(1W), G4(2W), G4(1S), G4(2S), MB4S
D	G9, MB9
E	MB4W

Table 1. Synopses of directly related reports (continued).



BARRIER	a (in)	b (in)
G4(1W)	7.625	17:063
G4(2W)	7.625	17:063
G4(1S)	7.625	17:063
G4(2S)	7.625	17:063
MB4W	7.625	20:063
MB4S	7.625	17:063

Figure 1.1 Containment Criteria, W-Beam Barrier.

Table 1. Synopses of directly related reports (continued).

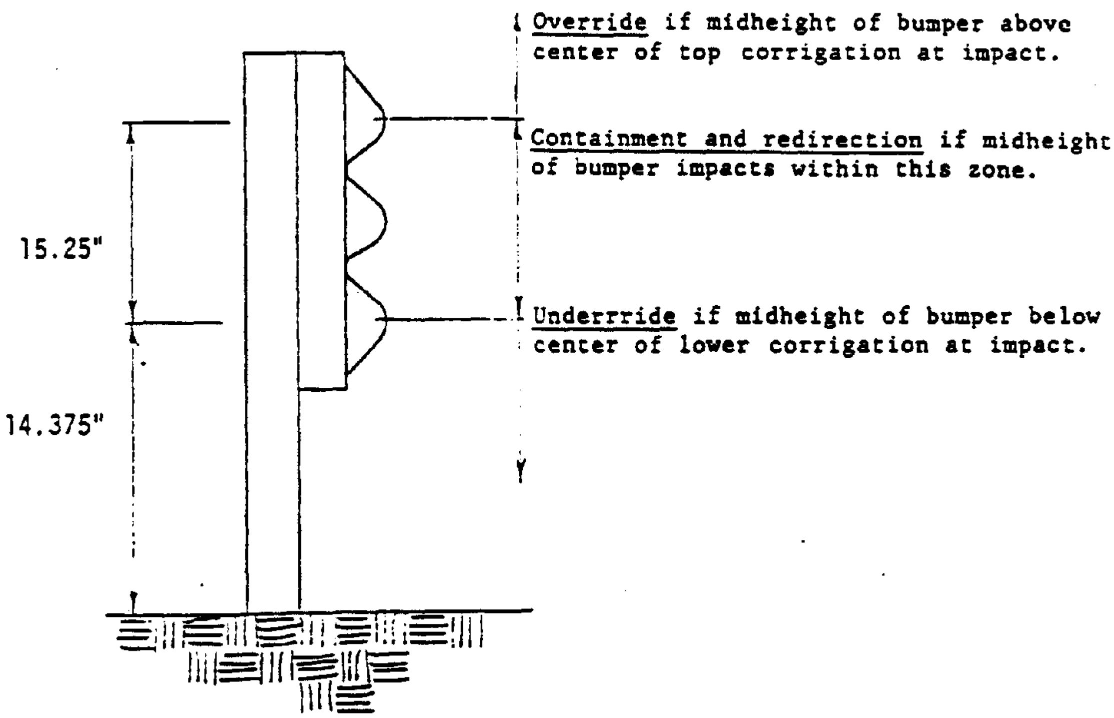


Figure 1.2 Containment Criteria,
Thrie Beam Barrier.

Table 1. Synopses of directly related reports (continued).

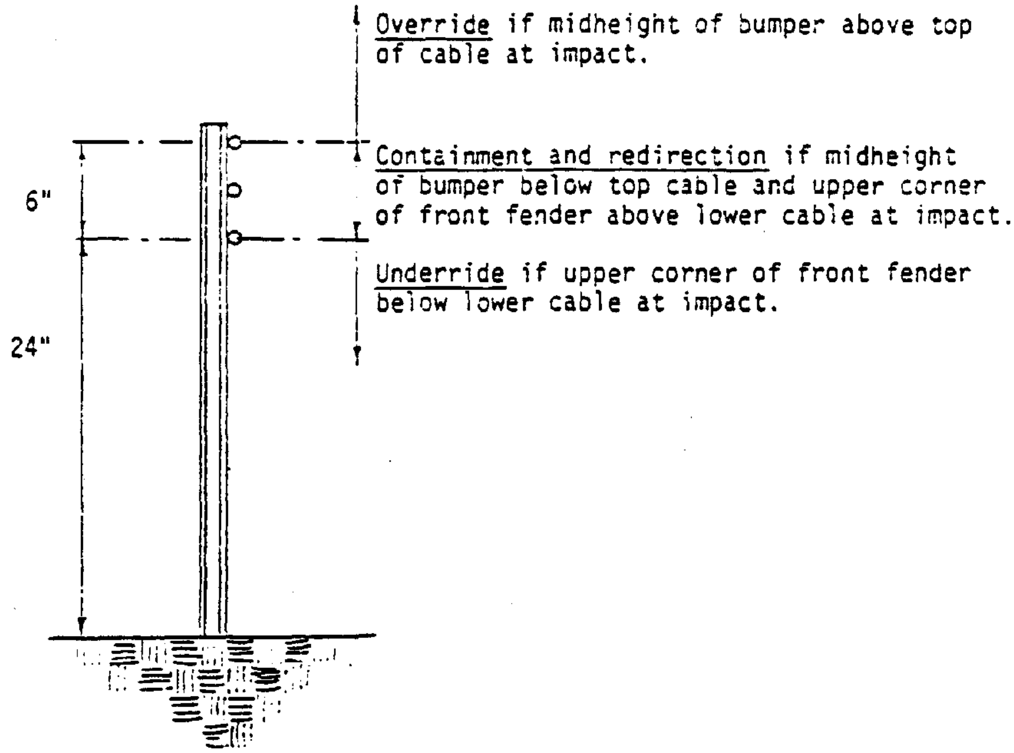


Figure 1.3 Containment Criteria, Cable Barrier.

Table 1. Synopses of directly related reports (continued).

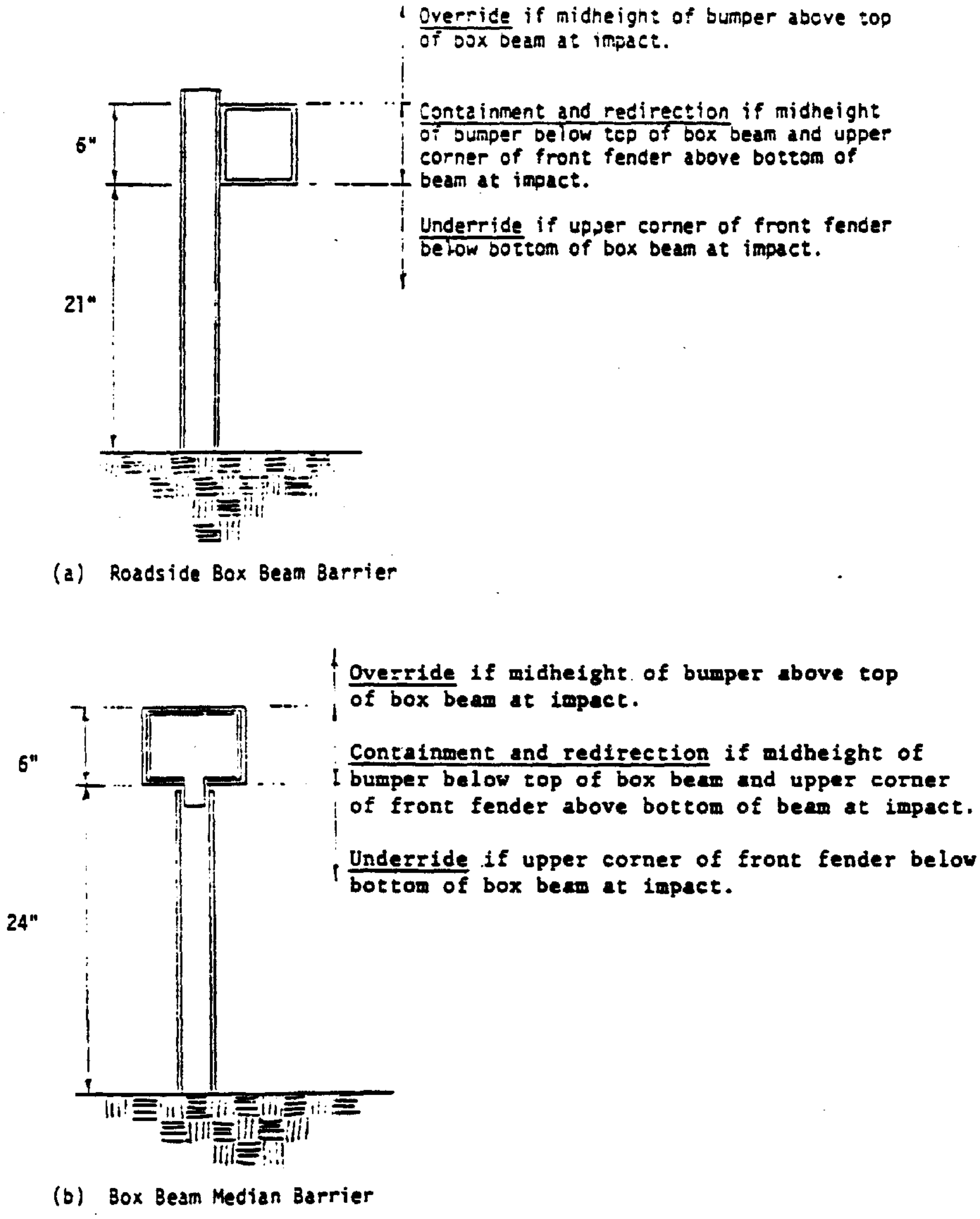


Figure 1.4 Containment Criteria, Box Beam Barrier.

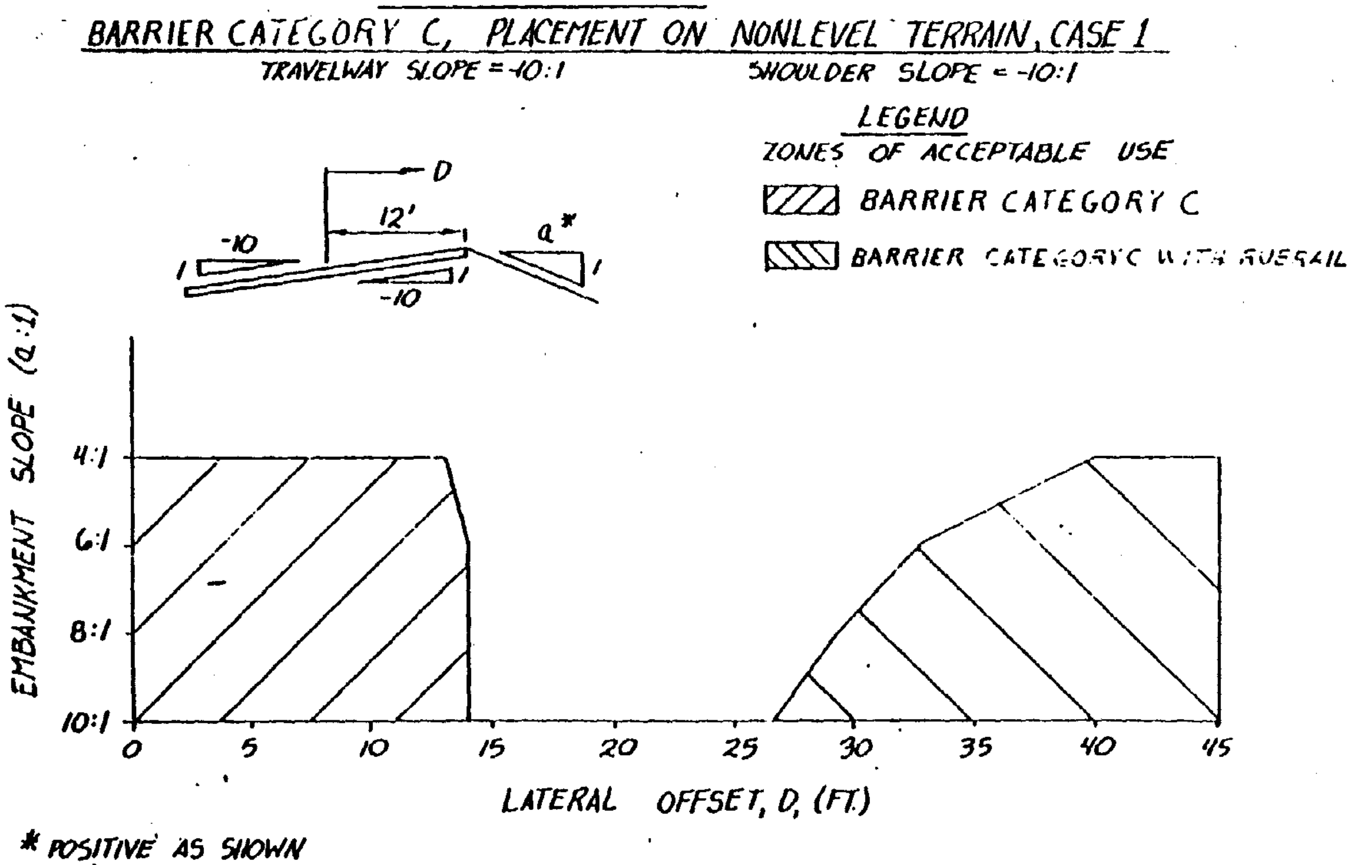

BARRIER CATEGORY C, PLACEMENT ON NONLEVEL TERRAIN, CASE 1
TRAVELWAY SLOPE = -10:1
SHOULDER SLOPE = -10:1
LEGEND
ZONES OF ACCEPTABLE USE
BARRIER CATEGORY C
BARRIER
D
12'
-10
1
-10
1
a*
1
EMBANKMENT SLOPE (a:1)
4:1
6:1
8:1
10:1
0
5
10
15
20
25
30
35
40
45
LATERAL OFFSET, D, (FT.)
* POSITIVE AS SHOWN

Figure 1.5

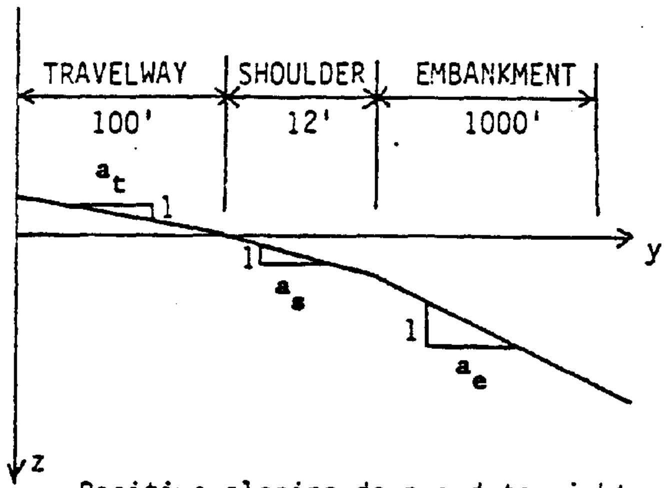
Table 1. Synopses of directly related reports (continued).

Table 1.2 An Index for Placement Guidelines by Figure Number.

NOTE: Figure numbers in table correspond to those given in Appendix D.

		TRAVELWAY SLOPE				
		$a_T=-20:1$		$a_T=-10:1$		$a_T=48:1$
		Shoulder Slope		Shoulder Slope		Shoulder Slope
Case	Barrier Category	$A_S=-20$	$A_S=20$	$A_S=-20$	$A_S=-10$	$A_S=20:1$
1	A	D-1	D-2	D-3	D-4	D-5
2	A	D-6	D-7	D-8	D-9	D-10
3	A	D-11	D-12	D-13	D-14	D-15
1	B	D-16	D-17	D-18	D-19	D-20
2	B	D-21	D-22	D-23	D-24	D-25
3	B	D-26	D-27	D-28	D-29	D-30
1	C	D-31	D-32	D-33	D-34	D-35
2	C	D-36	D-37	D-38	D-39	D-40
3	C	D-41	D-42	D-43	D-44	D-45
1	D	D-46	D-47	D-48	D-49	D-50
2	D	D-51	D-52	D-53	D-54	D-55
3	D	D-56	D-57	D-58	D-59	D-60
1	E	D-61	D-62	D-63	D-64	D-65
2	E	D-66	D-67	D-68	D-69	D-70
3	E	D-71	D-72	D-73	D-74	D-75

Table 2. Roadway/roadside geometric parameters.



Positive sloping downward to right.

a_t	+48	-20		-10	
a_s	+20	+20	-20	+20	-10
a_e	+ 4	+ 4	+ 4	+ 4	+ 4
	+ 6	+ 6	+ 6	+ 6	+ 6
	+ 8	+ 8	+ 8	+ 8	+ 8
	+10	+10	+10	+10	+10
	- 8	- 8		- 8	
	-4	- 4		- 4	

requested and received from TTI. A computer program was then prepared for graphical presentation of the data. A sample plot is shown in figure 2. The manner in which these curves were used to establish barrier height limits is discussed in chapter V.

B. Vehicle Survey

1. General. With the apparent importance of both bumper height and possibly bumper geometry in establishing critical barrier override/underride heights, a vehicle survey was undertaken to establish representative values and ranges. Sales figures for the more common vehicles sold in the United States were collected for the years 1980 through 1983. Field trips were then made to measure the bumper geometry and to collect brochures with photographs of the different bumper types.

Based on crash test results with W-beam traffic barrier, it was determined that the leading edge or surface of the bumper was critical for both underride and override. Using this relationship, the bumper geometries of current vehicles were grouped into six categories as shown in figure 3. The collected sales information was totaled and weighted to reflect the average bumper override/underride heights. As shown in table 3, the data was then divided into ranges of override and underride heights. Figures 4 and 5 are underride/override exceedance curves prepared from these results. Shown are heights at the 85-percentile levels, which produced different values for underride/override heights [18.8 in (48 cm) and 17.1 in (43 cm)]. It was decided to select a single value of 18 in (46 cm) for both underride and override heights. As shown in figure 4, this was the 98-percentile level for underride and, from figure 5, the 99-percentile level for underride. The exceedance curves in figures 4 and 5 describe what percent of cars purchased from 1980-1983 had bumper values that exceeded a given value. Example: 98% of the vehicles had bumper heights that were equal to or greater than 18.8 in for underride consideration as shown in figure 4. Thus, a design vehicle with a single 18-in

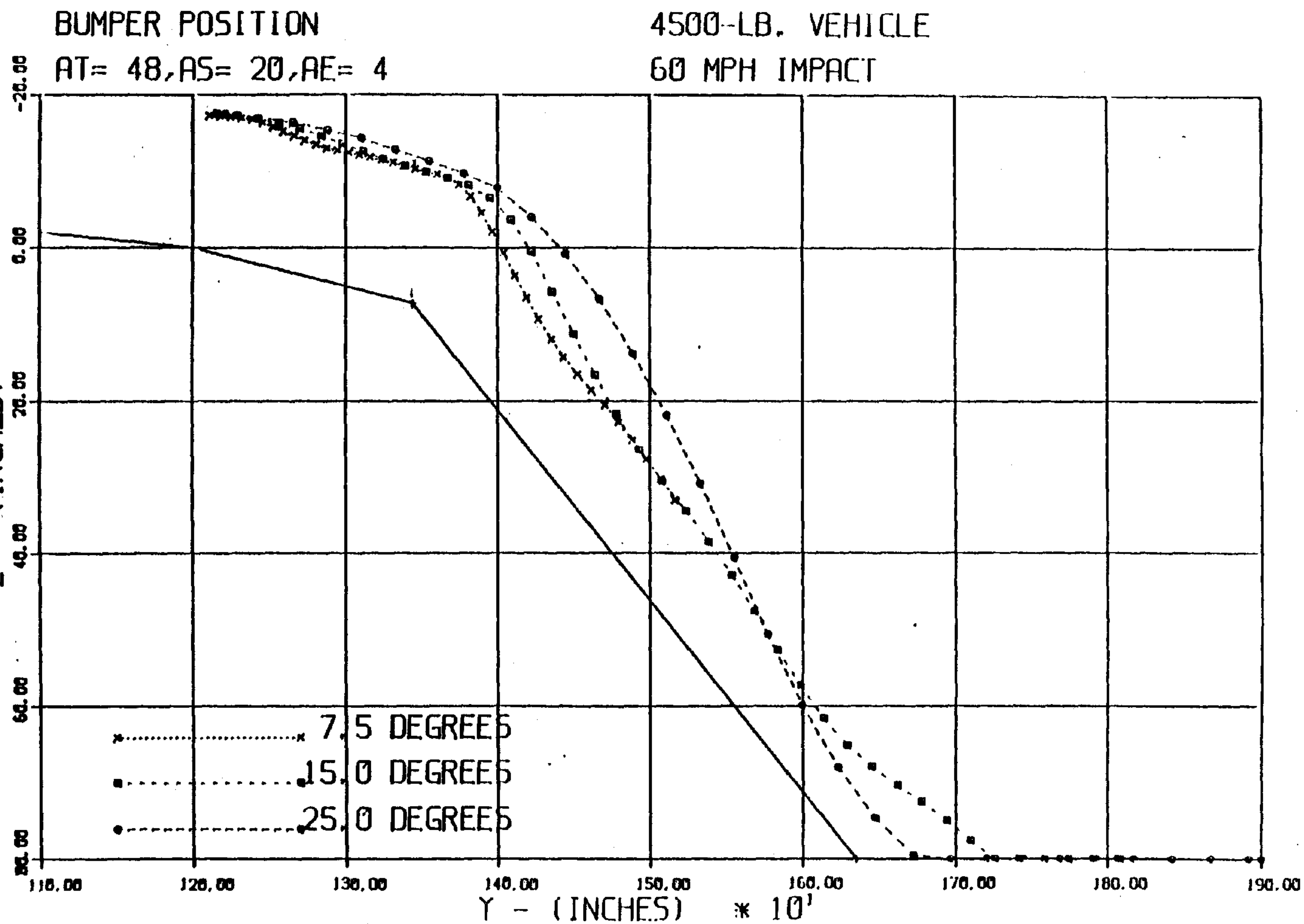
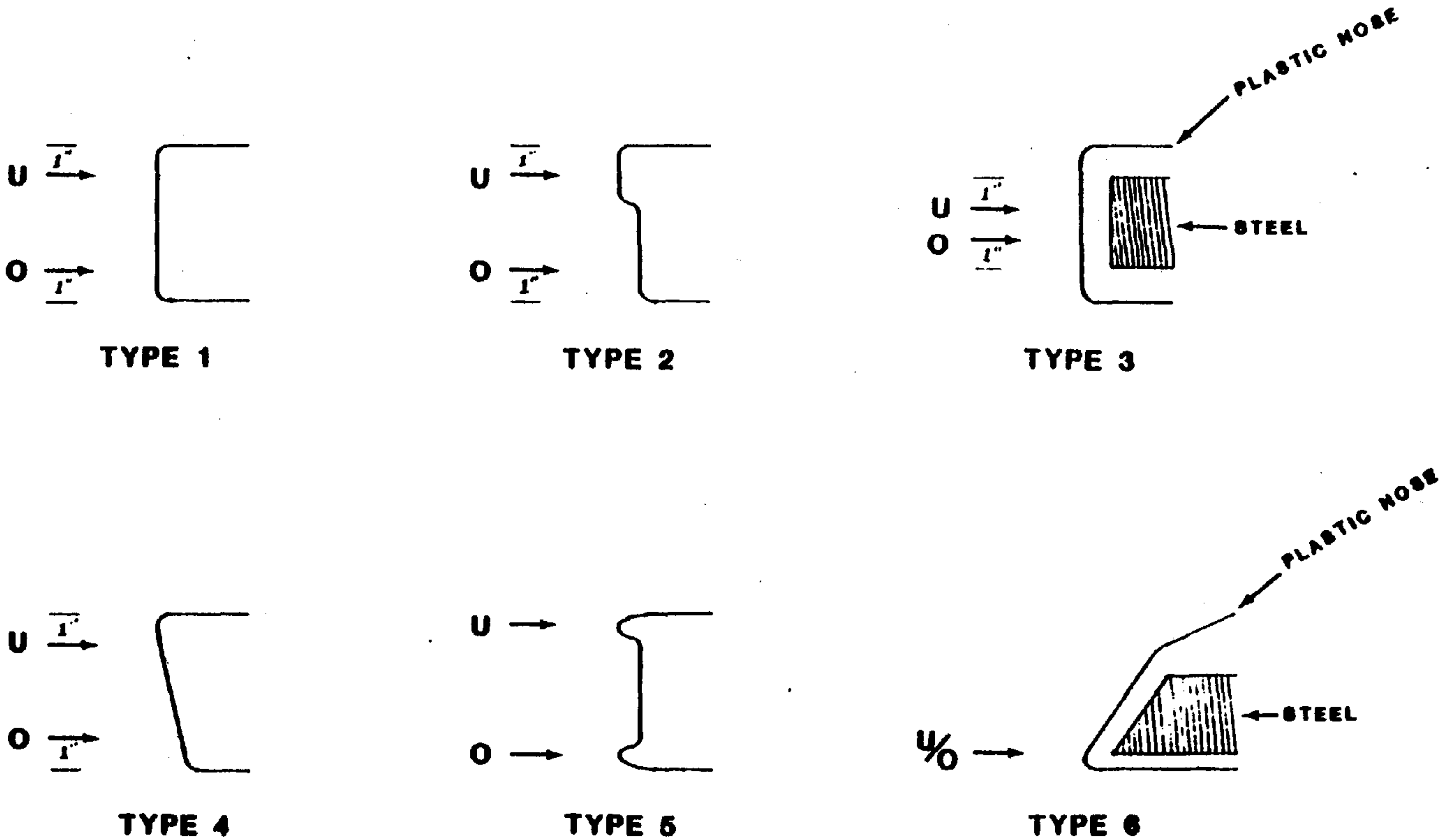


Figure 2. Sample plot of bumper height positions.



U - UNDERRIDE
O - OVERRIDE

Figure 3. Categories of bumper types.

Table 3. Vehicle survey data.

*****VEHICLE SALES 1980-83*****

		1980	1981	1982	1983	ACC. SALES	OVER	UNDER
AMC	ALLIANCE	0	0	30173	126008	156181	17.0	19.5
PLYM	HORIZON	78826	75377	46907	56763	257873	16.0	18.5
	GRAND FURY	13682	1408	18255	15101	48446	16.5	19.8
	RELIANT	104836	196997	146762	157247	605842	15.5	21.0
CHRY-	LE BARON M/K	65319	46991	88575	80309	281394	16.0	21.0
	NEW YORKER STN	0	5894	62725	73729	142348	14.5	17.5
	NEW YORKER E	0	0	119	50091	50210	16.0	21.0
DODGE	OMNI	61240	56038	40002	50451	207731	16.0	18.5
	CHARGER/024	0	51743	41275	45975	138993	15.0	20.0
	ARIES	80876	149653	113076	119400	463005	16.5	20.0
	DATONA	0	0	0	8761	8761	15.0	19.0
	600/400	0	3150	28946	28488	60584	16.3	19.5
	DIPLOMAT	33157	25598	24866	22603	106224	15.0	18.0
FORD	ESCORT	60196	284907	337667	326333	1009103	17.0	19.8
	MUSTANG	225290	154985	119526	116976	616777	17.0	20.0
	TEMPO	0	0	0	136148	136148	17.8	20.8
	T-BIRD	127248	69775	42585	134710	374318	16.0	20.5
	LTD	3012	0	26820	165396	195228	16.5	20.0
	CROWN VICTORIA	142819	113109	126065	119905	501898	16.0	20.8
	EXP	0	54502	39021	19754	113277	16.0	19.5
MER.	LYNX	18196	92809	95959	78876	285840	17.0	20.0
	XR-7	51857	28706	15609	87027	183199	15.0	20.5
	MARQUIS	0	0	10645	65184	75829	16.0	19.5
	GRAND MARQUIS	52645	53145	77348	96659	279797	16.5	21.5
LINC.	LINCOLN	30114	29733	42537	59626	162010	16.5	21.5
	MARK VI	35371	29733	27920	28257	121281	16.5	20.0
GM.BUICK.	SKYHAWK	5388	0	46942	72998	125328	18.0	20.0
	SKYLARK	175741	200460	141766	102763	620730	17.3	19.5
	CENTURY FD	0	2691	99873	150280	252844	16.0	19.0
	REGAL SED/COUP	345101	332005	222169	234035	1133310	15.0	19.3
	LE SABRE	89429	82263	108909	151555	432236	15.0	19.5
	ELECTRA	61792	57234	59599	80106	258731	15.5	19.5
	RIVIERA	42917	47964	43673	53346	187900	16.0	21.0
CADI.	CADILLAC	126151	138948	154229	176003	595331	15.0	18.0
	ELDORADO	52142	54389	57263	71624	235418	14.8	19.8
	CIMARRON	0	14604	13774	19188	47566	16.5	19.5
	SEVILLE	34709	22724	24029	33522	114984	14.0	17.8
CHEV.	CHEVETTE	373988	346307	231927	178759	1130981	15.0	18.8
	CAVALIER	150320	88072	121392	259397	619181	16.0	19.5
	CITATION	374706	300184	186848	92379	954117	16.5	19.5
	CAMARO	116824	94606	182848	178266	572544	17.0	21.0
	CELEBRITY	0	1351	101311	180354	283026	13.0	19.0
	MONTE CARLO	165638	161158	98954	105797	531547	16.0	20.0
	CORVETTE	36507	29039	22477	27144	115167	12.5	12.5
	CHEV/CAPRICE	261819	210424	204193	238930	915366	15.0	20.0
OLDS.	OMEGA	87262	109981	72392	49818	319453	16.5	18.8
	CUTLASS /CIE	210784	187952	113921	191720	704377	17.5	20.0
	CUTLASS /SUP	258789	266070	280566	331179	1136604	15.0	19.0
	OLDS 88	147997	156662	180840	228770	714269	14.8	19.5
	OLDS 98	73464	84583	89222	119526	366795	16.5	19.5
PONT.	2000/SUNBIRD	132630	75884	57048	88313	353875	17.0	20.5
	PHOENIX	98952	82285	49527	24362	255126	17.5	19.5
	FIREBIRD	81592	52188	105686	90777	330243	16.0	19.0
	6000	0	1325	55794	92513	149632	16.0	19.0
	BONNEVILLE	77911	73988	76063	84122	312084	16.5	19.0
	GRAND PRIX	118414	128236	83598	89355	419603	16.0	20.0
	PONT/PARISIMNE	105398	82620	4176	26929	219123	15.0	19.5
CHRY/MIT	COLT	50689	42796	75031	73671	242187	16.5	18.0
HONDA	CIVIC	138735	154698	132469	127856	553758	15.5	18.5
	ACCORD	185977	172557	195524	171736	725794	16.0	18.5
	PRELUDE	50676	43450	37872	41188	173186	16.0	19.5
MAZDA	GLC	62593	62195	54348	51313	230449	16.5	19.5
	626	55281	60475	58740	69561	244057	15.5	18.5
	RX-7	43743	43418	50062	52514	189737	15.8	18.5
NISSIAN	310/PULSAR	96204	77980	52813	60233	287230	16.0	20.0
	SENTRA	0	0	131789	209889	341678	16.5	19.5
	STANZA	0	8523	59152	64429	132104	16.0	20.0
	MAXIMA	9440	35853	54187	76209	175689	15.5	18.0
	200SX	92514	77062	48436	31158	249170	17.0	20.3
	280/300ZX	71533	62800	57260	71144	262737	15.8	15.8

Table 3. Vehicle survey data (continued).

SUBARU	(ALL)	142968	152062	150335	156840	602205	16.3	18.0
TOYOTA	COROLLA	257300	241603	175198	143430	817531	16.0	19.0
	TERCEL	99000	121328	135896	147965	504189	16.5	19.5
	CELICA	162400	103879	115690	117836	499805	16.0	19.5
	SUPRA	0	16146	34046	26972	77164	16.0	18.5
	CAMRY	0	0	0	52654	52654	17.0	20.0
	CRESSIDA	11628	29583	37448	39755	118414	15.3	17.8
VW	RABBIT	177140	162445	91166	85045	515796	16.0	19.0
0 ACCUMULATED TOTALS		6699070.	6679313.	6441934.	7965005.	27985322.		
PERCENT OF TOTAL SALES		74.6	78.3	83.3	86.8	80.7		
0 THE AVE. OVERRIDE HEIGHT IS		16.0						
THE AVE. UNDERRIDE HEIGHT IS		19.4						

ADJUSTED
******* OVERRIDE HEIGHTS *******

14.0 TO 14.9	15.0 TO 15.9	16.0 TO 16.9	17.0 TO 17.9	OTHERS
4.31	30.05	46.87	17.91	.86

ADJUSTED
******* UNDERRIDE HEIGHTS *******

17.0 TO 17.9	18.0 TO 18.9	19.0 TO 19.9	20.0 TO 20.9	21.0 TO 21.9	OTHERS
1.34	19.40	46.01	24.26	7.65	1.35

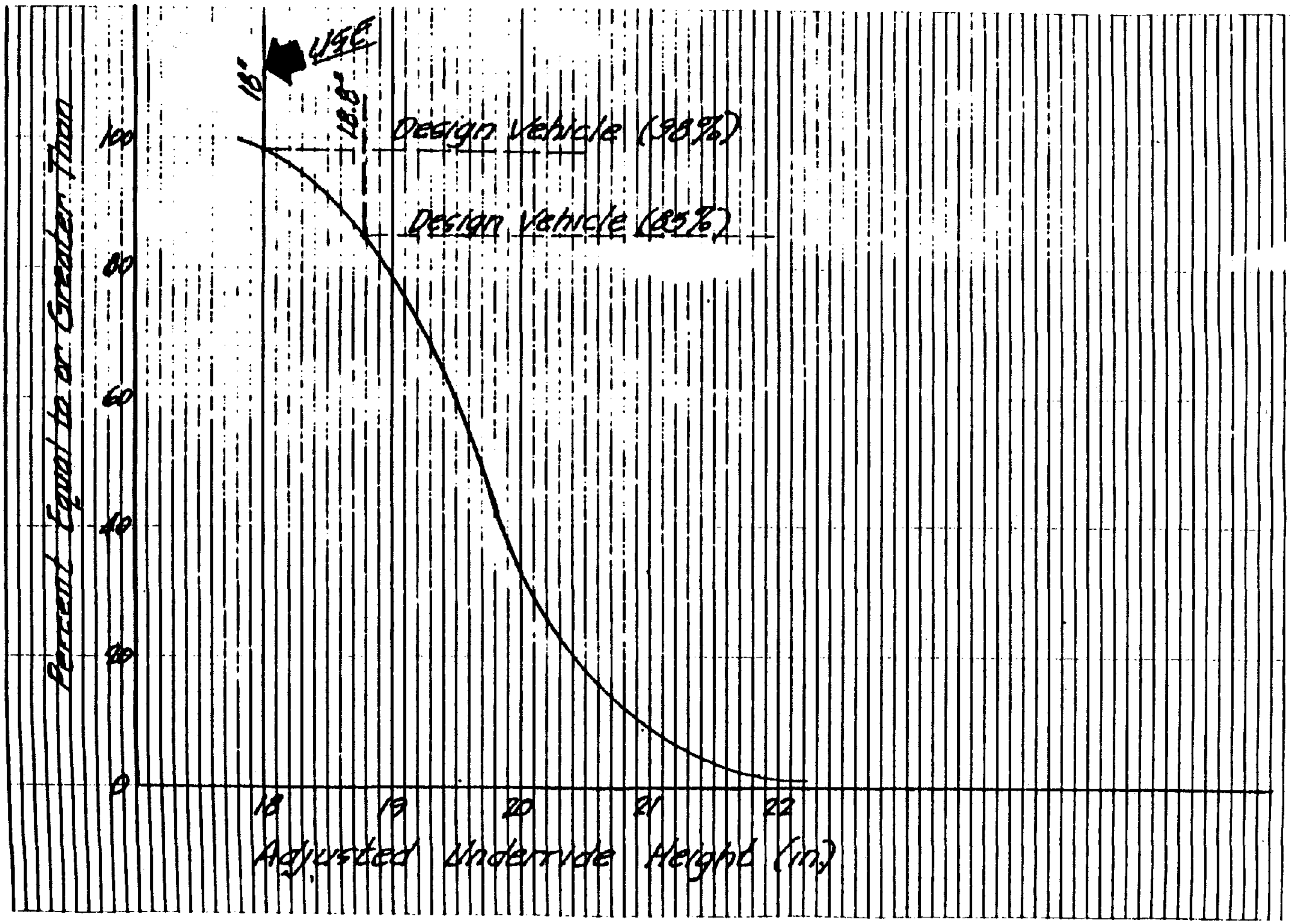


Figure 4. Design vehicle underride height.

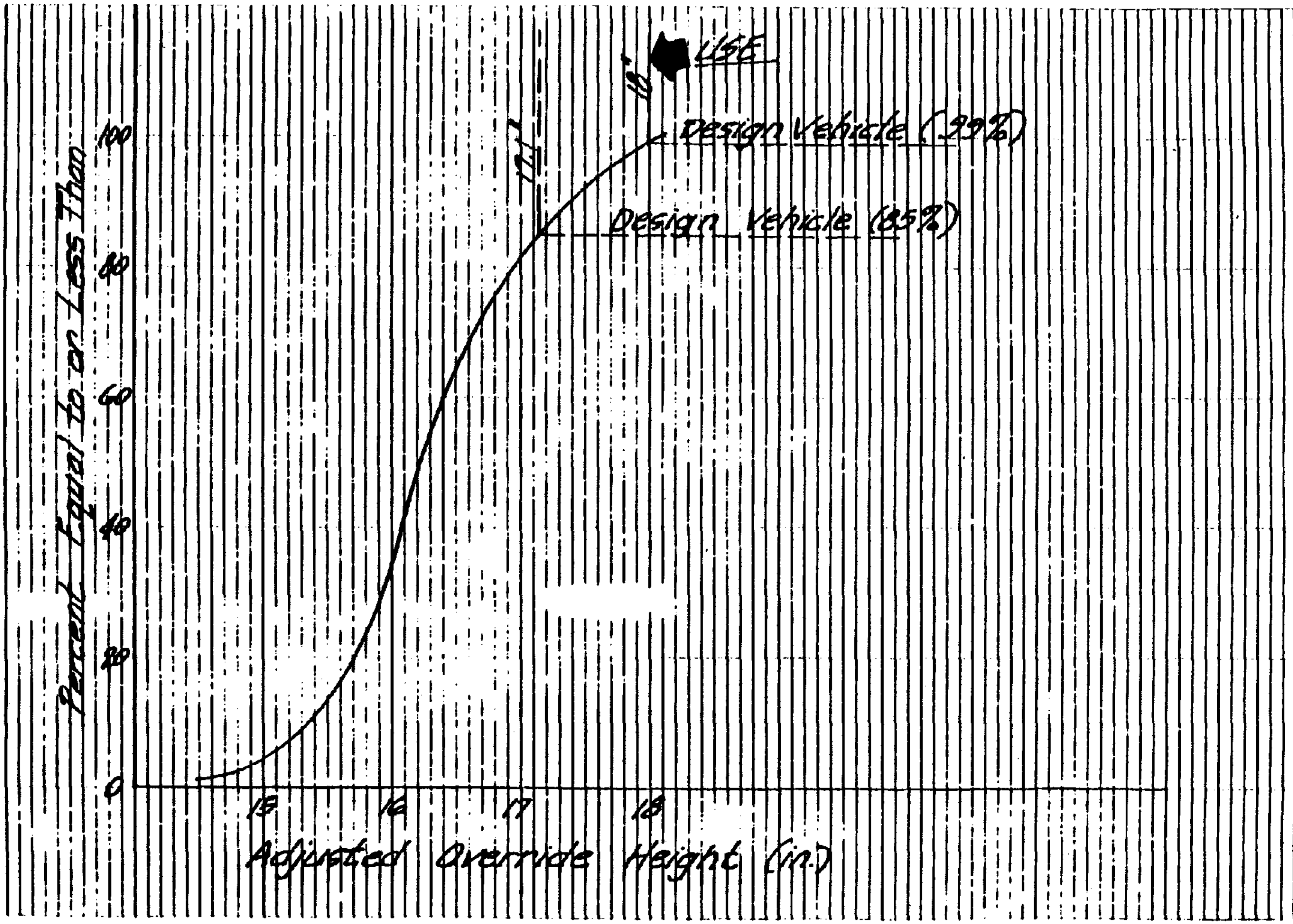
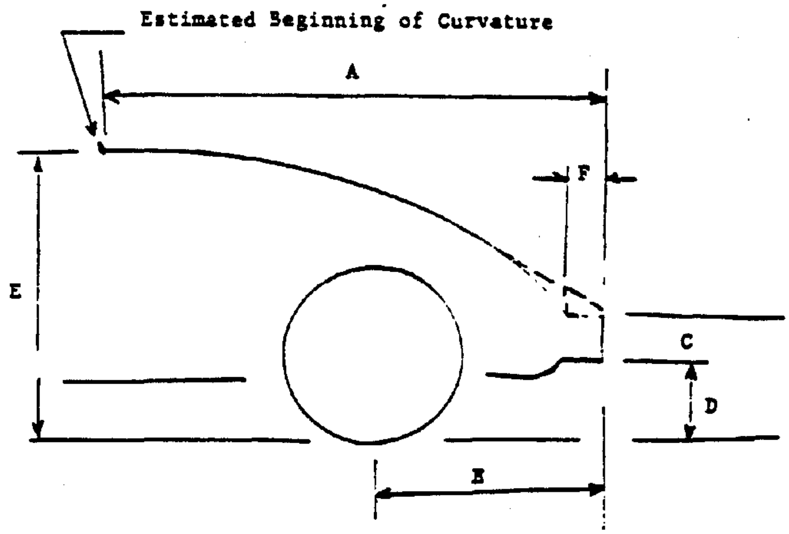


Figure 5. Design vehicle override height.

(46-cm) bumper underride and override height was selected for subsequent use in establishing the barrier height limits.

2. Aerodynamically Styled Vehicles. Later in the project a minimal effort was expended in investigating the influence of the low front profile cars and possible associated problems with barrier mounting height. Figure 6 gives data from a limited survey. One full-scale crash test was conducted with the Datsun 260ZX shown at the bottom of the list.



AERODYNAMICALLY STYLED FRONT ENDS

Car	Year	A	B	C	D	E	F
280ZX	80	38	36	6	13	33	
Dodge Datona	85	58	42	9	10 1/2	37	
280ZX	83	44	40	4 1/2	15	33	
Chevy Z28	86	38	44	7 1/2	12 1/2	34	
Porche 924	81	62	34 1/2	4 1/2	13	35	5 1/2
Mazda RX7	83	32	35	5 1/2	15 1/2	31	
300 ZX	85	24	35 1/2	7	14	32	
Corvette	85	49	41	7 1/2	10 1/2	33	
Firebird	85	49 1/2	44	10	12 1/2	35	
Mazda RX7	86	31 1/2	35	6	13 1/2	32	
Datsun 260ZX	74	33	39	4	14 3/4	32	3 3/4

Figure 6. Aerodynamically styled car geometries.

III. ANALYTICAL STUDY

A. Selection of Simulation Program

As indicated in chapter II, an apparent lack of definitive performance information existed in the general literature for the effects of varying barrier railing heights. Determination of critical override/underride heights for the five barrier categories of table 1.1 by full-scale crash tests was not economically feasible. Thus, a major effort was directed in this study toward the development of an analytical model to provide simulation guidance for these effects.

The computer program selected for simulation use was HVOSM, Version RD2.[5] Other codes considered were GUARD[6] and CRUNCH[7]. Preliminary reasons for making this selection are discussed in appendix B. Other justifications for utilizing HVOSM-RD2 as the most applicable code of available programs were based on the following:

- It had what was believed to be the most advanced vehicle model. In particular, it had a steering/wheel degree of freedom (DOF) while the GUARD vehicle model simulated a "locked" wheel condition. The DOF associated with the HVOSM wheels might have a pronounced effect on wheel snag vehicular behavior.

- It had the capability of simulating vehicle side and bottom sheet metal/barrier interaction forces. The GUARD vehicle was limited to only side panels for the sheet metal and wheels. Notably, interaction between the vehicle bottom and barrier rail top might significantly enhance vaulting potential.

- HVOSM had been extensively used by several research organizations. This had attributed to significant validation data being collected over a number of years. On the other hand, programs such as CRUNCH and GUARD had not been validated to a degree which would warrant their use in this particular hardware development program.

