EXTRA

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 115

GUARDRAIL PERFORMANCE AND DESIGN

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **115**

GUARDRAIL PERFORMANCE AND DESIGN

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AREAS OF INTEREST:
HIGHWAY DESIGN
HIGHWAY SAFETY

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1971

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectvity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP Report 115

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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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FOREWORD

By Staff
Highway Research Board

This report is recommended to highway design engineers, safety engineers, researchers working with traffic barrier systems, and others concerned with highway safety. It contains an overview of guardrail and median barrier technology, summarizes the results of 25 full-scale crash tests, and reports on the relative performance of the designs tested. The findings reinforce material published previously in *NCHRP Report 54* and offer additional information on traffic barrier systems.

There is a need to provide highway design engineers with a choice of effective guardrail and median barrier systems. The volume of research conducted in the past on the more commonly used designs (W-beam, standard cable, box beam) prompted the need for a comparison and critical analysis to determine what further investigations were necessary to refine structural details and obtain more effective barrier performance. Full-scale testing, necessary to fill in the apparent gaps in previously concluded investigations, was required.

Southwest Research Institute (SwRI), San Antonio, Texas, undertook the research need outlined above as a follow-on to initial state-of-the-art work conducted by Cornell Aeronautical Laboratory under NCHRP Project 15–1 and reported in *NCHRP Report 36,* "Highway Guardrails—Review of Current Practice." Further work on establishing the state-of-the-art and synthesizing the information available was conducted by SwRI as an early part of NCHRP Project 15–1(2) and was reported as *NCHRP 54,* "Location, Selection, and Maintenance of Highway Guardrail and Median Barriers."

The remainder of the research effort on Project 15–1(2) is presented in this document—the third in the series of NCHRP Reports on guardrails and median barriers. The findings reported herein generally reinforce data presented in *NCHRP Report 54* and offer additional insight into the relative performance of various designs, guardrail-bridge rail transitions, and guardrail terminal designs. Information is included on mathematical modeling, full-scale crash tests, and various evaluation techniques for comparing the relative effectiveness of the designs investigated. Findings on vehicle response and damage might be particularly interesting.

A 16-mm sound and color motion picture (10 minutes), entitled "Guardrail Performance and Design," summarizes the results of the SwRI work under Project 15–1(2). Loan copies of the film are available by contacting the Program Director, NCHRP.

The research reported herein brought to light that *NCHRP Report 54* could be updated to include the latest knowledge available; that it was an appropriate time to consider the incorporation of all available knowledge on warrants, service requirements, and design criteria for all types of traffic barrier systems into one document; that new concepts for end and transition designs for guardrail and median barrier are required; and that promising new design concepts should be evaluated through a program of full-scale crash testing.

In response to these additional research needs, NCHRP contracted with Southwest Research Institute to undertake additional work, scheduled to be completed in November 1971. There is a possibility that NCHRP publications will be issued in the near future to update *NCHRP Report 54* and also to provide a design guide for all traffic barrier systems. A report on end and transition designs is anticipated to be issued by NCHRP in early 1972.

CONTENTS

ACKNOWLEDGMENTS

The work reported herein was conducted at Southwest Research Institute by the Department of Structural Research. Jarvis D. Michie, Group Leader, and Lee R. Calcote, Senior Research Engineer, served as principal investigators. Assisting the principal investigators were Maurice E. Bronstad, Senior Research Engineer, who supervised the full-scale crash test program; L. F. Greimann and R. E. Kirksey, who performed many of the computer tasks; J. R. Cromack, who provided technical assistance with crash severity and damage evaluation; W. H. McGinnis, who was responsible for electronic instrumentation; and C. A. Walker and L. B. Ferguson, who were responsible for crash test photography. R. C. DeHart, Director, and L. U. Rastrelli, Assistant Director, served in the capacity of technical and administrative advisors.

