

FHWA/RD-87/096

EVALUATION OF DESIGN ANALYSIS PROCEDURES
AND ACCEPTANCE CRITERIA FOR ROADSIDE HARDWARE

Volume I: Executive Summary



August 1987
Final Report

This document is available to the public
through the National Technical Information
Service, Springfield, Virginia 21161.

Prepared for
Safety Design Division
FEDERAL HIGHWAY ADMINISTRATION
6300 Georgetown Pike
McLean, VA 22101-2296

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The contents of this report reflect the views of Southwest Research Institute, which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official policy of the Department of Transportation.

This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the object of this document.

1. Report No. FHWA/RD-87/096		2. Government Accession No. PB88 169610IAS		3. Recipient's Catalog No.																						
4. Title and Subtitle EVALUATION OF DESIGN ANALYSIS PROCEDURES AND ACCEPTANCE CRITERIA FOR ROADSIDE HARDWARE Volume I. Executive Summary				5. Report Date July 31, 1987																						
				6. Performing Organization Code 06-7321																						
7. Author(s) M. H. Ray				8. Performing Organization Report No.																						
9. Performing Organization Name and Address Southwest Research Institute 6220 Culebra Road, P.O. Drawer 28510 San Antonio, TX 78284				10. Work Unit No.																						
				11. Contract or Grant No. DTFH61-82-C-00086																						
12. Sponsoring Agency Name and Address Safety Design Division FEDERAL HIGHWAY ADMINISTRATION 6300 Georgetown Pike McLean, VA 22101-2296				13. Type of Report and Period Covered Final Report October 1982 - August 1987																						
				14. Sponsoring Agency Code																						
15. Supplementary Notes FHWA Contract Manager: Martin Hargrave (HSR-20)																										
16. Abstract This research was conducted to identify and investigate aspects of NCHRP <u>Report 230</u> which require additional technical research. This report deals with five broad areas of concern: (1) the importance and effect of soil conditions on the dynamic performance of barriers, (2) methods for re-evaluating pre- <u>Report 230</u> test results in light of the current <u>Report 230</u> criteria, (3) linking the occupant risk factor to "real-world" accident cases, (4) assessing the potential hazards of the redirected vehicle, and (5) replacement of the 4500-lb test car. This is the first of a six-volume report dealing with specific technical topics in NCHRP <u>Report 230</u> . The others in the series are: <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Vol. No.</th> <th style="text-align: left;">FHWA No.</th> <th style="text-align: left;">Title</th> </tr> </thead> <tbody> <tr> <td>I</td> <td>RD-87/096</td> <td>Executive Summary</td> </tr> <tr> <td>II</td> <td>RD-87/097</td> <td>The Effect of Soil Strength on Longitudinal Barrier Performance</td> </tr> <tr> <td>III</td> <td>RD-87/098</td> <td>Evaluating Pre-<u>Report 230</u> Crash Tests</td> </tr> <tr> <td>IV</td> <td>RD-87/099</td> <td>The Importance of the Occupant Risk Criteria</td> </tr> <tr> <td>V</td> <td>RD-87/100</td> <td>Hazards of the Redirected Car</td> </tr> <tr> <td>VI</td> <td>RD-87/101</td> <td>Replacing the 4500-lb Passenger Sedan in <u>Report 230</u> Tests</td> </tr> </tbody> </table>						Vol. No.	FHWA No.	Title	I	RD-87/096	Executive Summary	II	RD-87/097	The Effect of Soil Strength on Longitudinal Barrier Performance	III	RD-87/098	Evaluating Pre- <u>Report 230</u> Crash Tests	IV	RD-87/099	The Importance of the Occupant Risk Criteria	V	RD-87/100	Hazards of the Redirected Car	VI	RD-87/101	Replacing the 4500-lb Passenger Sedan in <u>Report 230</u> Tests
Vol. No.	FHWA No.	Title																								
I	RD-87/096	Executive Summary																								
II	RD-87/097	The Effect of Soil Strength on Longitudinal Barrier Performance																								
III	RD-87/098	Evaluating Pre- <u>Report 230</u> Crash Tests																								
IV	RD-87/099	The Importance of the Occupant Risk Criteria																								
V	RD-87/100	Hazards of the Redirected Car																								
VI	RD-87/101	Replacing the 4500-lb Passenger Sedan in <u>Report 230</u> Tests																								
17. Key Words Report 230, Crash tests, Full-scale crash test, Evaluation criteria, Performance criteria			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.																							
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 31	22. Price																					

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 m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
----	------------------------	----------------------------	---------------------	----

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	hectares (10 000 m ²)	2.53	acres	ac

MASS (weight)

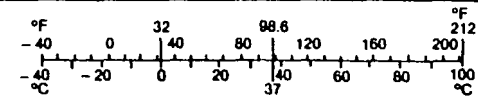
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

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.