- Documentation associated with GUARD and CRUNCH was very limited to the unfamiliar user. In turn, an inordinate amount of time would be required to be able to utilize these codes with the same efficiency as when using the HVOSM-RD2 program.

B. HVOSM Modifications

The tape of HVOSM-RD2 was furnished by FHWA at the start of the task. Modifications were first made to convert the program to operational status on the Institute's CDC equipment. Two sample cases (one rigid and one flexible) were then run and compared with previous results. Both runs checked out satisfactorily. Thus, the program was ready for the proposed wheel snagging (underride) and vaulting (override) modifications.

As modifications were tried, problem areas arose in the basic program involving the correct passing of variables via common blocks from one subroutine to another. Notably, an error was found involving the lack of COMMON block INTG in subroutine EGYSUM. This error had not been discovered previously because the earlier runs did not use EGYSUM.

Work continued on modifying the HVOSM-RD2 program and fixing further unexpected errors that appeared in the code as the work progressed. The extensive modifications that were made in the code included the following:

- Capability to include post stiffness characteristics that differ in the longitudinal and lateral directions.
- Wheel interaction with post (wheel snagging capability).
- A reaction force capability that is imposed on the right front wheel if the top of the tire is below the bottom of the rail (wheel underriding capability).
- A vaulting or overriding capability of the barrier rail.
- User ability to specify barrier blockouts.
- The vehicular response due to the vertical (downward) deformation of the barrier railing).

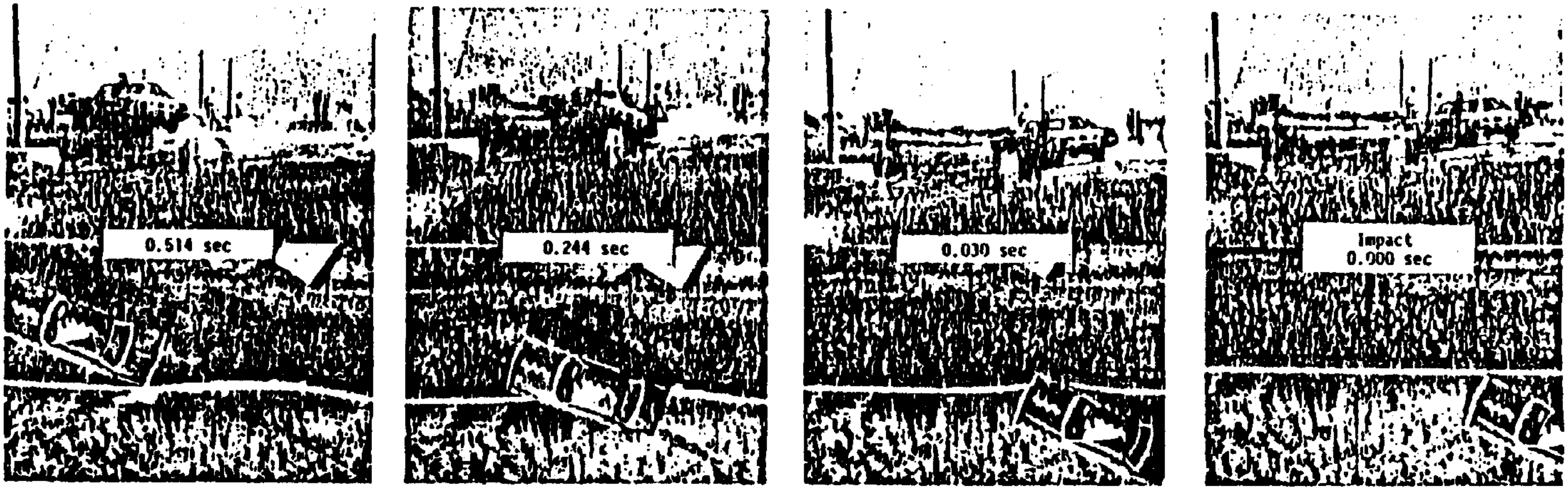
One problem that arose was that the overriding aspect could not be simulated in the original RD2 code. This was verified by the simulated redirection of a 4300-lb (2000-kg) vehicle by a 5-in (13-cm) high flexible barrier system. Output data showed reaction force locations on the vehicular body well above the top of the rail. Changes were made to eliminate these erroneous vehicular-barrier forces.

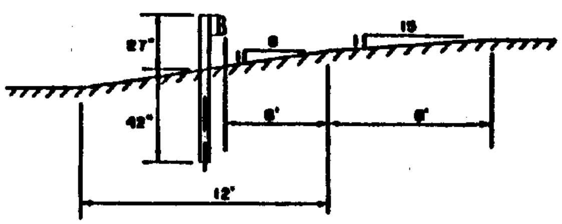
With these changes and modifications, the program was considered ready for the validation efforts.

C. HVOSM Validation Efforts

To verify the changes and modifications of HVOSM-RD2, the program predictions were compared with full-scale crash test data. The first tests were two conducted on slopes by the Texas Transportation Institute (TTI), as shown in figures 7 and 8.[4] Table 4 shows HVOSM validation results involving the vehicular vaulting of these tests. In particular, Case Nos. 4 and 7 were validation runs. Cases No. 5 and 6 were performed to verify that the vehicle would not vault the barrier when the railing height became great enough. Note in TTI test 3659-1 that the vehicle vaulted the railing with less redirection than in test 3659-3. This aspect was reflected by the two validation runs (cases 4 and 7). Specifically, the maximum recorded lateral displacement of the bumper monitoring point (BMP) was greater in case 7. With respect to the 50-ms acceleration levels, very low longitudinal and lateral values were simulated in case 7 because of the HVOSM vehicle sheet metal making contact with the very top of the railing. This induced primarily a vertical reaction force, which indicated the need for the incorporation of vertical vehicle-barrier interaction as delineated in section B of this chapter.

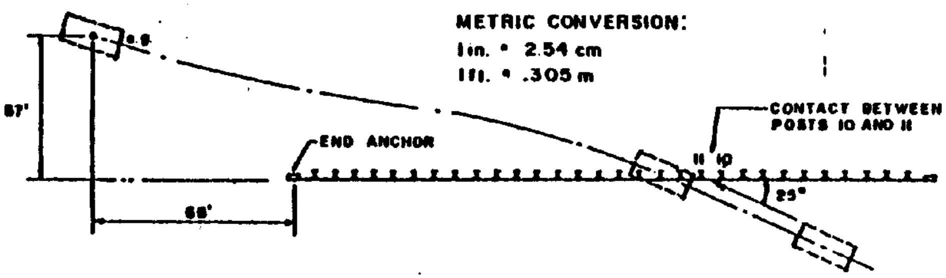
Five full-scale validation tests were then conducted in this study (see chapter IV and appendix A). Override (vaulting) was first checked. Difficulties initially arose when effort was made to simulate the vaulting of a 22-in (56-cm) barrier system (Tests BH-2 and BH-5) and the redirection





G4(1S)
BLOCKED OUT "W" BEAM (STEEL POST)

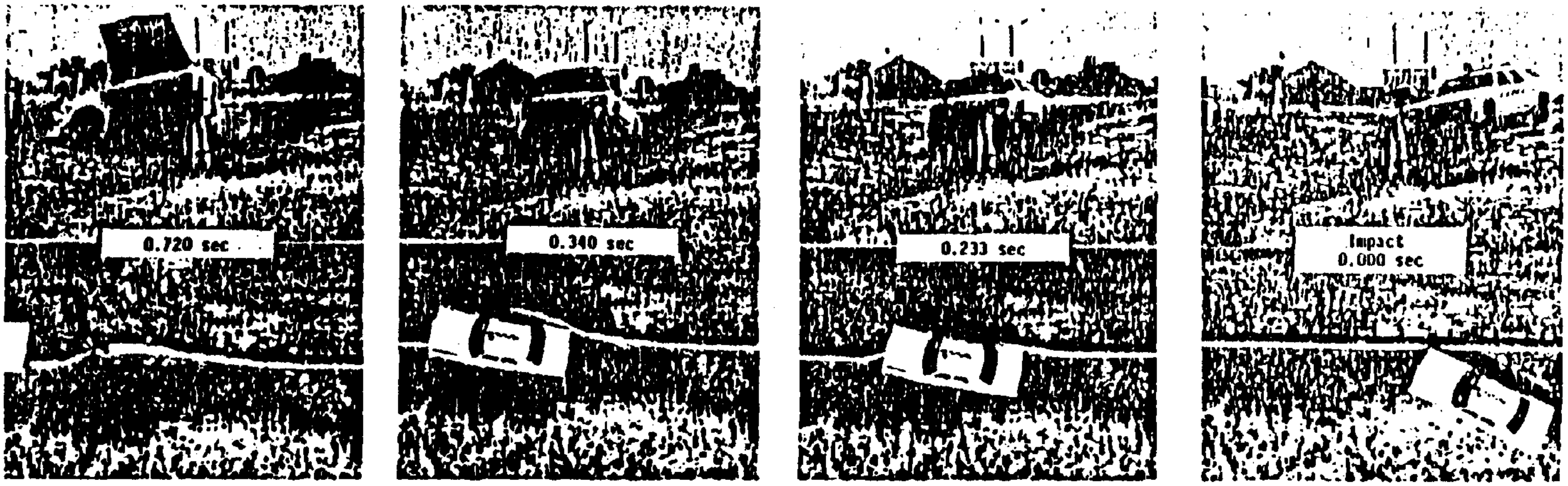
FIGURE 8. SUMMARY SHEET FOR TEST I.

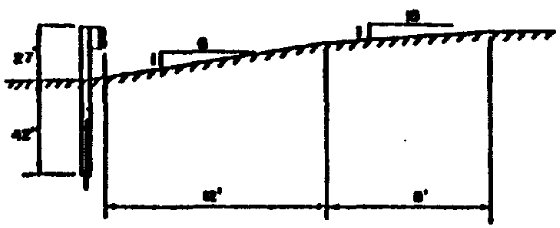


Test No. 3659-1
Date 5/23/78
Drawing. . . . . .G4(1S)
Beam Rail. . . . . . . .12 ga Steelx12.5 ft (3.8 m)
Post . . . . .W6x8.5 x 6.75 ft(1.7 m)
Post Embedment . . . . . .42 in. (1.1 m)
Post Spacing . . . . . .6.26 ft (1.9 m)
Length of Installation .200 ft (61 m)
Ground Conditions. . . .Wet
Beam Rail Deflection
  Maximum Dynamic. . . .1.3 ft (0.40 m)
  Maximum Permanent. . .0.96 ft (0.29 m)
Vehicle. . . . . .1974 Plymouth
Vehicle Mass . . . . . .4500 lbs (2045 kg)

Impact Speed. . . . . .62.83 mph (101.09 km/h)
Impact Angle. . . . . .25°
Exit Speed. . . . . .44.35 mph (71.36 km/h)
Exit Angle. . . . . .Vaulted Rail
Vehicle Acceleration
  (max 0.050 sec avg)
  Longitudinal. . . . . . . .6.99 g
  Transverse. . . . . .9.45 g
  Vertical. . . . . .4.47 g
Vehicle Rebound Distance. . .Vaulted Rail
Vehicle Damage
  TAD 01RFQ3
  SAE 01RFEE1

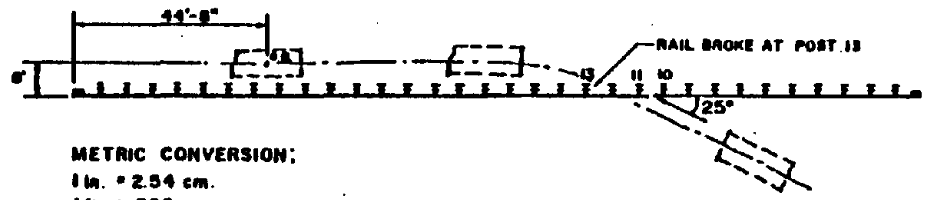
Figure 7. TTI Test 3659-1.





G4(1S)
BLOCKED-OUT "W" BEAM (STEEL POST)

FIGURE 25. SUMMARY SHEET FOR TEST 3.



METRIC CONVERSION:
1 in. = 2.54 cm.
1 ft. = .305 m

Test No. 3659-3
Date 7/13/78
Drawing. . . . . G4(1S)
Beam Rail. . . . . 12 ga Steel x 12.5 ft (3.8 m)
Post . . . . W6x8.5 x 5.75 ft (1.7 m)
Post Embedment . . . . . 42 in. (1.1 m)
Post Spacing . . . . . . 6.25 ft (1.9 m)
Length of Installation . 200 ft (61 m)
Ground Conditions. . . . Dry
Beam Rail Deflection
  Maximum Dynamic. . . . 4.1 ft (1.24 m)
  Maximum Permanent. . . --
Vehicle. . . . . 1974 Plymouth
Vehicle Mass . . . . . . 4500 lbs (2045 kg)

Impact Speed. . . . . 62.9 mph (101.21 km/h)
Impact Angle. . . . . 26.25°
Exit Speed. . . . . 31.13 mp (50.09 km/h)
Exit Angle. . . . . Penetrated Rail
Vehicle Acceleration
  (max 0.050 sec avg)
  Longitudinal. . . . . 8.52 g
  Transverse. . . . . 5.97 g
  Vertical. . . . . 5.87 g
Vehicle Rebound Distance. . . Penetrated Rail
Vehicle Damage
  TAD 01RFQ5
  SAE 01RYEE2

Figure 8. TTI Test 3659-3.

Table 4. HVOSM simulation summary.

Case No	Description	Accel Levels (G's) Long	Lat	Vert	MAX BMP† (in)	Barrier Location (Y_B)	Comments
4	TTI Test 3659-3	6.4 (8.5)*	5.2 (6.0)	2.2 (5.9)	399"	340"	27-in Barrier (figure 7) Vehicle Vaults Barrier
5	Test 3659-3 w/30-in Barrier	9.3	7.7	4.6	395"	340"	Vehicle Straddles Barrier
6	Test 3659-3 w/33-in Barrier	8.2	7.0	3.7	387"	340"	Vehicle Redirected
7	TTI Test 3659-1	0.5 (7.0)*	1.8 (9.5)	2.6 (4.5)	451"	268"	27-in Barrier (figure 6) Vehicle Vaults Barrier

†Location of Bumper Monitoring Point (in) at termination or maximum lateral location.

*Test Results

of the vehicle with a 24-in (61-cm) rail height (Test BH-4). Review of test films showed the vehicle bumper striking the upper sloped portion of the W-rail for Tests BH-2 and BH-5. This induced a significant vertical uplifting force that contributed to vaulting. In HVOSM, however, the barrier was represented by a flat vertical plane as was the vehicle side panel. Thus, the program could not simulate this phenomenon. Accordingly, additional changes were made to the code to effectively simulate this aspect if the vehicle bumper struck the upper portion of the rail. This entailed the user's setting a FLAG in the input data deck if simulating a full-size sedan impact into a flexible barrier having W-beam or thrie beam geometry.

Three simulations were performed to validate this modification through comparison with full-scale Tests BH-2, BH-4 and BH-5. Test results of these 60-mph (95-km/h)/25-degree impacts into a 22-in (56-cm) and 24-in (61-cm) high flexible barrier and corresponding simulation results are given in table 5. Notably, vehicular vaulting was predicted with the HVOSM code for Tests BH-2 and BH-5. Barrier deformation and number of post failures compared favorably for Test BH-2. Good results also existed for Test BH-4, where the vehicle redirected in both full-scale test and simulation run.

Validation of the modified HVOSM-RD2 program by comparison of simulation results with full-scale underride Tests BH-1 and BH-3 was next conducted. Results, as shown in table 5, demonstrated a slightly stiffer barrier response in the simulations over actual tests. Simulation of Test BH-1 resulted in two post failures versus four in the actual test, while the BH-3 simulation had five post failures compared to seven during the crash test. Notably, however, the simulations did correctly predict vehicular (bumper) underride for Test BH-3 and no underride for Test BH-1. Further, the simulation results (BH-3) included a pitching down motion of the vehicle as the right front bumper caught under the barrier railing with the railing impeding any uplifting motion during redirection. As anticipated, the longitudinal acceleration from the simulation of Test BH-1 was

Table 5. Validation test/HVOSM simulation comparisons.

Test No	Barrier Height (in)	Vehicle Weight (lb)	Impact Speed (fps)	Impact Angle (degrees)	Dynamic Deflection (in)	No of Failed Posts	Maximum 50-ms Accelerations* Long (g's)	Lat (g's)	Remarks
UNDERRIDE TESTS									
BH-1	30 coupled	4735	89.6	25.9	35.2	4	4.2/NA	5.7/NA	Vehicle redirected - Left front wheel torn off
Simulation					27.0	2	7.3	6.4	Vehicle redirected
BH-3	32 coupled	4675	87.5	25.0	Rail Separated	7	6.3/6.3	3.2/6.3	Rail fractured - Vehicle pocketed and stopped
Simulation					22.5	5	5.6	4.6	Vehicle underrode barrier - redirected
OVERRIDE TESTS									
BH-2	22 coupled	4633	87.5	26.8	(14" static)	2	3.5/6.1	2.8/3.6	Vehicle vaulted @ Heading Angle = 18.2°**
Simulation					10.5	1	5.3	3.8	Vehicle vaulted @ Heading Angle = 24.9°
BH-4	24 coupled	4699	88.5	24.4	27.6	5	2.7/2.9	6.6/7.9	Vehicle redirected
Simulation					18.0	6	8.4	7.0	Vehicle redirected
BH-5	22 uncoupled	4762	89.8	26.5	NA	4	3.2/2.7	2.4/4.2	Vehicle vaulted @ Heading Angle = 19.9°
Simulation					11.0	1	5.2	3.7	Vehicle vaulted @ Heading Angle = 24.5°

* Values as determined from (cine/transducer). NA = Not Available
** Measured as right front wheel passed over barrier.

significantly higher (7.3 g's) compared to the test results (4.2 g's). This was believed due to the wheel being torn off during the full-scale test, a phenomenon well beyond the capabilities of the HVOSM code.

Based on favorable validation results from test results of the TTI slope study and the five validation tests that had been conducted, modification and validation of the HVOSM program were considered complete. A briefing with FHWA was then scheduled to discuss findings to date and to direct subsequent work. The following summarizes the modifications that had finally been made for the HVOSM-RD2 code to permit the evaluations of vehicle override/underride:

- Defined discrete posts, up to 36 posts
  - x, dimension
  - spacing, x
  - location of axis of rotation
  - stiffness, x,y
  - maximum displacement for post failure, x,y
  - location of base of post.
- Defined barrier system
  - BARRIER VII[8] used to obtain 5th order polynomial for rail-post interaction (allows post to deform without vehicle contact).
  - Modification made to allow vehicle to vault or ramp over the system.
  - Modification permitting transfer of railing vertical force component to vehicle; i.e., vertical stiffness of rail is input
    - upward for override condition
    - downward for underride condition.
- Vehicle model modification
  - diameter and width of hub specified to interact with posts.

D. HVOSM Sensitivity Analyses

Based on comments made at a project briefing, there was some concern about sensitivity of certain HVOSM parameters as they affected vehicle trajectories prior to barrier impact. The parameters mentioned included suspension damping and steering/braking. Thus, a limited series of sensitivity analyses were conducted to check these concerns.

1. Suspension. The first sensitivity study was performed with HVOSM-RD2 on the viscous damping coefficients and the suspension load deflection rates to determine their effects on the bumper location above a given terrain. The model used for the studies was a 1978 Honda Civic with suspension properties measured in a previous University of Michigan study. Figure 9 shows a plot of two bumper heights with respect to a cross section of the terrain. Used in the calculations were slopes of the lower and upper portions of the curves in figure 10 for the front/rear damping coefficients and corresponding offsets. A small variation in the rebound height is indicated in figure 9. When the damping coefficients were varied by ±20 percent, the change in bumper height was less than 1 percent as shown in figure 11.

The load deflection rates as represented in figure 12 were varied by ±50 percent, and the bumper height variation is shown graphically in figure 13. As shown, this affected the bumper height very slightly.

Figure 14 compares the response of the Honda with the response of a VW Rabbit modeled under a separate FHWA contract. The load deflection rates and offset values were quite different for each vehicle, yet the change in bumper height was insignificant.

Based on these analyses, it was concluded that suspension load deflection rate and damping had no significant effect on the bumper heights of a vehicle traversing a side slope.

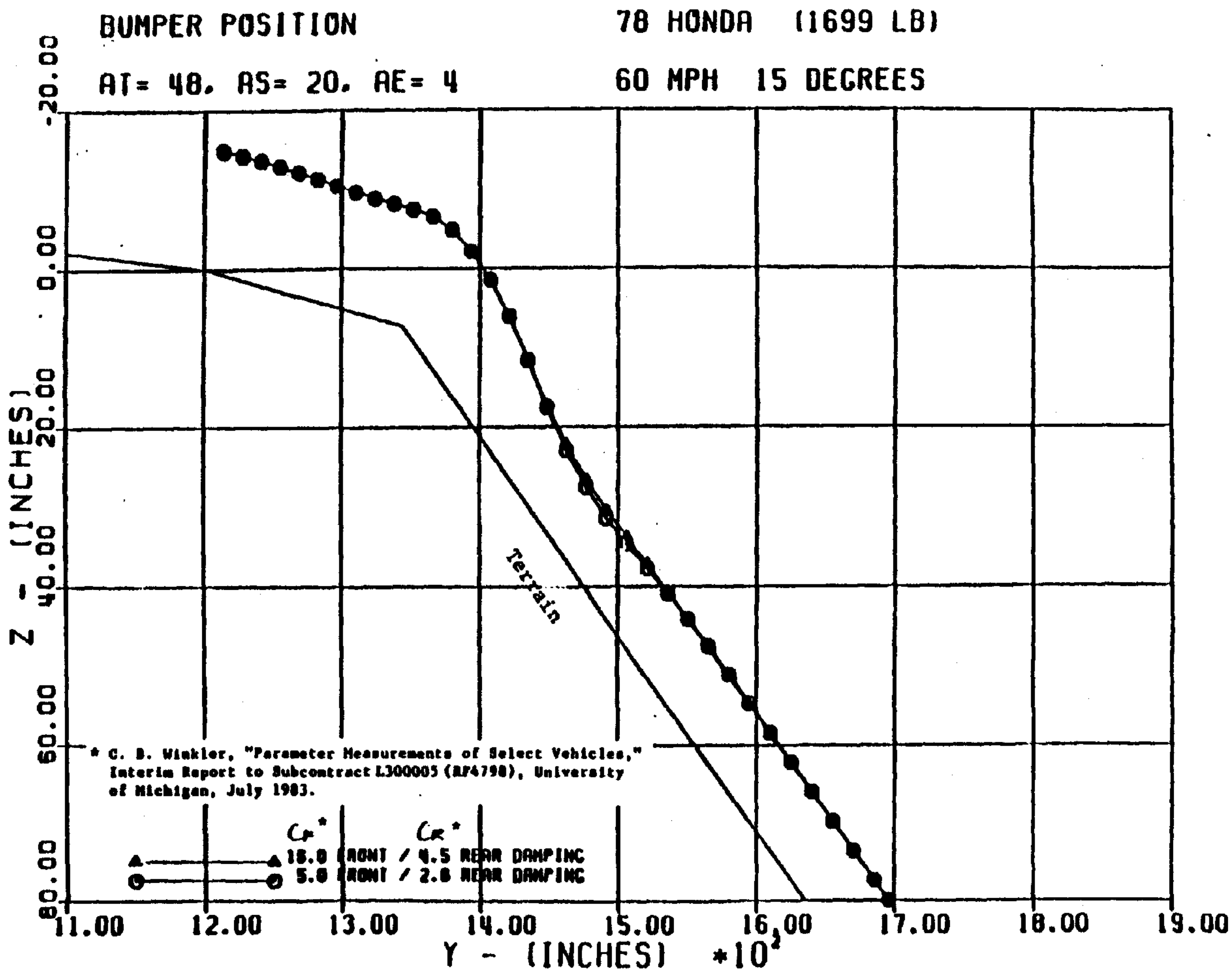


Figure 9. Bumper height for high damping characteristics and low piston velocity.

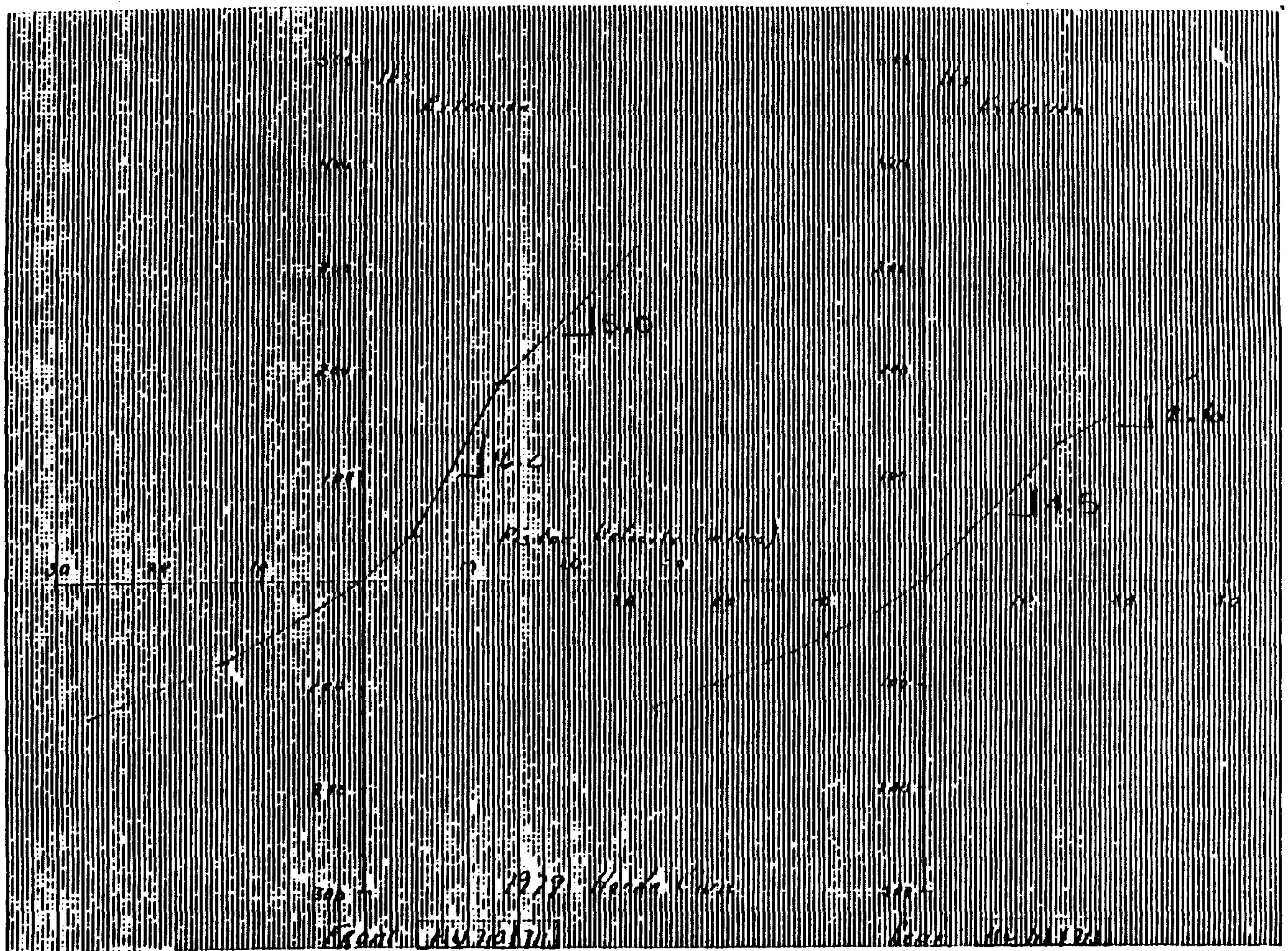


Figure 10. Front and rear damping curves for, 1978 Honda Civic.*

* UM report.

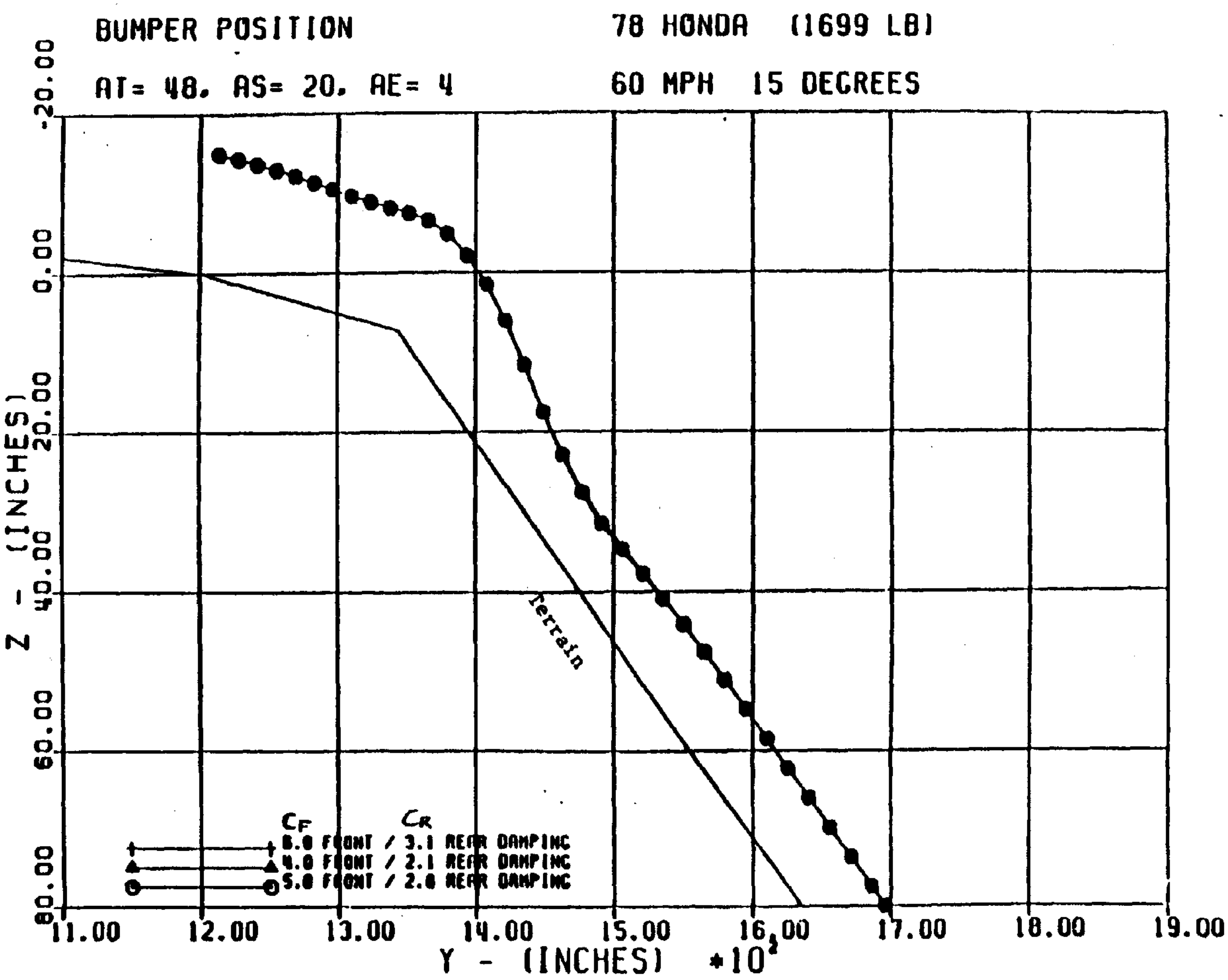
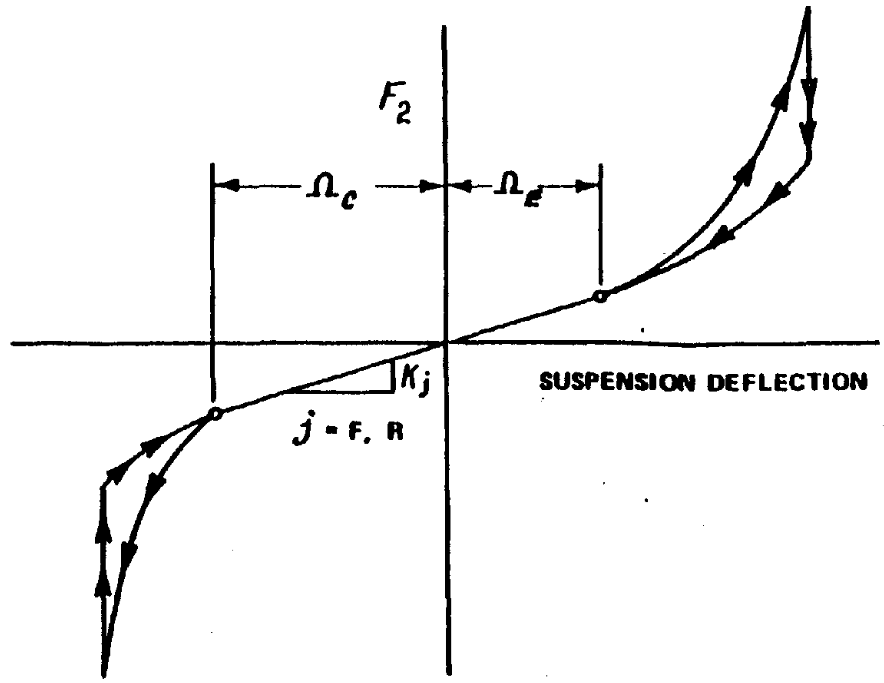


Figure 11. Bumper height sensitivity to damping coefficient.



GENERAL FORM OF SIMULATED SUSPENSION BUMPER CHARACTERISTICS

Figure 12. Suspension load deflection variables.

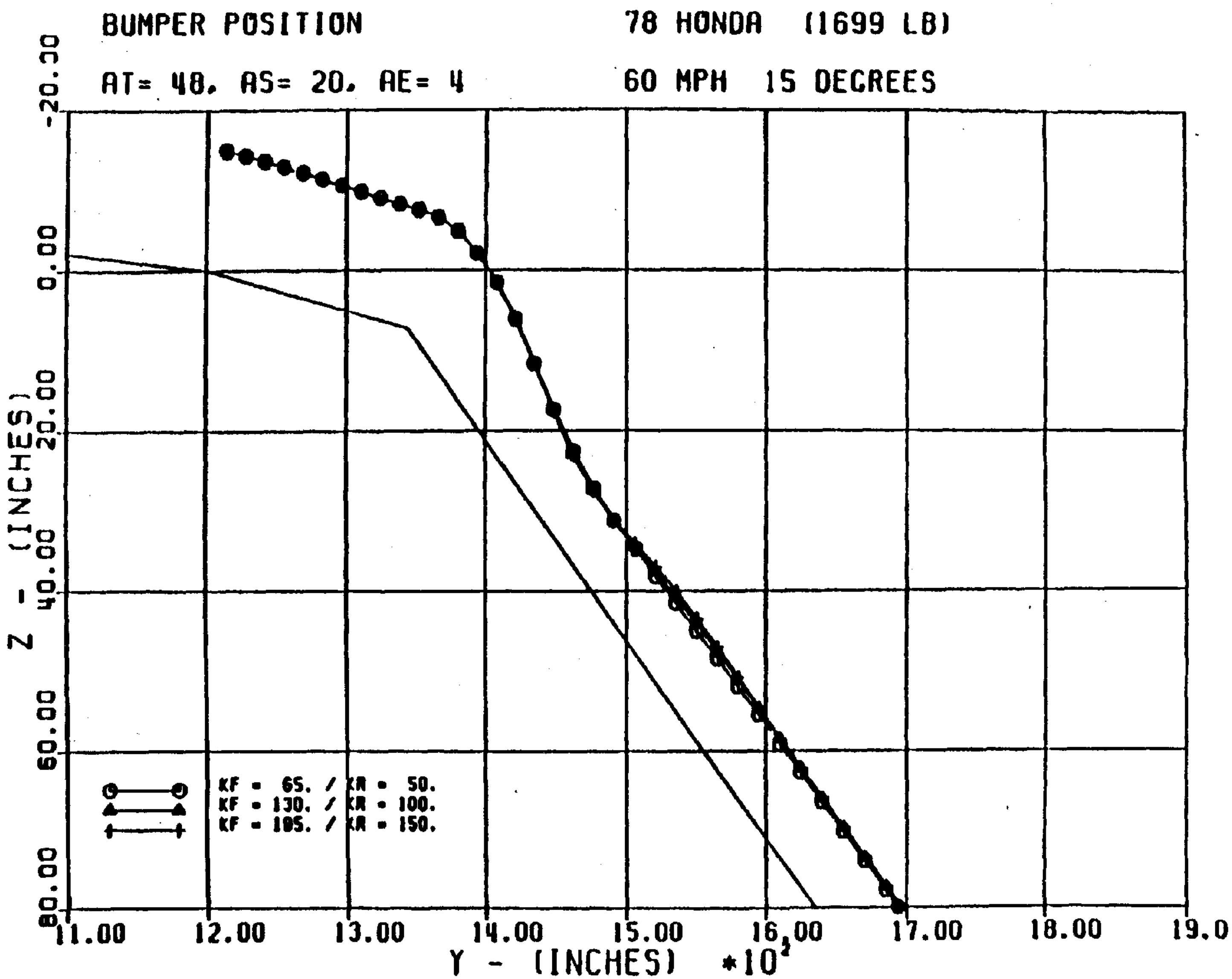


Figure 13. Bumper height sensitivity to suspension load deflection rate.

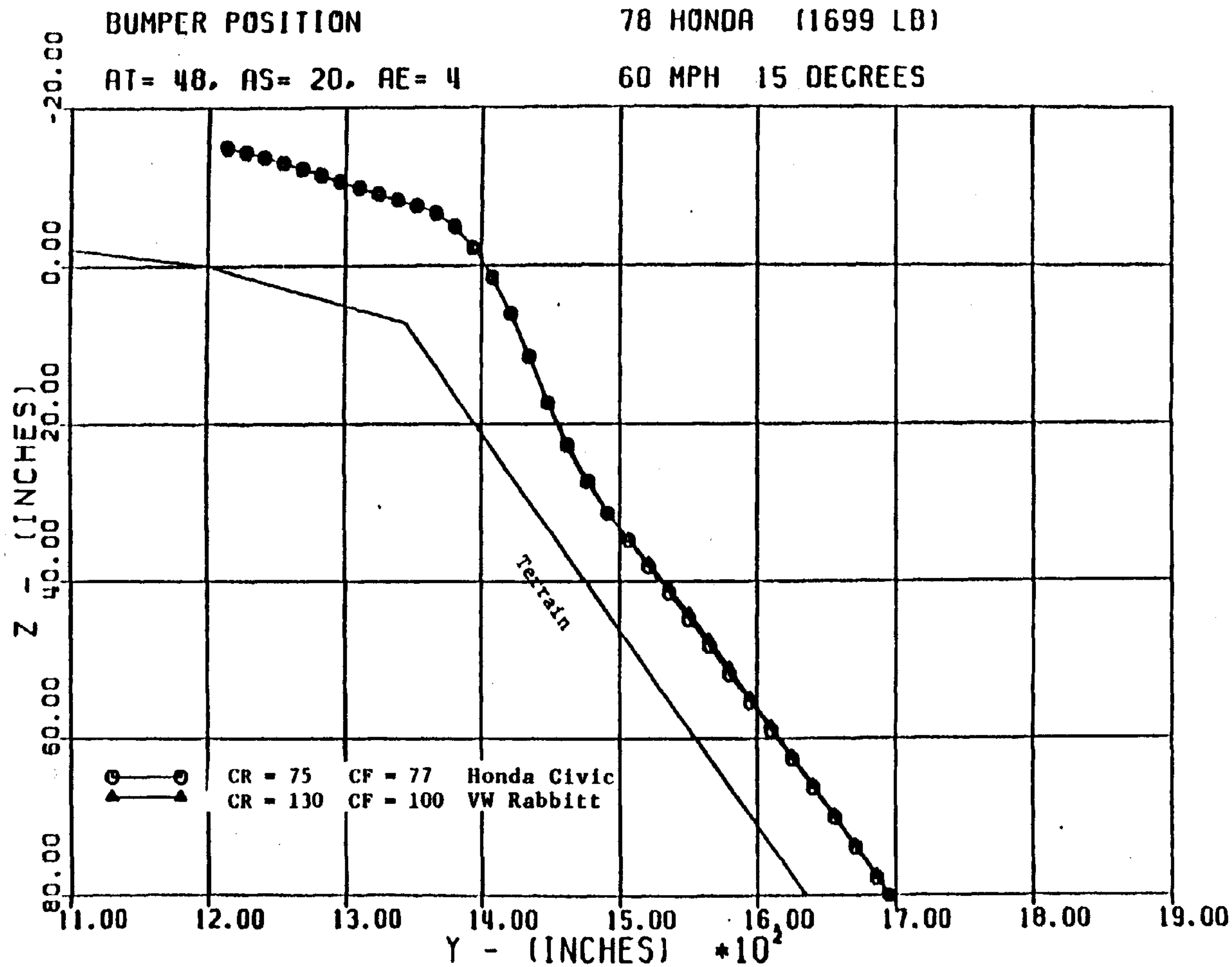


Figure 14. Bumper height for Honda Civic and VW Rabbit suspension load deflection rates.

2. Steering/Braking. The sensitivity analysis of steering/braking could not be conducted with the RD-2 version of HVOSM because the version did not include steering/braking inputs. Thus, the original TTI version was selected for use. However, this version did not include the bumper height subroutines and had to be modified to include the subroutine before the analysis could be started.

The first set of runs was made on an embankment slope of 4:1. Torques were applied to the wheels to simulate full braking, and steering angles of 20°, 0°, and -20° were specified as driver input. As shown in figure 15, the effects on bumper heights were insignificant. On inspecting the vehicle c.g. lateral and longitudinal displacements, it was found that no changes occurred between the three cases until wheels of the airborne vehicle made good contact with the ground (between Y = 1400 and Y = 1500 inches in figure 16). This was reasonable and indicated that a flatter slope should be used to reduce the airborne tendency. Thus, runs were made on a 10:1 embankment slope, as shown in figure 17. Effects on bumper height and vehicle lateral/longitudinal trajectory were even less pronounced.

This lack of change, particularly in the vehicle lateral/longitudinal trajectory, did not look reasonable. In the two sets of runs, the specified coefficient of friction between the tires and ground was $\mu = 0.25$. A value of $\mu = 0.50$ was used to calculate the wheel torques for full braking. With locked wheels and the low coefficient of friction as the vehicle moved down the slope, the low effect of steering was not as unreasonable. Thus, the second set of runs was repeated with $\mu = 0.25$ for partial braking torque and $\mu = 0.50$ for the tire/ground coefficient of friction. Results are shown in figure 18, where it can be seen that steering toward the road (+20°) did stop the vehicle's downward travel and turned it back. The change in bumper height was not significant except for a small zone down from the slope break where a variation of ±1 1/2 in is indicated.