The assistance and cooperation of many persons in state highway departments, manufacturing firms, and government agencies are gratefully acknowledged. In particular, cooperation from personnel with the California Division of Highways, the New York Department of Transportation, the General Motors Proving Grounds, the Bureau of Public Roads, and the Texas Transportation Institute proved invaluable to the program. Cornell Aeronautical Laboratory provided many reference documents collected under Project 15-1. The General Motors Proving Grounds provided the anthropometric dummy used in all full-scale crash tests; guardrail and median barrier materials used in the 25 full-scale crash test installations were donated by Armco Steel Corporation, U.S. Steel Corporation, Aluminum Association, Texas Wood Preservers Advisory Council, Syro Steel Company, and Carroll Manufacturing Company.

GUARDRAIL PERFORMANCE AND DESIGN

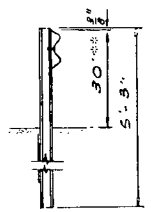
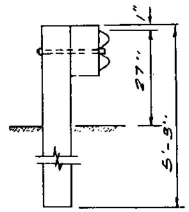
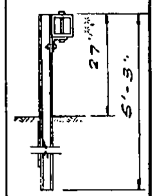
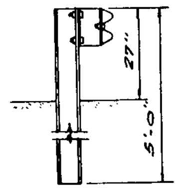
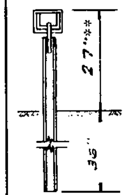
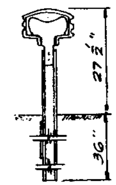
SUMMARY

This research involved the in-depth study of the more common highway guardrail and median barrier systems. Findings are derived from three interdependent areas: (1) state-of-the-art review, (2) theoretical examination of the vehicle-barrier collision, and (3) 25 full-scale crash tests of selected barrier systems.

The purpose of a highway barrier is to reduce the severity of ran-off-the-road accidents. Barrier installations are warranted (or justified) only at highway locations where the consequence of an errant vehicle leaving the roadway is judged to be more hazardous than the impact with the barrier installation. This relative accident severity determination is valid regardless of whether one or one thousand vehicles leave the highway at a site. Hence, accident frequency is not a principal factor in determining barrier warrants; however, accident frequency factors do assist in establishing a preferred order of construction of two or more *warranted* installations.

A six degree-of-freedom mathematical model was found to be useful in describing dynamic behavior of a vehicle during impact. Predictions of vehicle and barrier behavior correlated with results obtained from full-scale crash tests. Crash conditions simulated with a computer were used to identify and evaluate vehicle static and dynamic as well as barrier parameters. *Vehicle* weight, yaw mass moment of inertia, and deformation constant were found to be significant. As expected, such vehicle dynamic parameters as impact speed and angle were the most important factors in vehicle-guardrail interaction. The significant *barrier* parameters were ascertained to be those related to post strength, vehicle-barrier coefficient of friction, soil modulus, and beam tension; these appreciably influence the acceleration intensities induced in the vehicle during redirection. For the systems examined, it was found that vehicle lateral accelerations were higher with respect to suggested human tolerance levels than the longitudinal accelerations with respect to their corresponding suggested levels. For a standard test (i.e., 4000-lb vehicle, 60 mph, and 25-degree impact), the vehicle acceleration predictions when compared to suggested human tolerance levels indicate that occupants need both lap belt and chest harness restraints to avoid serious injuries.

To facilitate comparisons of barrier systems on the basis of dynamic performance, the order in which the three most significant factors need be considered was established as being: (1) barrier structural integrity as determined by whether or not a system can redirect a selected errant vehicle, (2) vehicle accelerations during redirection, and (3) post-impact trajectory of the vehicle. Unless a system has demonstrated the ability to redirect a vehicle such that it does not vault over, wedge under, or break through an installation, there is no need to give further consideration to performance criteria related to subsequent events. On the other

SYSTEM DESIGNATION	G2/W-Beam			G4/Blocked-Out W-Beam			G3/Box Beam	G5/Blocked-Out W-Beam (Steel Post)				MB3/Box Beam	MB7/Alum. Beam	
														