* SI is the symbol for the International System of Measurements

TABLE OF CONTENTS

VOLUME I: EXECUTIVE SUMMARY

<u>Section</u>	<u>Page</u>
Introduction.....	1
The Effect of Soil Strength on Longitudinal Barrier Performance.....	2
Evaluating Pre-Report 230 Crash Tests.....	2
The Occupant Risk Criteria.....	3
Hazards of the Redirected Car.....	4
Replacing the 4500-lb Car.....	5
References.....	6

VOLUME II: THE EFFECT OF SOIL STRENGTH ON LONGITUDINAL BARRIER PERFORMANCE

<u>Section</u>	<u>Page</u>
Objectives.....	1
Characterizing the Force-Deflection Properties of Posts in Soil.....	3
Effect of Soil Strength on Barrier Performance.....	8
Computer Simulations.....	8
Full-Scale Crash Tests.....	10
Conclusions and Recommendations.....	5
Conclusions.....	15
Recommendations.....	15
Appendix A. Pendulum Tests.....	17
Test Procedures.....	17
Test Data.....	19
Appendix B. Soil-Post Interaction Crash Tests.....	37
Introduction.....	37
Conclusion.....	38
Test SPI-1.....	41
Test SPI-2.....	59
Test SPI-3.....	76

TABLE OF CONTENTS (continued)

VOLUME III: EVALUATING PRE-REPORT 230 CRASH TESTS

<u>Section</u>	<u>Page</u>
Objective	1
Data Processing.....	2
Estimating Occupant Risk With Vehicle Acceleration Data.....	8
Introduction.....	8
Relative Displacements.....	11
Relative Velocities.....	14
Yaw Rate Considerations.....	16
Summary.....	22
Estimating Occupant Risk Without Vehicle Acceleration Data.....	23
References.....	28

VOLUME IV: THE IMPORTANCE OF THE OCCUPANT RISK CRITERIA

<u>Section</u>	<u>Page</u>
Introduction.....	1
The Flail Space Model.....	1
Anthropometric Dummy Sled Tests.....	5
Accident Analysis of Occupant Injuries.....	12
Typical Values in Full-Scale Crash Tests.....	23
Discussion.....	26
Conclusions and Recommendations.....	30
Conclusions.....	30
Recommendations.....	31
References.....	33
Appendix A. A Survey of Passenger Compartment Geometry.....	34
Objective.....	34
Analyses and Results.....	34
Conclusions and Recommendations.....	62

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Page</u>
Appendix B. Sled Tests.....	63
Introduction.....	63
Experimental Procedures.....	63
Findings.....	68
Conclusions and Discussion.....	77

**VOLUME V: EVALUATION OF DESIGN ANALYSIS PROCEDURES AND ACCEPTANCE
CRITERIA FOR ROADSIDE HARDWARE**

<u>Section</u>	<u>Page</u>
Introduction.....	1
Accident Data.....	2
Fault-Tree Analysis.....	4
Conclusions and Recommendations.....	13
Conclusions.....	13
Recommendations.....	14
References.....	15
Appendix A. Examining the Hazard of the Redirected Vehicle Using Accident Report Narratives.....	16
Statement of the Problem.....	16
Analysis of Accident Narratives.....	16
Method.....	16
Results.....	20
Discussion of Preliminary Examination.....	26
Analysis of Hard Copy Accident Data.....	28
Introduction.....	28
Method.....	30
Results.....	36
Discussion.....	47

**VOLUME VI: REPLACING THE 4500-LB PASSENGER SEDAN IN REPORT 230
TESTS**

<u>Section</u>	<u>Page</u>
Introduction.....	1
Objective.....	1
Background.....	1

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Page</u>
Vehicle Selection Considerations.....	3
Historical Considerations.....	3
Acceptance Criteria Considerations.....	4
Impact Speed Considerations.....	4
Impact Angle Considerations.....	5
Vehicle Mix Considerations.....	9
Vehicle Mass Considerations.....	9
Impact Severity Considerations.....	11
Candidate Vehicles.....	14
Desirable Features of a Replacement Vehicle.....	14
4000-lb (1816-kg) Passenger Sedan Alternative.....	18
Pickup Truck Alternative.....	22
Conclusions and Recommendations.....	64
Conclusions.....	64
Recommendations.....	68
References.....	70
Appendix A. Full-Scale Crash Tests.....	72
Test WE4-1.....	72
Test WE4-2.....	91
Test WE4-3.....	107
Test PU-1.....	122
Test PU-2.....	142
Test PU-3.....	170
Test PU-4.....	198
Test PU-5.....	224
Test CIAS.....	253
Test GREAT-1.....	272
Appendix B. Proposed Pickup Specification For Full-Scale Crash Tests.....	273

LIST OF TABLES

VOLUME I: EXECUTIVE SUMMARY

<u>Table</u>	<u>Page</u>
1. 5400-lb pickup truck test matrix.....	8

VOLUME II: THE EFFECT OF SOIL STRENGTH ON LONGITUDINAL BARRIER
BARRIER PERFORMANCE

<u>Table</u>	<u>Page</u>
1. Pendulum test summary.....	4
2. BARRIER VII post properties.....	9
3. Comparison of soil-post interaction crash tests.....	12
4. Soil condition summary.....	18
5. Accelerometer data, test SD-6.....	21
6. Accelerometer data, test SD-7.....	23
7. Accelerometer data, test SD-8.....	25
8. Accelerometer data, test SD-9.....	27
9. Accelerometer data, test SD-10.....	29
10. Accelerometer data, test SD-11.....	31
11. Accelerometer data, test SD-12.....	33
12. Accelerometer data, test SD-13.....	35
13. Comparison of soil-post interaction crash tests.....	40
14. Permanent barrier deflections, test SPI-1.....	50
15. Film analysis data, test SPI-1.....	51
16. Transducer data, test SPI-1.....	55
17. Permanent barrier deflections, test SPI-2.....	67
18. Film analysis data, test SPI-2.....	68