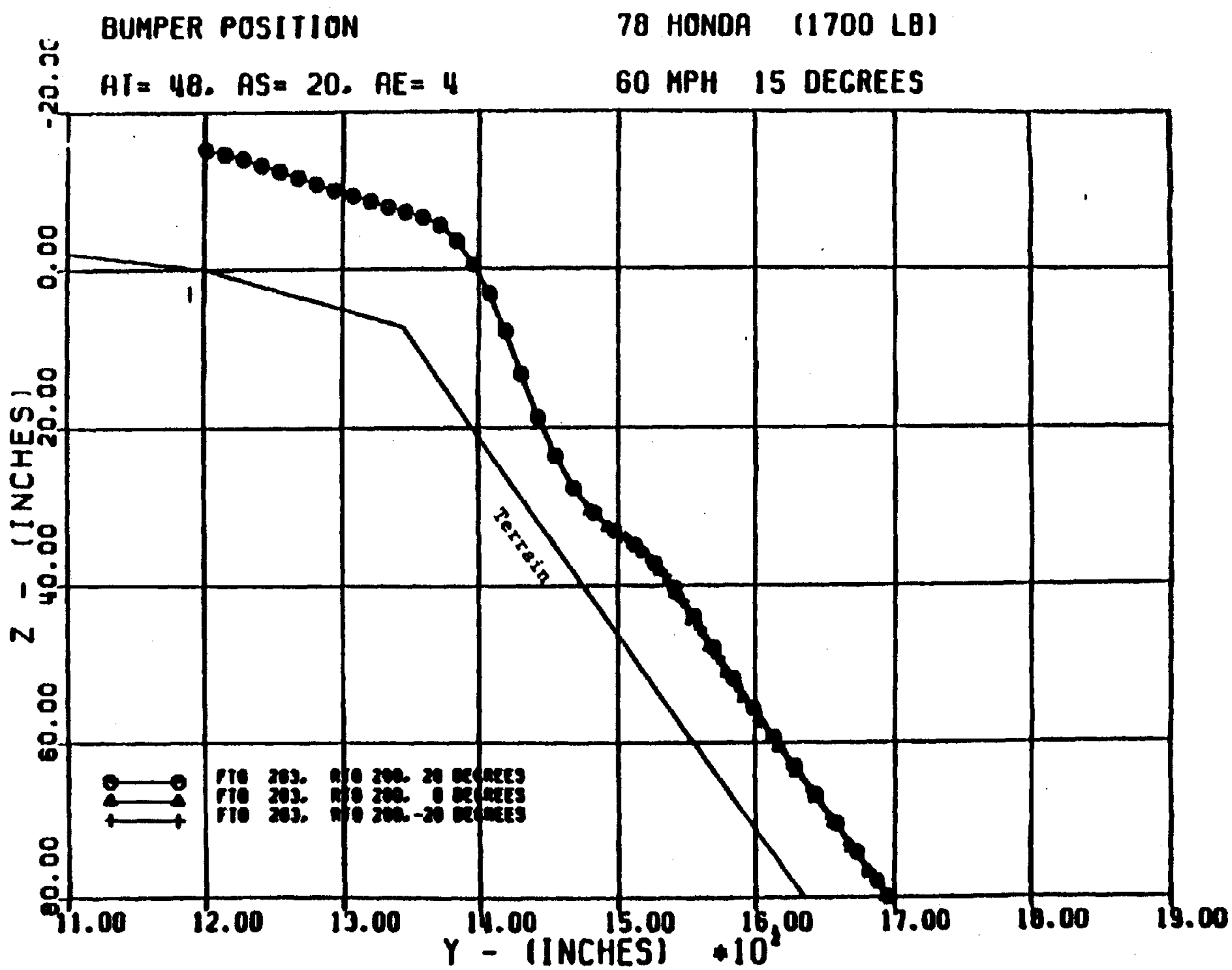
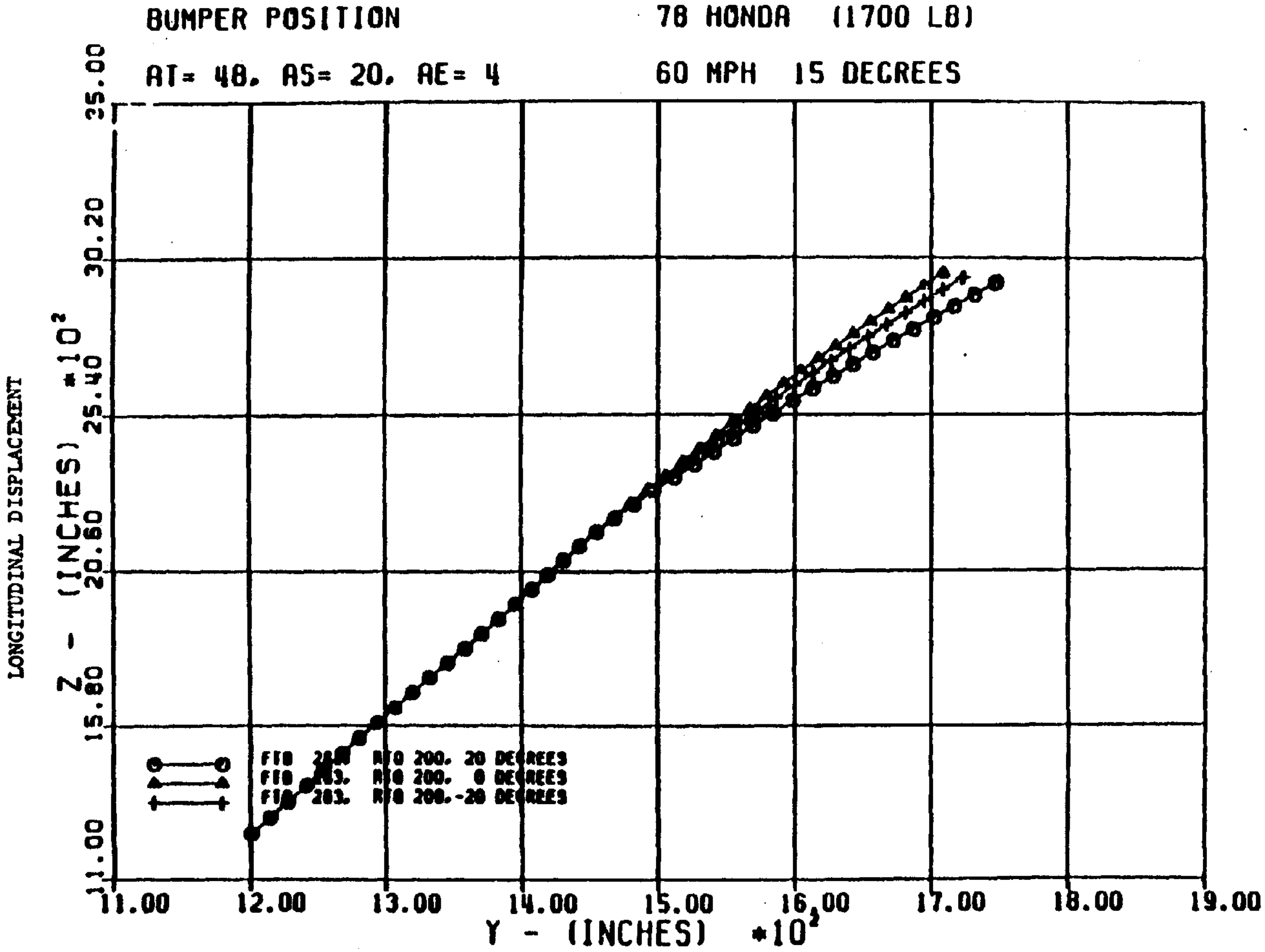


Figure 15. Steering/braking effects on 4:1 embankment slope.



LONGITUDINAL DISPLACEMENT

LATERAL DISPLACEMENT

Figure 16. Lateral and longitudinal displacements.

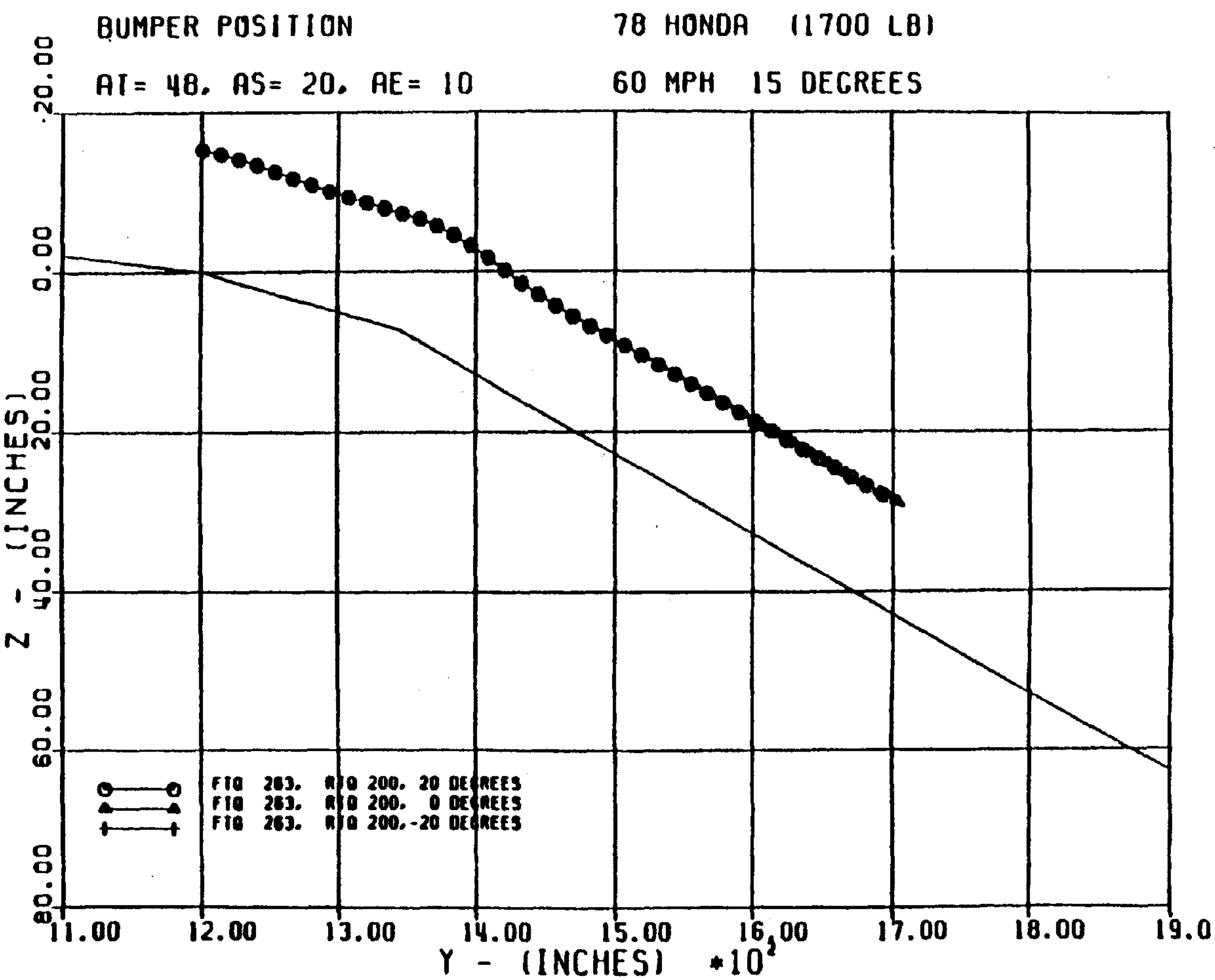


Figure 17. Steering/braking effects on 10:1 embankment slope.

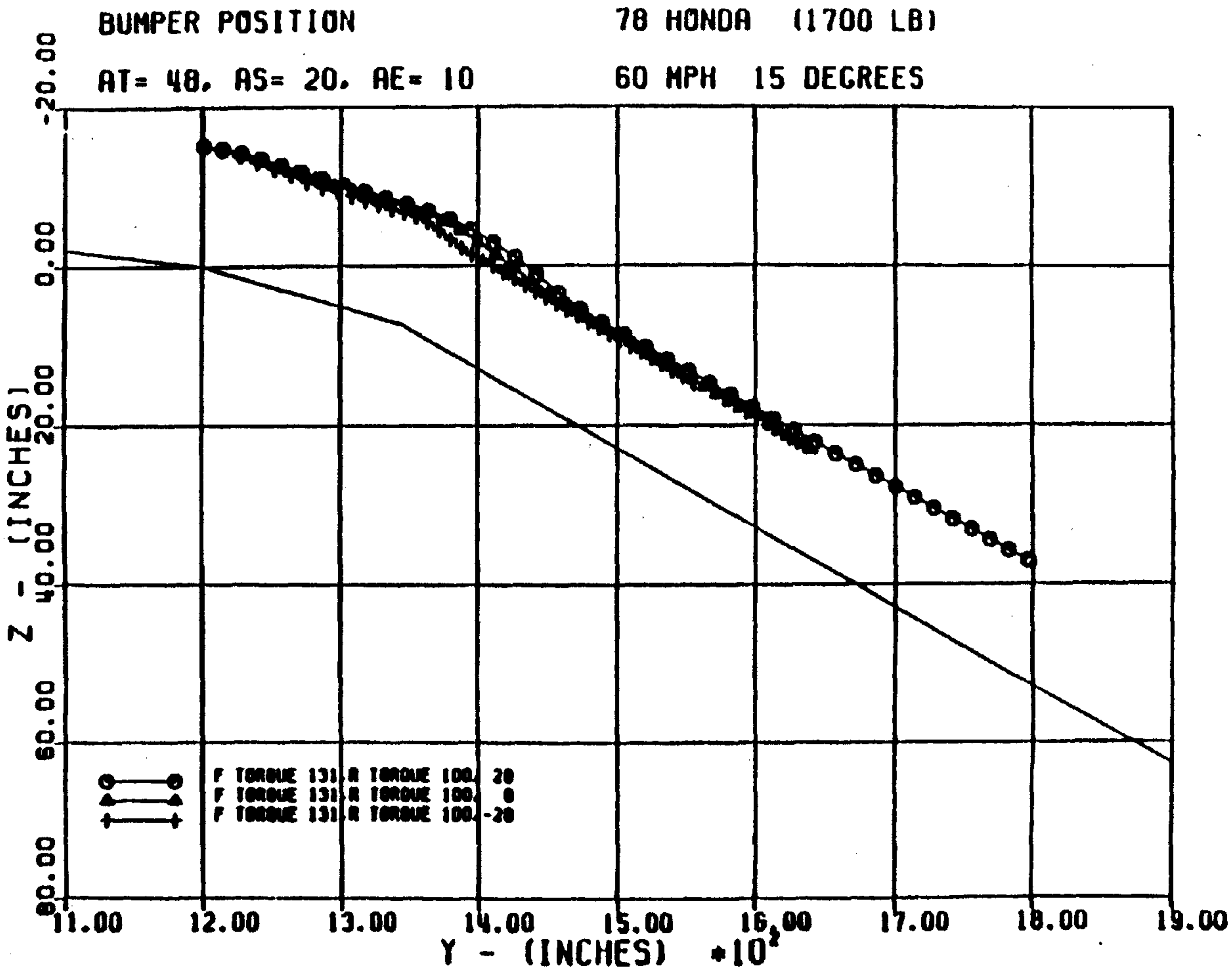


Figure 18. Steering/braking effects with coefficient of friction = 0.50.

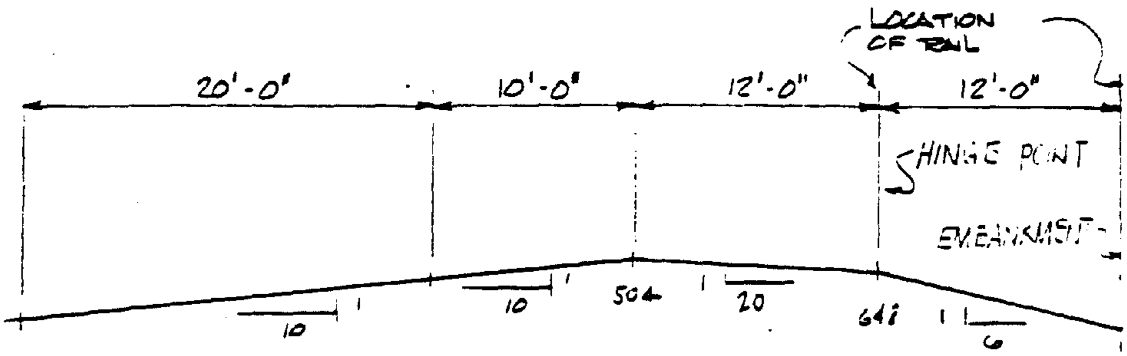
Based on these results, it was concluded that reasonable steering/braking variations had minimal effect on bumper heights.

E. Final Checks on and Disposition of HVOSM

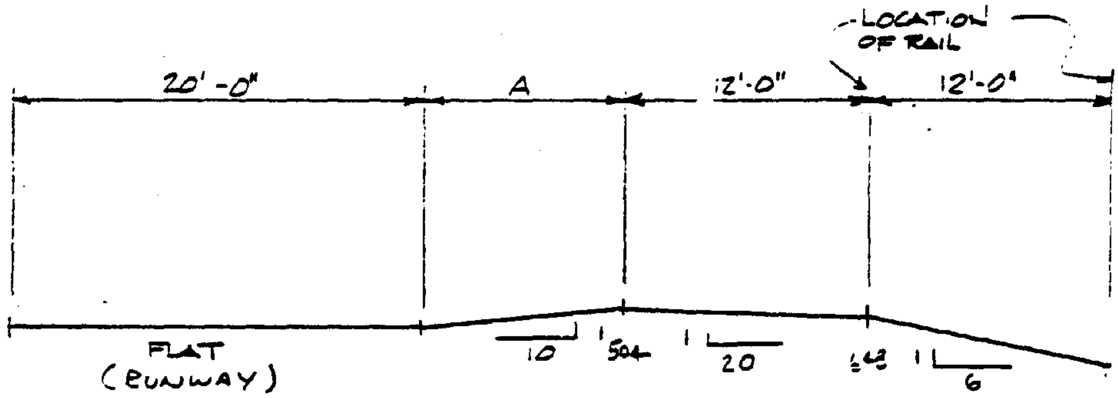
Tests BH-7 through BH-10 were conducted on barriers placed on side slopes (see chapter IV and appendix A). Prior to construction of the test installation, concern was expressed by FHWA regarding the effects of traversing the flat runway approach to the 10:1 superelevation. As shown in figure 19(b), the width A had originally been proposed to be 10 ft (3.0 m). In order to examine the difference between traversing the cross sections shown in figure 19, a series of HVOSM simulations were conducted. As shown in the summary of results in table 6, a width A of 10 ft (3.0 m) produced significantly different bumper heights at the barrier locations than the constant 10:1 slope of figure 19(a). A width of A of 15 ft (4.6 m) produced bumper heights that were essentially the same as the constant slope. Thus, based on these simulations, the test geometry was revised to A = 15 ft (4.6 m).

To provide guidance in establishing test railing heights for vehicle underride/override, the HVOSM program was exercised. The underride height (grade to lower point of rail) on the test vehicle for Test BH-6 had been measured at 20 in (51 cm). Table 7 shows agreement with the test in that underride occurred at the 32-in (81-cm) overall barrier height. The simulation shows in the table that vehicle redirection would have occurred with a 30-in (76-cm) overall height.

For the sloping terrain Tests 7 through 10, a single underride/override height of 18 in (46 cm) was used, corresponding to the design vehicle. Table 7 shows a threshold height of 30 in (76 cm) for Test No. 7. A height of 30 in (76 cm) is indicated for Test No. 8, but the impact angle should be changed to the more critical 15°. A 22-in (56-cm) height should be used for Test No. 9. A 26-in (66-cm) height should be used for Test No. 10, but the impact angle should be changed to the more critical 25°.



(a) Proposed Sloping Terrain



(b) Test Geometry

Figure 19. HVOSM simulation geometry.

Table 6. Summary of HVOSM simulations - sloping terrain.*

Case	Figure 19 Geometry	A	Vehicle Bumper Height, in 504	648
1	(a)	--	0.80	-27.15
2	(b)	10	-3.23	-30.10
3	(b)	15	0.94	-27.13

* All simulations used 1800 lb car, 60 mph, 25-degree conditions.

Table 7. Critical underride/override barrier mounting heights as determined by simulation results.

Vehicle Angle	Impact Angle	Test Criteria	Barrier Ht 32"	30"	28"	26"	24"	22"	Remarks
1800	25°	Underride	S (T)	R					hinge point tests
1800	25°	Override	OT*	OT* (T)	R	**			
4500	25°	Override	R (T)	V					
1800	15°	Underride	S	S (T)	R	R			
4500	15°	Underride	S	S (T)	R				
1800	25°	Override	S	S	S	S (T)	R (T)	V/OT	embankment tests
4500	25°	Override	S	S	S	S (T)	R (T)	V/OT	
1800	15°	Underride	S	S	S (T)	R			
4500	15°	Underride	S	S (T)	R				

S - snagging and/or underriding
R - redirecting
V - vaulting
OT - overturning
* - overturn was toward the road
** - unpredictable results because of HVOSM program limitations
(T) - Threshold mounting height is between the 2 height values shown

On completion of the test facility and conduct of the first of the slope tests (Test BH-7), simulation runs were made with the modified HVOSM program to compare predictions with measured test results. The comparisons of three of these runs are shown in table 8. As shown in the table, the largest discrepancy occurred in the bumper heights at impact. Several other runs were made with various input changes, but significant improvement in correlation was not achieved.

Because of the criticality of bumper heights in the important end result that was expected from the study (see chapter V), it was considered essential that satisfactory correlation between test and simulation be achieved. Thus, an extended effort was made to check the adjustments of additional HVOSM input parameters.

As a first step, the actual terrain of the test installation was surveyed for input into the existing HVOSM model. Various driver input steer angles and times of duration were then entered into the system to simulate the vehicle trajectory after breakaway from the guide cable. Table 9 shows the comparisons of test results and the various simulation predications. As shown in the table, no significant improvement in bumper height correlation was achieved. Because of the criticality of bumper heights, it was decided to add a large car underride test [4500 lb (2000 kg)/60 mph (95 km/h)/15°) for the next test BH-8.

Efforts continued to obtain satisfactory correlation of vehicle bumper heights. As shown in table 10, computer simulation 1 and the results of Test BH-8 compared very favorably. For a 19-degree departure angle, the HVOSM simulation predicted no underride, as confirmed by the test. Simulation 2 with the standard 15-degree impact did not predict underride.

The difference in bumper height between the two simulations of table 10 is substantial, indicating that the impact angle was a critical variable in these tests. In previous tests, vehicles had been released from the guidance cable at the edge of the concrete approach apron at the

Table 8. Comparison of HVOSM predictions with Test BH-7 results.

Item	Bumper Underride Height at Impact (in)	Impact Speed (mph)	Impact Angle (degrees)	Remarks
Test BH-7 Results	22.1	58.3	15.6	Values measured at impact with barrier. Speed trap speed at edge of apron = 58.8 mph
Simulation 1	19.46	58.3	16.77	Run with initial speed = 58.8 mph and initial angle = 18 degrees
Simulation 2	18.35	57.9	16.02	Same as Simulation 1 except for initial angle = 17 degrees
Simulation 3	18.63	58.2	15.66	Same as Simulation 1 except for increase in base material coefficient of friction and softening of vehicle suspension

NOTE: All simulations predicted underride of bumper and vehicle redirection.

Table 9. Comparison of HVOSM predictions with Test BH-7 results for steer angle input.

Item	Bumper Ht @ Impact (inches)	x Location @ Impact (inches)	Impact Angle (degrees)	Input Steer Angles (degrees)	Time of Steer Angles (sec)	Remarks
BH-7 Test Results	22.1	1758	15.6	--	--	
Simulation 1	19.07	1617	15.35	--	--	Run with actual surveyed terrain
Simulation 2	19.54	1800	12.0	-1	.001 to .008	Steering angle input to simulate vehicle break-away from steer cable.
Simulation 3	19.54	1680	15.75	-1	.001 to .002	"
Simulation 4	19.68	1710	15.2	-1	.001 to .003	"
Simulation 5	19.62	1690	15.54	-2	.001	"
Simulation 6	19.58	1709	15.21	-1 -.5	.001 - .002 .003 - .004	" "
Simulation 7	19.78	1736	14.92	-3	.001	"

NOTE: Simulations 2 through 7 did not predict underride. These simulations were also run with the surveyed terrain.

Table 10. Computer simulation/Test BH-8 comparison.

Test/Simulation	Test BH-8	Simulation 1	Simulation 2
Initial Speed	60 mph	60 mph	60 mph
Initial Angle	18° (estimated)	19°	15°
Impact Speed	59.5 mph	58.83 mph	59.55 mph
Impact Angle	19.5°	19.5°	15.6°
Impact Bumper Ht	28.5"	28.4"	23.5"
Remarks	Vehicle redirected	Predicted vehicle redirection	Predicted underride/ snag

test site. After disengagement, the vehicle moved up the 15-ft (4.6-m), 10:1 slope and then down the 12-ft (3.7-m), 20:1 slope to the barrier. On assuming that the vehicle would drift to the left, an angle of 18° had been laid out on the apron. In Test BH-7, the 1800-lb (800-kg) car did move to the left and impacted the barrier at 15.6°. However, the 4500-lb (2000-kg) car of Test BH-8 moved to the right for an impact angle of 19.5°. A repeat of this test (BH-9) with a 15-degree approach revealed a drift to the left with an impact angle that was too low. Because these differences in impact angle were so significant in vehicle response, problems involved not only the HVOSM correlations but also those associated with the test guidance system.

The last two slope tests (BH-9 and BH-10) were finally simulated using the modified HVOSM program. Table 11 summarizes the results. Although underride was not predicted by either simulation, which agreed with test results, the height of the bumper at impact was considerably lower in the simulations than observed in the tests.

It became evident both from the sloping terrain simulations and test results that the bumper height at impact was very sensitive. Despite the extensive efforts to achieve satisfactory bumper height correlation between the HVOSM predictions and test results, the recalcitrant problem persisted. The difficulty was in controlling the experiments accurately enough to identify threshold conditions on sloping terrain. The trajectories of vehicles crossing sloping terrain at various speeds and angles vary considerably; and in all cases, satisfactory performance was obtained in the experiments due to (in part) the variance from the desired impact conditions. Thus, it was decided to terminate work on the analytical study and to determine critical underride/override railing heights by full-scale tests. Because of the relative costs of simulations and tests, the scope of work necessarily had to be reduced. However, the problem of satisfactory correlation was apparently unresolvable.

Table 11. Comparison of test and simulation for Tests BH-9 and BH-10.

	Test BH-9	Simulation	Test BH-10	Simulation	Simulation
Initial Speed, fps		86.3		85.7	88.0
Initial Angle, deg*	15.0	14.5	15	15.0	15.0
Impact Speed, fps	85.7	85.6	85.1	85.1	87.4
Impact Angle, deg	12.5	12.6	13.6	13.6	15.6
Bumper Height, in	24.0	21.1	25.5	21.4	23.5
Underride predicted		no		no	yes

* Estimated for test, actual for simulation.

IV. SUMMARY OF FULL-SCALE CRASH TESTS

A. General

Sixteen full-scale crash tests were conducted in the project using primarily 4500-lb (2000-kg) and 1800-lb (800-kg) sedans. One low front profile car was used to examine barrier mounting height problems with this vehicle type.

The selected barrier systems were installed and evaluated by full-scale crash test according to the procedures of NCHRP Report 230. Data were recorded by high-speed cameras and electronic transducers. Drawings of the barriers evaluated in this project are shown in volume 2. Detailed descriptions of the tests are given in volume 2.

The purpose of these tests was to establish threshold mounting heights at 60 mph (95 km/h) for a range of three angles (7, 15, 25). The 15-degree impact angle was chosen as being consistent with NCHRP Report 230 that states on page 23:

> "It is stressed that test conditions given in Tables 3 and 4 are not all-inclusive. There are other conditions that may need to be examined due to the peculiarity of the test article or unique feature of the potential installation site" ...e.g., sloping terrain."

The crash tests are briefly described in the following sections; the tests are summarized in tables 12 through 14. In these tables, an assessment is made regarding compliance with the recommended evaluation criteria of NCHRP Report 230, table 7.

B. Critical Mounting Height Tests, Series 1

Six tests were conducted on G4(1S) guardrails installed at various heights on level terrain. The tests are summarized in table 12 and described briefly in the following paragraphs.

Table 12. Summary of critical barrier height tests, series 1.

Test No.	BH-1	BH-2	BH-3	BH-4	BH-5	BH-6
Barrier Height, in	30*	22*	32*	30*	22**	32*
Test Vehicle	1978 Dodge	1978 Dodge	1978 Dodge	1978 Dodge	1978 Dodge	1979 Dodge
Gross Vehicle Weight, lb	4735	4633	4675	4699	4762	2000
Impact Speed (film), mph	61.1	59.7	59.6	60.3	61.2	61.4
Impact Angle, deg	25.9	26.8	25.0	24.4	26.5	25.0
Impact Duration, sec	.58	.40	Rail Pocketed	.54	.45	Not Avail
Maximum Deflection, in						
Dynamic	35.2	Not Avail	Rail Fractured	27.6	Not Avail	3.5
Permanent	24.3	14.0	Rail Fractured	25.0	11.8	1.8
Exit Angle, deg						
Film	-12	Vehicle Vaulted	Did Not Exit	>-20	15.1	Did Not Exit
Yaw Rate Transducer	Not Avail	Vehicle Vaulted	Did Not Exit	>-20	12.7	Did Not Exit
Exit Speed, mph						
Film	36.5	Vehicle Vaulted	Did Not Exit	Not Avail	50.0	Did Not Exit
Accelerometer	Not Avail	Vehicle Vaulted	Did Not Exit	Not Avail	55.0	Did Not Exit
Maximum 50 ms Avg Accel (film/accelerometer)						
Longitudinal	-4.2/Not Avail	-3.5/-6.1	-6.3/-6.3	-2.7/-2.9	-3.2/-2.7	Not Avail/-6.7
Lateral	-5.7/Not Avail	-2.8/-3.6	-3.2/-6.3	-6.6/-7.9	-2.4/4.2	Not Avail/4.6
Occupant Risk, NCHRP _Report 230_ (film/accelerometer)						
ΔV long., fps (30)	20.0/Not Avail	14.3/17.1	23.6/Not Avail	Not Avail	13.4/8.6	Not Avail/23.1
ΔV lat, fps (20)	12.3/Not Avail	11.7/8.8	13.5/Not Avail	18.3/18.5	11.4/3.1	Not Avail/-14.8
Ridedown Acceleration, g's (accelerometer)						
Longitudinal (15)	-2.8 (film)	-0.5 (film)	-5.8 (film)	Not Avail	-2.8	-9.6
Lateral (15)	-5.7 (film)	-0.9 (film)	-3.0 (film)	-13.1	-31.6	5.7
NCHRP _Report 230_ Evaluation						
Structural Adequacy (A,D)	Passed	Failed	Failed	Passed	Failed	Failed
Occupant Risk (E)	Passed	Passed	Passed	Passed	Passed	Passed
Vehicle Trajectory (H,I)+	<15°	Failed	Failed	>15°	Failed	Passed
++	>15°			<15°		

* Beam attached to post using rectangular washer.
** No rectangular washer.
\+ 60% Exit Angle 15°
\++ ΔV = 15 mph

Table 13. Summary of sloping terrain tests.

Test No.	BH-7	BH-8	BH-9	BH-10
Barrier Height, in	32*	32*	32*	32*
Test Vehicle	1979 Honda	1978 Plymouth	1978 Plymouth	1978 Plymouth
Gross Vehicle Weight, lb	1950	4660	4650	4640
Impact Speed (film), mph	58.3	59.5	58.4	58.0
Impact Angle, deg	15.6	19.5	12.5	13.6
Impact Duration, sec	.17	.46	.35	.38
Maximum Deflection, in				
Dynamic	Not Avail	27.7	23.3	25.3
Permanent	3.3	18.3	9.3	16.0
Exit Angle, deg				
Film	-0.3	-6.2	-3.4	-5.7
Yaw Rate Transducer	-0.6	-3.2	-2.1	-6.3
Exit Speed, mph				
Film	52.1	46.8	52.0	50.9
Accelerometer	49.3	41.9	49.8	50.2
Maximum 50 ms Avg Accel (film/accelerometer)				
Longitudinal	-3.7/-1.6	-2.0/-3.3	-1.1/-2.7	-2.8/-1.6
Lateral	-6.0/-8.6	4.2/4.7	3.2/2.4	3.8/3.9
Occupant Risk, NCHRP Report 230 (film/accelerometer)				
ΔV long., fps (30)	3.6/12.9	10.2/16.6	10.3/10.2	1.4/8.6
ΔV lat, fps (20)	18.4/19.7	-14.4/-13.0	-13.6/-11.5	-13.5/-14.1
Ridedown Acceleration, g's (accelerometer)				
Longitudinal (15)	0.4	-4.9	-0.9	**
Lateral (15)	-12.0	6.9	-1.7	4.8
NCHRP Report 230 Evaluation				
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed
Occupant Risk (E,F,G)	Passed	Passed	Passed	Passed
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed

* No rectangular washer.
** Occupant did not travel required distance.

Table 14. Summary of critical barrier height tests, series 2.

Test No.	BH-11	BH-12	BH-13	BH-14	BH-15	BH-16
Barrier Height, in	33*	33*	33*	18*	22*	27 (GI system)
Test Vehicle	1978 Plymouth	1978 Plymouth	1978 Plymouth	1978 Dodge	1978 Dodge	1974 Datsun 260Z
Gross Vehicle Weight, lb	4715	4715	4650	4670	4670	2740
Impact Speed (film), mph	61.0	61.2	59.6	61.7	62.7	59.6
Impact Angle, deg	6.8	14.5	19.5	7.6	13.6	24.8
Impact Duration, sec	.38	.59	.62	.44	.39	.89
Maximum Deflection, in						
Dynamic	6.0	21.9	42.0	Not Avail	15.7	6.5 (ft)
Permanent	1.5	13.6	26.0	1.8	11.3	cables on ground
Exit Angle, deg						
Film	-1.9	-4.5	-0.2	-1.4	1.6	Not Avail
Yaw Rate Transducer	-2.1	Not Avail	Not Avail	Not Avail	2.0	Not Avail
Exit Speed, mph						
Film	56.9	48.1	30.0	57.9	51.8	Not Avail
Accelerometer	56.2	Not Avail	Not Avail	Not Avail	48.0	Not Avail
Maximum 50 ms Avg Accel (film/accelerometer)						
Longitudinal	-0.8/-1.7	-1.9/-3.8	-3.7/Not Avail	-2.0/-2.8	-2.9/-4.7	-2.3/-3.2
Lateral	2.5/2.9	3.5/4.3	3.4/Not Avail	2.4/2.0	4.7/5.1	-3.8/-6.6
Occupant Risk, NCHRP <u>Report 230</u> (film/accelerometer)						
ΔV long., fps (30)	7.1/7.2	13.5/13.9	19.4/Not Avail	3.1/16.0	14.0/16.5	12.9/11.3
ΔV lat, fps (20)	-12.3/-11.9	-14.2/-14.3	-14.0/Not Avail	-12.0/-8.2	-15.7/-14.8	14.1/15.9
Ridedown Acceleration, g's (accelerometer)						
Longitudinal (15)	**	-2.0	Not Avail	-2.2	-3.7	-5.1
Lateral (15)	2.2	8.5	Not Avail	-2.4	9.7	-7.9
NCHRP <u>Report 230</u> Evaluation						
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed	Passed	Passed
Occupant Risk (E,F,G)	Passed	Passed	Passed	Passed	Passed	Passed
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed	Passed	Passed

* No rectangular washer.
** Occupant did not travel required distance.

Test BH-1. The purpose of this test was to evaluate the G4(1S) guardrail (coupled) for underride with the W-beam mounted at 30 in (76 cm) above grade. The underride height for the test vehicle was 20 in (51 cm) as shown in figure 20. Impact conditions for the 4735-lb (2140-kg) gross weight vehicle were 61.1 mph (98.3 km/h) and 25.9°. The vehicle was redirected as shown in figure 21, although snagging occurred due to wheel contact with posts. The maximum dynamic deflection was 35.2 in (89.4 cm); vehicle and barrier damage are shown in figure 20.

Test BH-2. The purpose of this test was to evaluate the G4(1S) guardrail system for override with the top of the barrier at 22 in (56 cm) above grade as shown in figure 22. The critical override height for the test vehicle was 20 in (51 cm). Impact conditions for the 4633-lb (2101-kg) vehicle were 59.7 mph (96.0 km/h) and a 26.8-degree angle. As shown in figure 23, the test vehicle bumper immediately rode up over the W-beam, causing the vehicle to ramp. The vehicle remained in contact with the rail for 17.5 ft (5.3 m) before vaulting over the system. Damage to the barrier and vehicle are shown in figure 22.

Test BH-3. The purpose of this test was to evaluate G4(1S) system mounted at 32-in (31-cm) for underride as shown in figure 24. Test conditions included a 4675-lb (2120-kg) vehicle with a 20-in (51-cm) underride height impacting at 59.6 mph (95.9 km/h) and angle of 25.0°. As shown in figure 25, the test vehicle bumper immediately rode under the rail and snagged on the next downstream post. The left front tire/wheel assembly also snagged on this post, causing the post to detach from the beam. The next three posts also detached from the W-beam and pulled from the ground during impact. The vehicle continued without redirection until pocketing occurred at the fourth post contacted, causing the beam to separate at the next downstream post location. The beam had deflected 3.3 ft (1.0 m) before separation occurred. The downstream section of the separated rail impaled the vehicle in the grille area and into the engine compartment; no passenger compartment intrusion was noted. The vehicle stopped at the

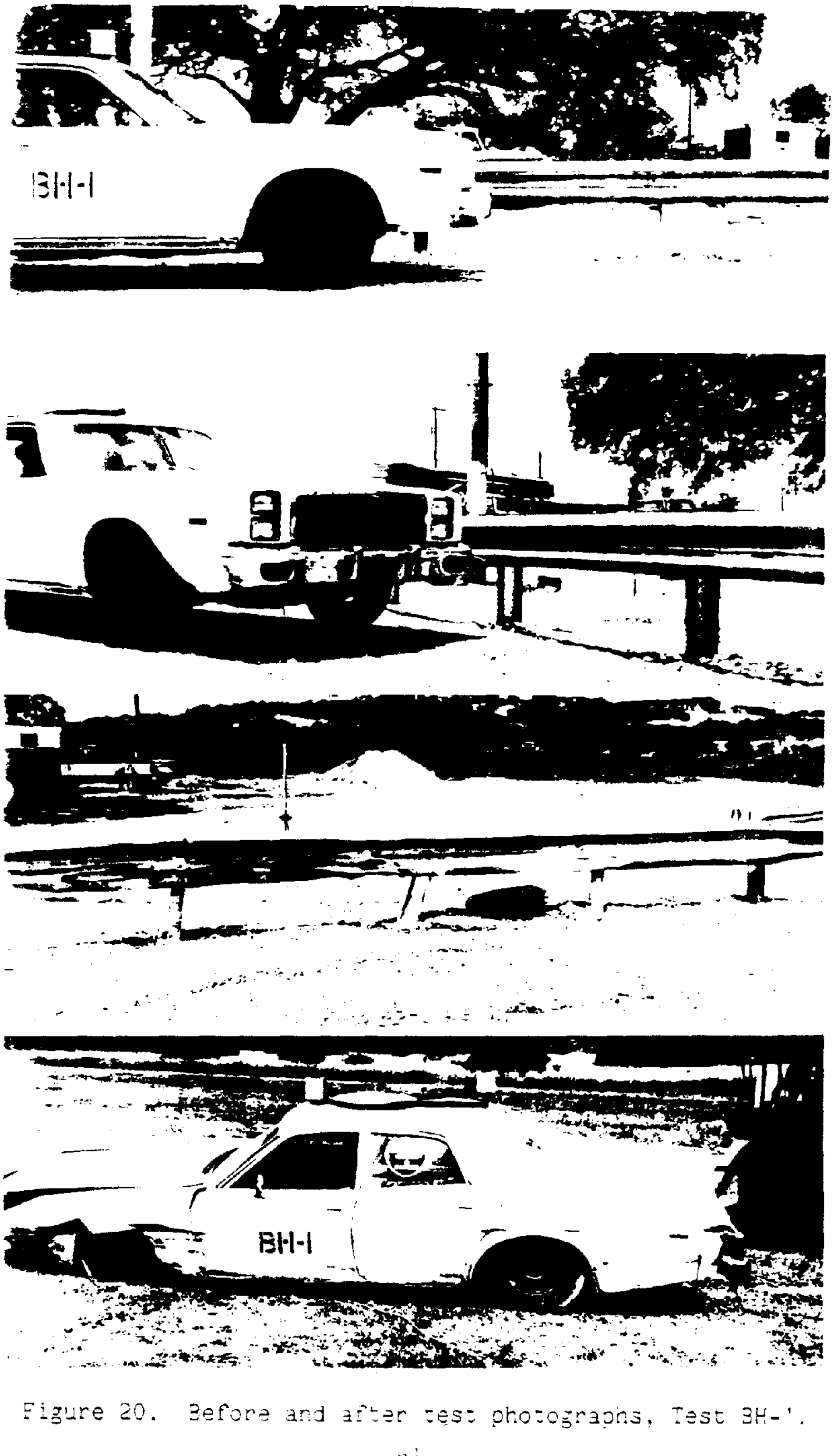


Figure 20. Before and after test photographs, Test BH-1.

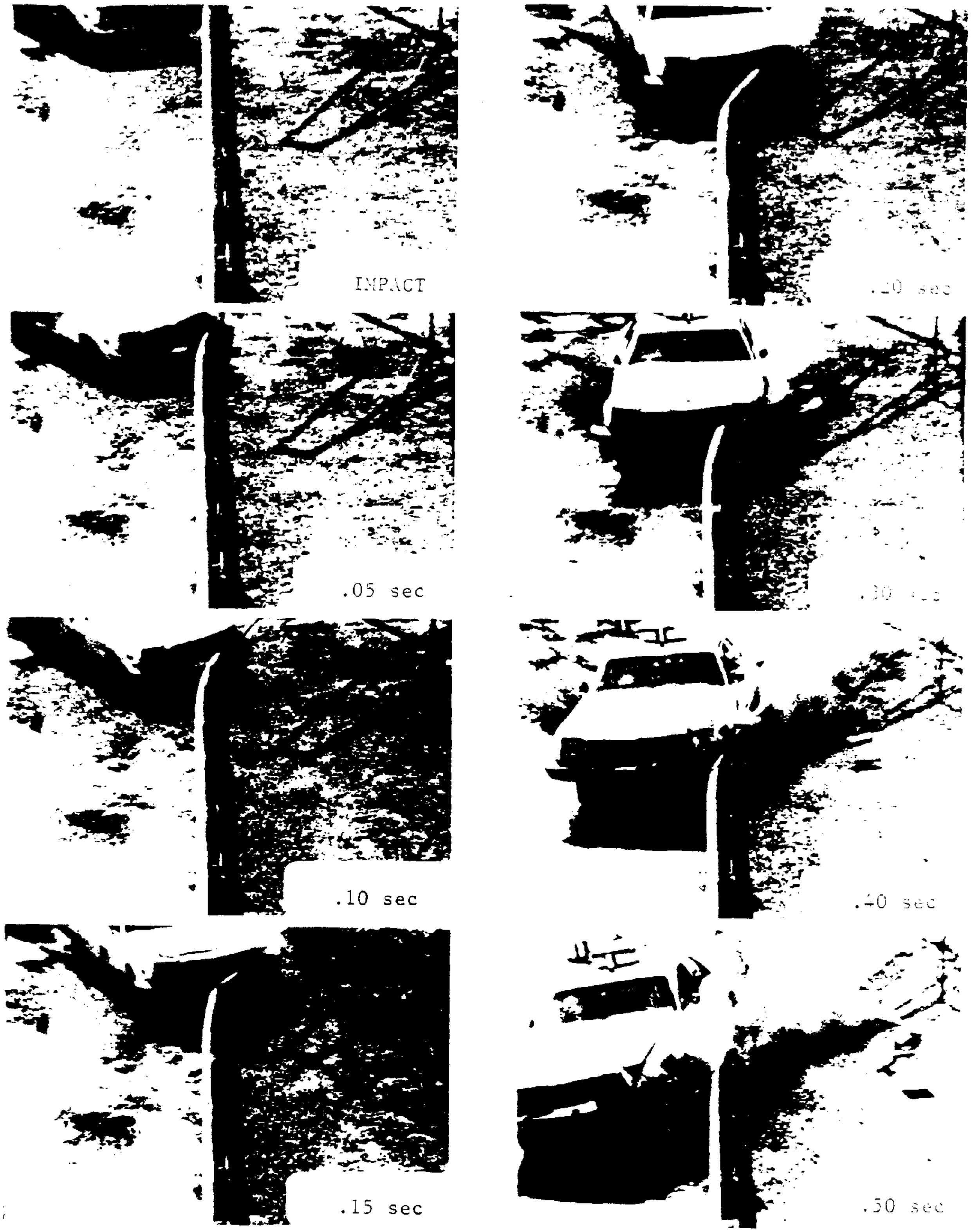


Figure 21. Sequential photographs, Test BH-1.