Test Number	105	123	124	101	102	103	114	119	120	121	122	112	109	110
INSTALLATION														
Beam	W	W	W	W	W	W	6 X 6 X 3/16	W	W	W	W	6 X 8 X 1/4	Alum.	Alum.
Post	3I5.7	3I5.7	3I5.7	8 X 8 Tim.	8 X 8 Tim.	8 X 8 Tim.	3I5.7	6B8.5	6B8.5	6B8.5	6B8.5	3I5.7		
Offset (in.)	None	None	None	8	8	8	N/A	None	6	12	12	N/A	N/A	N/A
Post Spacing (ft)	12.5	6.5	9.3	6.25	6.25	6.25	6.0	6.25	6.25	6.25	6.25	6.0	6.25	6.25
TEST CONDITIONS														
Vehicle Speed (mph)	59.2	64.3	60.7	55.3	54.7	60.1	57.7	53.4	56.8	56.2	62.9	51.0	41.3	56.5
Vehicle Weight (lb)	4051	3883	3904	4042	3856	4123	4031	4169	3813	4478	4570	3761	4078	4550
Impact Angle (deg)	27.8	27.1	26.4	30.5	25.2	22.2	26.0	30.2	28.4	27.4	25.3	26.9	25.0	25.0
DYNAMIC FACTORS*														
Barrier Strength	S	S	S	S	S	S	S	S(1)	S	S	S	S	S	U
Vehicle Long. Accel.	A	A	A	A	–	A	A	A	A	A	A	A	–	–
Vehicle Lateral Accel.	B	C	B	B	–	C	C	B	C	C	C	C	–	–
Vehicle Rebound	B	C	C	D	C	B	A	D	C	A	C	A	A	–
PROPERTY DAMAGE FACTORS*														
Barrier Damage	A	B	A	B	A	B	B	A	A	B	B	B	A	C
Vehicle Damage	B	B	B	C	C	C	C	C	C	B	C	B	B	D
BARRIER PERFORMANCE APPRAISAL	Good	Good	Good	Fair	Fair	Good	Excellent	Good	Good	Excellent	Good	Excellent	Good	Unsatisfactory

*A–excellent; B–good; C–fair; D–poor; S–satisfactory; and U–unsatisfactory.
**Recommended height of rail has been revised subsequent to test program.
(1) Beam was partially severed.

hand, for systems that satisfy this basic requirement the evaluation procedure next considers vehicle accelerations; these vehicle acceleration values serve as indicators of the severity of redirection and may be used in projecting possible injuries or fatalities among vehicle occupants. Finally, when the first two factors are equal or acceptable, vehicle exit trajectory becomes a critical criterion as it reflects the hazards presented to other traffic. The rebounding vehicle can be the cause of a multicar collision. The number of such accidents cannot be deduced from current accident statistics; however, it is conjectured to be quite small.

The 25 full-scale crash tests consisted of 14 general barrier performance tests, 8 end treatment tests, and 3 guardrail-to-concrete parapet transition tests. Appraisals of the general performance tests are given in the accompanying table. Findings included:

- The G2 system demonstrated good dynamic performance and caused moderate property damage. Post spacing can be decreased from the standard 12.5 ft to 6.25 ft to effect a 20 percent decrease in system dynamic deflection.
- Vehicles impacting the G4 system were redirected at moderate to large exit angles. The 8-in. blockout reduced the tendency but did not prevent wheel snagging at posts. Vehicle damage for this relatively rigid system was more severe than for the more flexible G2 system. Southern yellow pine was determined to be a suitable alternate to Douglas fir for the posts and blockouts.
- Vehicle "rebound" from the G3 and MB3 barrier system was excellent, as the test vehicles remained in contact with or very close to the box beam throughout the exit trajectories.
- The G5 system, consisting of a W-beam and 6B8.5 steel posts, demonstrated good to excellent dynamic performance and property damage appraisal.
- Aluminum Association strong beam median barrier demonstrated good dynamic performance for a moderate speed test; however, the installation was penetrated for standard test conditions. Metallurgical analysis of the failed beam splice by the Aluminum Association indicated that the beam had been extruded from an incorrect alloy. Results of subsequent full-scale crash test performed by the research agency on the aluminum barrier system indicated acceptable barrier performance.
- For the 14 tests, average barrier installation damage was \$228; average vehicle damage was \$910.