LIST OF TABLES (continued)

<u>Table</u>	<u>Page</u>
19. Transducer data, test SPI-2.....	72
20. Permanent barrier deflections, test SPI-3.....	84
21. Film analysis data, test SPI-3.....	85
22. Transducer data, test SPI-3.....	89

VOLUME III: EVALUATING PRE-REPORT 230 CRASH TESTS

<u>Table</u>	<u>Page</u>
1. Variation in digital counts due to filter class, test GR1.....	4
2. Variation in digital counts due to filter class, test ST-10.....	5
3. Data processing effect on findings from typical vehicle/barrier redirection, test GR1.....	9
4. Data processing effect on findings from typical guardrail terminal collision, test ST-10.....	10
5. Occupant risk calculations with the effects of yaw rate included, test WE4-1.....	17
6. Occupant risk calculations with the effects of yaw rate excluded, test WE4-1.....	18
7. Occupant risk calculations with the effects of yaw rate included, test SPI-1.....	19
8. Occupant risk calculations with the effects of yaw rate excluded, test SPI-1.....	20
9. Comparison of occupant risk factors where yaw rate is excluded and included.....	21
10. Comparison of the collision model of occupant risk to full-scale crash tests.....	19

LIST OF TABLES (continued)

VOLUME IV: THE IMPORTANCE OF THE OCCUPANT RISK CRITERIA

<u>Table</u>		<u>Page</u>
1.	Typical passenger compartment clearance dimensions.....	4
2.	Sled test results.....	8
3.	Distribution of most harmful events where the first object struck is a longitudinal barrier.....	13
4.	Characteristics of 81 bridge rail accidents.....	15
5.	Distribution of injury in three data bases.....	17
6.	Relationship between AIS of 7 and police reported accident severity.....	19
7.	Summary of cases with serious to unsurvivable injuries.....	20
8.	Occupant risk values for 15 bridge rail crash tests.....	25
9.	Synopsis of the trends shown in the clearance dimension plots.....	38
10.	Complete new car assessment program data set.....	39
11.	Data recording and processing equipment.....	69
12.	Results from sled tests.....	70

VOLUME V: EVALUATION OF DESIGN ANALYSIS PROCEDURES AND ACCEPTANCE CRITERIA FOR ROADSIDE HARDWARE

<u>Table</u>		<u>Page</u>
1.	Cases screened from the data bases.....	3
2.	Rebound distances of vehicles after redirection from a longitudinal barrier.....	12
3.	Selected key variables.....	17
4.	1980 two-vehicle accidents.....	21
5.	1981 two-vehicle cases.....	22

LIST OF TABLES (continued)

<u>Table</u>	<u>Page</u>
6. 1980 and 1981 two-vehicle accident data combined.....	23
7. 1980 single-vehicle accidents.....	24
8. 1981 single-vehicle accidents.....	25
9. 1980 and 1981 single-vehicle accident data combined.....	27
10. Distribution of North Carolina accident cases by year.....	31
11. Cases excluded from final analysis.....	35
12. Percentage of A+K injuries observed in North Carolina longitudinal barrier accident cases.....	37
13. Vehicle reaction after impacting barrier.....	39
14. Injury severity as a function of number of lanes crossed prior to impact.....	39
15. Reporting officer's estimated impact speed.....	40
16. Rebound characteristics.....	45

VOLUME VI: REPLACING THE 4500-LB PASSENGER SEDAN IN REPORT 230 TESTS

<u>Table</u>	<u>Page</u>
1. Properties of pickup trucks.....	25
2. Survey of pickup truck bumper heights on the SwRI grounds...	28
3. Comparison of tests SPI-1 and WE4-2.....	32
4. Comparison of tests NRB-1 and PU-1.....	35
5. Comparison of concrete safety shape crash tests found in the literature.....	37
6. Comparison of tests PU-3 and RBCT-18.....	40
7. Comparison of tests PU-5 and SYRO-1.....	43
8. Comparison of tests BN-7 and BN-12.....	45

LIST OF TABLES (continued)

<u>Table</u>	<u>Page</u>
9. Comparison of tests CIAS and TTI 4765-8.....	56
10. Comparison of tests GREAT-1 and EASI 096-28.....	62
11. Planned pickup truck tests in other FHWA contracts.....	63
12. <u>Report 230</u> minimum crash test matrix.....	65
13. Summary of full-scale crash test results.....	67
14. Alternative crash test matrix.....	69
15. Test vehicle properties, test WE4-1.....	77
16. Permanent barrier deflections, test WE4-1.....	81
17. Film analysis data, test WE4-1.....	82
18. Transducer data, test WE4-1.....	85
19. Test vehicle properties, test WE4-2.....	94
20. Permanent barrier deflections, test WE4-2.....	97
21. Film analysis data, test WE4-2.....	98
22. Transducer data, test WE4-2.....	101
23. Test vehicle properties, test WE4-3.....	110
24. Permanent barrier deflections, test WE4-3.....	113
25. Film analysis data, test WE4-3.....	114
26. Transducer data, test WE4-3.....	117
27. Test vehicle properties, test PU-1.....	126
28. Film analysis data, test PU-1.....	130
29. Transducer data, test PU-1.....	133
30. Comparison of test vehicles.....	138
31. Comparison of evaluation factors, tests PU-1 and NBR-2.....	139