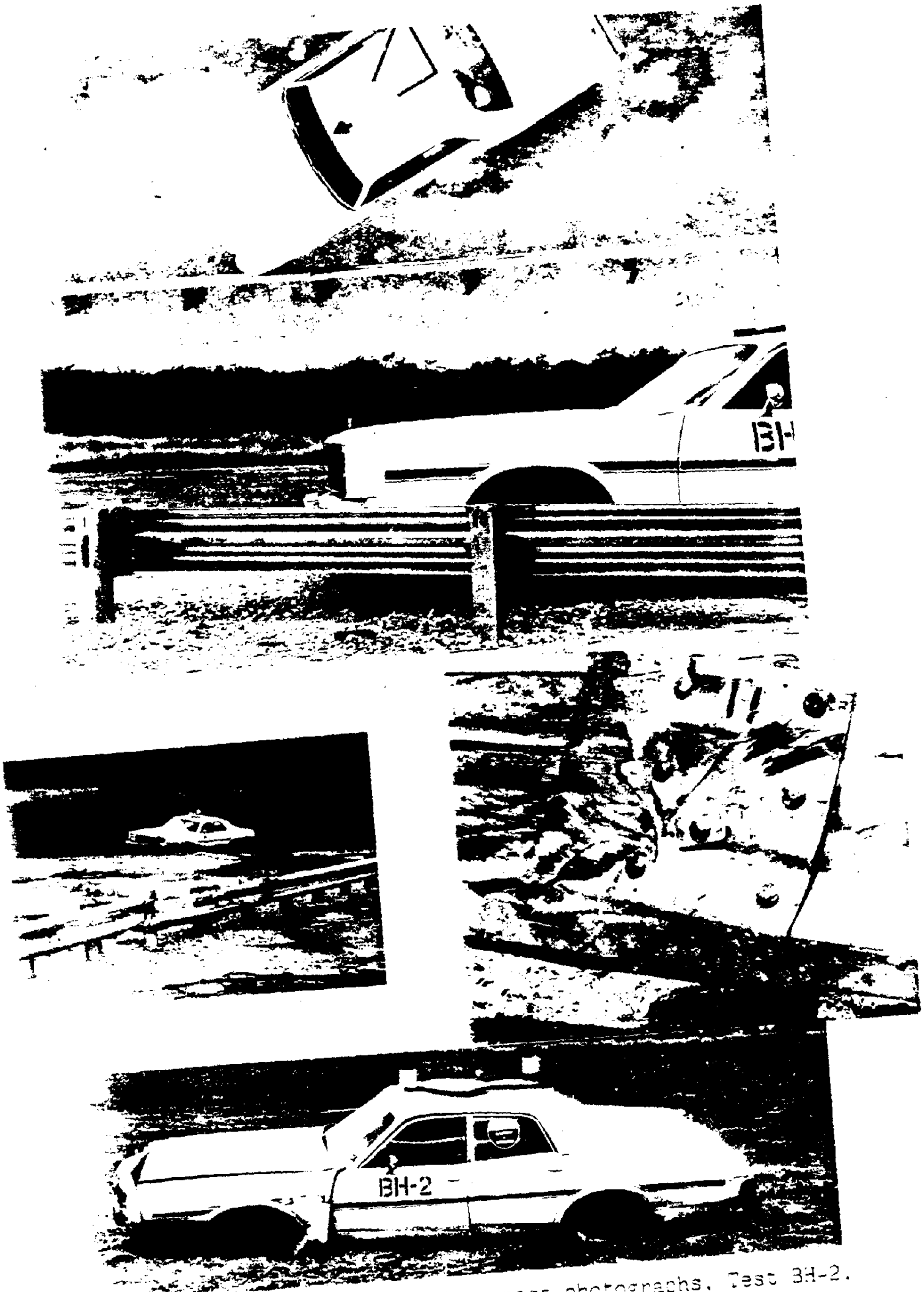


Figure 22. Before and after test photographs. Test BH-2.

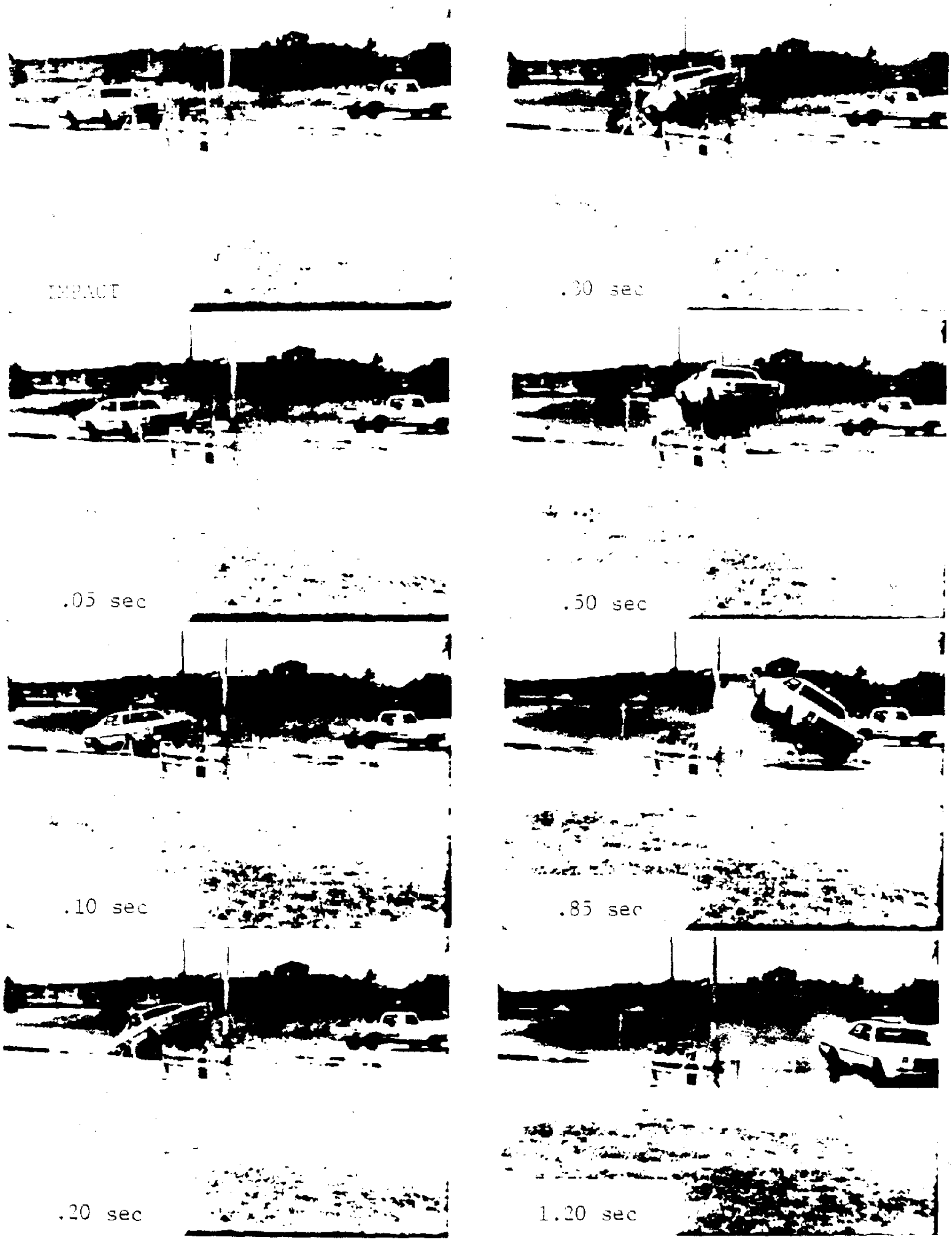


Figure 23. Sequential photographs, Tests BH-2.

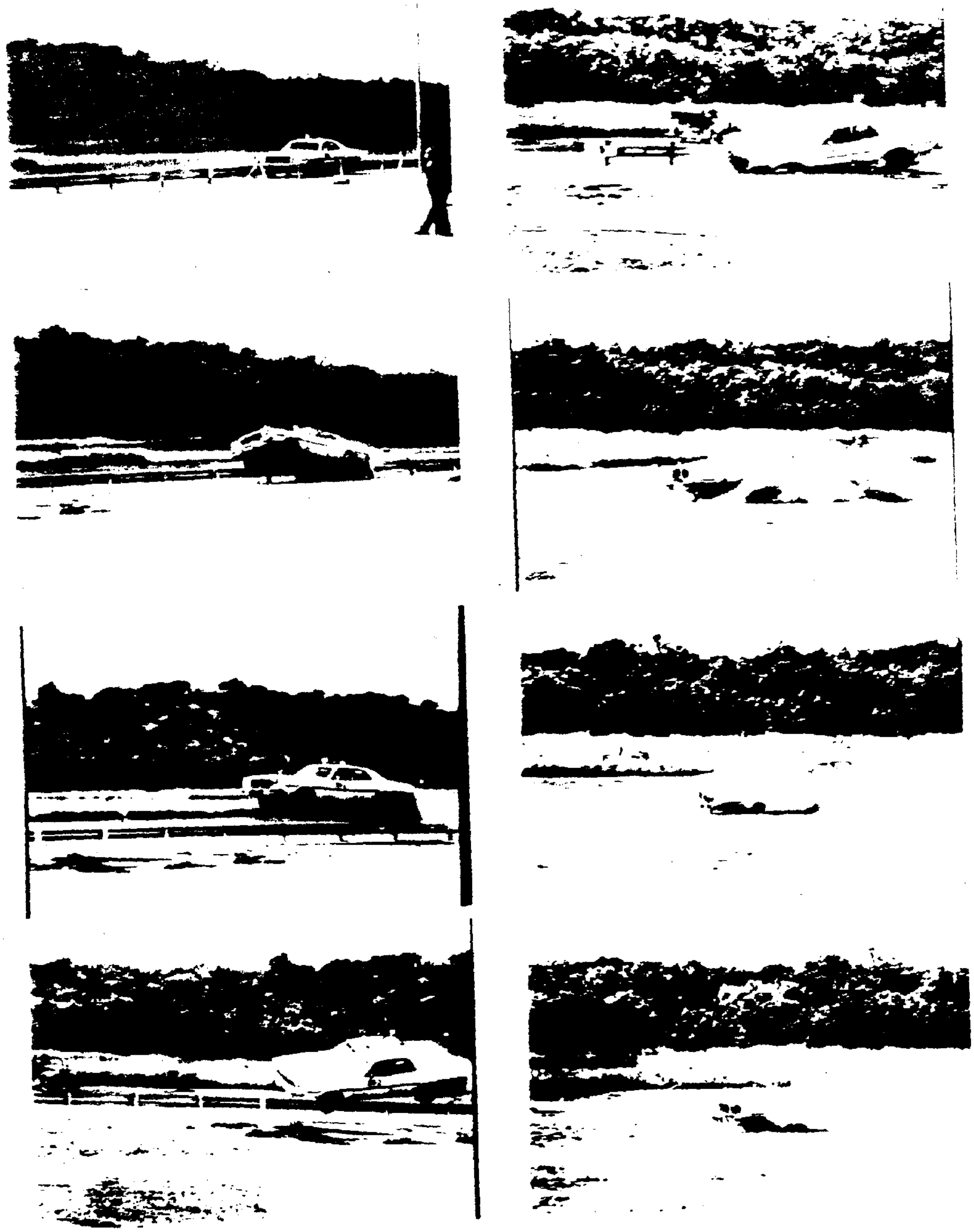


Figure 23. Sequential photographs, Test BH-2 (continued).

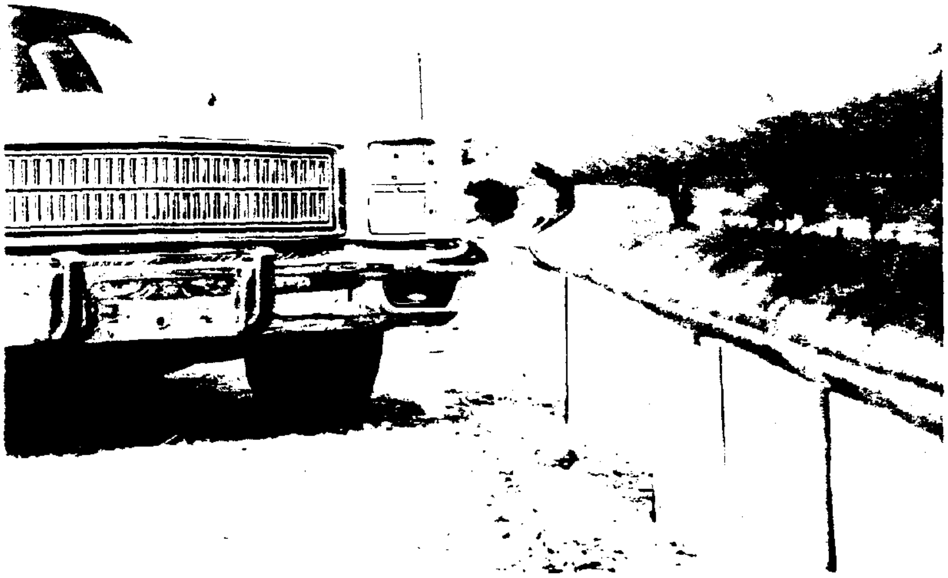


Figure 24. Before and after test photographs, Test BH-3.

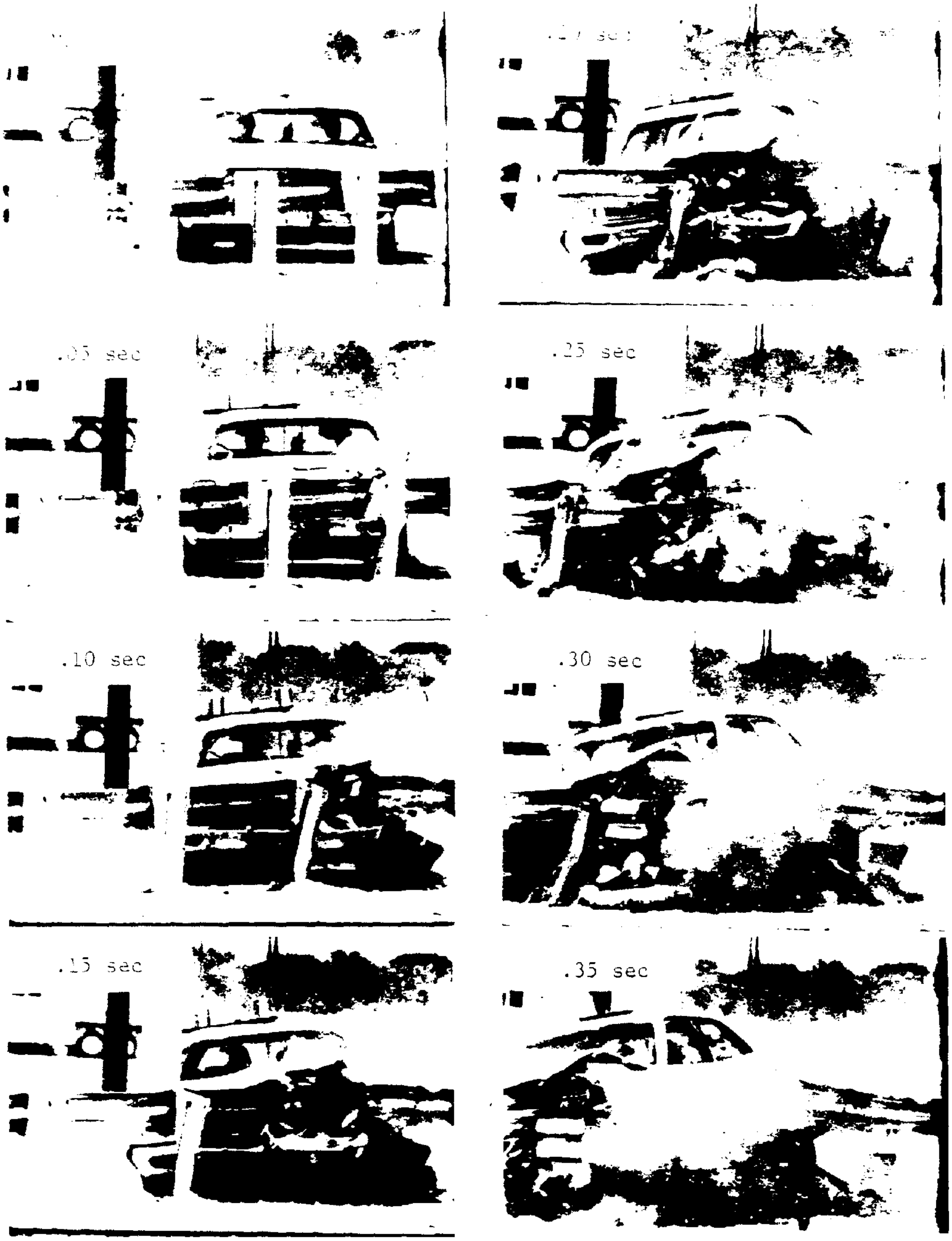


Figure 25. Sequential photographs, Test BH-3.

sixth post contacted. Damage to the vehicle and barrier is shown in figure 24.

Test BH-4. The purpose of this test was to evaluate the G4(1S) guardrail system for underride with the beam mounted at 30 in (76 cm) high as shown in figure 26. Test conditions included a 4699-lb (2131-kg) vehicle with a 20-in (51-cm) underride height impacting at 60.3 mph (97.1 km/h) and angle of 24.4°. As shown in figure 27, the vehicle remained in contact with the barrier for 25 ft (7.6 m) before redirection at a 17.3-degree angle. No significant snagging of the rail or line posts was noted. Damage after the test is shown in figure 26.

Test BH-5. The purpose of this test was to evaluate the G4(1S) guardrail system for override with the beam mounted at 22 in (56 cm) above grade as shown in figure 28. Unlike Test BH-2 which included the use of rectangular washers under the beam/post attachment bolt head, this system used no washers and was considered "uncoupled." Test conditions included a 4762-lb (2160-kg) vehicle with a 20 in (51 cm) override dimension impacting at 61.2 mph (98.5 km/h) and at a 26.5-degree angle. As shown in figure 29, the vehicle bumper immediately rode up over the W-beam which resulted in the vehicle ramping over the barrier after 18 ft (5.5 m) of contact. Photographs after the test are shown in figure 28.

Test BH-6. The purpose of this test was to determine if the 32-in (81.3-cm) high G4(1S) system was also a critical underride height for the 1800-lb (800-kg) car at 60 mph (95 km/h) and 25-degree angle. Since the 1800-lb (800-kg) test car had the same 20-in (51-cm) underride height as the 4500-lb (2000-kg) sedan used in previous tests, the test would determine if a higher height could be tolerated for the smaller car. Figure 30 contains photographs before the test. The 1835-lb (832-kg) vehicle impacted at 61.4 mph (98.8 km/h) and an angle of 25°. As shown in figure 31, the vehicle was redirected by the barrier until significant wheel snagging on the posts caused the vehicle to yaw and spin out from the barrier. Photographs after test are shown in figure 30.

Figure 26. Before and after test photographs, Test BH-4.

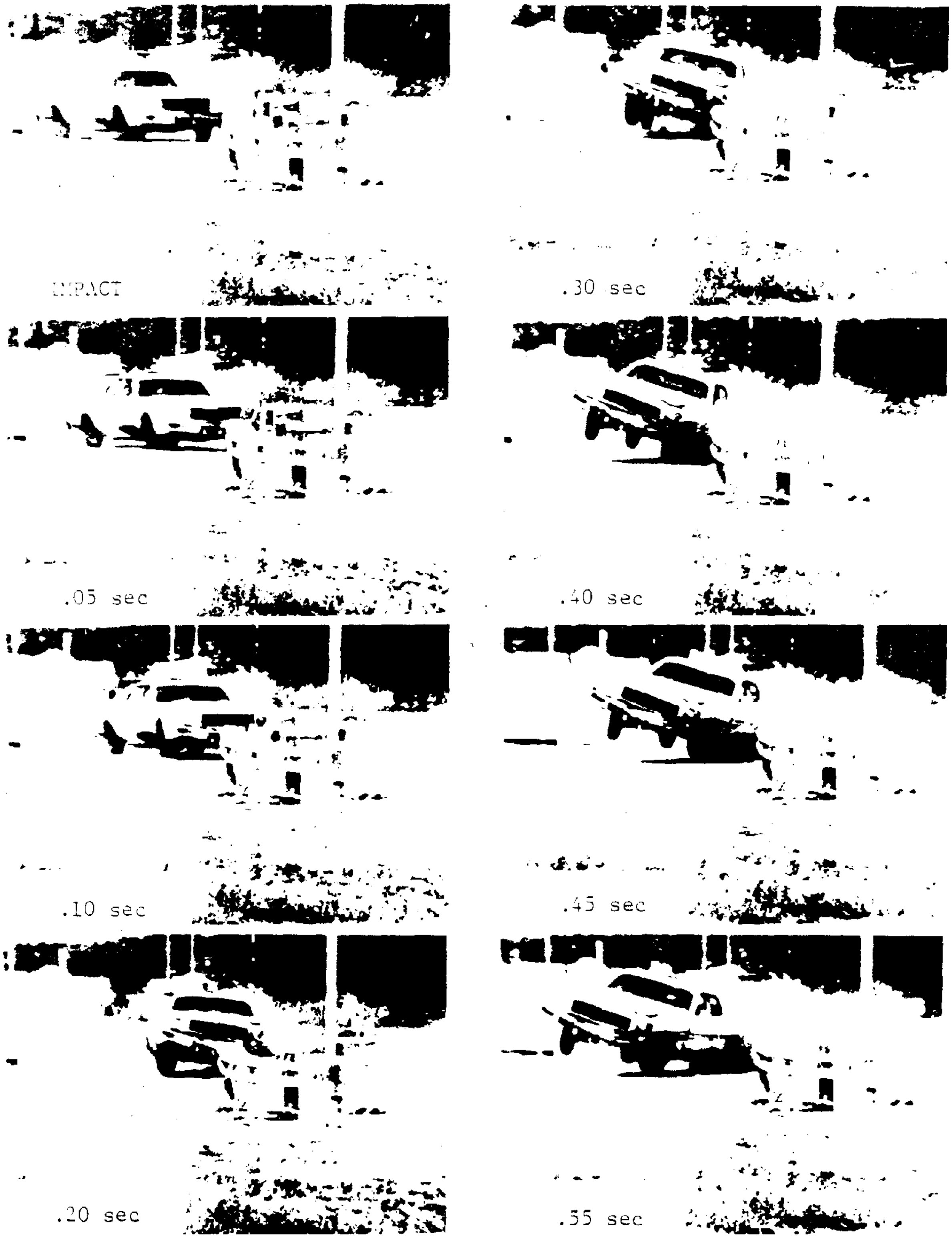


Figure 27. Sequential photographs, Test BH-4.

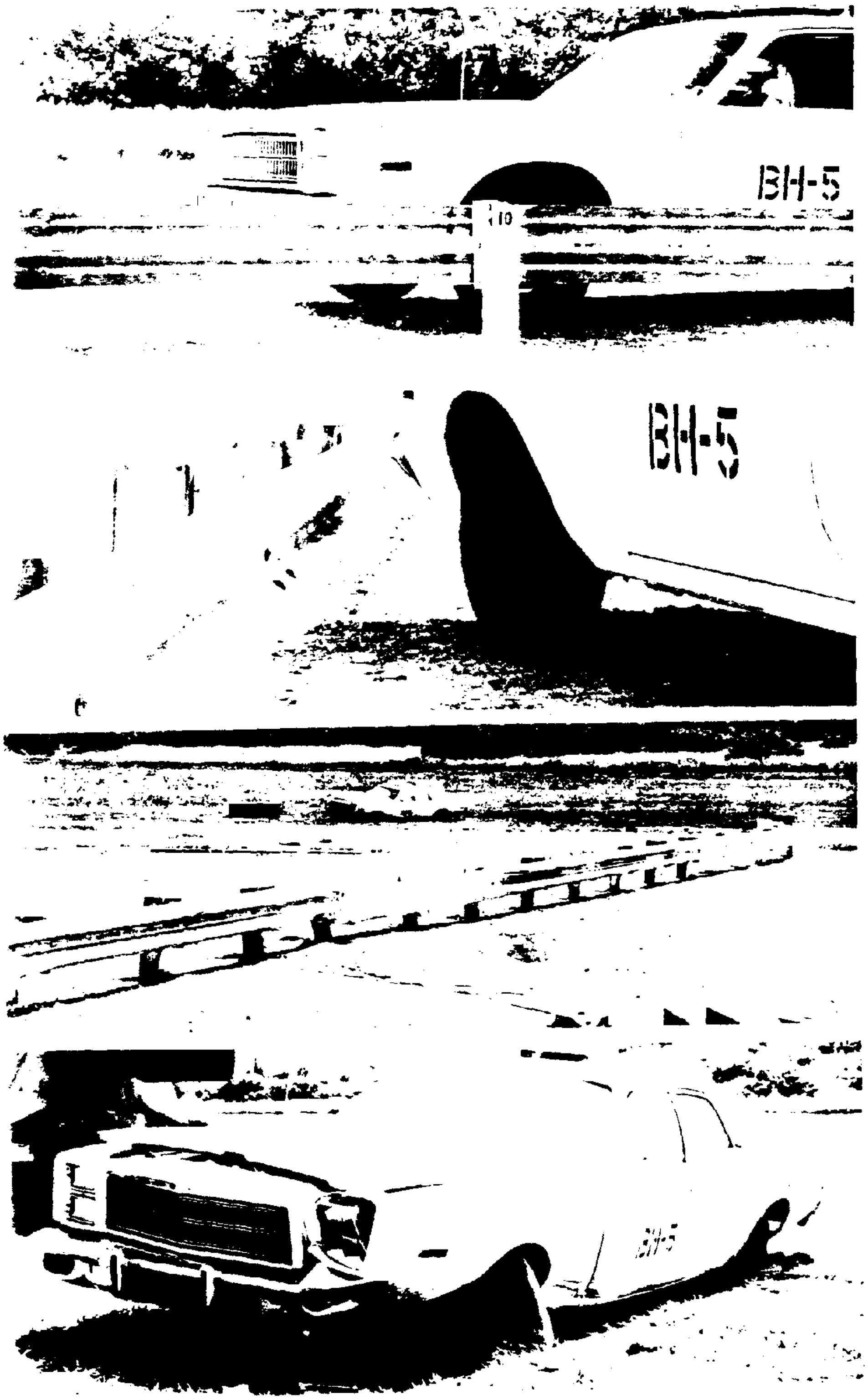


Figure 28. Before and after test photographs, Test BH-5.

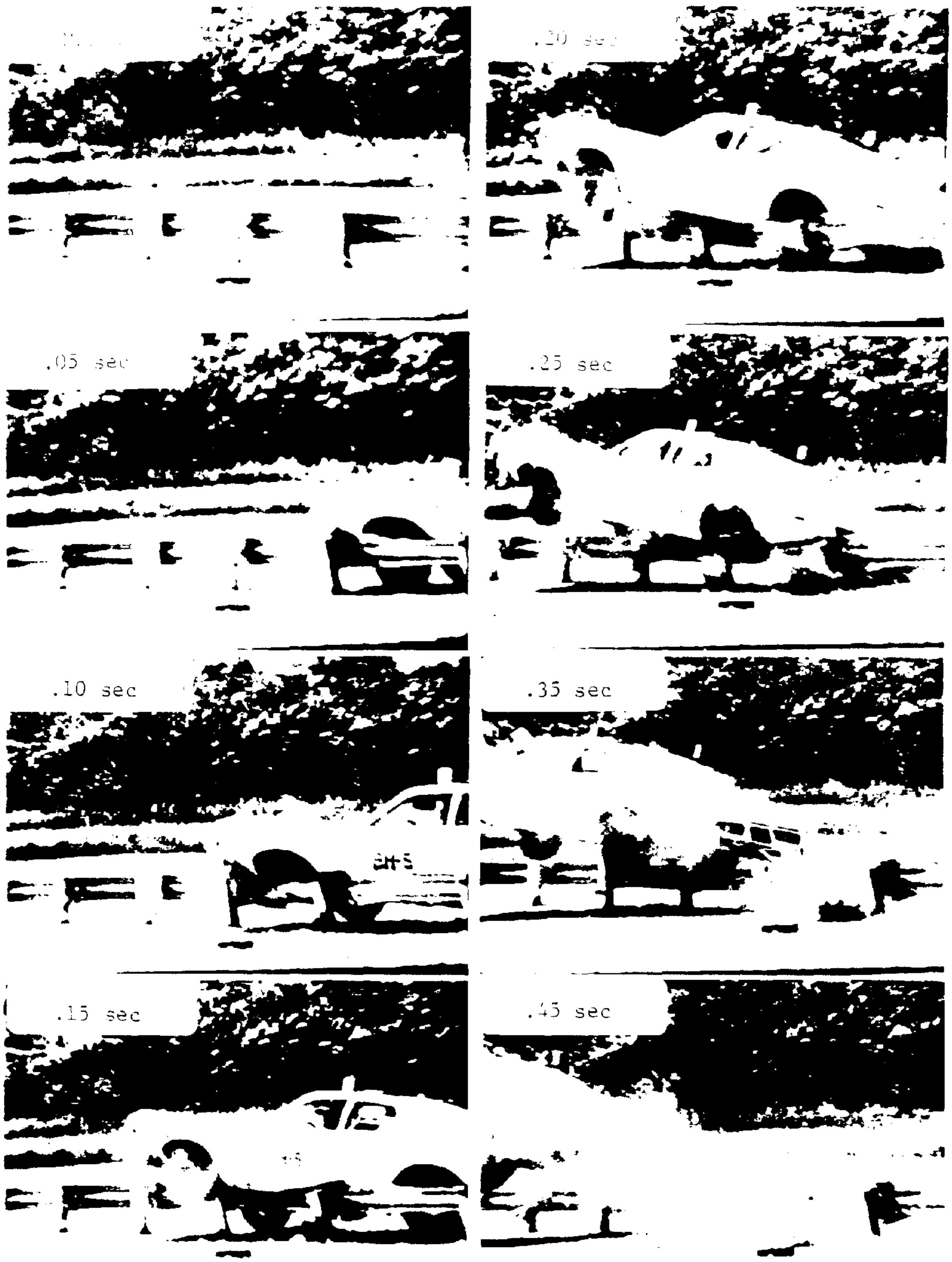


Figure 29. Sequential photographs, Test BH-5.

Figure 30. Before and after test photographs, Test BH-6.

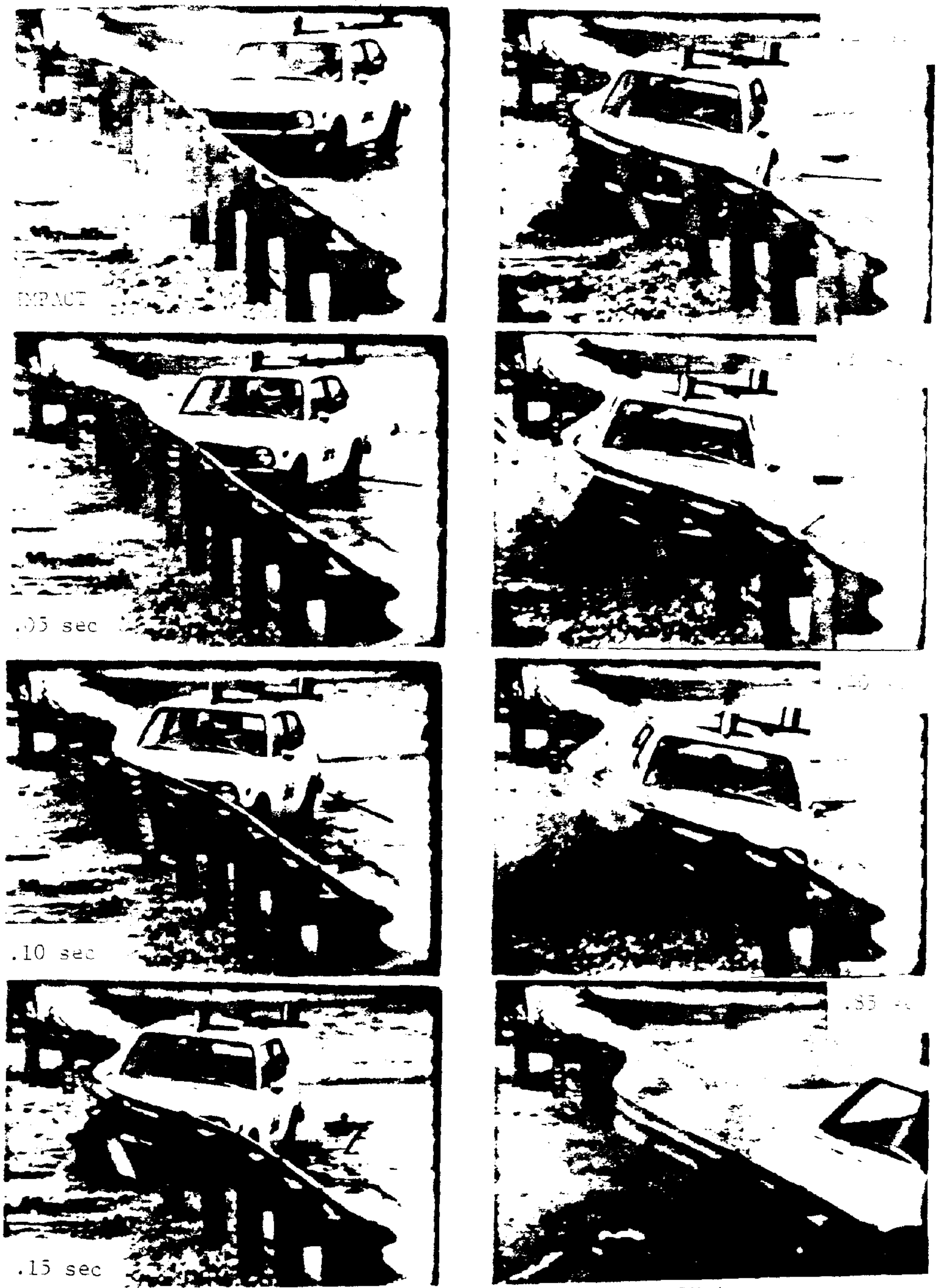


Figure 31. Sequential photographs, Test BH-6.

C. Sloping Terrain Tests

Four tests were conducted on the sloping terrain geometry described in figure 32. A great amount of difficulty was realized in the conduct of these tests. For the first three tests, the guidance cable used to steer the vehicle was terminated at the level apron edge. Thus, for a constant 15-degree approach to the barrier, the test vehicles would travel almost 100 ft on the sloping terrain without steering control. Another factor is the somewhat unpredictable steering input imparted to the vehicle when the steering bracket is sheared off. For level terrain tests, the "break-off" point is generally less than a car length which enhances the precision of the impact angle. The combination of bracket break-off steering input and traversal of sloping terrain for approximately 100 ft caused the first three test conditions to vary widely.

For the fourth test, the steering cable termination point was moved up to the crest of the superelevated slope; thus for a constant 15-degree angle, the freewheeling vehicle would traverse only 41.5 ft (12.7 m) before impacting the barrier. Steering inputs were incorporated into the HVOSM simulations in an attempt to reconcile the difference between actual impact conditions and those predicted in the simulations. Due to the combination of steering input and sloping terrain traversal, it was difficult to reach closure on this problem.

For reasons previously described in chapter III and this section, testing on the sloping terrain using the cable guidance system presented many problems. Remote steering was contemplated, but this method has its own sources of possible error also. It was decided that the problems were real and solutions beyond the scope of the project. The four tests are briefly described.

Test BH-7. This test evaluated the G4(1S) guardrail when installed at the hinge point (see figures 32 and 33). The top of rail was set at 32 in (81 cm) for the 20-in (51-cm) high underride height of the 1950-lb (884-kg)

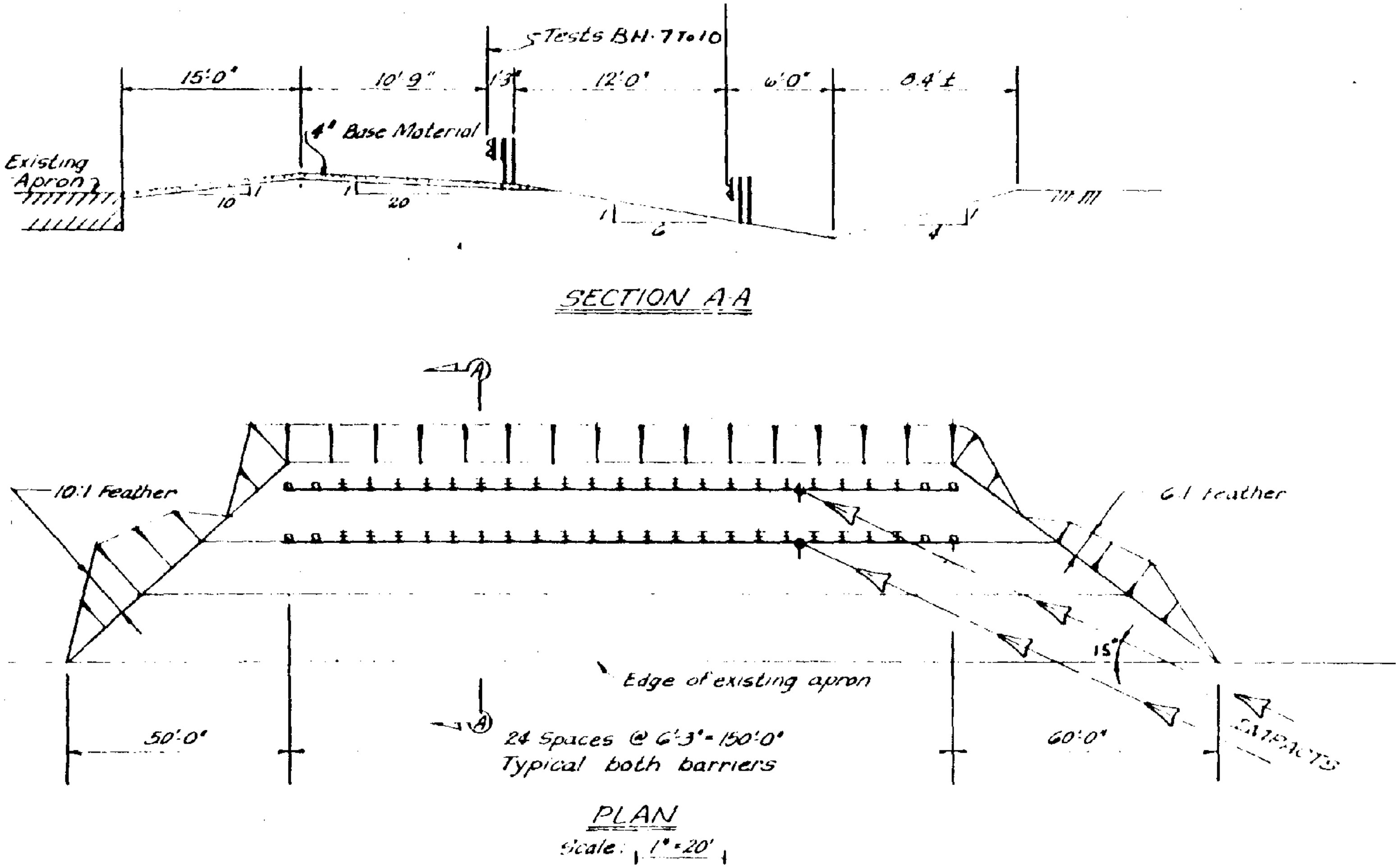


Figure 32. Barrier construction details, Test BH-7.

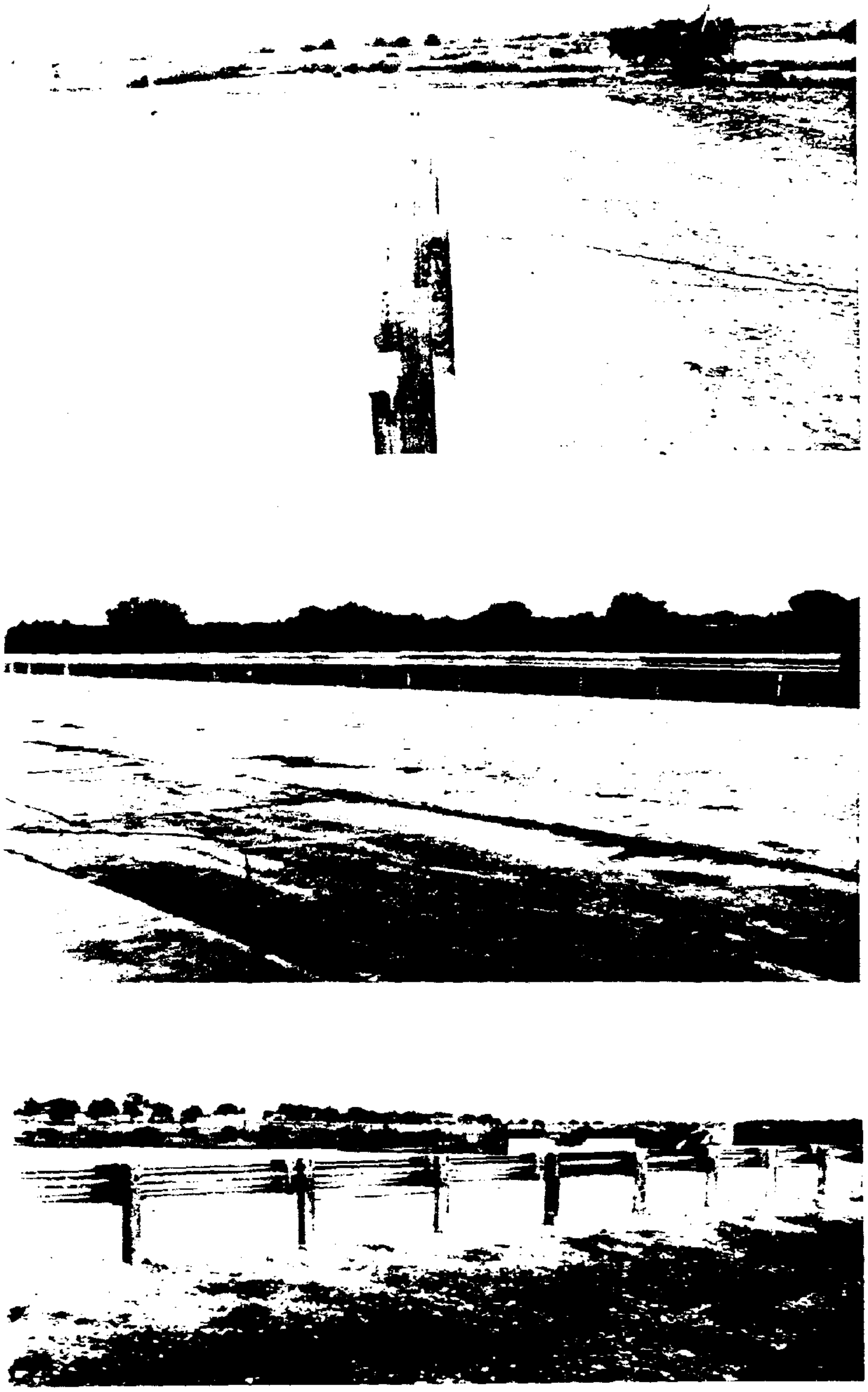


Figure 33. Barrier installation on sloped terrain.

Honda. The vehicle impacted the barrier at 58.3 mph (94 km/h) and 15.6-degree angle. Immediately on impact, the vehicle bumper rode under the rail and subsequently contacted two posts before redirection as shown in figure 34. No wheel or bumper snagging occurred. Photographs before and after the test are shown in figure 35.

Test BH-8. The purpose of this underride test was to evaluate the same installation as BH-7 for a 4500-lb (2000-kg) vehicle impacting at 60 mph (95 km/h) and 15°. Due to the trajectory of the vehicle after breaking away from the guide cable the actual impact conditions were 59.5 mph (95.8 km/h) and 19.5-degree impact angle. The higher than planned impact angle could not be explained after much investigation. As shown in figure 36, the vehicle remained in contact with the barrier for 28.9 ft (8.8 m) before smooth redirection at a 4.2-degree exit angle. The front bumper did not underride the beam and although tire contact with posts was noted, no snagging occurred. Figure 37 contains photographs before and after the test.