LIST OF TABLES (continued)

<u>Table</u>	<u>Page</u>
32. Test vehicle properties, test PU-2.....	149
33. Vehicle kinetics, from film analysis of test PU-2.....	152
34. Vehicle kinetics, from analysis of transducer data from test PU-2.....	153
35. Occupant risk summary, from film analysis of test PU-2.....	156
36. Occupant risk summary, from analysis of transducer data, test PU-2.....	157
37. Driver dynamics summary, test PU-2.....	162
38. Passenger dynamics summary, test PU-2.....	167
39. Test vehicle properties, test PU-3.....	177
40. Vehicle kinetics from film analysis of test PU-3.....	180
41. Vehicle kinetics from transducer data, test PU-3.....	181
42. Occupant risk summary from film analysis, test PU-3.....	184
43. Occupant risk analysis from transducer data, test PU-3.....	185
44. Driver dynamics summary, test PU-3.....	189
45. Passenger dynamics summary, test PU-3.....	195
46. Test vehicle properties, test PU-4.....	204
47. Vehicle kinetics summary from film analysis, test PU-4.....	208
48. Vehicle kinetics summary from transducer data, test PU-4....	209
49. Occupant risk summary from transducer analysis, test PU-4...	212
50. Occupant risk summary from film analysis, test PU-4.....	213
51. Driver dynamics summary, test PU-4.....	217
52. Passenger dynamics summary, test PU-4.....	222
53. Test vehicle properties, test PU-5.....	230
54. Vehicle kinetics from film analysis, test PU-5.....	233

LIST OF TABLES (continued)

<u>Table</u>		<u>Page</u>
55.	Vehicle kinetics from transducer data, test PU-5.....	235
56.	Occupant risk summary from film analysis, test PU-5.....	239
57.	Occupant risk summary from transducer data, test PU-5.....	241
58.	Driver dummy responses, test PU-5.....	246
59.	Passenger dummy responses, test PU-5.....	251
60.	Test vehicle properties, test CIAS.....	259
61.	Vehicle kinetics from film analysis, test CIAS.....	262
62.	Vehicle kinetics from transducer data, test CIAS.....	264
63.	Occupant risk summary from film analysis, test CIAS.....	267
64.	Occupant risk summary from transducer data, test CIAS.....	269
65.	Test vehicle properties, test GREAT-1.....	276
66.	Vehicle kinetics from film analysis, test GREAT-1.....	279
67.	Vehicle kinetics from transducer data, test GREAT-1.....	281
68.	Occupant risk summary from film analysis, test GREAT-1.....	284
69.	Occupant risk summary from transducer data, test GREAT-1....	286

LIST OF FIGURES

VOLUME II: THE EFFECT OF SOIL STRENGTH ON LONGITUDINAL BARRIER
BARRIER PERFORMANCE

<u>Figure</u>		<u>Page</u>
1.	Grain size distribution of <u>Report 230</u> Type S1 soil.....	2
2.	Force-rotation curve, test SD-9.....	5
3.	Force-horizontal deflection curve, test SD-9.....	6
4.	Ultimate load as a function of soil density.....	7

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
5.	Effect of soil compaction on G4(1S) deflection.....	12
6.	Post failure, SPI-1.....	14
7.	Soil failure, SPI-2.....	14
8.	Pendulum test details.....	20
9.	Force-deflection curve, test SD-6.....	22
10.	Force-deflection curve, test SD-7.....	24
11.	Force-deflection curve, test SD-3.....	26
12.	Force-deflection curve, test SD-9.....	28
13.	Force-deflection curve, test SD-10.....	30
14.	Force-deflection curve, test SD-11.....	32
15.	Force-deflection curve, test SD-12.....	34
16.	Force-deflection curve, test SD-13.....	36
17.	Barrier deflection of a G4 system as a function of soil density.....	39
18.	Barrier system for tests SPI-1, SPI-2, SPI-3.....	43
19.	Barrier and vehicle pretest details, test SPI-1.....	44
20.	Sequential photographs, test SPI-1.....	45
21.	Summary of results, test SPI-1.....	46
22.	Vehicle and barrier damage, test SPI-1.....	48
23.	Vehicle accelerations, test SPI-1.....	49
24.	Pre-impact vehicle and barrier details, test SPI-2.....	61
25.	Sequential photographs, test SPI-2.....	62
26.	Summary of results, test SPI-2.....	63
27.	Vehicle and barrier damage, test SPI-2.....	65

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
28.	Vehicle accelerations, test SPI-2.....	66
29.	Pre-impact barrier and vehicle details, test SPI-3.....	78
30.	Sequential photographs, test SPI-3.....	79
31.	Summary of results, test SPI-3.....	80
32.	Barrier and vehicle damage, test SPI-3.....	82
33.	Vehicle accelerations, test SPI-3.....	83