Test BH-9. This test was considered a repeat of the previous test. In this test, the vehicle drifted away from the barrier as had been anticipated in previous tests and had occurred with the 1800-lb (800-kg) car in Test BH-7. However, based on a drift toward the barrier in the 4500-lb (2000-kg) car test (BH-8), the cable termination had been set expecting this same phenomenon. Instead, the vehicle drifted away from the barrier and actual impact angle was 12.5° as shown in figure 38. The vehicle impacted at 58.4 mph (85.7 fps), the bumper underrode the beam, and wheel/post contact occurred, but no snagging was noted. The lack of snagging was attributed to the small deflection of the barrier system. Photographs before and after the test are shown in figure 39.

Test BH-10. The guide cable termination point was moved up the 10:1 slope for this repeat of the previous test. The actual impact angle of 13.6° was still below the 15-degree angle. As shown in figure 40, the vehicle impacted at 58 mph (93 km/h) and remained in contact with the

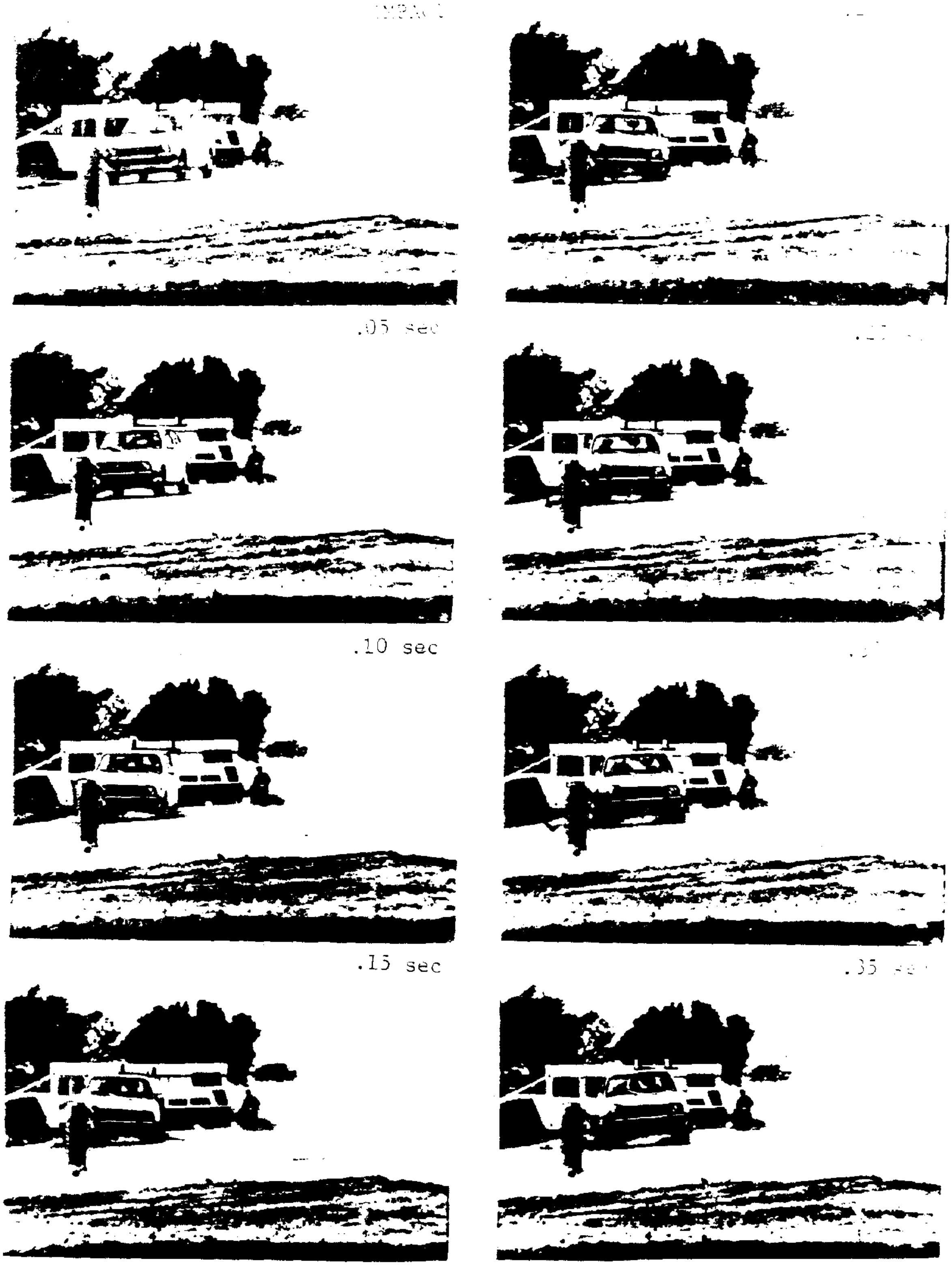


Figure 34. Sequential photographs, Test BH-7.

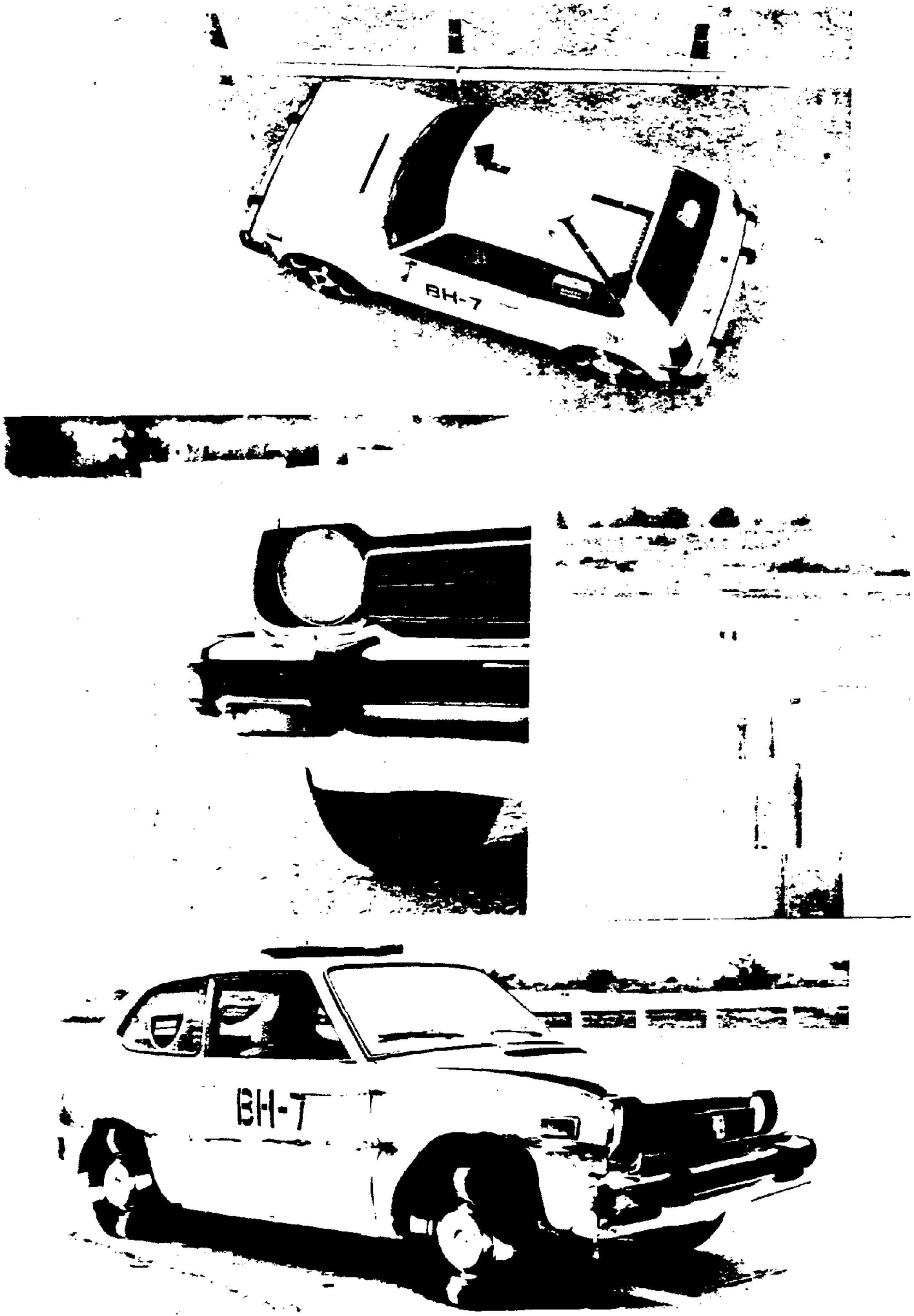


Figure 35. Before and after test photographs, Test BH-7.

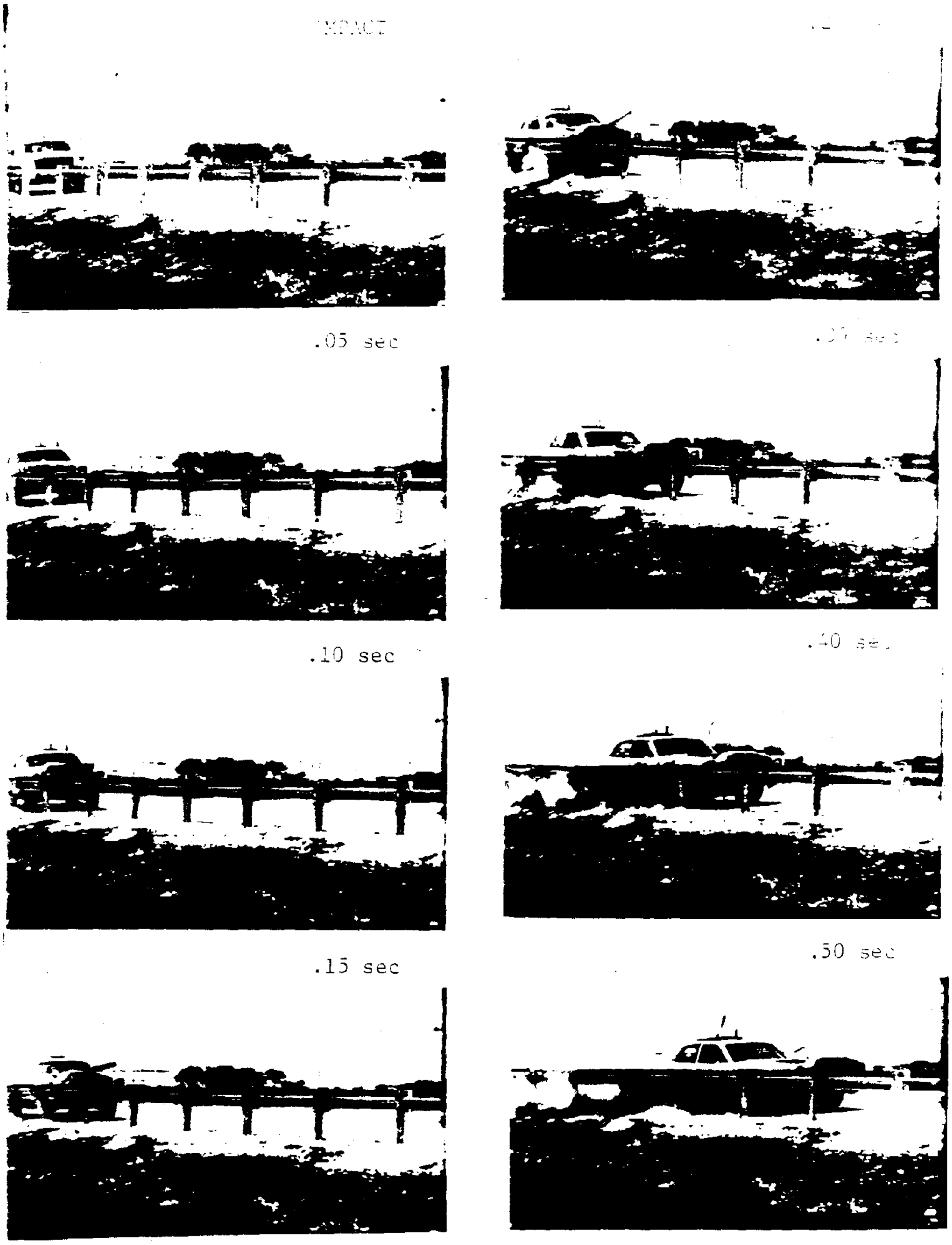


Figure 36. Sequential photographs, Test BH-8.

Figure 37. Before and after test photographs, Test BH-3.

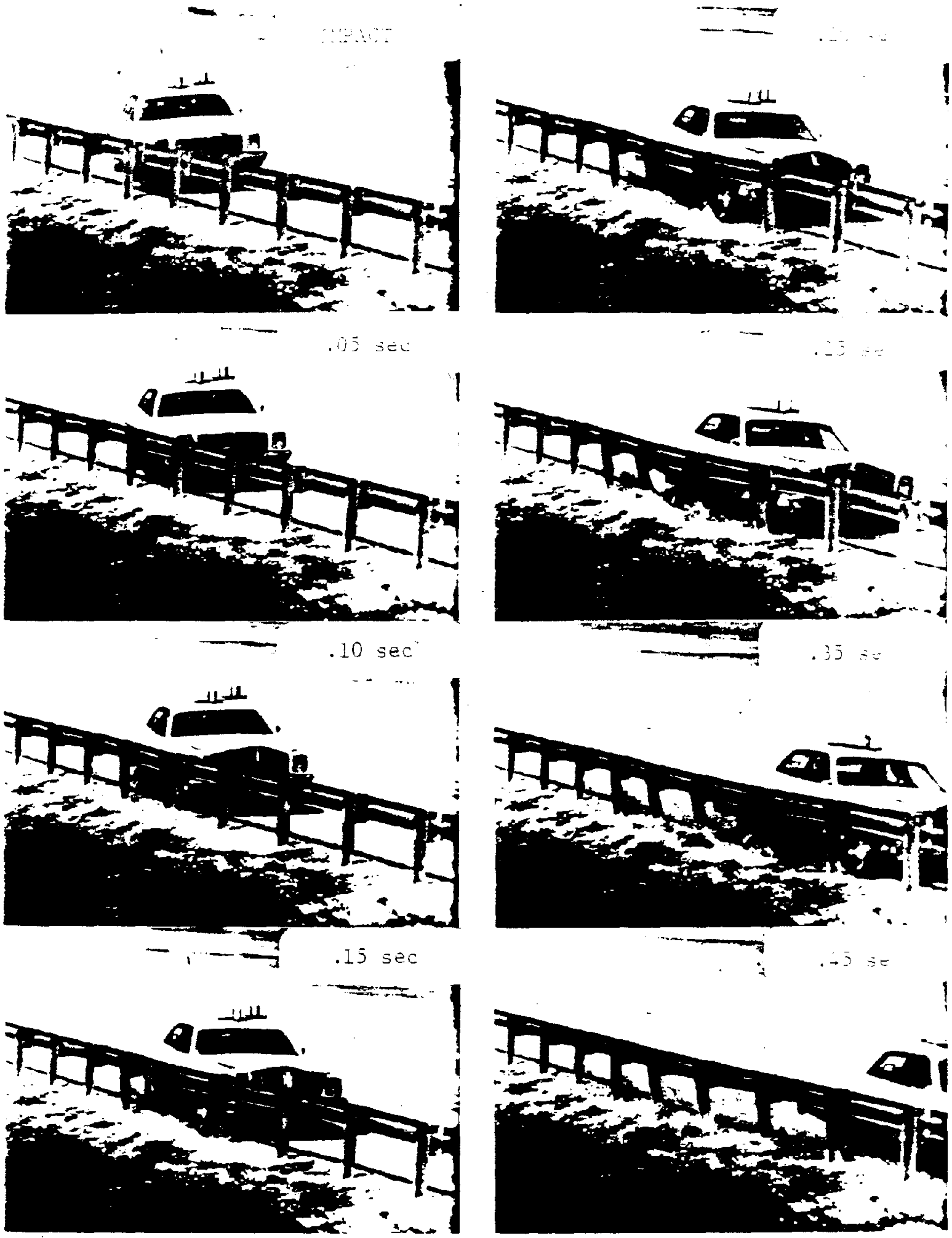


Figure 38. Sequential photographs, Test BH-9.

Figure 39. Before and after test photographs, Test BH-9.

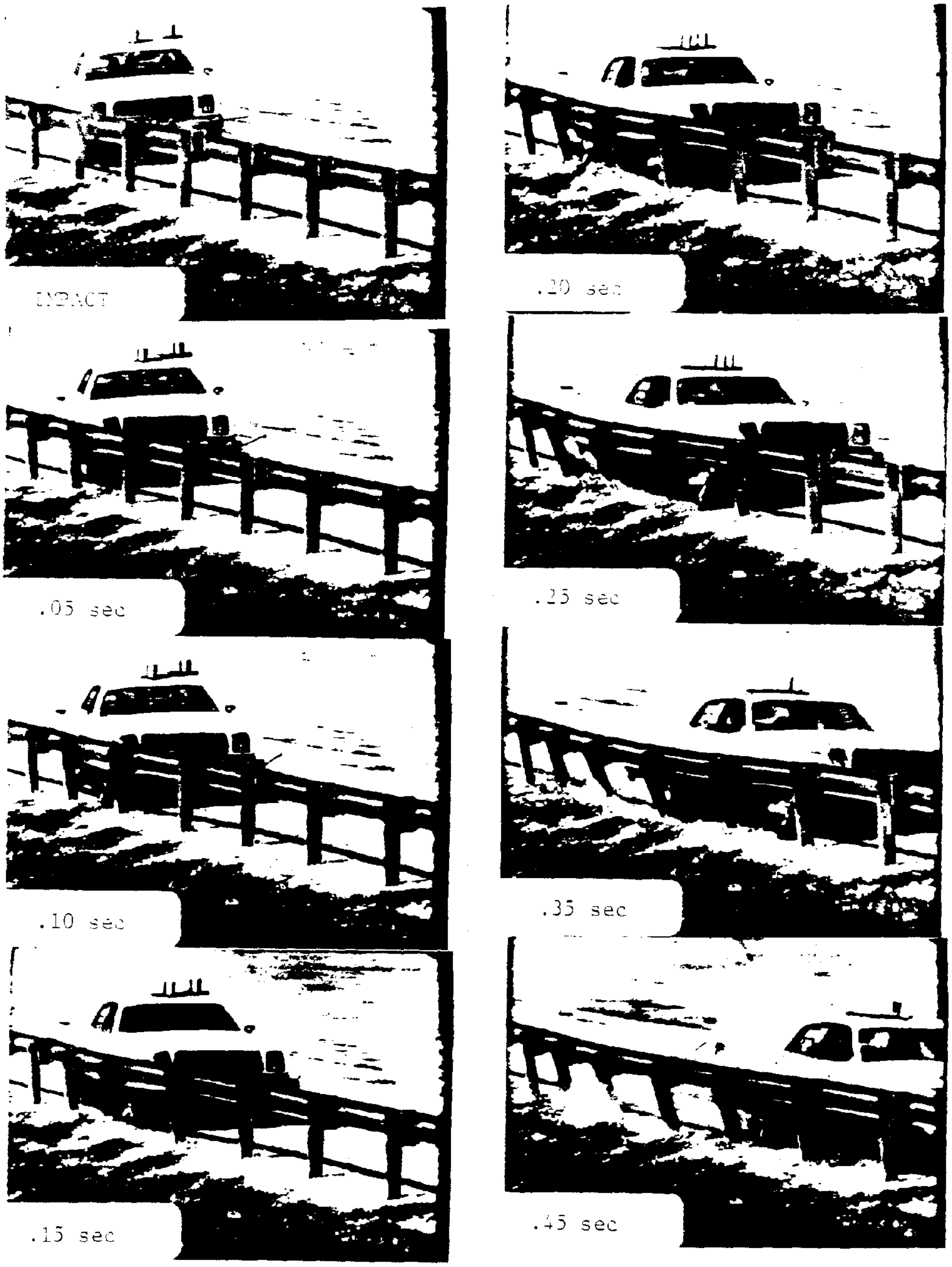


Figure 40. Sequential photographs, Test BH-10.

barrier for 31.0 ft (9.4 m) before smooth redirection at an exit angle of 5.7° occurred. The front bumper did not underride the barrier and wheel/post contact was not sufficient to cause snagging. Photographs after the test are shown in figure 41.

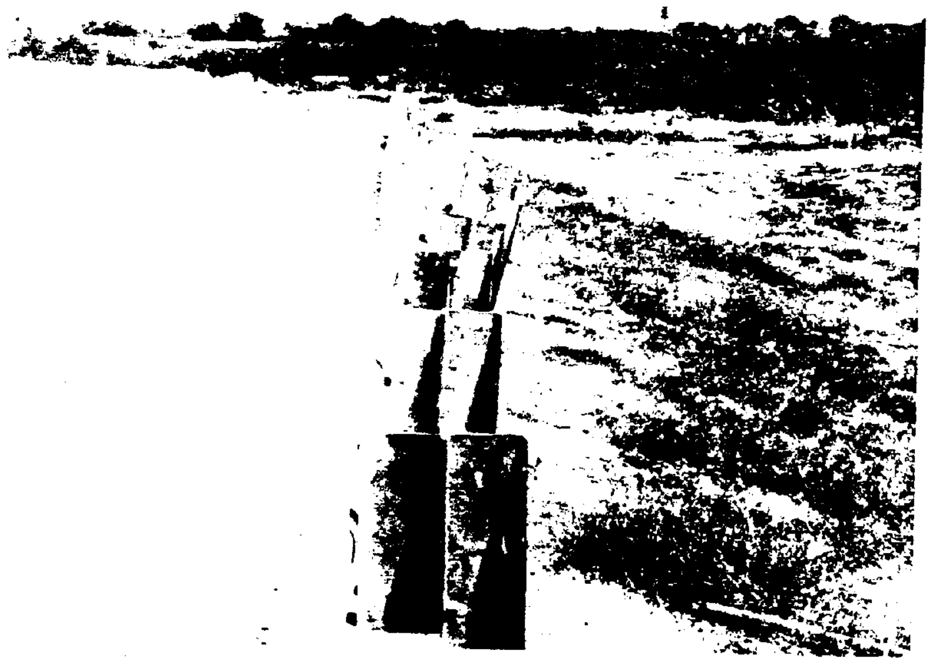
D. Critical Mounting Height Tests, Series 2

After the sloping terrain tests were dismissed due to test condition difficulties, another series of tests was conducted to further determine critical mounting heights. It had been observed on the sloping terrain tests that vehicle bumper underride had occurred without severe consequences due to the relatively low deflection values for the 15-degree angle impacts. Accordingly, this test series focused on impact angle as a variable in the critical barrier height determination. The tests were conducted on level terrain with angles of impact from 7 to 20°.

In addition, a low profile car was used to evaluate the G1 cable guardrail system.

Test BH-11. The purpose of this test was to establish the G4(1S) system critical mounting height for underride for 60-mph (95-km/h), 7.5-degree angle impacts. The beam was mounted at 33 in (84 cm) and critical bumper height of 20 in (51 cm) as shown in figure 42. The 4715-lb (2138-kg) vehicle impacted the barrier at 61.0 mph (98.2 km/h) and an angle of 6.8°. As shown in figure 43, the vehicle was smoothly redirected with no bumper snagging although bumper underride occurred. Insignificant contact of the rear tire with the traffic face of one post was the only post/wheel contact noted. Photographs after the test are shown in figure 42.

Test BH-12. The purpose of this test was to evaluate the same barrier installation as BH-11 (see figure 44) with an impact angle of 15°. The 4715-lb (2138-kg) vehicle impacted at 61.2 mph (98.5 km/h) and a 14.5-degree angle. As shown in figure 45, the right front fender deformed



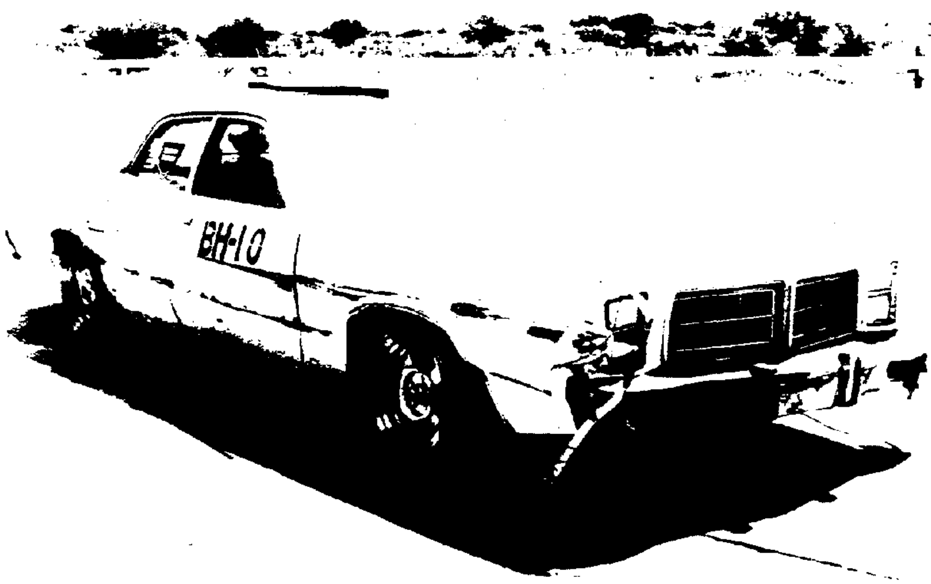


Figure 41. After-test photographs, Test BH-10.

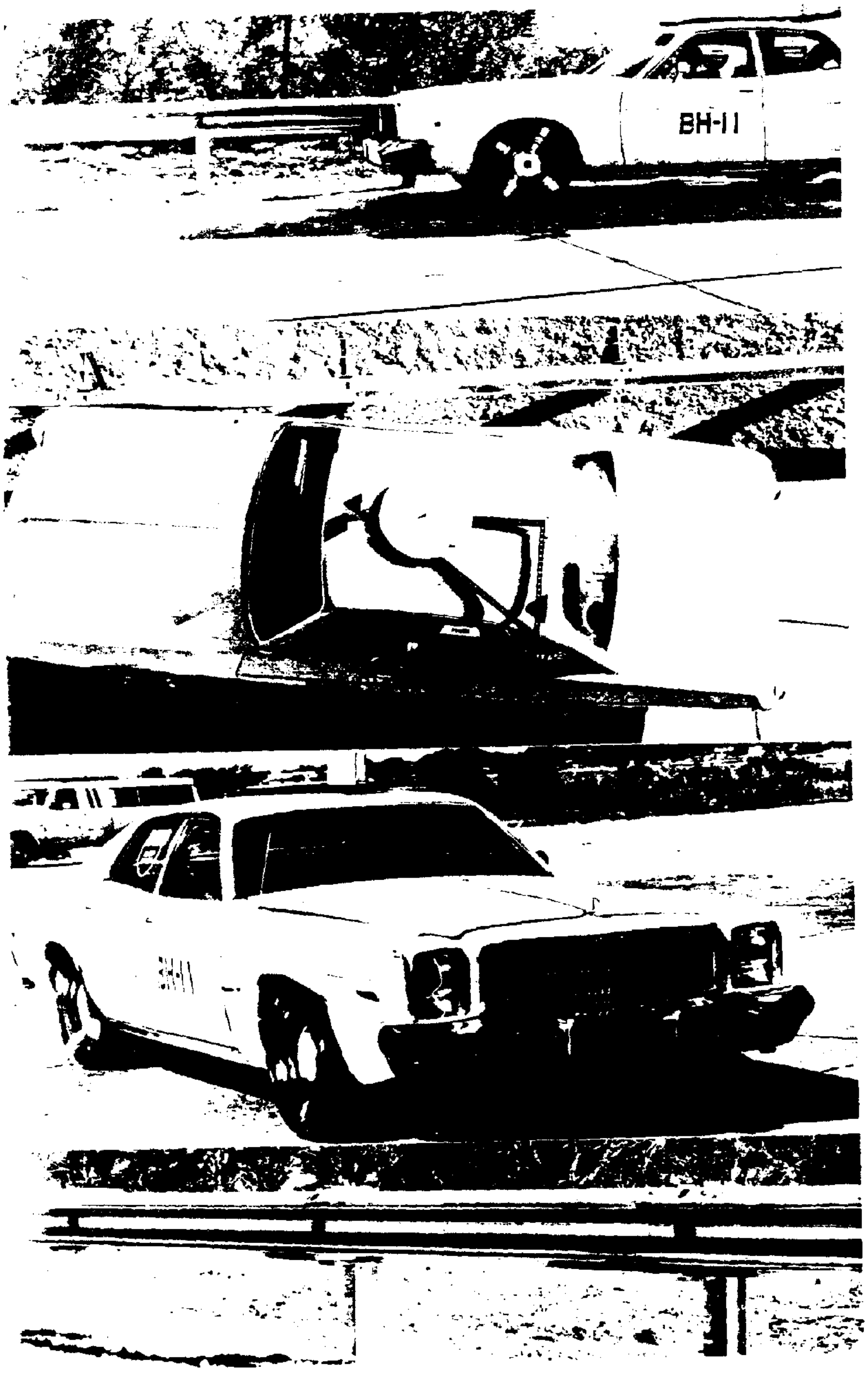


Figure 42. Before and after test photographs, Test BH-11.

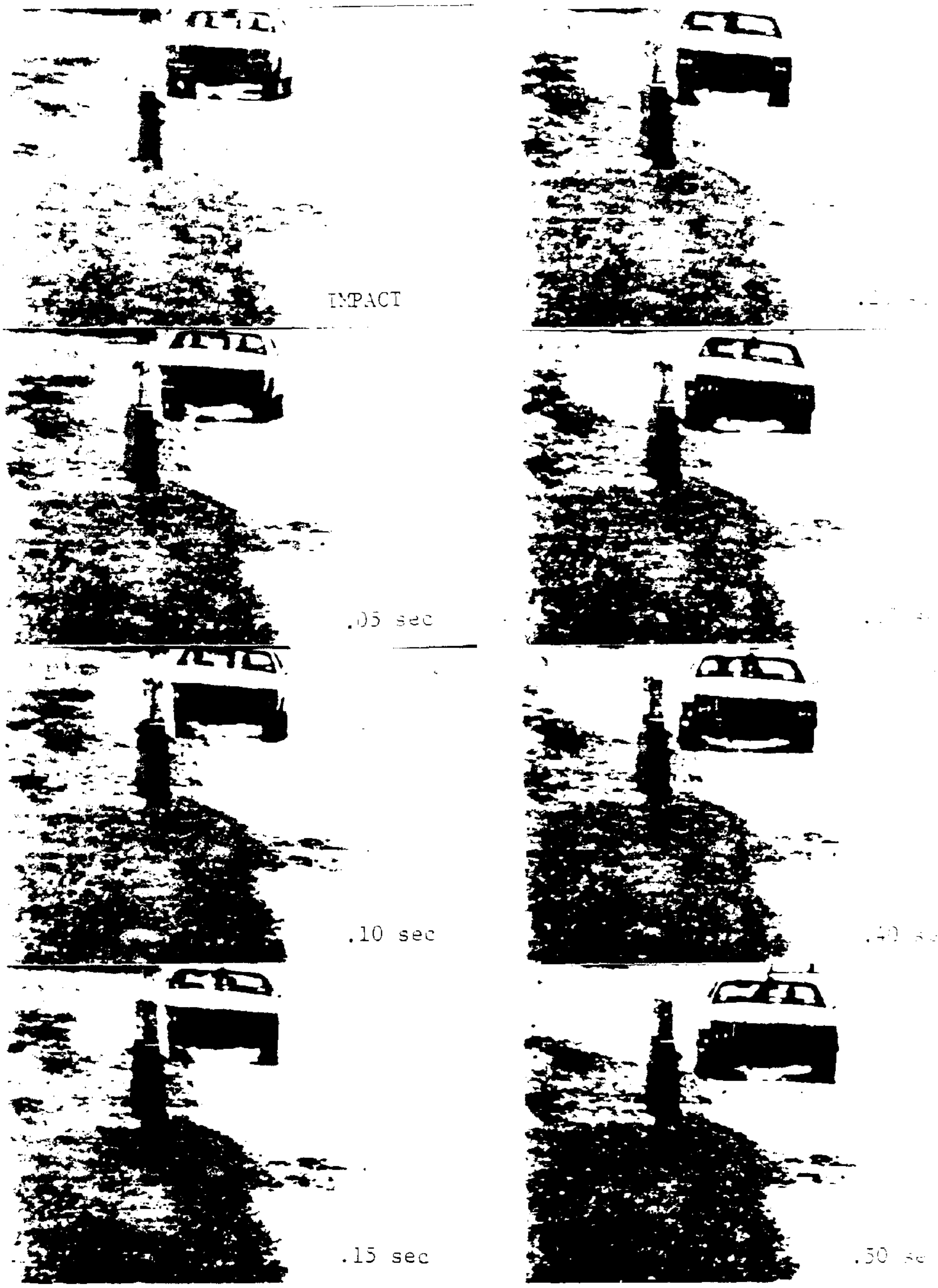


Figure 43. Sequential photographs, Test BH-11.

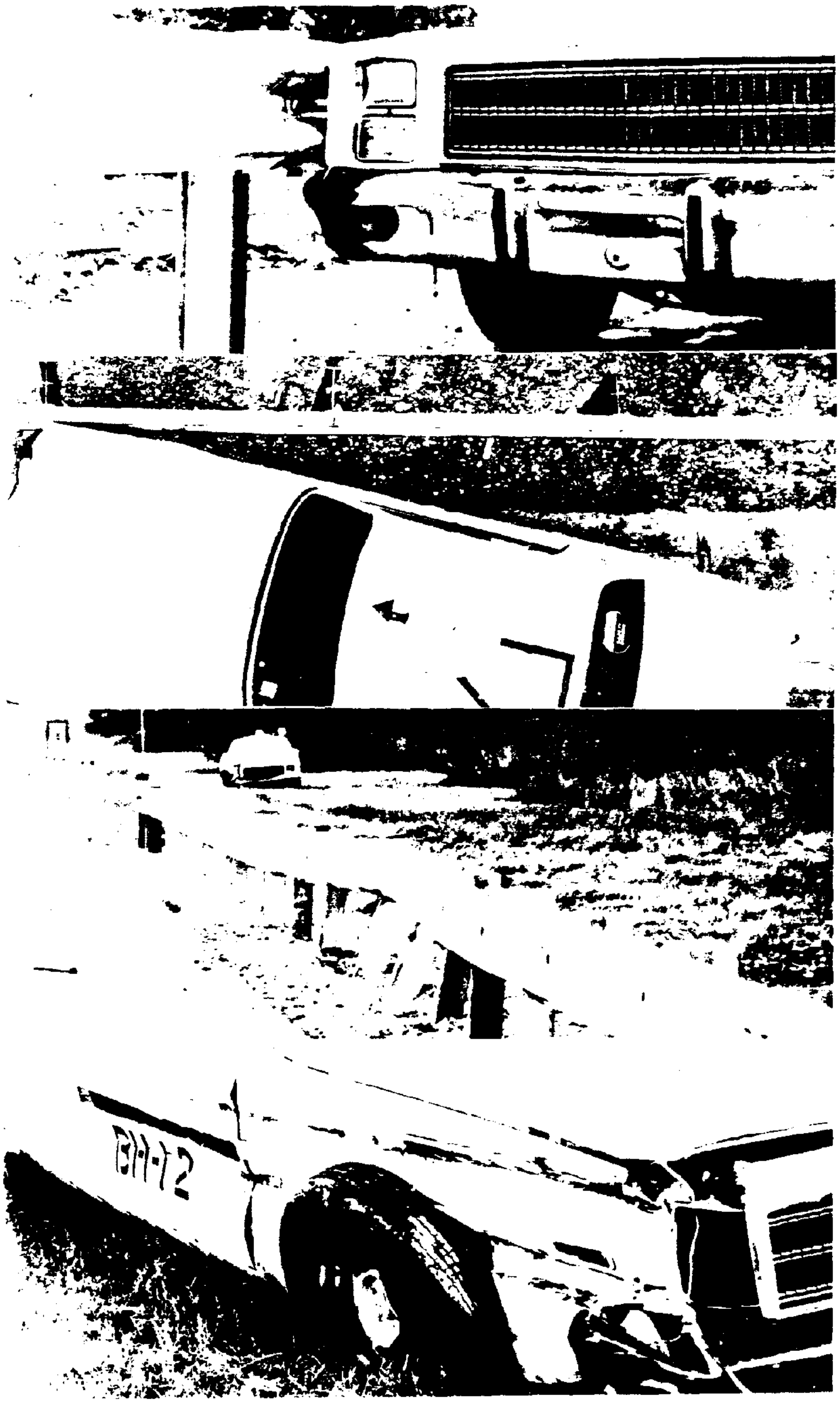


Figure 44. Before and after test photographs, Test BH-12.

Figure 45. Sequential photographs, Test BH-12.

inward, allowing the right front tire and wheel to ride under and behind the W-beam. Although the front bumper underrode the beam, snagging four posts, sufficient vehicle velocity was maintained for normal redirection. The vehicle remained in contact for 31.5 ft (9.6 m) before redirection at a 4.5-degree exit angle. Photographs after the test are shown in figure 44.

Test BH-13. The purpose of this test was to evaluate the G4(1S) guardrail mounted at 33 in (83.8 cm) high with an impact angle of 20° as shown in figure 46. As shown in figure 47, the 4650-lb (2104-kg) vehicle impacted the barrier at 59.6 mph (95.8 km/h) and a 19.5-degree angle. Immediately after impact the front bumper underrode the W-beam, allowing the right front wheel to engage the next six posts. Although the vehicle began to redirect, impact with the posts caused the rear of the vehicle to begin to yaw away from the barrier. The vehicle continued this "spin out" but impact with the barrier further downstream caused redirection of the vehicle parallel to the barrier. The initial barrier contact length was 37 ft (11 m) with a maximum deflection of 3.5 ft (1.1 m). The secondary impact was 84 ft (26 m) downstream of initial impact and continued 9.5 ft (2.9 m) until the barrier ended. Photographs after test are shown in figure 46.

Test BH-14. The purpose of this test was to evaluate the G4(1S) guardrail system with the top of the beam mounted at 18 in (0.5 m) as shown in figure 48. The 4670-lb (2118-kg) vehicle impacted the barrier at 61.7 mph (99.3 km/h) and 7.6-degree angle as shown in figure 49. The front bumper rode over the W-beam at impact and the right front tire engaged the rail, causing redirection to occur. The vehicle remained in contact with the barrier for 20.3 ft (6.2 m) before redirection at a 1.4-degree exit angle occurred. Photographs after test are shown in figure 48.

Test BH-15. The purpose of this test was to establish critical mounting height for the G4(1S) system for an angle of impact of 15° at 60 mph (95 km/h). Photographs before test are shown in figure 50. The beam was installed at 22 in (56 cm) above level grade. The 4670-lb

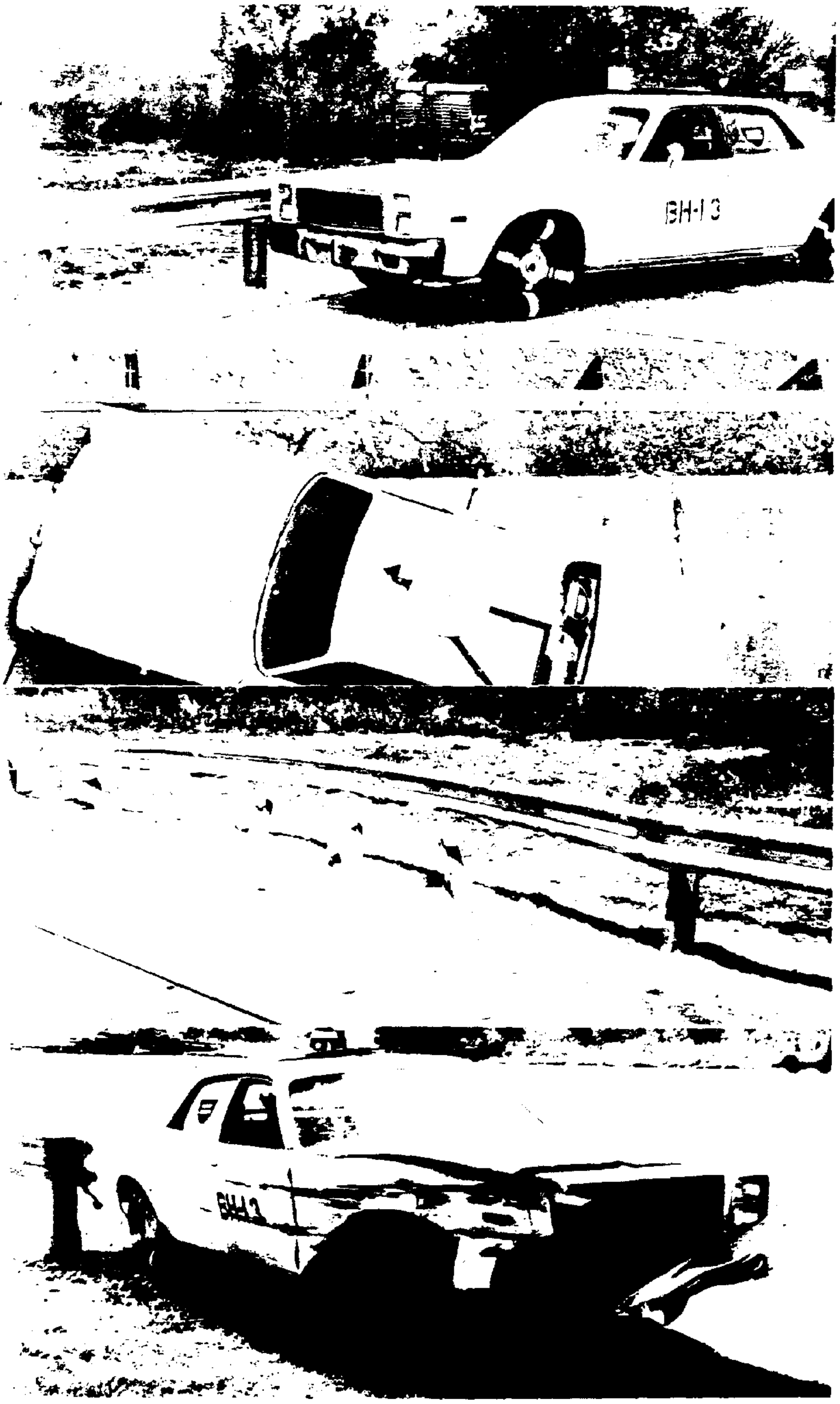


Figure 46. Before and after test photographs, Test BH-13.