VOLUME III: EVALUATING PRE-REPORT 230 CRASH TESTS

<u>Figure</u>		<u>Page</u>
1.	Visual effects of filtering on typical vehicle accelerations produced during redirected impact.....	6
2.	Visual effects of filtering on typical vehicle accelerations produced during end-on collision with terminal.....	7
3.	Flail space concept.....	12
4.	Collision model of the lateral occupant risk factor.....	27

VOLUME IV: THE IMPORTANCE OF THE OCCUPANT RISK CRITERIA

<u>Figure</u>		<u>Page</u>
1.	Typical frontal impact.....	6
2.	Typical side impact.....	7
3.	Probability of injury versus TTI.....	11
4.	Typical accident reconstruction summary sheet, Case NASS 82-02-078V.....	22
5.	Occupant injury vs the lateral occupant risk factor.....	24
6.	Example of a multiple impact accident case.....	27
7.	Effect of occupant position on the occupant risk factor.....	29

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
8.	MVMA specification form.....	35
9.	Occupant clearance dimensions.....	36
10.	Head to windshield (HW) for right front passenger.....	44
11.	Head to windshield (HW) dimension for the driver by weight..	45
12.	Chest to dash (CD) for right front passenger.....	46
13.	Chest to dash (CD) for driver.....	47
14.	Chest to steering wheel (CS) for driver.....	48
15.	Head to side window (HS) for right front passenger.....	49
16.	Head to side window (HS) for driver.....	50
17.	Arm to door (AD) for right front passenger.....	51
18.	Arm to door (AD) for driver.....	52
19.	Hip to door (HD) for right front passenger.....	53
20.	Hip to door (HD) for driver.....	54
21.	Head to windshield header (HH) for right front passenger....	55
22.	Head to windshield header (HH) for driver.....	56
23.	Head to side header (HR) for right front passenger.....	57
24.	Head to side header (HR) for driver.....	58
25.	Knees to dash (KD) for right front passenger.....	59
26.	Knees to dash (KD) for driver.....	60
27.	Sled test setup.....	65
28.	Typical frontal impact using lexan windshield.....	72
29.	Typical results - frontal impact using lexan windshield....	73
30.	Typical frontal impact using glass windshield.....	75

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
31.	Typical results - frontal impact using glass windshield.....	76
32.	Typical side impact.....	78
33.	Typical results - side impact tests.....	79
34.	Plot of HIC vs occupant.....	81
35.	Comparison of experimental to computed time of head/windshield impact.....	82
36.	Dummy chest accelerations as a function of occupant to dash impact velocity.....	83

VOLUME V: EVALUATION OF DESIGN ANALYSIS PROCEDURES AND ACCEPTANCE CRITERIA FOR ROADSIDE HARDWARE

<u>Figure</u>		<u>Page</u>
1.	Fault tree schematic of possible longitudinal barrier collision scenarios.....	5
2.	Fault tree for New York accident data.....	7
3.	Fault tree for weighted North Carolina accident data.....	8
4.	Vehicle rebound characteristics of collisions with a longitudinal barrier collision, North Carolina data.....	11
5.	Fault tree for weighted North Carolina accident cases.....	41
6.	Fault tree for single-vehicle North Carolina accidents.....	42
7.	Fault tree for two-vehicle North Carolina accidents.....	43

VOLUME VI: REPLACING THE 4500-LB PASSENGER SEDAN IN REPORT 230 TESTS

<u>Figure</u>		<u>Page</u>
1.	Frequency of impact angles from 1982 and 1983 longitudinal barrier special studies.....	8
2.	Sequential photographs, test WE4-1.....	20

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
3.	Sequential photographs, test WE4-3.....	23
4.	Distribution of pickup gross vehicle weights.....	27
5.	Sequential photographs, test WE4-2.....	30
6.	Comparison of a Nevada bridge rail and the concrete safety shape.....	31
7.	Sequential photographs, test PU-1.....	34
8.	Sequential photographs, test PU-3.....	39
9.	Sequential photographs, test PU-5.....	44
10.	Sequential photographs, test BN-12.....	46
11.	Side view sequential photographs, test PU-2.....	48
12.	Suspension stiffness of 4500-lb car and 5400-lb pickup.....	51
13.	Approximate height of the center of gravity of sand barrels and typical vehicles.....	52
14.	Side view sequential photographs, test CIAS.....	54
15.	Pickup truck impact with a GREAT system.....	58
16.	Overhead sequential photographs, test GREAT-1.....	60
17.	G4(1S) barrier system details.....	76
18.	Barrier and vehicle details, test WE4-1.....	78
19.	Summary of results, test WE4-1.....	79
20.	Vehicle and barrier damage, test WE4-1.....	89
21.	Vehicle accelerations, test WE4-1.....	90
22.	Barrier and vehicle details, test WE4-2.....	93
23.	Summary of results, test WE4-2.....	95
24.	Barrier and vehicle damage, test WE4-2.....	105

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
25.	Vehicle accelerations, test WE4-2.....	106
26.	Barrier and vehicle details, test WE4-3.....	109
27.	Summary of results, test WE4-3.....	111
28.	Vehicle and barrier damage, test WE4-3.....	120
29.	Vehicle accelerations, test WE4-3.....	121
30.	Barrier construction details, test PU-1.....	124
31.	Test vehicle and barrier details, test PU-1.....	125
32.	Roll torsion and yaw flexure distortions (dynamic).....	127
33.	Summary of results, test PU-1.....	128
34.	Vehicle and barrier damage, test PU-1.....	136
35.	Vehicle accelerations, test PU-1.....	137
36.	Comparison of vehicle and barrier damage, tests NBR-2 and PU-1.....	140
37.	Comparison of sequential photographs, tests NBR-2 and PU-1..	141
38.	Sand-barrel attenuator installation, test PU-4.....	147
39.	Barrier installation and pretest vehicle, test PU-2.....	148
40.	Overhead sequential photographs, test PU-2.....	150
41.	Summary of test results, test PU-2.....	151
42.	Vehicle accelerations, test PU-2.....	155
43.	Driver head accelerations, test PU-2.....	159
44.	Driver chest accelerations, test PU-2.....	160
45.	Driver femur loads, test PU-2.....	161
46.	Passenger head accelerations, test PU-2.....	164
47.	Passenger chest accelerations, test PU-2.....	165

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
48.	Passenger femur loads, test PU-2.....	166
49.	Vehicle and barrier damage, test PU-2.....	169
50.	Eccentric loader BCT installation, test PU-3.....	175
51.	Barrier and vehicle details, test PU-3.....	176
52.	Summary of results, test PU-3.....	178
53.	Vehicle accelerations, test PU-3.....	182
54.	Barrier and vehicle damage, test PU-3.....	183
55.	Driver head accelerations, test PU-3.....	186
56.	Driver chest accelerations, test PU-3.....	187
57.	Driver femur loads, test PU-3.....	188
58.	Passenger head accelerations, test PU-3.....	192
59.	Passenger chest accelerations, test PU-3.....	193
60.	Passenger femur loads, test PU-3.....	194
61.	Test installation photographs, test PU-4.....	203
62.	Side-view sequential photographs, test PU-4.....	205
63.	Overhead sequential photographs, test PU-4.....	206
64.	Summary of results, test PU-4.....	207
65.	Vehicle accelerations, test PU-4.....	210
66.	Vehicle and barrier damage, test PU-4.....	211
67.	Driver head accelerations, test PU-4.....	214
68.	Driver femur loads, test PU-4.....	215
69.	Driver chest accelerations, test PU-4.....	216
70.	Passenger head accelerations, test PU-4.....	219

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
71.	Passenger chest accelerations, test PU-4.....	220
72.	Passenger femur loads, test PU-4.....	221
73.	Vehicle-attenuating terminal.....	228
74.	Pretest installation and vehicle, test PU-5.....	229
75.	Overhead sequential photographs, test PU-5.....	231
76.	Summary of results, test PU-5.....	232
77.	Vehicle accelerations, test PU-5.....	237
78.	Vehicle and barrier damage, test PU-5.....	238
79.	Driver head accelerations, test PU-5.....	243
80.	Driver chest accelerations, test PU-5.....	244
81.	Driver femur loads, test PU-5.....	245
82.	Passenger head accelerations, test PU-5.....	248
83.	Passenger chest accelerations, test PU-5.....	249
84.	Passenger femur loads, test PU-5.....	250
85.	Connecticut impact attenuator system.....	257
86.	Test installation photographs, test CIAS.....	258
87.	Overhead sequential photographs, test CIAS.....	260
88.	Summary of results, test CIAS.....	261
89.	Vehicle accelerations, test CIAS.....	266
90.	Vehicle and attenuator damage, test CIAS.....	271
91.	Pretest photographs, test GREAT-1.....	275
92.	Sequential photographs, test GREAT-1.....	277
93.	Summary of test results, test GREAT-1.....	278

LIST OF FIGURES (continued)

<u>Figure</u>		<u>Page</u>
94.	Vehicle accelerations, test GREAT-1.....	283
95.	Vehicle and barrier damage, test GREAT-1.....	288
96.	Definitions of pickup truck dimensions.....	289
97.	Effective top of bumper for various bumper shapes.....	290

Introduction

NCHRP Report 230,⁽¹⁾ "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," was published in 1981 as an attempt to refine and standardize procedures for the testing and evaluation of roadside appurtenances. The first attempt by the highway safety community at standardizing testing procedures was made in 1962 with the publication of "Highway Research Correlation Services Circular 482."⁽²⁾ Since 1962 several documents have expanded the scope, revised the content, and reviewed these evaluation and test procedures. Thus, NCHRP Report 153,⁽³⁾ Transportation Research Circular 191,⁽⁴⁾ and finally NCHRP Report 230 have all resulted in more standardized test procedures and more objective methods of performance evaluation.

It is, however, the nature of specifications that they become outdated and require change. Each new testing and evaluation criteria has brought new understanding of the complex interactions between roadside appurtenances and motor vehicles. The objective of this research project was to identify and investigate areas in Report 230 which required further technical investigation. Five particular areas were investigated; they were:

- the effect of soil strength on longitudinal barrier performance,
- evaluating pre-Report 230 crash tests by Report 230 standards,
- the importance and validity of the occupant risk criteria,
- the importance of the redirected vehicle trajectory and secondary impacts and,
- identifying a replacement for the 4500-lb test vehicle.

One volume of this report is devoted to each of the five areas listed above.