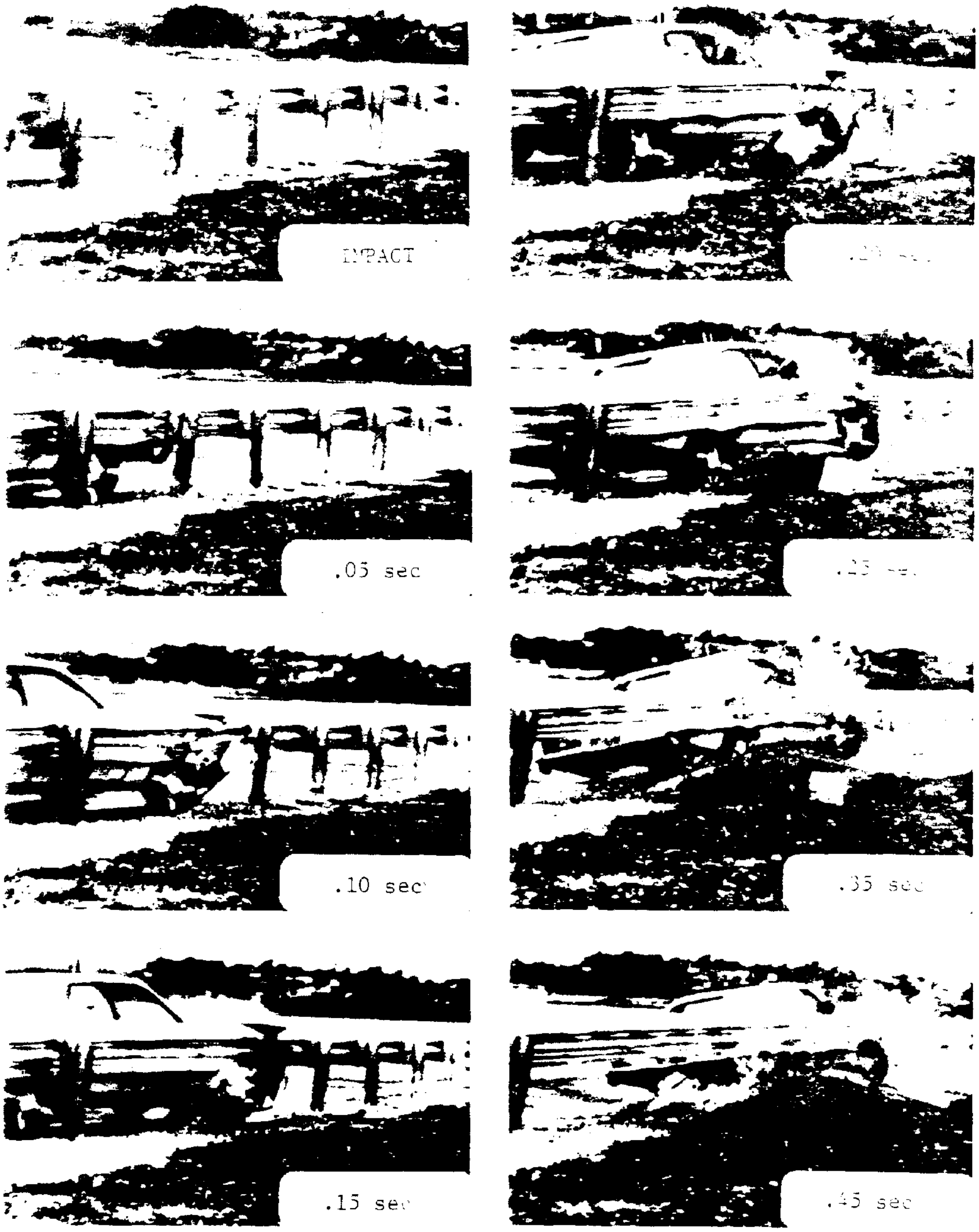


Figure 47. Sequential photographs, Test BH-13.

Figure 48. Before and after test photographs, Test BH-14.

IMPACT

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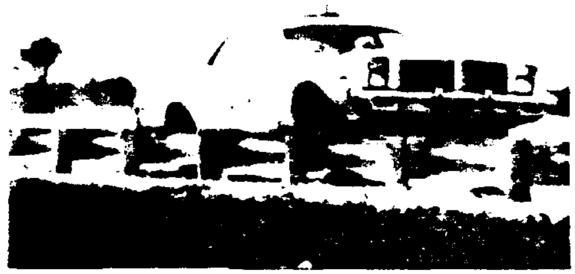

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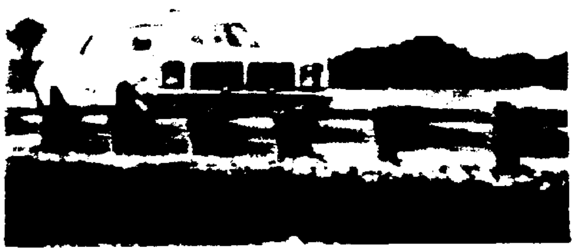

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Figure 49. Sequential photographs, Test BH-14.

Figure 50. Before and after test photographs, Test BH-15.

(2118-kg) vehicle impacted at 62.7 mph (100.9 km/h) and a 13.6-degree angle. As shown in figure 51, the vehicle became airborne and reached a maximum roll angle of 66° before recontacting the ground on the left side. Vehicle and barrier damage are shown in figure 49.

Test 3H-16. The purpose of this test was to examine the performance of a low front profile car with a cable guardrail system. The most commonly specified cable guardrail in the country is the G1 cable guardrail shown in the AASHTO Barrier Guide[9]. This barrier had been extensively tested during development[10] and more recently tested by New York[11] and Southwest Research Institute for NCHRP[12]. The G1 cable system shown in the Barrier Guide has the top cable at 30 in (76 cm) above grade. Recently, New York (see ref. 1) has contemplated changing the height to 27 in (69 cm). Tests conducted recently by New York and SwRI have indicated this is more desirable. A test conducted at SwRI resulted in a 4300-lb (1950-kg) van redirecting after a 60-mph (95-km/h), 25-degree angle impact.[11] Thus, it had been demonstrated that 27 in (69 cm) was sufficiently high to redirect a higher c.g. vehicle.

The top cable was set at 27 in (69 cm) for the test as shown in figure 52. The test vehicle was selected based on a survey described in figure 6. The 1974 Datsun 260Z weighing 2740 lb (1243 kg) impacted the barrier at 59.6 mph (95.8 km/h) and angle of 24.8°. As shown in figure 53, the top cable rode up over the hood but was contained by the A pillar and C pillar without any passenger compartment intrusion. The two lower cables remained captured by the deformed sheet metal along the left side of the car. Vehicle contact with subsequent posts caused the rear of the vehicle to begin yawing away from the barrier. Elastic spring of the cables pushed the vehicle laterally away from the system. The vehicle lost contact with the barrier after 64 ft (20 m) and recontacted the barrier 7 posts downstream from the initial contact. This second contact caused the vehicle to spin out and begin traveling backward, coming to rest as shown in figure 52.

Figure 51. Sequential photographs. Test BH-15.

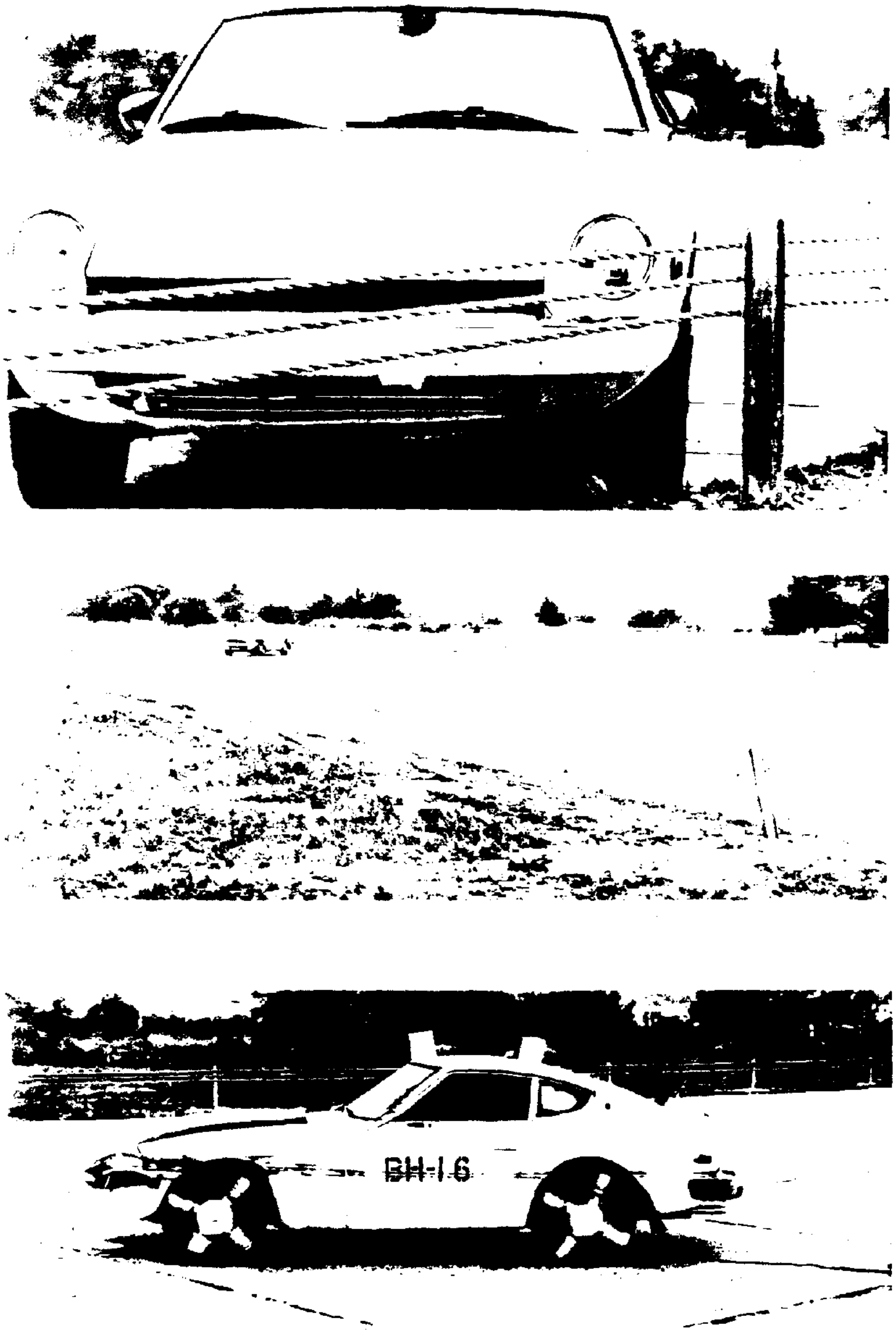


Figure 52. Before and after test photographs, Test BH-16.

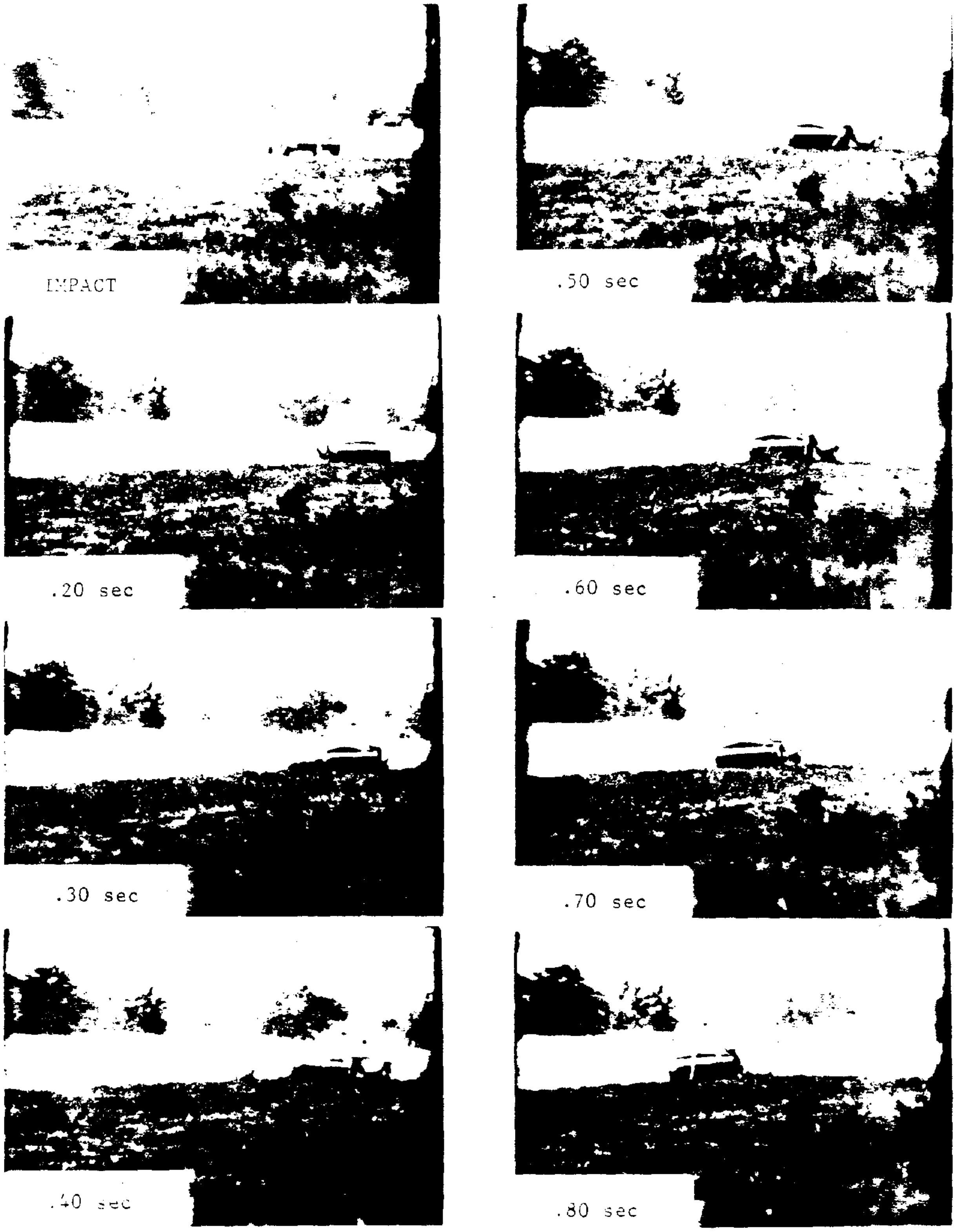


Figure 53. Sequential photographs, Test BH-16.

V. CONCLUSIONS AND DESIGN GUIDELINES

A. Findings

As a result of the full-scale crash tests and computer simulations conducted in this study, some important findings were revealed that affect the performance of barriers with varying railing heights. These findings were as follows:

- Bumper heights were shown to be very sensitive to the impact conditions. Though the computer simulations indicated underride for the nominal impact conditions, the small deviations in actual test impact conditions affected not only the bumper heights but also the barrier response. When the actual test conditions were duplicated with the simulation, the change in barrier response (from underride to no underride) followed. However, the persistent problem of discrepancies between bumper heights of tests and sloping terrain simulations could not be resolved; this is principally attributed to the trajectory of the car after traversing two slopes from 40 to 100 ft (12 to 30 m) after release from the guide cable. The simulation model accurately predicts bumper height if known trajectories are input.

- Bumper heights alone are not sufficient to predict underride. Though the bumper did underride the railing in Test BH-9 (see chapter IV), the barrier deflection was not sufficient for the bumper to snag the posts and pocket the vehicle. In fact, the slope tests BH-7 through BH-10 showed that underride was not likely to be a problem for impacts of less than 20° with reasonable barrier heights. This was validated with subsequent flat and level tests.

- Within the range of standard impact conditions, small car underride was not shown to be critical because of insufficient barrier deflection to permit vehicle contact with the posts. This is based on the fact that for a given speed and angle, the large car is more critical in both cases because of the larger deformation of the barrier which is crucial for both underride and override. The bumper heights are basically the same.

• The finding that barrier deflection, in addition to the relative railing/bumper heights, affected underride implied that it also affected override. That is, the bumper might override the railing without sufficient lean of the barrier to launch the vehicle. On considering the continued vehicle wheel and undercarriage contact with the rail, this was not as likely as the firmer vehicle body contact in underride situations.

• Uncoupling the railing from the posts by eliminating the restraining washers did not significantly affect the barrier response in underride or override conditions.

• On slope tests BH-7 through BH-10, it was found to be practically impossible to achieve accurate impact conditions because of left or right vehicle drift after release from the guidance system. Thus, threshold underride/override barrier heights were established from flat and level tests. Table 15 shows the critical railing heights for the common corrugated railing systems (W-beam or thrie beam). Thresholds for other railing types were not established.

• Based on computer simulations, the effects of suspension variations were not judged to be critical. Thus, the bumper trajectories predicted by the computer should be accurate for a wide range of suspension values.

• Based on computer simulations, the effects on steering/braking on level terrain are not significant; however, steering can affect the trajectory of vehicles traversing slopes and result in changes in the bumper height at impact. The infinite number of possible steering input variations did not permit consideration of this variable in the project.

Table 15. Threshold railing heights.

Condition	Angle of Impact (degrees)*		
	7.5	15	25
Underride	34 (+2)**	34 (+2)	32 (+0)
Override	18 (-2)	22 (+2)	22 (+2)

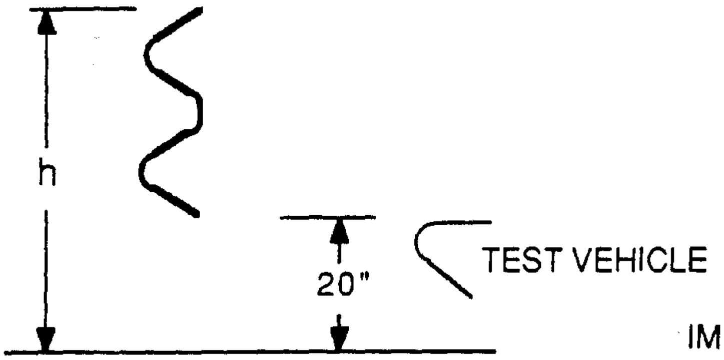
* All tests were with nominal 4500-lb vehicles at 60 mph. Pickups were not included in this study. Smaller cars are not included due to the third conclusion on page 102.

** Numbers in parentheses show relative railing heights with respect to the 20-inch underride/override heights of the test vehicles. These numbers are to the bottom of the railing for underride and to the top of the railing for override.

- The single test of the low profile car indicated satisfactory performance with the G1 cable system mounted at 27 in (70 cm) high. Recent experience with a test by New York indicated totally unsatisfactory performance with the G1 system mounted at 30 in (75 cm). The test vehicle (a mid-70 Plymouth Fury 2-door hardtop) suffered severe passenger compartment damage due to cables severing the A and C pillars.(10) In an NCHRP project at SwRI, a 4300-lb (1950-kg) van was successfully redirected at 60 mph and 25-degree angle with the top cable at 27 in (70 cm). Thus, it would appear that the G1 cable system mounting height as shown in the AASHTO Barrier Guide should be lowered to 27 in (70 cm).

- The 1977 AASHTO Barrier Guide(9) sets top of railing height for W-beam systems G4(1S) and G4(1&2W) at 27 inches (68.6 cm). For the G9 thrie beam system the top of rail height is set at 32 inches (81.3 cm). Since the findings of this study were based on passenger cars, it would seem that a beam mounting height as high as possible would achieve the most favorable results in the field. Since most of the smaller cars are represented by the Honda, the higher beam mounting height would make the barriers more responsive to vehicles weighing more and with higher c.g.s than the 4500-lb (2025-kg) vehicle. Thus, for the design bumper height of 18 in (45.7 cm), an ideal mounting height would be 30 in (76.2 cm) for the W-beam and 38 in (96.5 cm) for the thrie beam as illustrated in Figure 54. Allowing for some factor of safety (for uneven terrain, braking, etc.), the W-beam mounting height of 27 in (68.6 cm) could remain a good choice, but the thrie beam mounting height could be raised from 32 to 35 in (81.3 to 88.9 cm) using the same rationale. Using a similar rationale, a user agency should seriously consider upgrading where an installation height is below 20+3 or 23 in (58.4 cm). The selection of the 3 in (7.5 cm) value is somewhat arbitrary and not based on any real precision.

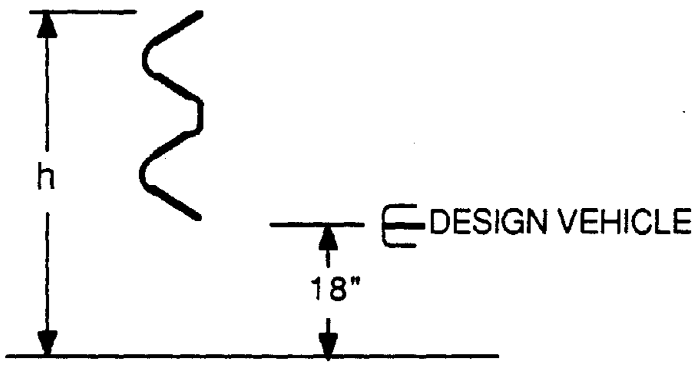
The difficulty in achieving desired test conditions for barriers mounted on sloping terrain prevented closure on certain questions regarding the effects of the vehicle attitude (i.e., pitch and trajectory direction) before and during the impact events. Using conventional steering



IMPACT ANGLE	h* h_u	h* h_o
7.5	34	18
15.0	34	22
25.0	32	22

* u - UNDERRIDE
o - OVERRIDE

(a) CRASH TEST RESULTS



IMPACT ANGLE	h* h_u	h* h_o
7.5	32	16
15.0	32	20
25.0	30	20

* u - UNDERRIDE
o - OVERRIDE

(b) DESIGN BUMPER CONSIDERATIONS

Figure 54. Barrier height considerations.

techniques (i.e., guide cable), control of the location and angle of impact cannot be satisfactorily controlled for determining threshold values. Some form of remote steering or fixed guidance channel might be more accurate although the former could have its own set of problems. It is recommended that if significant questions arise regarding the findings of this project in this regard that improved steering techniques on sloping terrain be investigated and crash tests conducted accordingly.

B. Design Guidelines

The threshold underride/override railing heights as established by full-scale tests are shown above in table 15. This information, along with the HVOSM data supplied by the Texas Transportation Institute (TTI) (see chapter II), was used to develop design guidelines. The manner in which these guidelines were developed and explanation of their use follow.

As indicated in chapter II (table 2), the TTI study included 26 roadway/roadside geometric parameters. For each of these roadway/roadside cross sections, HVOSM runs were conducted for two vehicle sizes [1800 lb (800 kg) and 4500 lb (2000 kg)] and three impact angles (7.5, 15, and 25°) all at a single speed of 60 mph (95 km/h). This produced a total of 26 x 2 x 3 = 156 HVOSM runs. Output from each run included the bumper mid-height as the vehicle traveled across the section. A computer program was first prepared for graphical presentation of this output data.

The TTI data represented bumper mid-heights of 17.2 in (43.7 cm) for the 1800-lb (800-kg) car and 17.5 in (44.5 cm) for the 4500-lb (2000-kg) vehicle. The first modification was to add 0.8 in (2.0 cm) and 0.5 in (1.3 cm), respectively, to reach the single underride/ override height of 18.0 in (45 cm) for the design vehicle (see figures 4 and 5 of chapter II). Further modifications were to adjust the heights by the relative distances for underride/override as shown in table 15 above. Table 16 shows the 12 final adjustments of the TTI data for the bottom of the railing for underride and the top of the railing for override.

Table 16. Adjustments of TTI data for underride/override.

	Impact Angle (degrees)		
Vehicle	7.5	15	25
Underride (adjustments to bottom of railing)			
1800-lb	+2.8	+2.8	+0.8
4500-lb	+2.5	+2.5	+0.5
Override (adjustments to top of railing)			
1800-lb	-1.2	+2.8	+2.8
4500-lb	-1.5	+2.5	+2.5

The 12 adjustments shown in table 16 were plotted on each of the 26 roadway/roadside cross sections. Figure 55 shows an example of the resulting plots. By shading in the area from the lowermost underride curve (bottom of railing) to the uppermost override curve (top of railing), the required range of railing width along the roadside could be established.

The 26 roadway/roadside conditions are repeated in table 17. Numbers in parentheses refer to the corresponding numbers of the figures that follow.

Figure 56 illustrates how the curves of figures 57 through 82 can be used. By preparing an overlay scale corresponding to the Z-axis and placing it at the guardrail position of interest, the required width and height of the railing can be determined. Note that if the band width exceeds the 12-in (30-cm) width of the W-beam, either a 20-in (50-cm) wide thrie beam or an added rub rail should be used. If the band width is less than the railing width, tolerances in railing height can be established. That is, the railing can be moved up or down as long as the railing width covers the band. An agency could opt for a tolerance to account for bumper height variations (for any reason) by reducing the effective band width of the beams.

Note that these barrier limit curves are only for corrugated railings (W-beam or thrie beam). Underride/override thresholds were not established in the study for other types of railings. Also, the underride/override heights shown were established from flat and level full-scale tests. The limits might be changed somewhat by downward or upward trajectories of the vehicles at the guardrail points of interest. These effects could not be established because of the problems associated with the modified HVOSM code in simulations and vehicle drift in full-scale slope tests. However, with the relatively small deflections that would be expected with the G4 or G9 guardrail systems for most impacts, these effects are not considered to be significant.

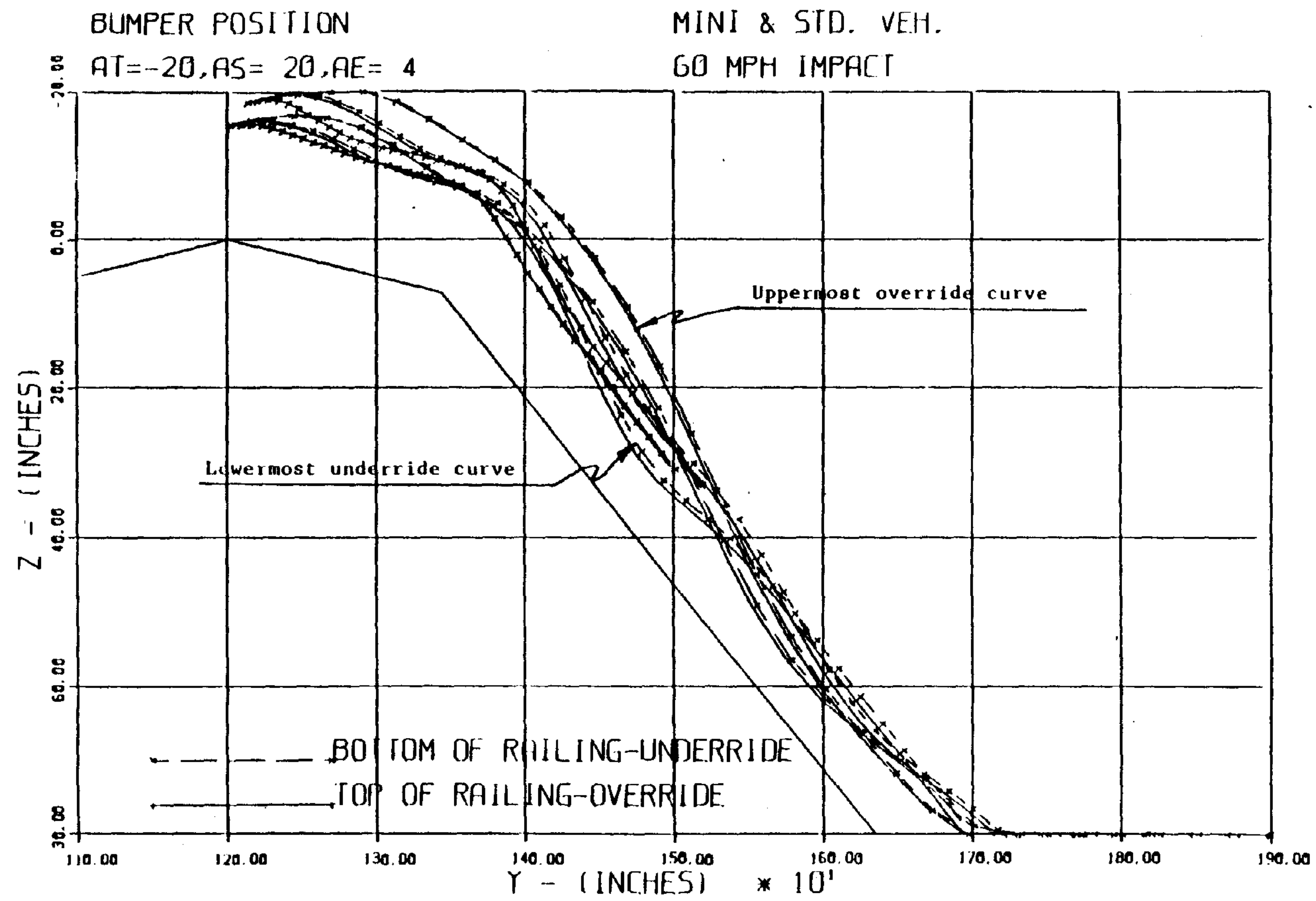
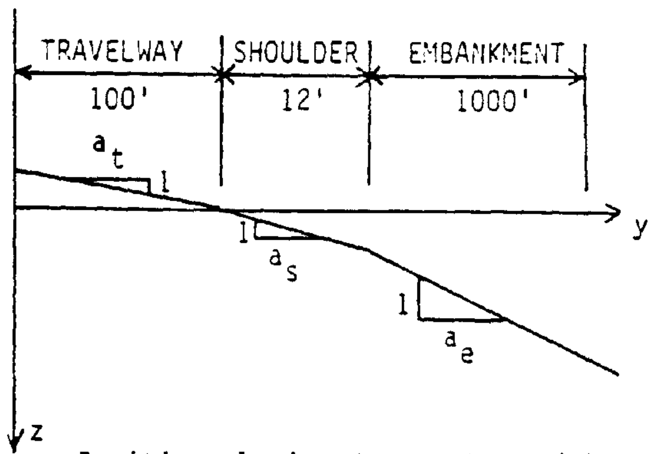


Figure 55. Example of underride/override plots for mini and standard vehicles at 7.5°, 15°, and 25° to determine barrier height limit envelope.

Table 17. Roadway/roadside geometric parameters.

a_t	+48	-20		-10	
a_s	+20	+20	-20	+20	-10
	+4 (57)*	+4 (63)	+4 (69)	+4 (73)	+4 (79)
	+6 (58)	+6 (64)	+6 (70)	+6 (74)	+6 (80)
a_e	+8 (59)	+8 (65)	+8 (71)	+8 (75)	+8 (81)
	+10 (60)	+10 (66)	+10 (72)	+10 (76)	+10 (82)
	-8 (61)	-8 (67)		-8 (77)	
	-4 (62)	-4 (68)		-4 (78)	

* Numbers in parentheses refer to corresponding figure numbers.



Positive sloping downward to right.

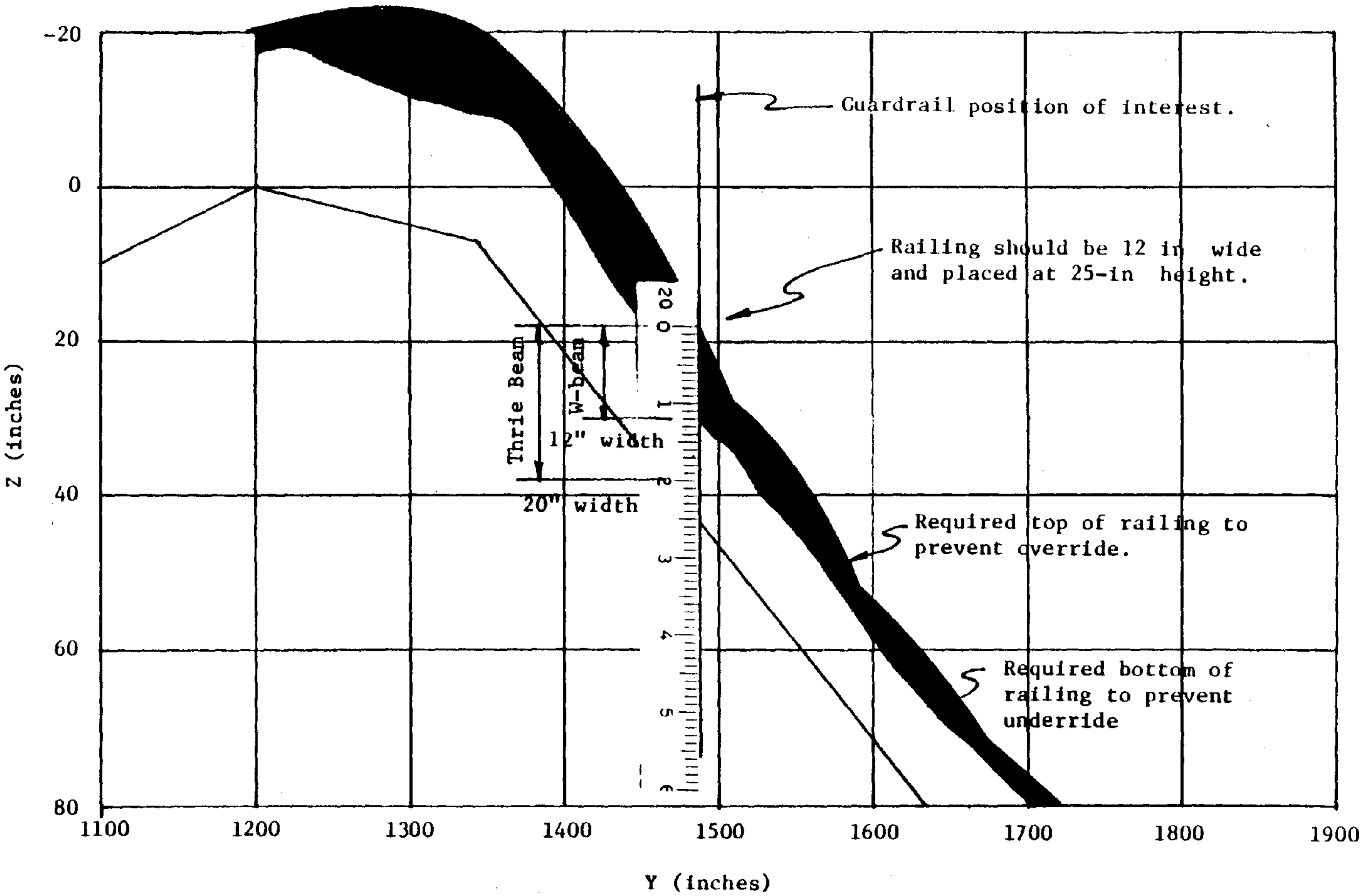


Figure 56. Barrier height limit envelope (G4(1S) system, $a_t = -10$, $a_s = 20$, $a_e = 4$).

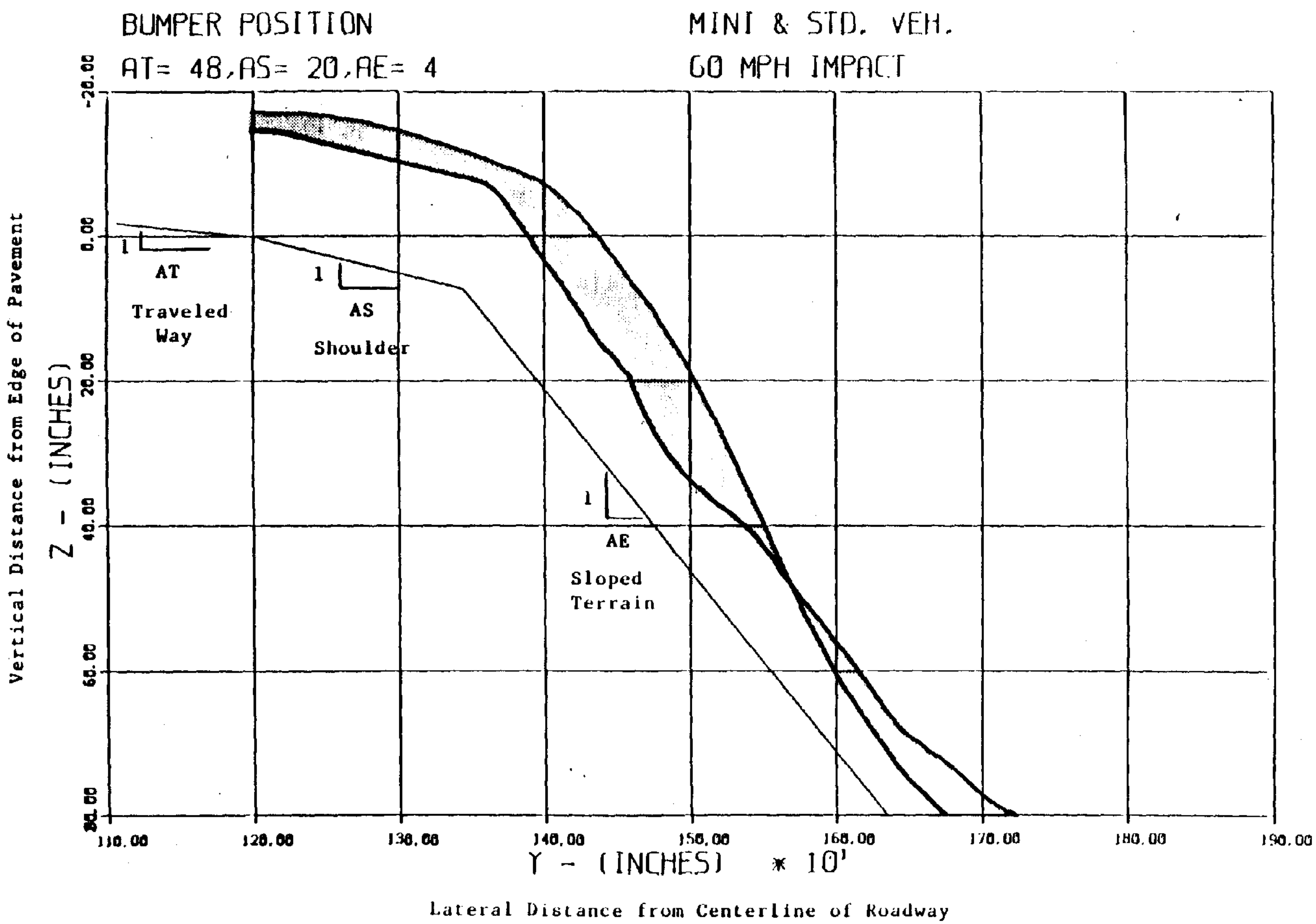


Figure 57. Barrier height limit envelope (G4(1S) system, AT = 48, AS = 20, AE = 4).

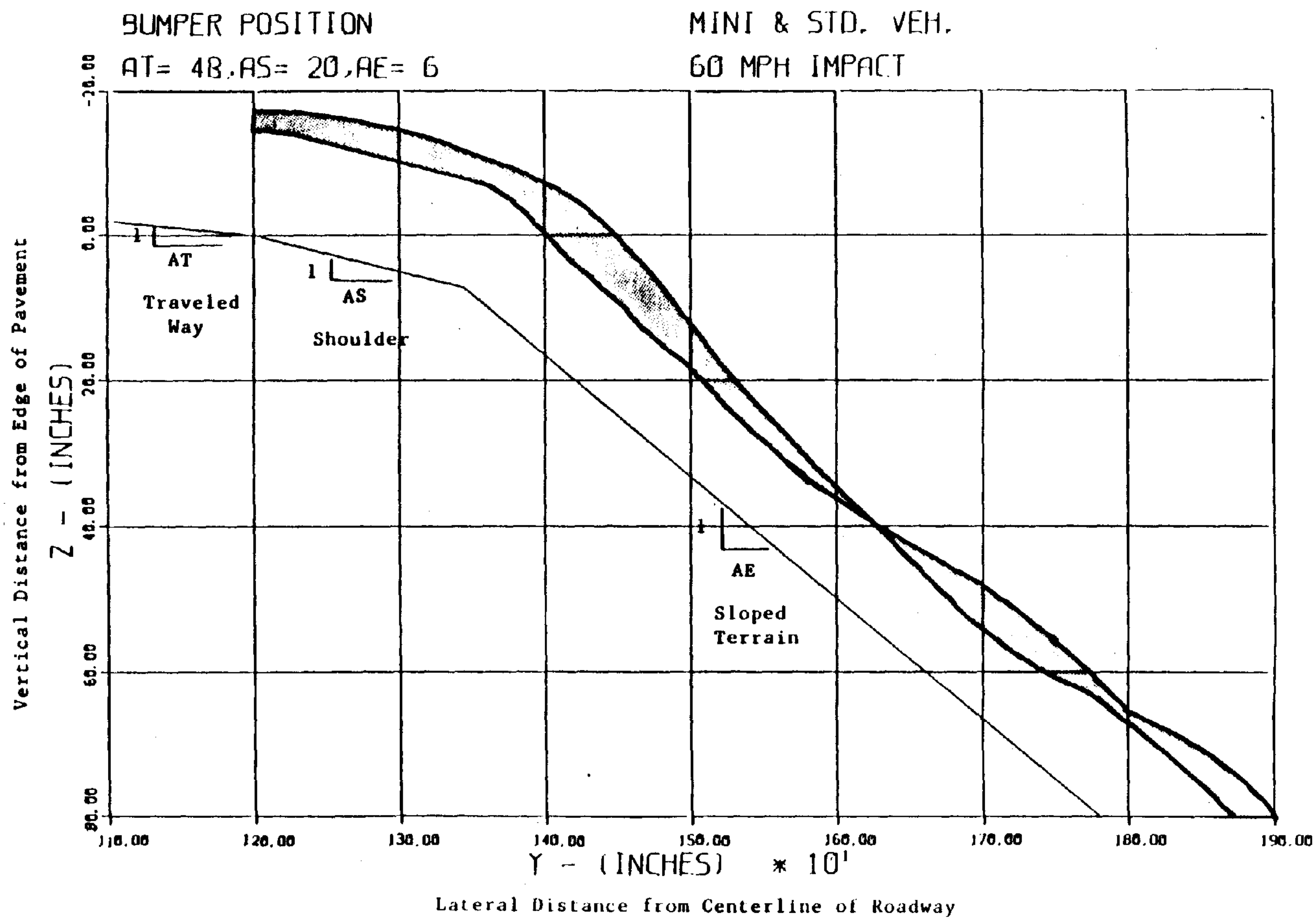


Figure 58. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = 6).

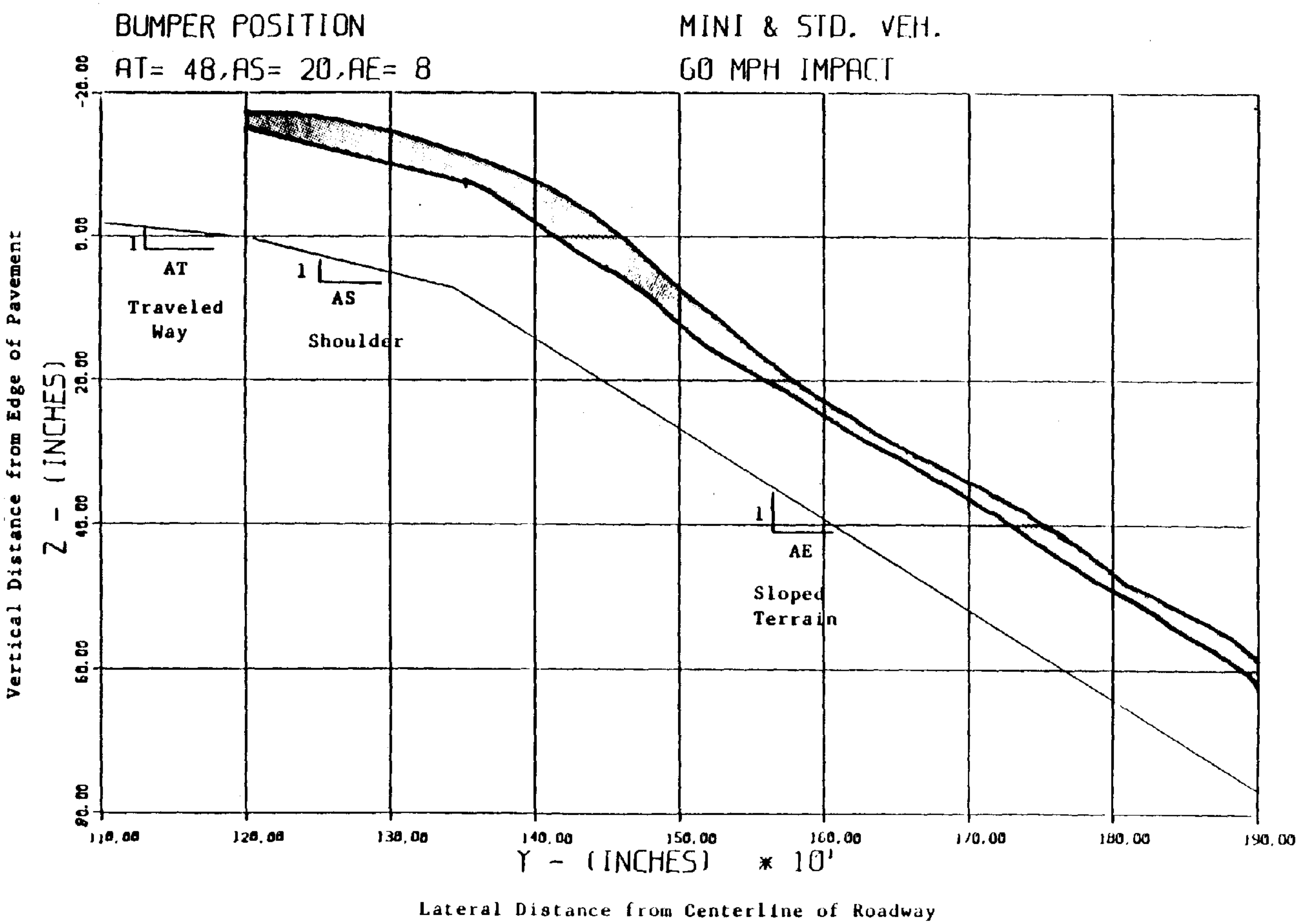


Figure 59. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = 8).