The Effect of Soil Strength on Longitudinal Barrier Performance

One of the most critical components of any roadside appurtenance is the soil foundation. Any load that is transmitted to the system is dissipated either through deformation of the barrier components or deformation of the soil. Soil strength is particularly important in flexible barrier systems since the soil deformation is one of the principal means of dissipating energy. Volume II describes an investigation of the effect of compaction on soil strength.

Soil compaction is one variable which is very important in developing soil strength. This research investigated the change in soil stiffness, ultimate load, and "fracture" energy when different levels of soil compaction were used. Using computer simulations, the effect on barrier performance of different soil-strength properties was investigated.

It was found that when the Report 230 S1 soil is compacted about 90 percent standard proctor, the soil provides rigid support for guardrail systems. The soil-strength parameters were found to be a function of compaction and moisture content. The present Report 230 standards for soil compaction and moisture content were therefore found to be adequate and should not be altered.

Although this research was directed at assessing the Report 230 specifications for soil conditions during full-scale crash tests, the results are also applicable to actual field installations. Soil placement in the field is as important for achieving proper performance in the "real world" as it is in experimental testing activities. Barrier system will not perform as designed if its soil is not compacted to 90 percent standard proctor density.

Evaluating Pre-Report 230 Crash Tests

Hundreds of full-scale crash tests were performed before the Report 230 specification came into effect in 1981. These tests often were performed using different transducer sampling speeds and filtering specifications. Volume III contains results of an investigation of whether tests performed using non-Report 230 specifications could still yield useful information by Report 230 standards.

Two full-scale crash tests, an end-on test and an oblique angle test were analyzed using a variety of data processing methods. The investigation showed data processed using lower SAE filter classes still produced data that was comparable to the Report 230 specified SAE J211b 1000 data.⁽⁵⁾

Another investigation concerned calculating the occupant risk given the vehicle acceleration data from a full-scale crash test. An algorithm is presented which derives the occupant kinematics from basic dynamics. This method is shown to correlate well with crash test experience.

The final topic of volume III was developing a method for estimating the occupant risk factor given only the gross performance of the vehicle in terms of impact and exit conditions as well as barrier damage. A method for estimating the occupant risk was developed using Olson's⁽⁶⁾ method for estimating dynamic crash test parameters. The simplified method was used to predict the occupant risk in 16 full scale crash tests. The actual and estimated occupant risk factors were within 10 percent of each other in 63 percent of the tests and all 16 tests were within 24 percent of the correct value. This method was found to yield reasonable information in many cases although the method should only be used when no other information is available.

The Occupant Risk Criteria

One of the most innovative aspects of Report 230 was the introduction of the flail space concept and the occupant risk criteria. This investigation, which is documented in volume IV of this report, provided several interesting and unexpected conclusions.

The first task performed in this portion of the research was to validate the flail space concept. The flail space concept presumes that the occupant behaves like a free missile in a collision. A series of sled tests were performed to test this hypothesis. The sled tests indicated that the flail space assumption does predict the actual occupant-interior impact velocity quite well. The flail space concept slightly overestimates the occupant risk at low acceleration levels and is very accurate at higher acceleration levels thus providing a degree of conservatism.

A survey of passenger compartment geometries indicated that the 1-foot (0.3-m) lateral and 2-foot (0.6-m) longitudinal flail distances were representative of the actual vehicle fleet. These dimensions were found to be adequate upper limits for vehicle compartment geometries.

Hard copy accident data was analyzed to determine if there is a linkage between the occupant risk factor and the degree of injury in terms of the Abbreviated Injury Scale (AIS-80).⁽⁷⁾ When vehicles were smoothly redirected the investigation indicated that the risk of severe injury was small. In the absence of snagging, barrier penetration or rollover, it was unlikely that high values of occupant risk would occur. Therefore, the occupant risk criteria does not appear to be discerning for redirection tests since Report 230 already requires smooth redirection and an upright vehicle during the post collision phase.

The occupant risk criteria, evaluation criteria F in Report 230, should be eliminated as a required evaluation factor in the Report 230 redirection tests: tests 10, 11, 12, and 30. Although the occupant

risk criteria does not appear to be discerning for redirection tests, it remains a very important evaluation criteria in terminal, crash cushion, and breakaway support tests and its use should be continued in those tests.

An alternative to eliminating the occupant risk criteria entirely is to increase the allowable lateral occupant impact velocity from 20 fps (6.1 m/s) to a higher value such as 30 fps (9.1 m/s). The data indicated that severe injury did not occur at occupant risk values of less than 40 fps (12.2 m/s). If the factor of safety used for longitudinal occupant risk is applied to the 40-fps (12.2-m/s) threshold value a design limit of 30 fps (9.1 m/s) is obtained.

The research also indicated that anthropometric dummy responses obtained in full-scale crash tests are generally far below the critical responses specified by FMVSS 208.⁽⁸⁾ Very little useful information is gained from the use of fully instrumented dummies in full-scale crash tests although their use can significantly increase the cost of testing. Uninstrumented anthropometric dummies should be used to provide photographic documentation of the occupant's trajectory inside the vehicle. The uninstrumented dummy will meet the need for a human-like mass in the passenger compartment and provide useful information about the occupant trajectory at much less cost.

Hazards of the Redirected Car

The analysis of accident data in volume IV also indicated that many of the severe and serious injuries that occur in longitudinal barrier collisions are a result of a secondary collision with another fixed object or following traffic rather than the primary longitudinal barrier collision. In order to supplement the accident data obtained in the previous task, data from New York and North Carolina were analyzed to determine if there was a link between secondary collisions and higher occupant injury. Volume V contains an analysis of these data.