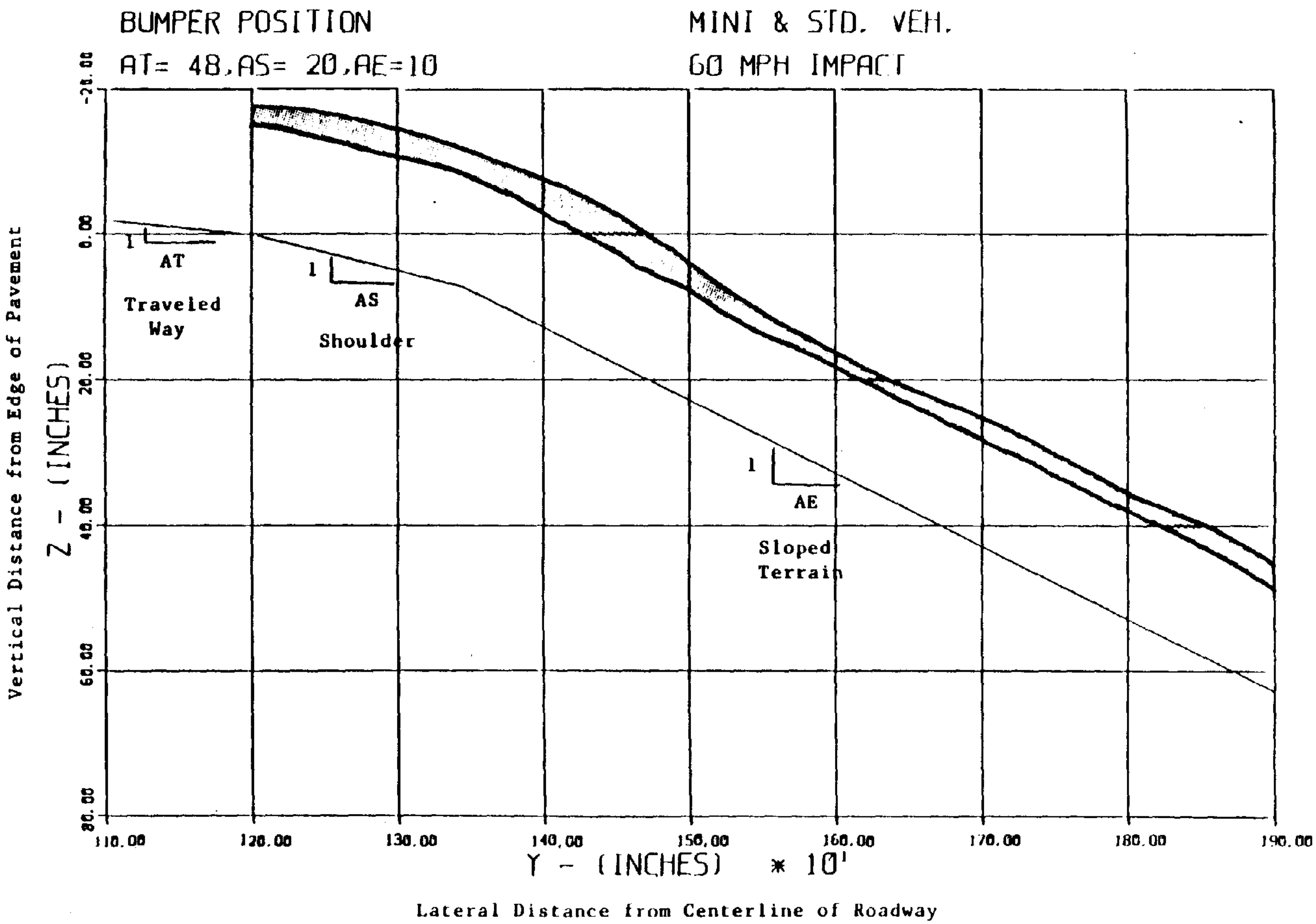


Figure 60. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = 10).

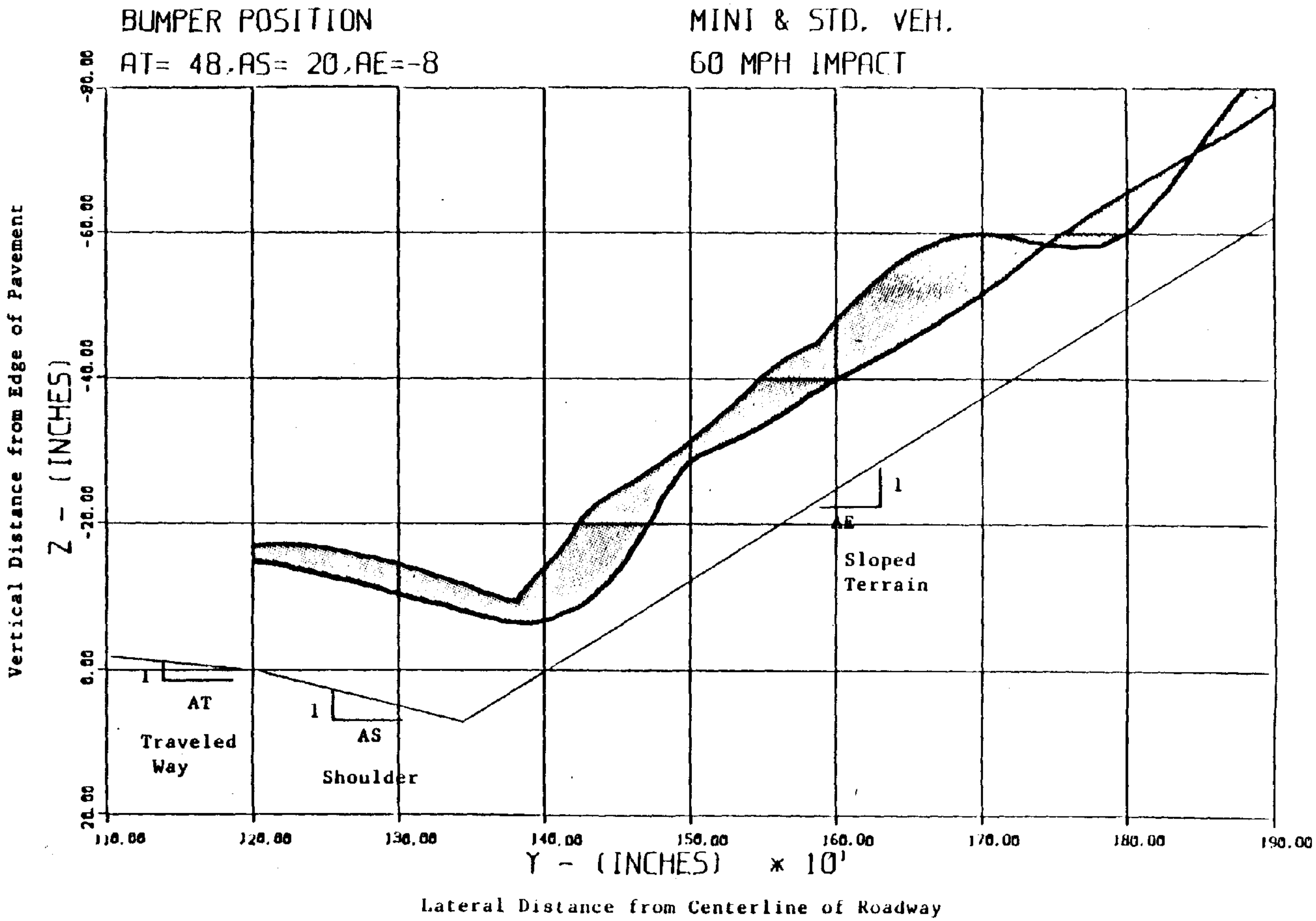


Figure 61. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = -8).

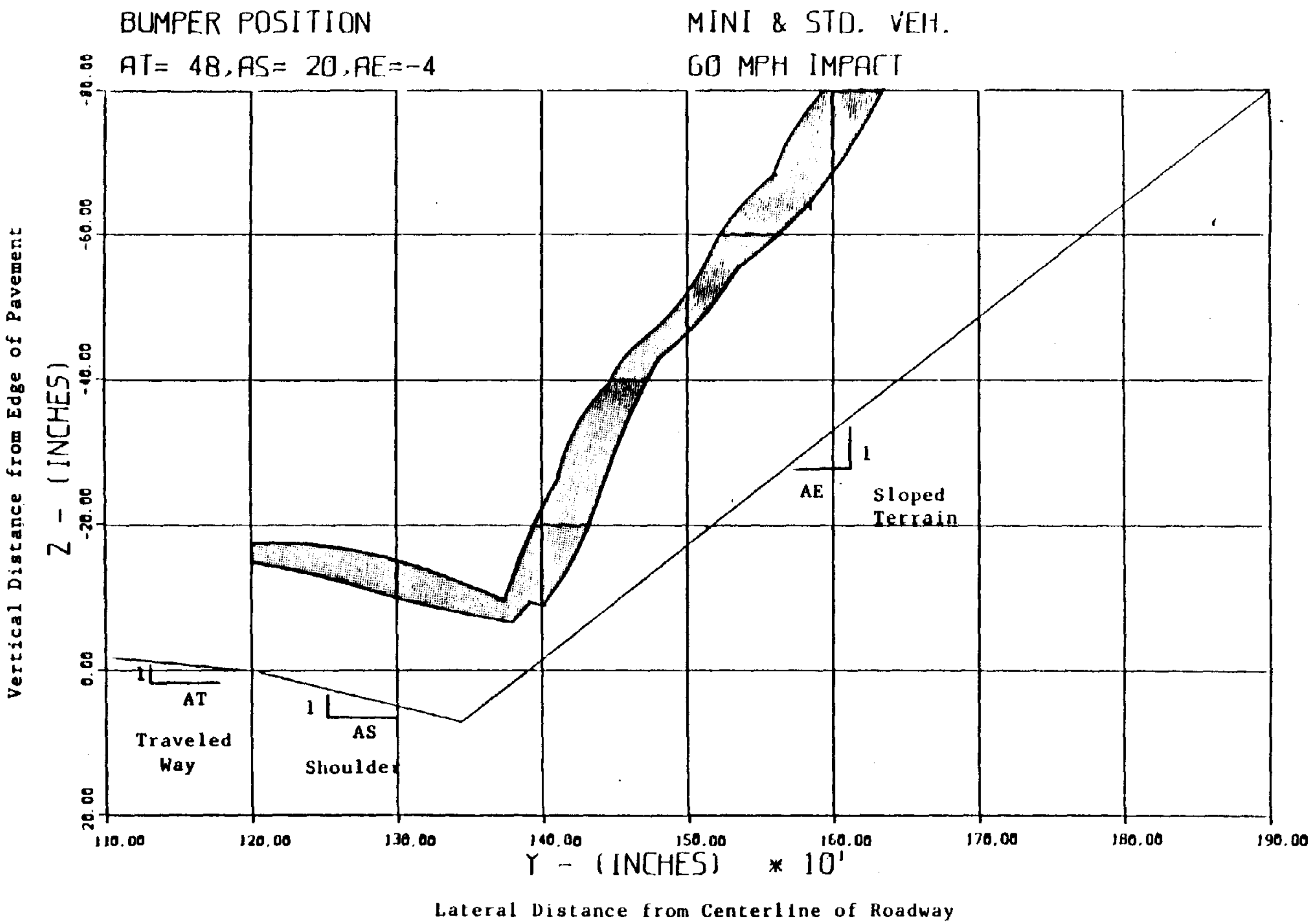


Figure 62. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = -4).

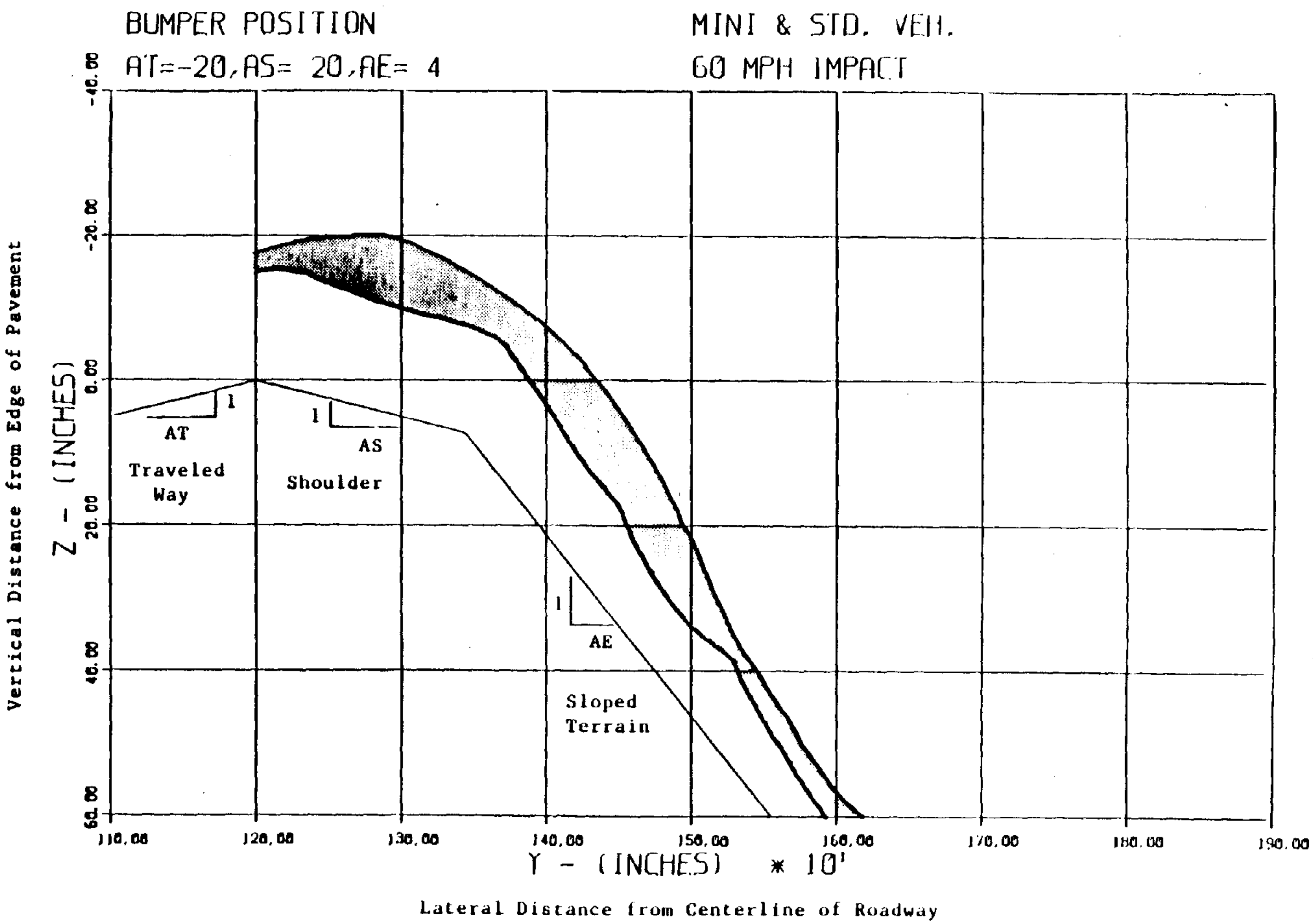


Figure 63. Barrier limits (G4(1S) system, AT = 48, AS = 20, AE = 4).

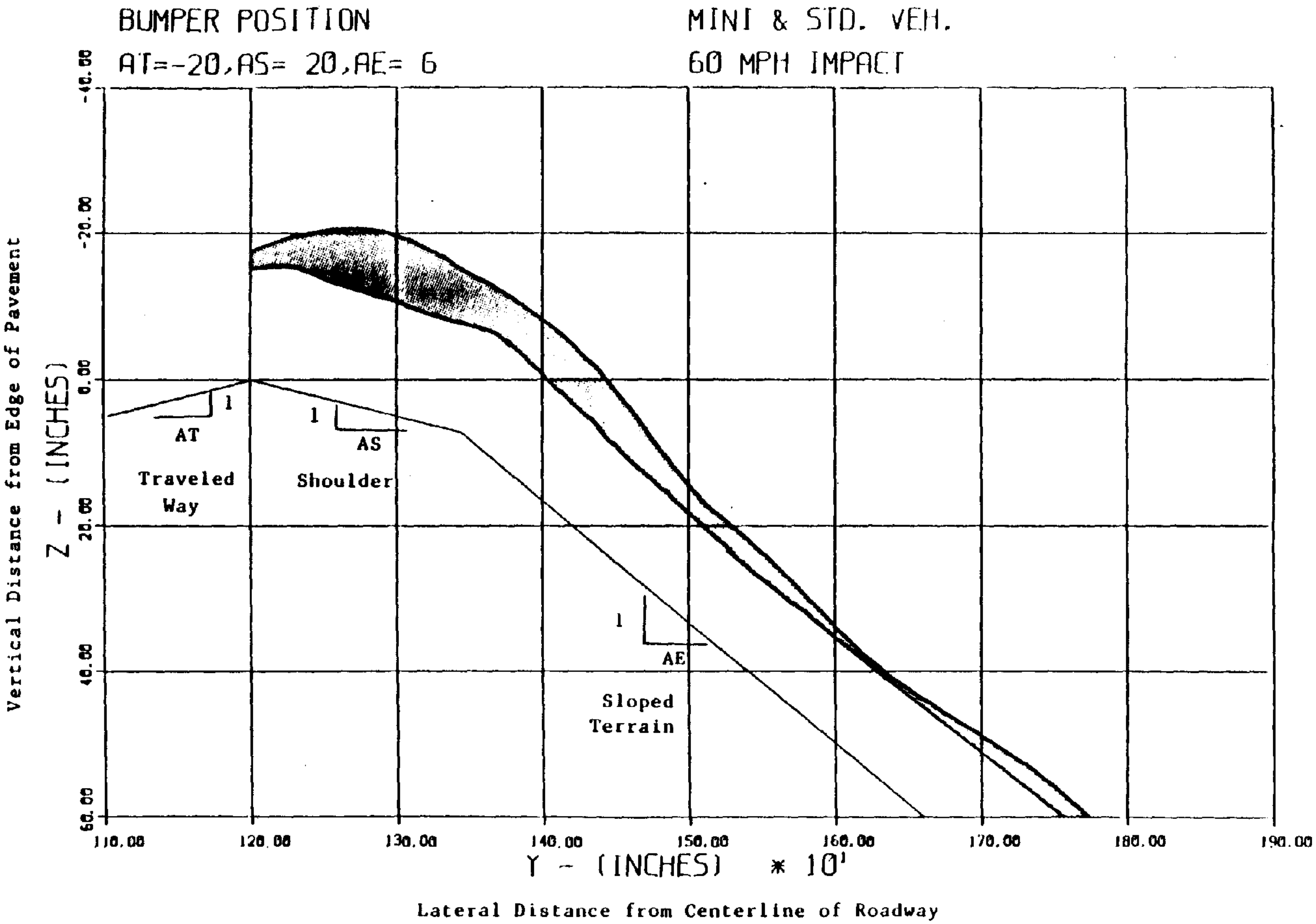


Figure 64. Barrier limits (G4(1S) system, AT = -20, AS = 20, AE = 6).

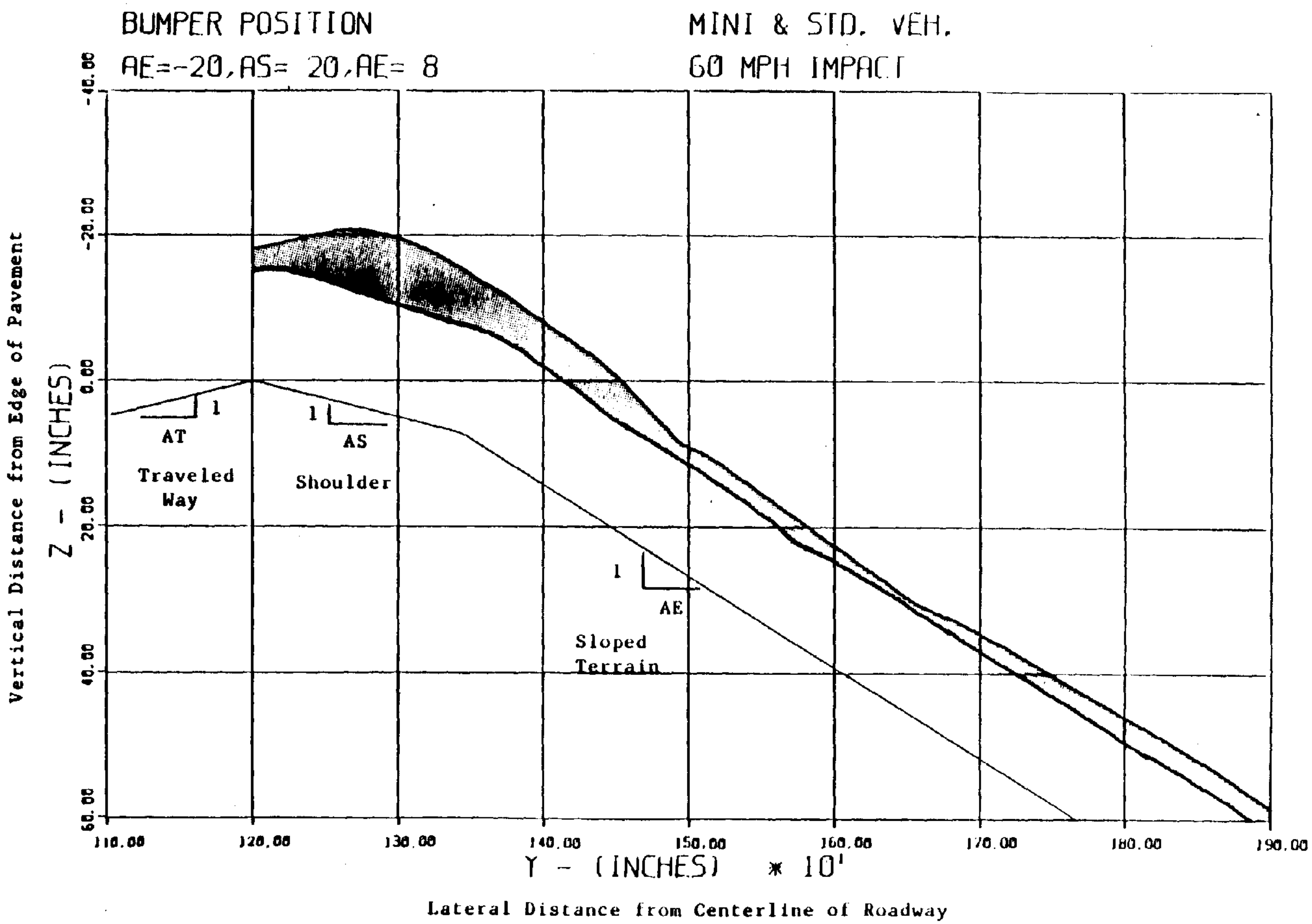


Figure 65. Barrier limits (G4(1S) system, AT = -20, AS = 20, AE = 8).

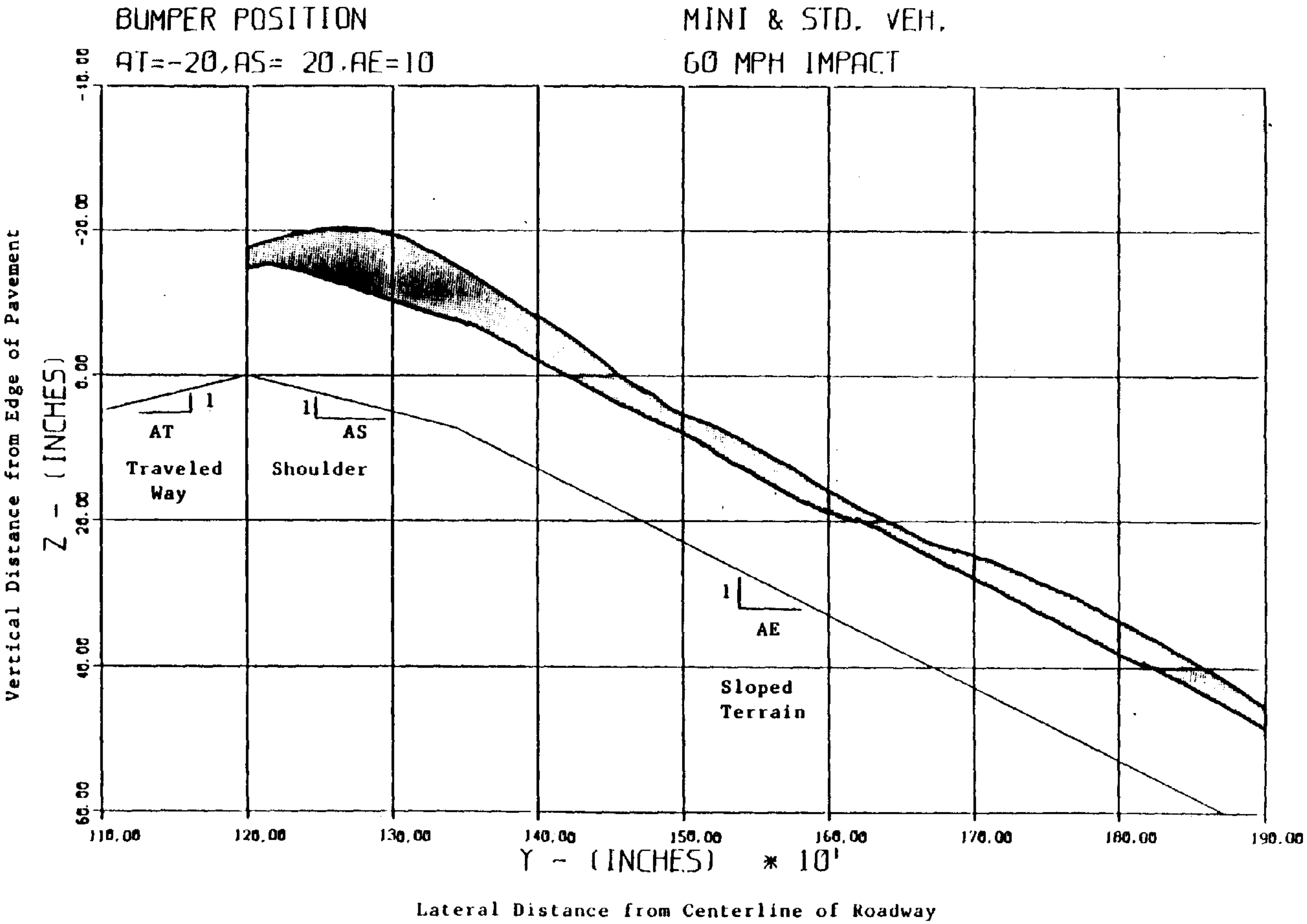


Figure 66. Barrier limits (G4(1S) system, AT = -20, AS = 20, AE = 10).

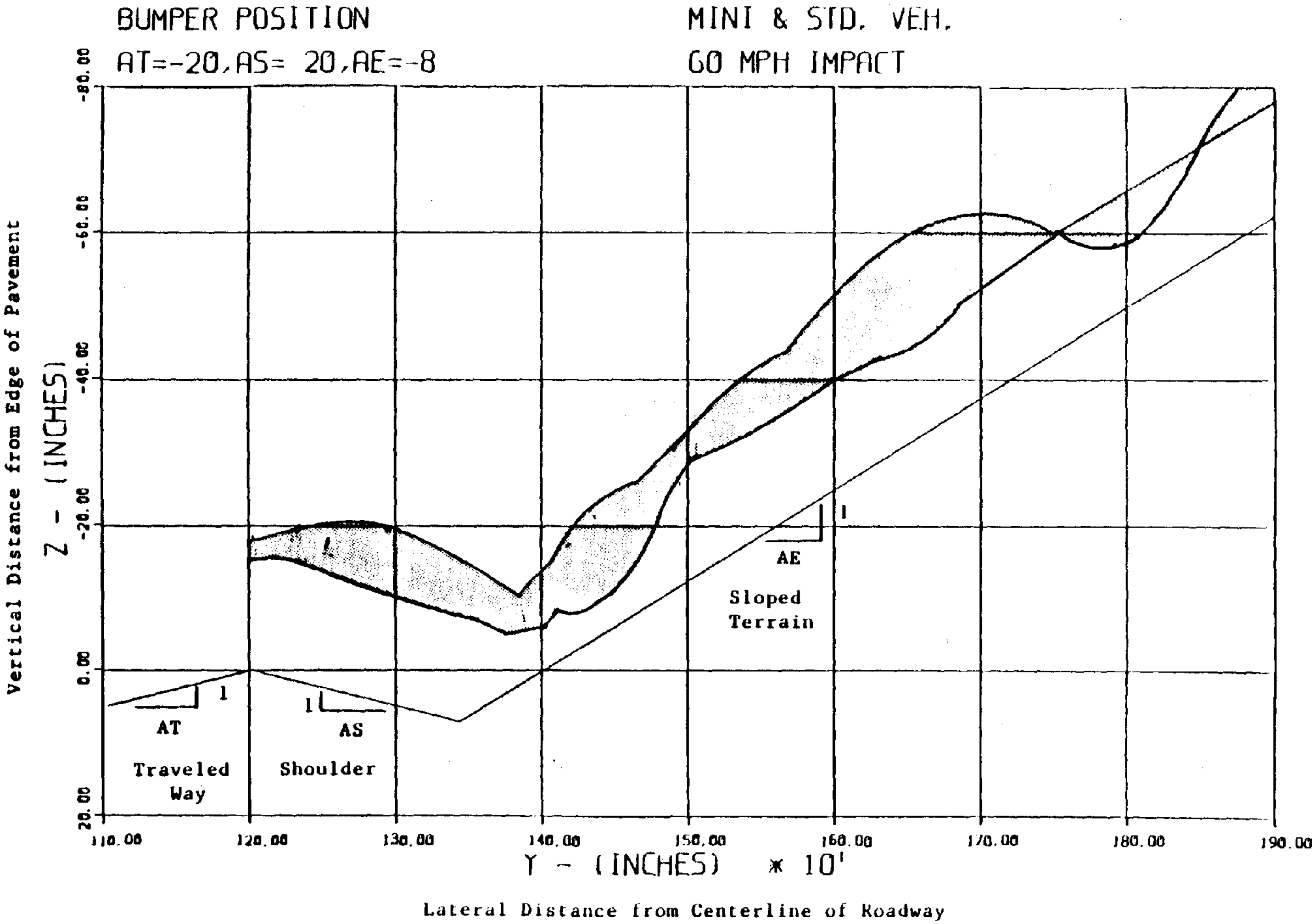


Figure 67. Barrier limits (G4(1S) system, AT = -20, AS = 20, AE = -8).

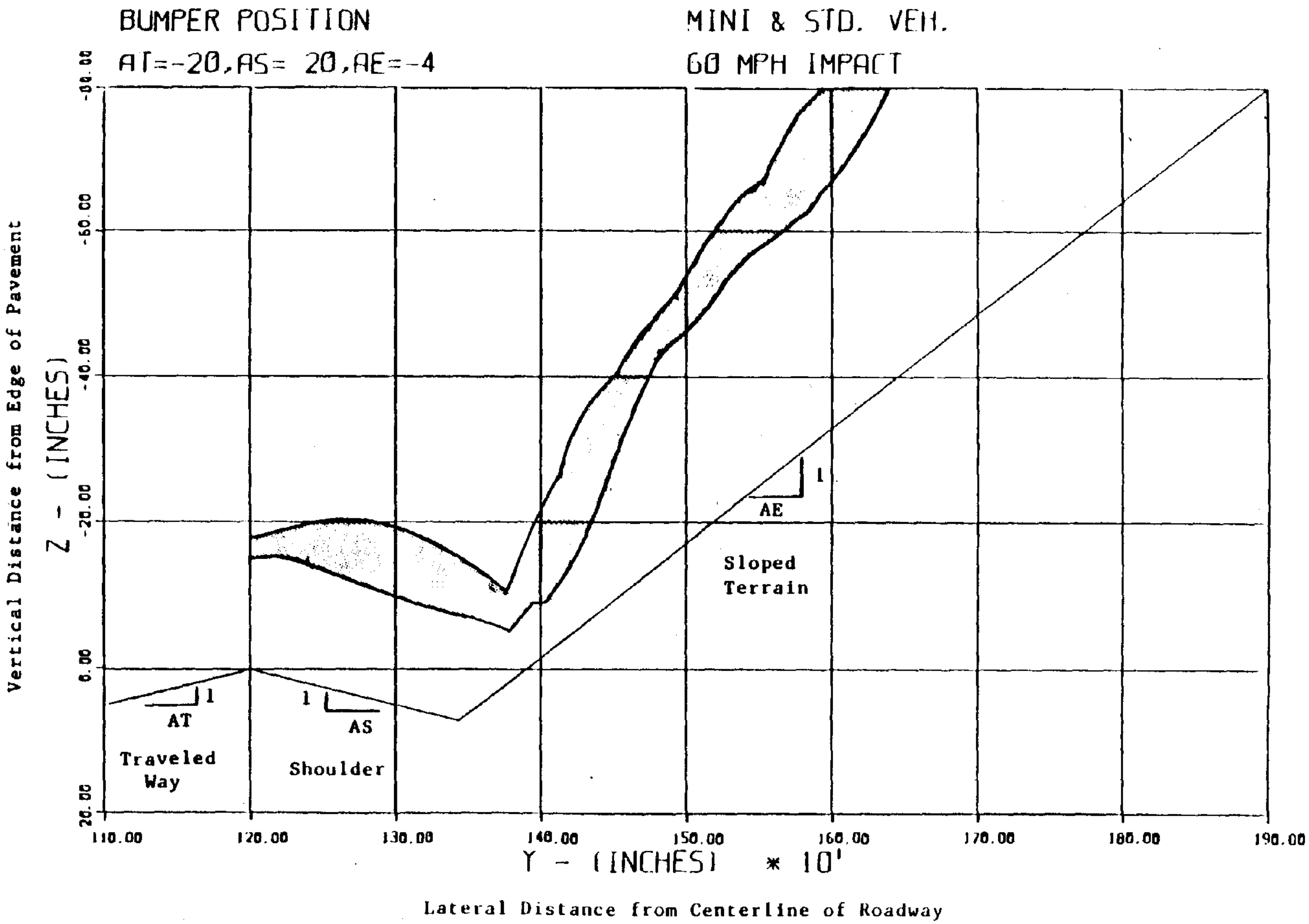


Figure 68. Barrier limits (G4(1S) system, AT = -20, AS = 20, AE = -4).

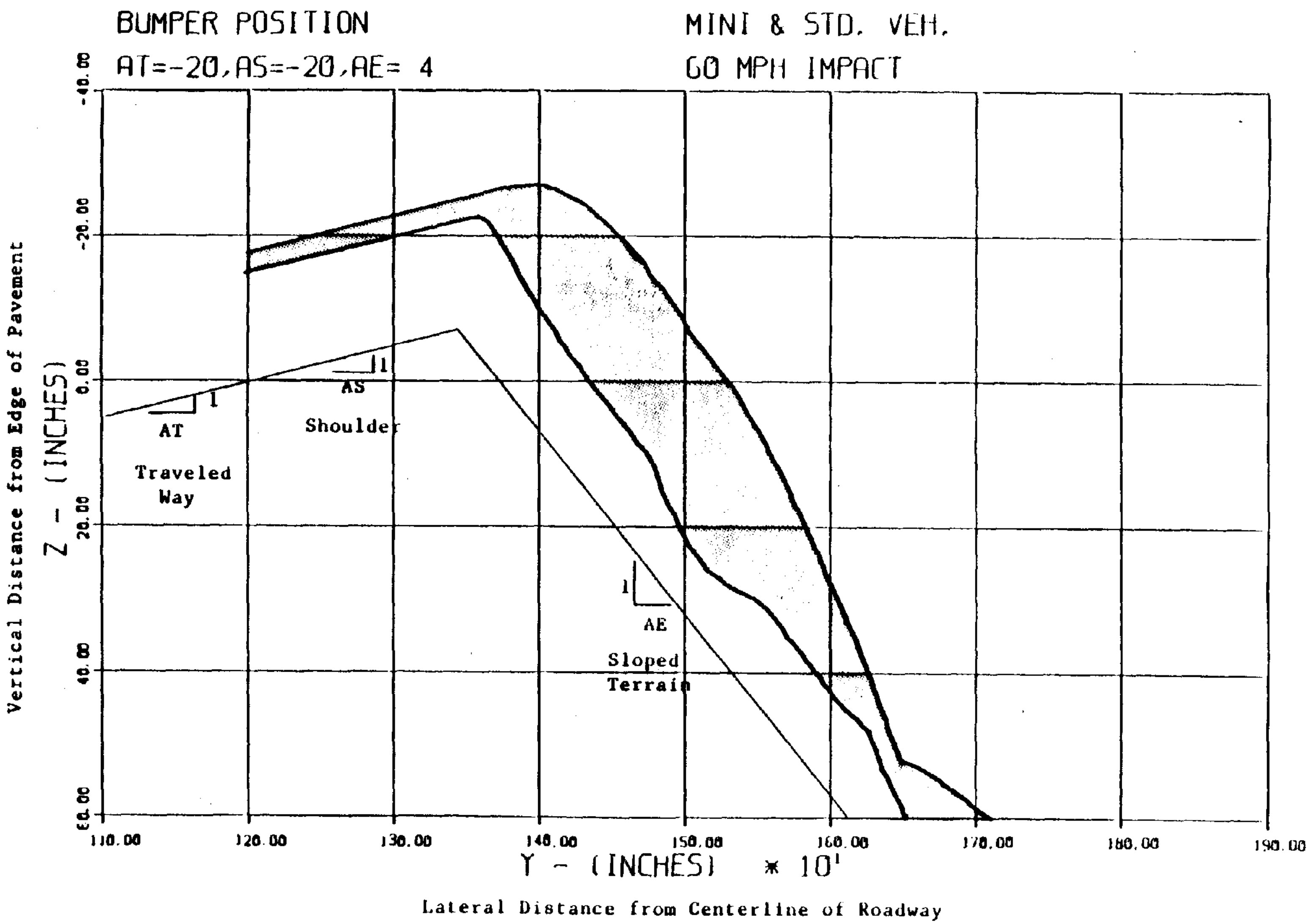


Figure 69. Barrier limits (G4(1S) system, AT = -20, AS = -20, AE = 4).

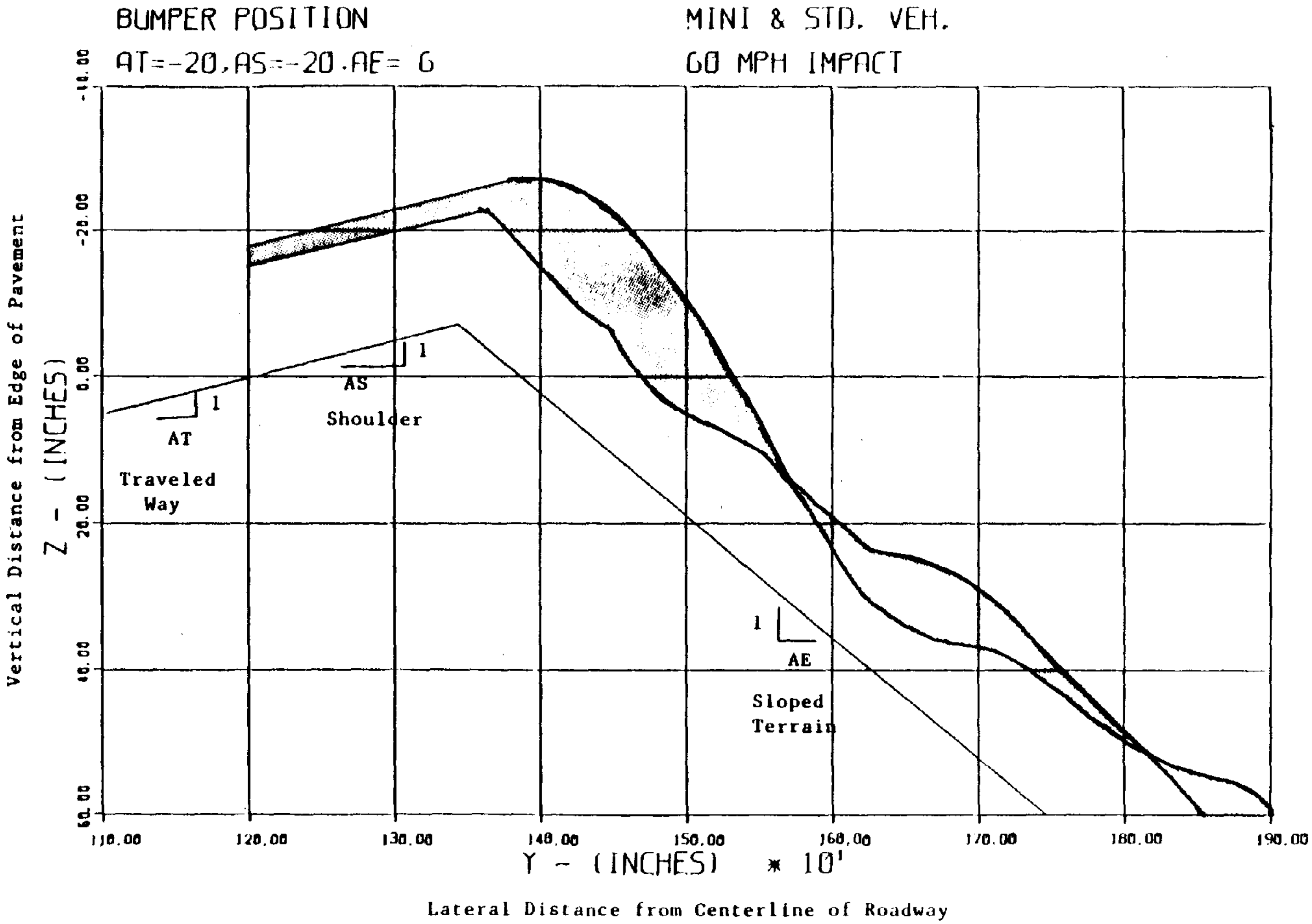


Figure 70. Barrier limits (G4(1S) system, AT = -20, AS = -20, AE = 6).

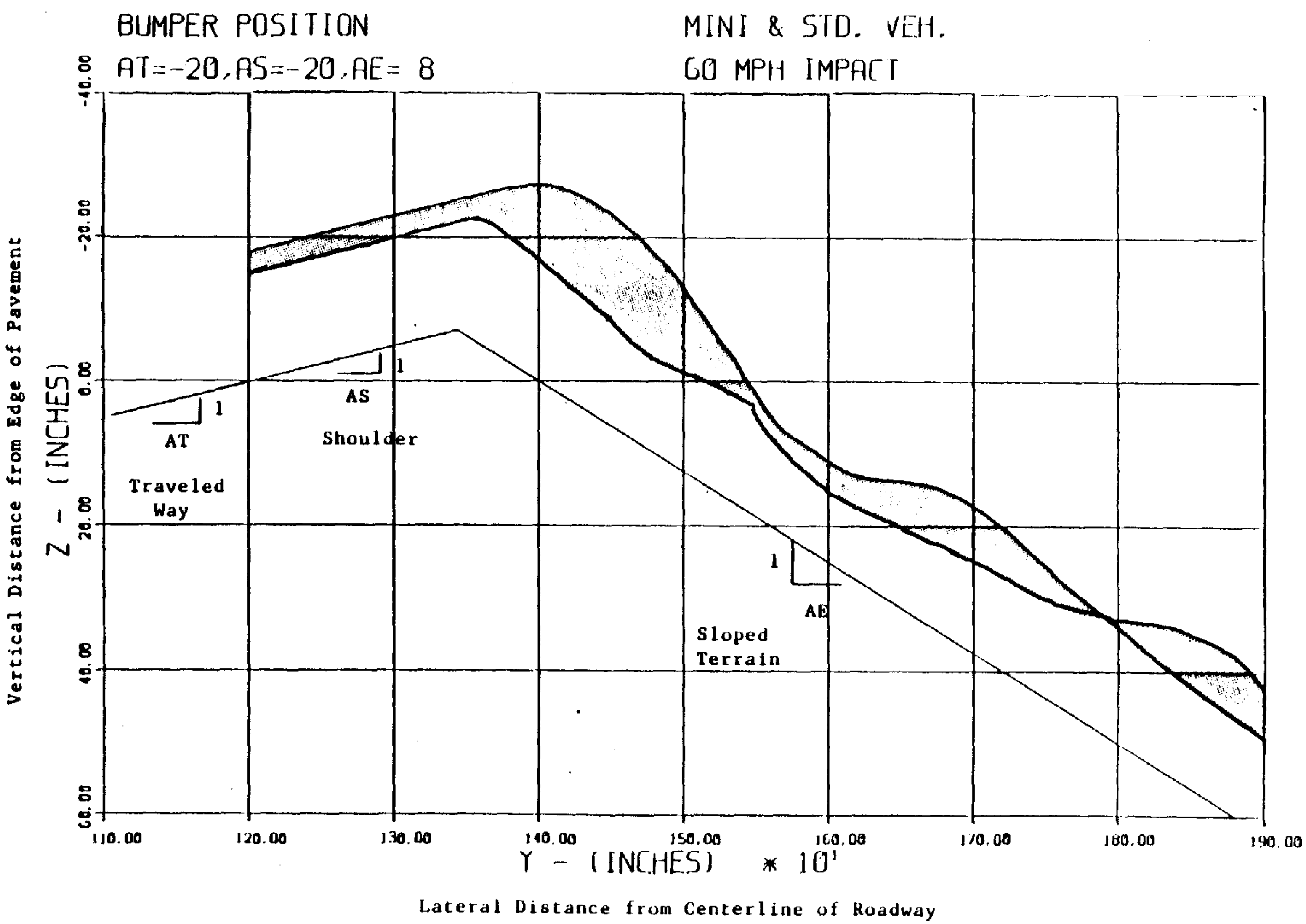


Figure 71. Barrier limits (G4(1S) system, AT = -20, AS = -20, AE = 8).

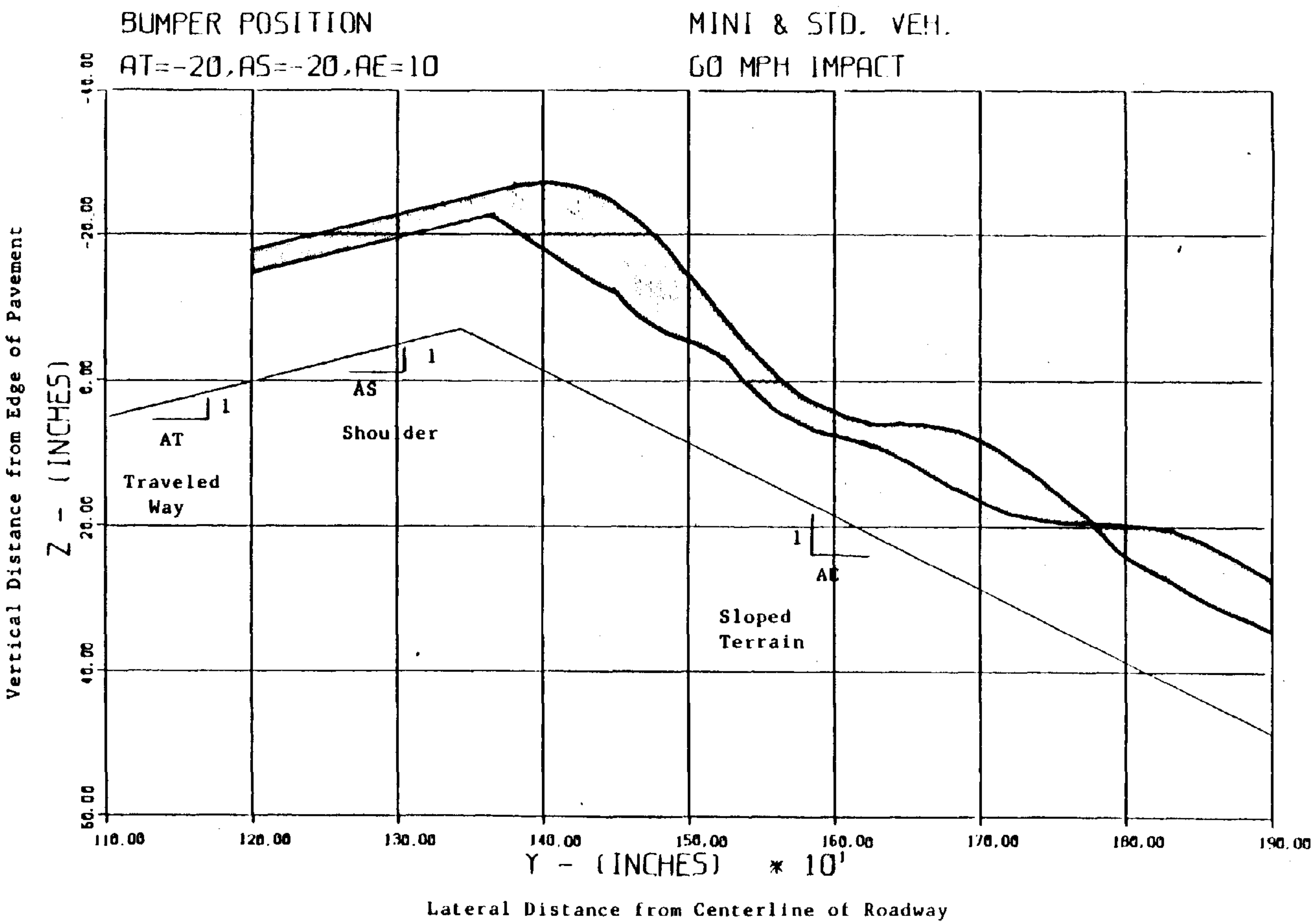


Figure 72. Barrier limits (G4(1S) system, AT = -20, AS = -20, AE = 10).

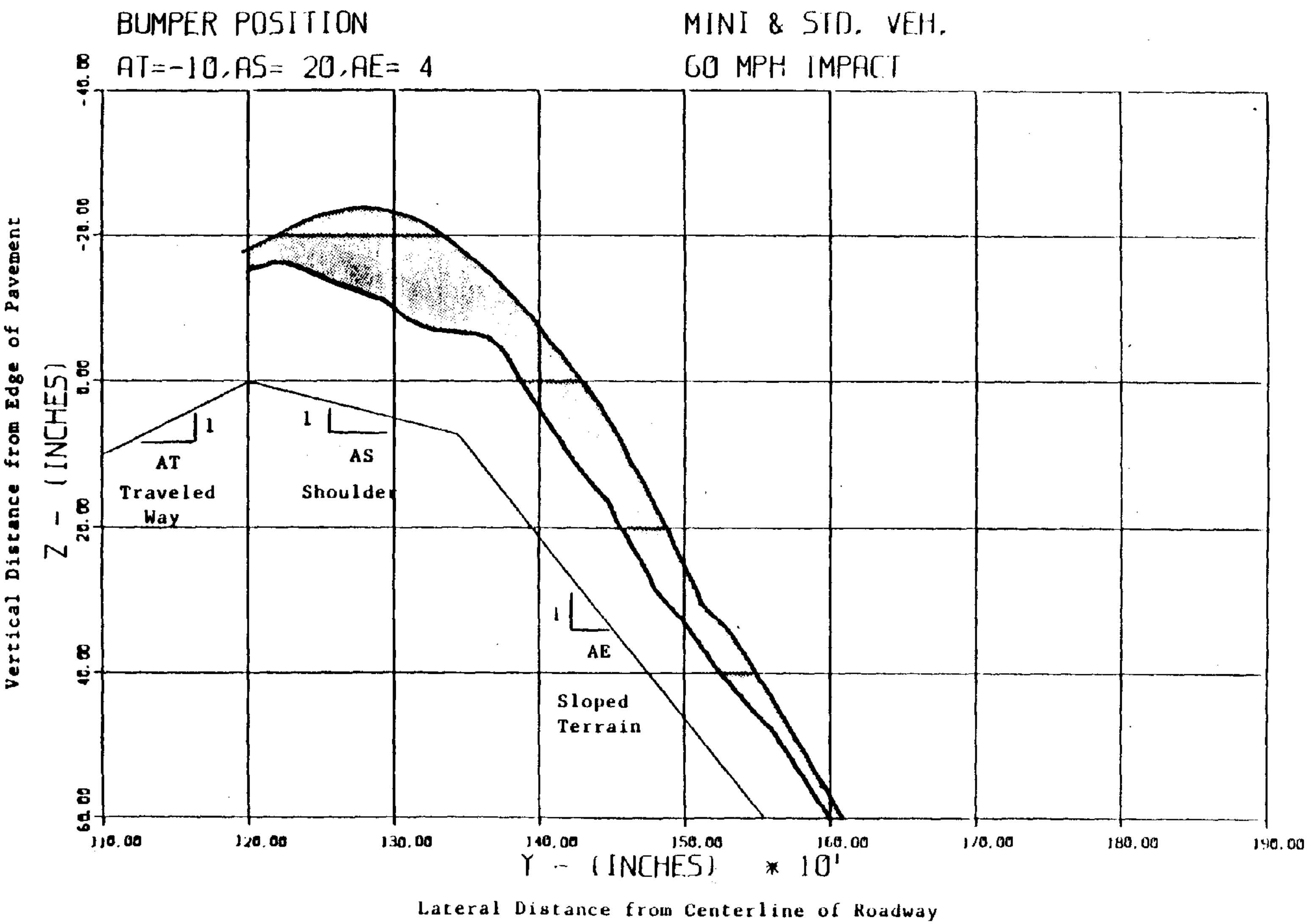


Figure 73. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = 4).

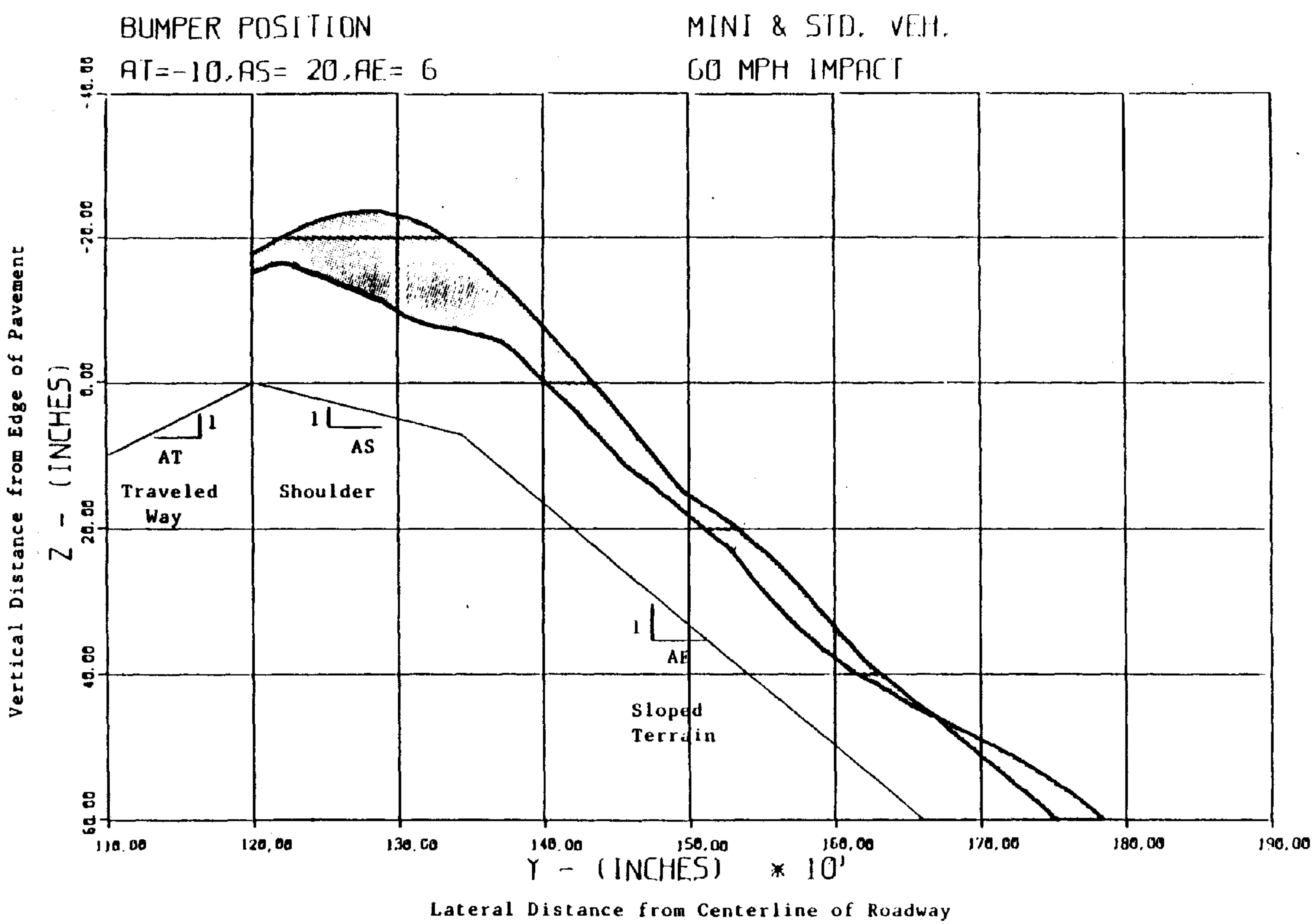


Figure 74. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = 6).

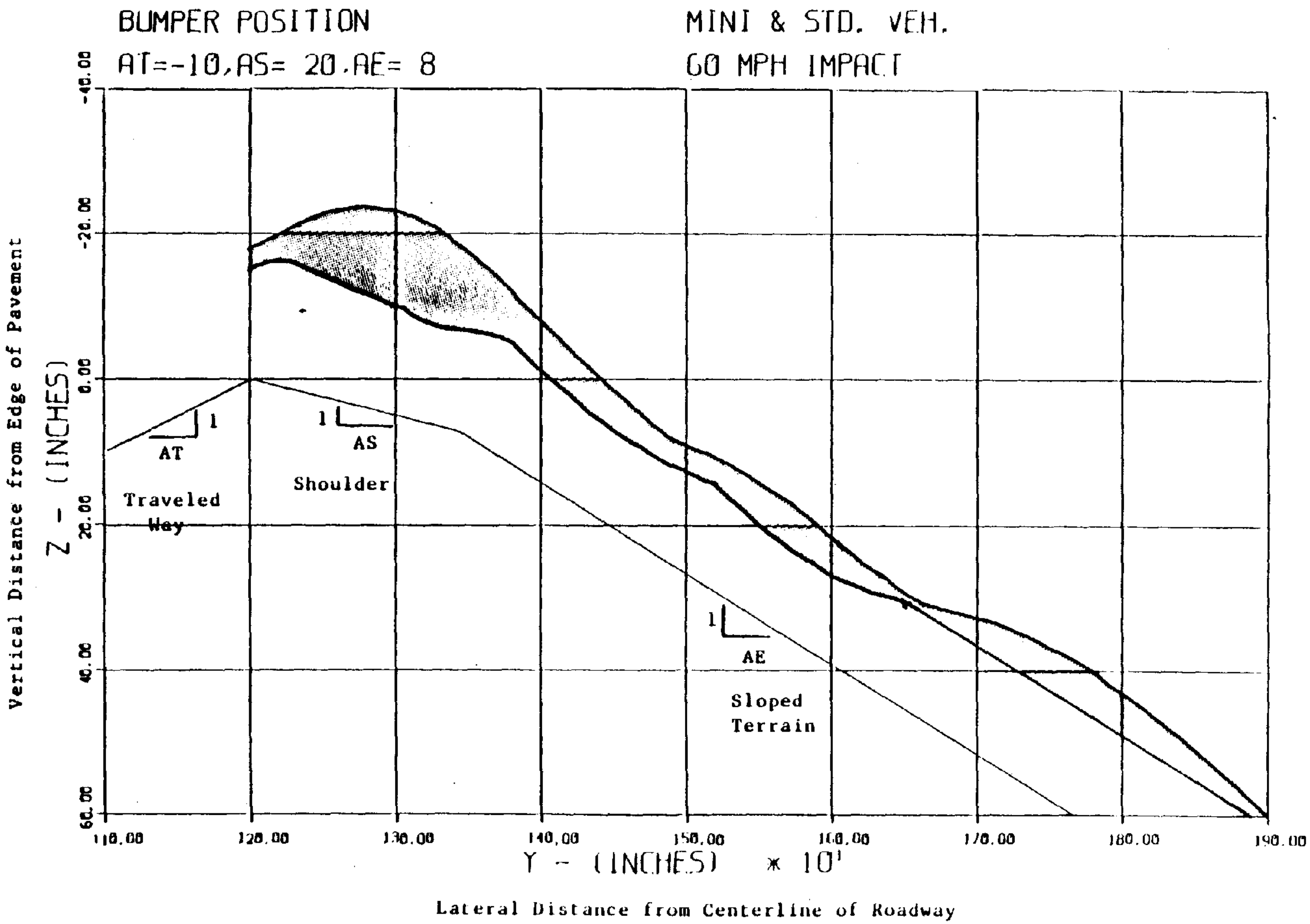


Figure 75. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = 8).

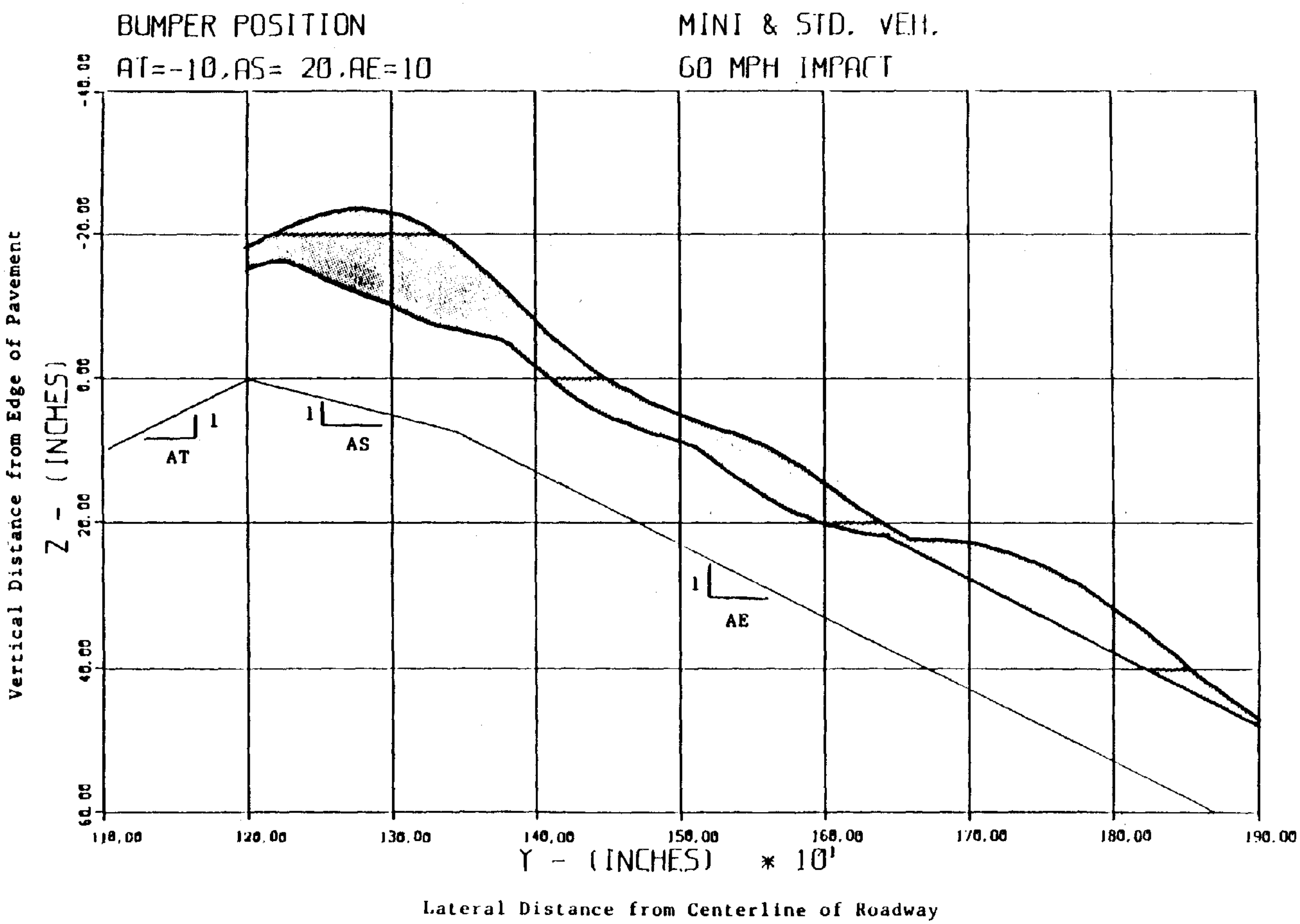


Figure 76. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = 10).

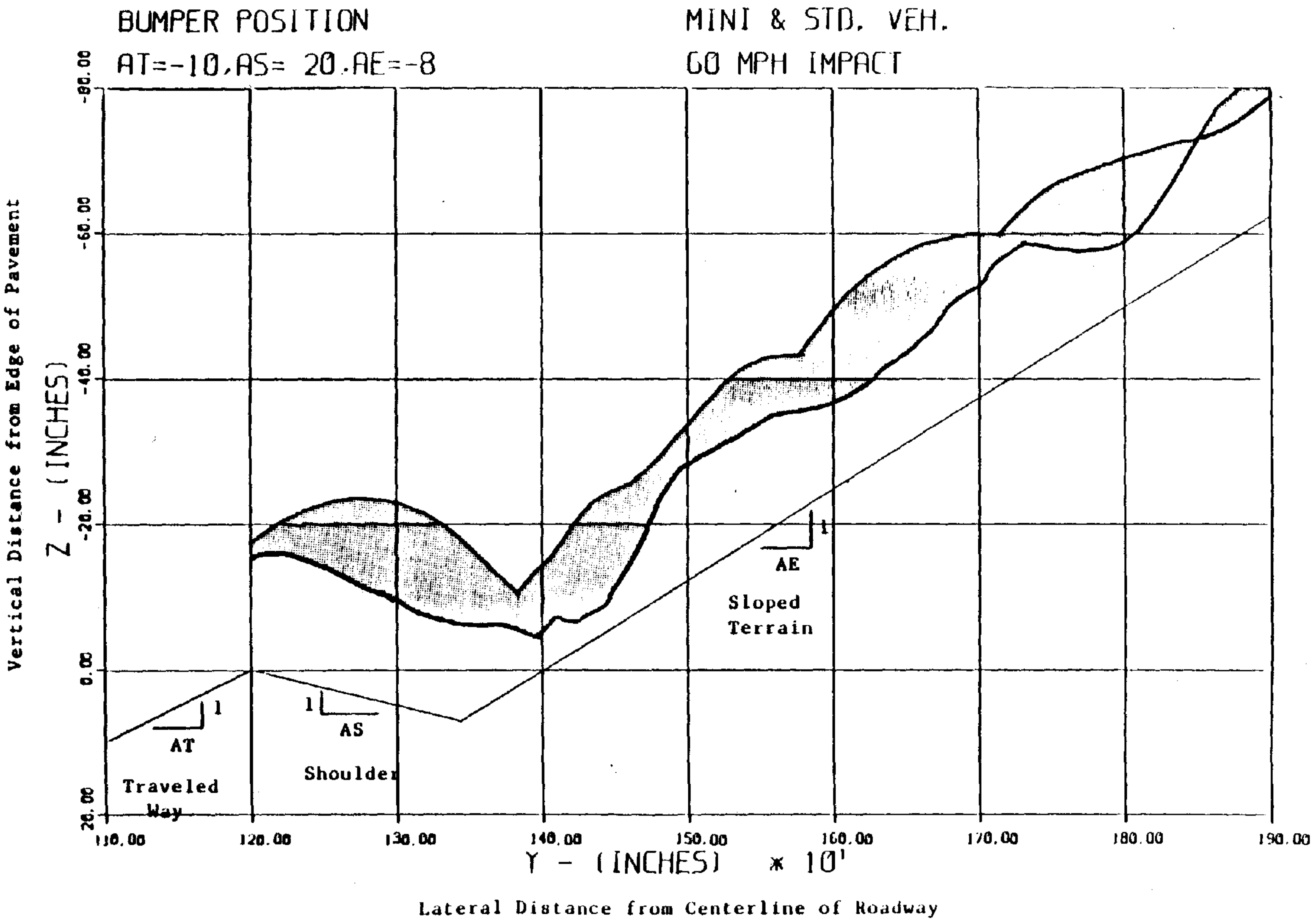


Figure 77. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = -8).

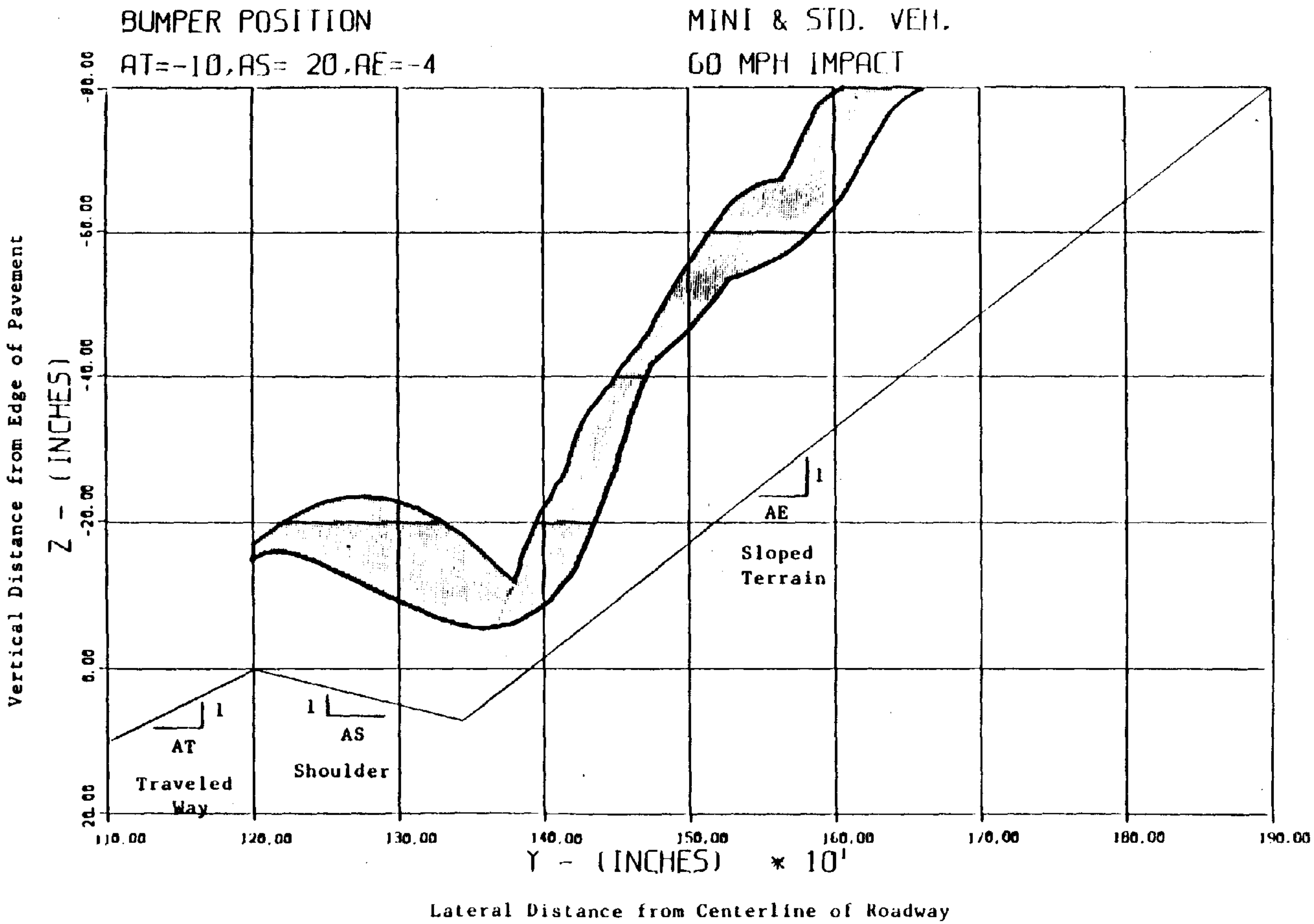


Figure 78. Barrier limits (G4(1S) system, AT = -10, AS = 20, AE = -4).

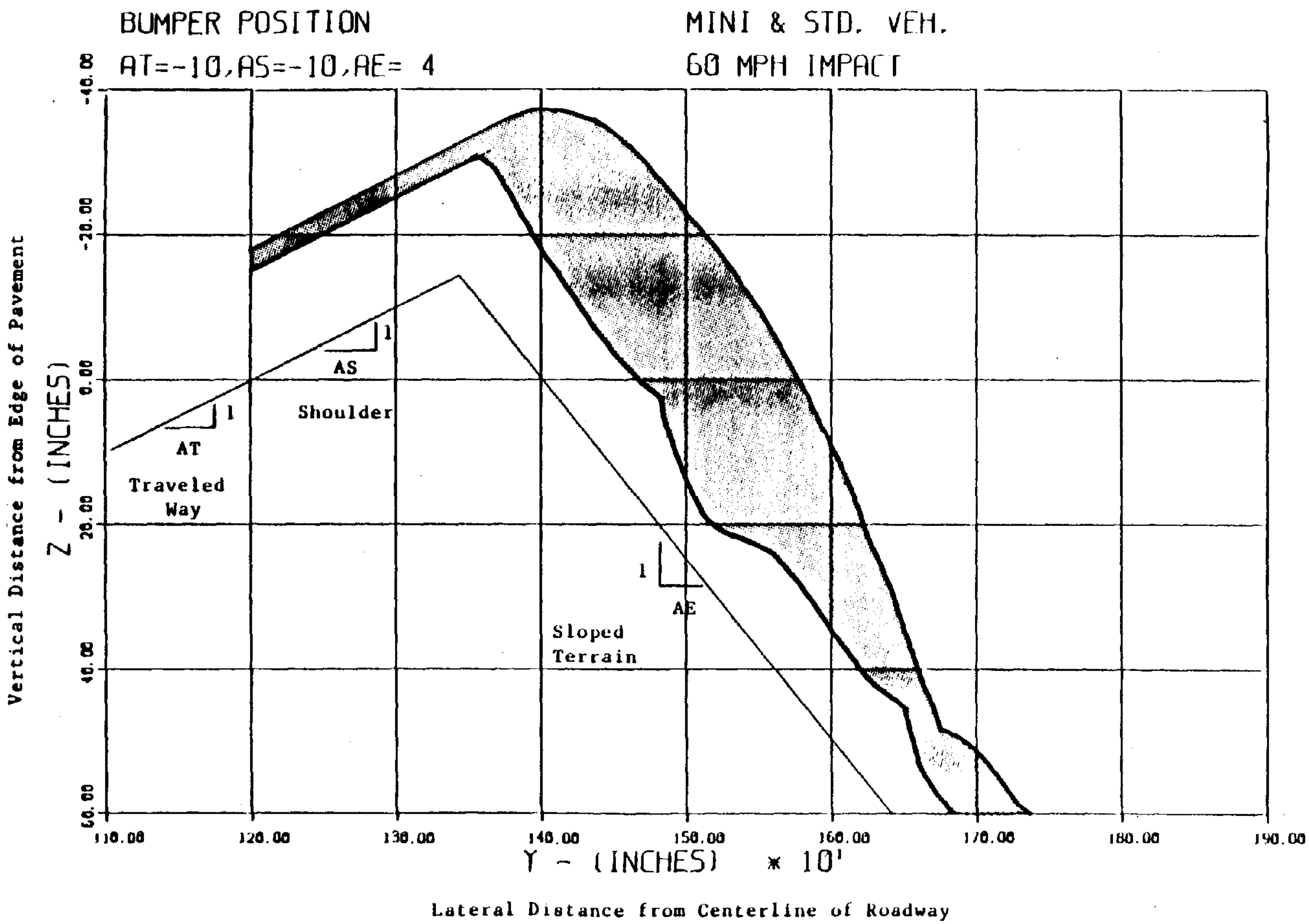


Figure 79. Barrier limits (G4(1S) system, AT = -10, AS = -10, AE = 4).

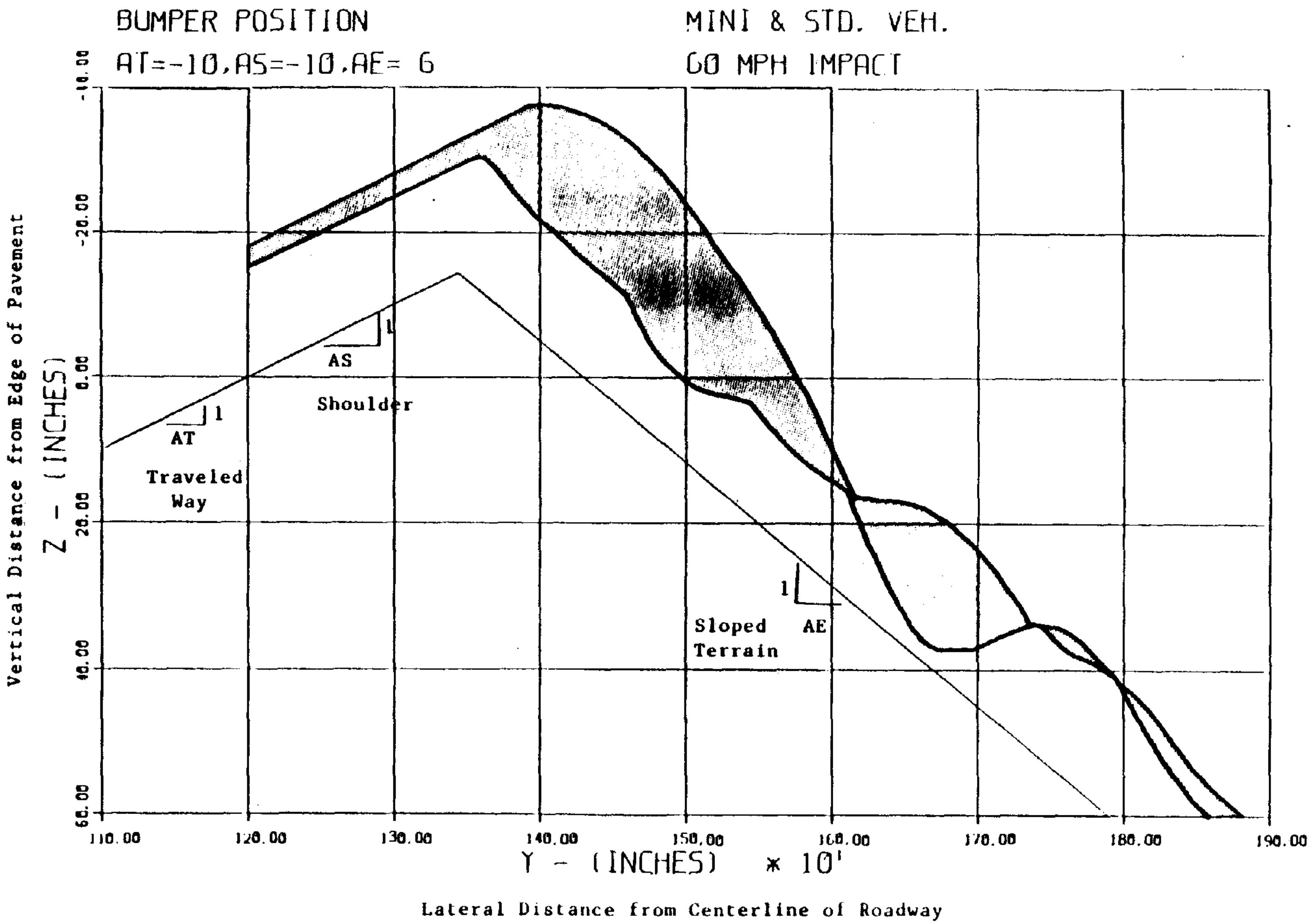


Figure 80. Barrier limits (G4(1S) system, AT = -10, AS = -10, AE = 6).

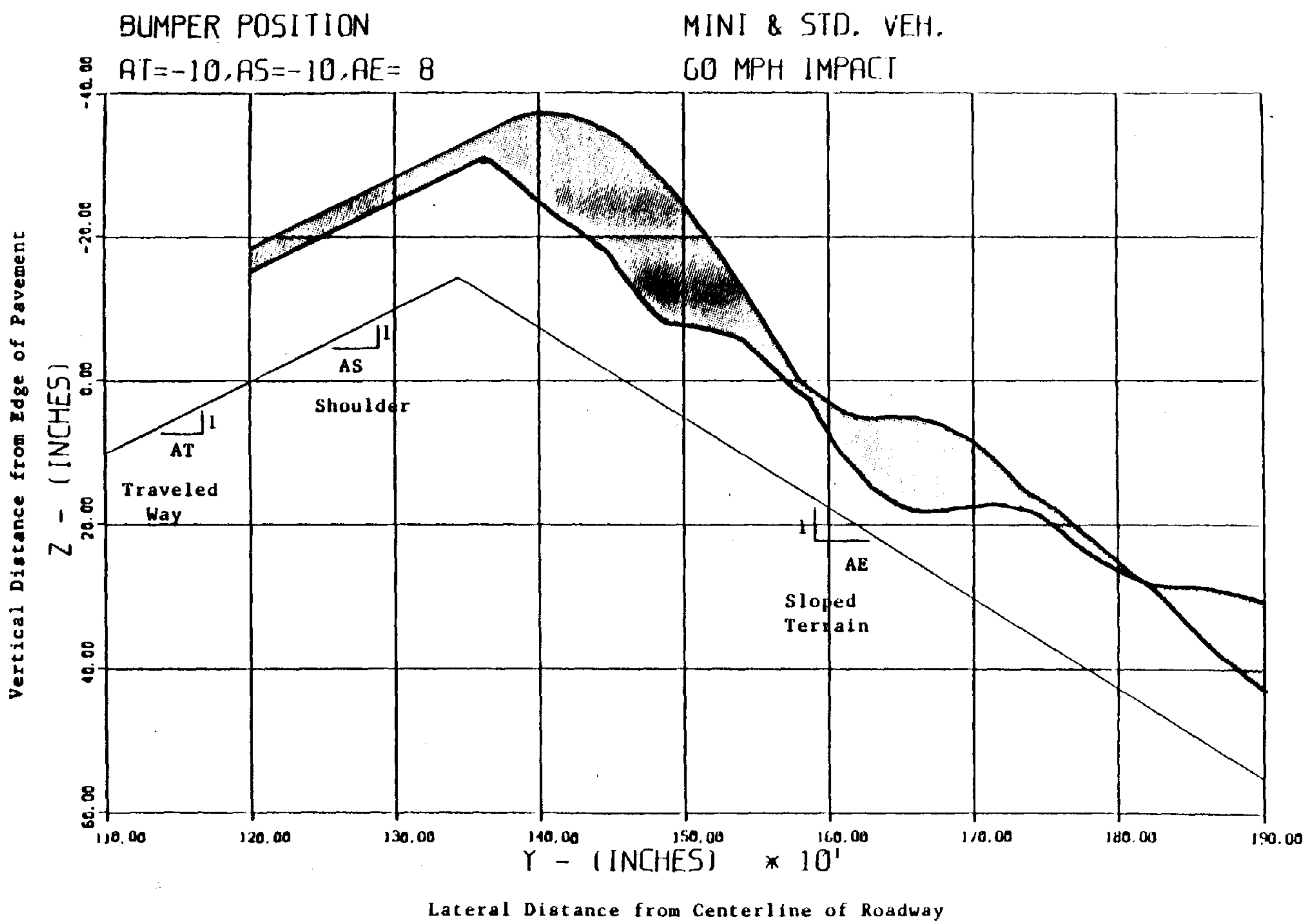


Figure 81. Barrier limits (G4(1S) system, AT = -10, AS = -10, AE = 8).

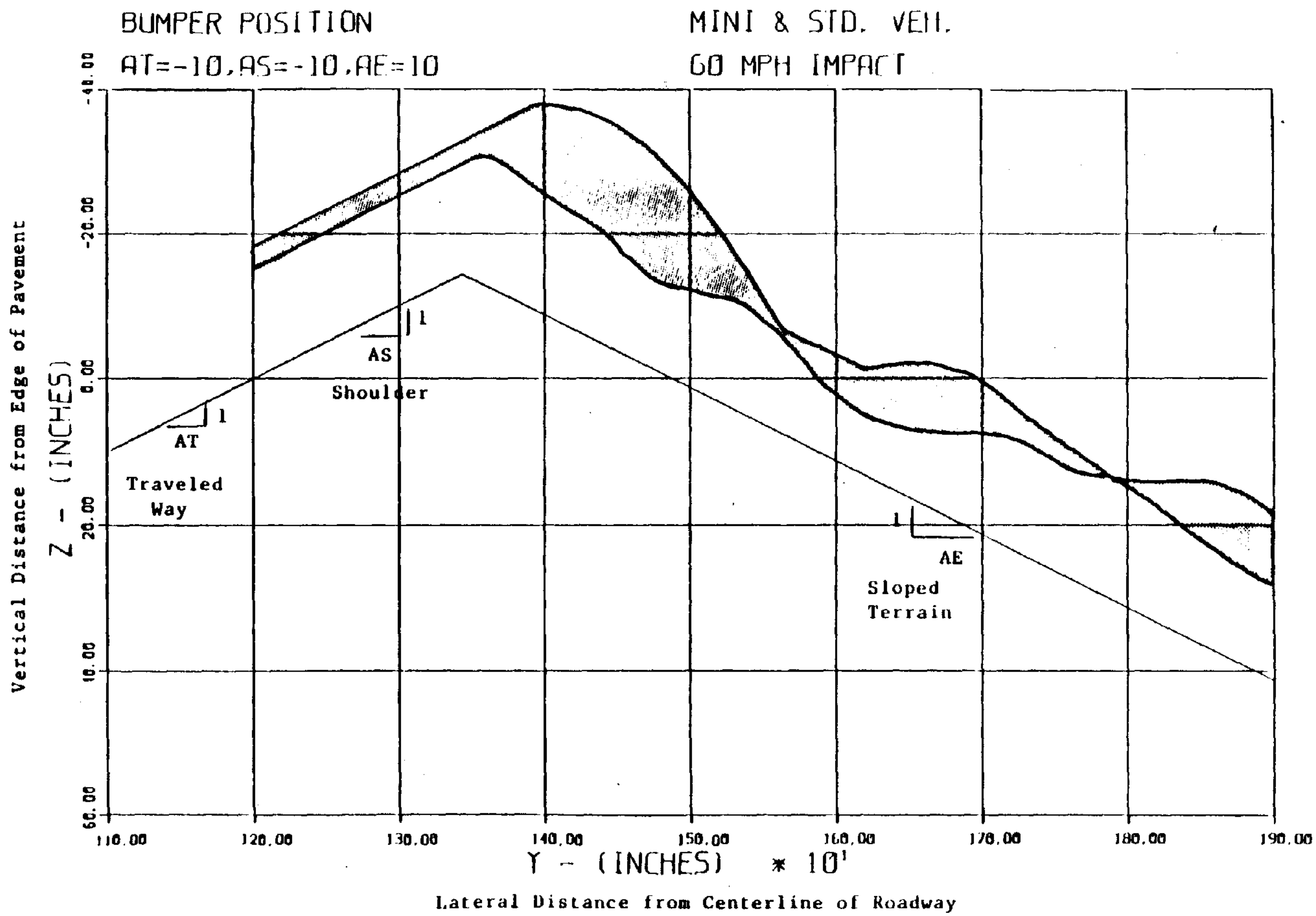


Figure 82. Barrier limits (G4(1S) system, AT = -10, AS = -10, AE = 10).

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote these projects.*

FCP Category Descriptions

1. **Improved Highway Design and Operation for Safety**

   Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. **Reduction of Traffic Congestion and Improved Operational Efficiency**

   Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. **Environmental Considerations in Highway Design, Location, Construction and Operation**

   Environmental R&D is directed toward identifying and evaluating Highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. **Improved Materials Utilization and Durability**

   Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. **Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety**

   Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. **Prototype Development and Implementation of Research**

   This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. **Improved Technology for Highway Maintenance**

   Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

*The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22101 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.