The analysis showed that occupants of vehicles which experienced a second collision were between three and five times more likely to suffer a severe injury or be fatally injured as those who experienced no second event. This analysis demonstrated the great importance of effecting a controlled post impact trajectory.

The accident data also indicated that 77 percent of the reported accident cases contained vehicles which re-entered or crossed the roadway. This would indicate that only 23 percent of "real-world" collisions meet redirection criteria specified in Report 230 for full-scale crash tests. Researchers and testing agencies should place more emphasis on obtaining good redirection performance in full-scale crash tests and in the field.

Replacing the 4500-lb Car

The 4500-lb (2043-kg) passenger car is a fast diminishing segment of the vehicle population in the United States. The 4500-lb (2043-kg) car has also been the primary test vehicle for more than 20 years. The objective of this task was to identify and test a vehicle which could be used as a replacement for the 4500-lb (2043-kg) car in the Report 230 test matrix.

The task of replacing the 4500-lb (2043-kg) passenger sedan evolved into a problem much thornier than was originally anticipated. The most preferable outcome of this study would have been a blanket replacement of the 4500-lb (2043-kg) car tests in Report 230. This blanket replacement would exactly replicate the performance and severity observed in more than 20 years of 4500-lb (2043-kg) car crash-test experience. Such was not the case.

It soon became apparent that the selection of a replacement vehicle was intimately linked with changes in the impact conditions. Thus, speeds were changed to achieve the equivalent 4500-lb (2043-kg) car test energy while preserving the kinematic similitude of the tests and impact angles

were altered to try and minimize the differences observed due to different types of vehicle construction.

The typical mid-sized passenger car has been so radically downsized, its weight reduced and structure changed, that providing the same impact severity required either a great deal of ballast or very high impact speeds, both of which present experimental difficulties. The van was rejected because its center of gravity is both high and far to the front of the vehicle. This asymmetrical center of gravity location was thought to be the cause of the van's instability in crash tests investigated in the literature. The only practical alternative remaining was, therefore, the pickup truck.

Although most of the pickup truck tests discussed in volume VI were satisfactory performance matches, the pickup truck alternative was not investigated without experiencing troublesome problems. Several devices, most notably the sand barrel attenuator and the eccentric loader terminal, were found to exhibit either unacceptable behavior or ambiguous results. Some test conditions yielded both excellent and poor results as was observed in exploring the test 41A conditions. The eccentric loader terminal was a marginal test although under the same conditions the VAT performed exceptionally well. The tests of the sand barrel attenuator were dramatic failures using the proposed test 50A conditions although the CIAS system exhibited performance very similar to the large sedan. There are, therefore, devices that have a good record of 4500-lb (2043-kg) car performance which simply do not perform as well when struck by a pickup truck. It is likely, regardless of the replacement vehicle selected, that certain devices now in common use on the roadside would experience failure under the new test conditions whereas other, similar devices will continue to pass. In short, there are no easy one-for-one replacement vehicles available.

The ballasted 5400-lb (2452-kg) pickup truck is recommended as a suitable replacement for the 4500-lb (2043-kg) passenger car for full-

scale crash testing. Experience gained in the testing program performed in this research has indicated general good conditions between pickup truck and passenger car behavior. A matrix of new pickup truck tests is presented in table 1 as an alternative to the Report 230 matrix of 4500-lb (2043-kg) car tests. Most impacts performed using the pickup truck matrix will yield similar if not identical results to the former 4500-lb (2043-kg) car matrix.

Table 1. 5400-lb pickup truck test matrix.

5400-lb PICKUP TRUCK TEST MATRIX					
Appurtenance	Old Test No.	Alternative Test No.	Speed (mph)	Angle (deg.)	Impact Point
Longitudinal	10	10A	65	20	Between posts in span with splice
Transitions	30	30A	65	20	15 feet upstream of second system
Terminals	40	40A	65	20	Beginning of length-of-need
Terminals	41	41A	55	0	Center of device nose
Crash Cushions	50	50A	55	0	Center of device nose
Crash Cushions	53	53A	55	0	Along midlength
Crash Cushions	54	54A	55	10-15	0-3 feet offset from device nose

References

- (1) Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, Transportation Research Board, Washington, DC, March 1981.
- (2) "Proposed Full Scale Testing Procedures for Guardrails," Committee on Guardrail and Guide Posts, Highway Research Board Circular 482, Washington, DC, September 1962.
- (3) Bronstad, M.E. and Michie, J.D., "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances," NCHRP Report 153, Transportation Research Board, Washington, DC, 1974.
- (4) "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances," Transportation Research Circular 191, Transportation Research Board, Washington, DC, February 1978.
- (5) "Instrumentation for Barrier Collision Tests," SAE J211b, Society of Automotive Engineers, New York, 1970.
- (6) Hirsch, T.J., "Introduction to Roadside Crash Force Concepts," 27th Annual Proceedings, American Association for Automotive Medicine, Morton Grove, IL, October 1983.
- (7) "The Abbreviated Injury Scale (AIS-80)," American Association for Automotive Medicine, Morton Grove, IL, 1980.

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.