Ramped terminal treatments presented in *NCHRP Report 54* were found to cause the test vehicles to launch, roll, and tumble. Only the G3 flare treatment performed satisfactorily; a single test, however, cannot be considered as conclusive evidence of design adequacy.

In the guardrail-to-rigid bridge rail transition tests, it was demonstrated that errant vehicles can be redirected; however, the redirection may be abrupt. Principal features of the transition are that the approach barrier beam is securely anchored to the concrete parapet and is laterally stiffened in the vicinity of the parapet by larger and more closely spaced posts.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The objectives of NCHRP Project 15-1(2) were to: (1) critically analyze existing data on guardrail performance and identify the most significant needs for additional applied research and basic engineering studies, (2) conduct such full-scale performance tests as were deemed necessary, and (3) evaluate the performance of various guardrail and median barrier systems by utilizing vehicle response, occupant injury vulnerability, and property damage as a measure of accident severity.

This report is the third of three documents reporting on results of NCHRP Project 15-1. *NCHRP Report 36,* authored by Cornell Aeronautical Laboratory, presents a state-of-the-art review of barrier technology prior to 1967. *NCHRP Report 54,* "Location, Selection, and Maintenance of Highway Guardrails and Median Barriers," was prepared as an interim report * to Project 15-1(2). Its purpose was to provide an up-to-date, concise instructional manual for highway design engineers with respect to various features of the commonly used, tried, and proven systems in existence. *NCHRP Report 54* will be referred to occasionally in this report; however, an attempt was made to minimize duplication of content.

During the study, information pertaining to all phases of barrier technology was assembled, reviewed, and appraised. The information was acquired from technical literature, test reports, and state highway department design standards, as well as from interviews and discussions with engineers knowledgeable in one or more aspects of the subject. This information provided necessary background for establishing a state-of-the-art in guardrail and median barrier design requirements and deficiencies in performance.

Initially, the project staff planned to acquire barrier performance data from (1) mathematical modeling, (2) subscale laboratory modeling, and (3) full-scale crash tests. However, the subscale laboratory modeling effort was discarded early in the program because it did not appear to have the same payoff as that offered by the other two approaches.

In the chapters that follow, program findings are presented. Initially, a brief summary of the technology is discussed in order to establish a frame of reference within which the program results are identified; included are location warrants and guardrail and median barrier system ground rules. Results from 25 full-scale crash tests are compared and analyzed. Data obtained from the parametric studies performed with the six degree-of-freedom mathematical model are depicted in plots and discussed. A subsequent appraisal of the program results contains interpretive commentaries on their application and the type of action that may be necessary to implement the findings to advantage. The last chapter deals with conclusions and suggested research. The appendices contain treatments of technical areas and detailed test data considered appropriate to the objectives of the project.

* A special NCHRP advisor group (consisting of John L. Beaton, California Division of Highways; Malcolm D. Graham, New York Department of Transportation; James Lacy, Federal Highway Administration; and Paul C. Skeels, General Motors Proving Ground) advised and counseled the program staff as to content of the report.

CHAPTER TWO

GUARDRAILS AND MEDIAN BARRIERS— A SUMMARY OF THE TECHNOLOGY

As traffic barrier systems located along highways, the primary function of guardrails and median barriers is to safely redirect errant vehicles. Guardrail installations on shoulders prevent vehicle access to steep embankments or fixed objects, whereas median barriers are used between the roadways of divided highways to prevent "across-the-median" collisions with opposing traffic. Properly designed installations accomplish the redirection of errant vehicles in such a manner as to minimize the vulnerability of vehicle occupants as well as the involvement of following and adjacent traffic. Other desirable guardrail and median barrier characteristics include minimal damage to vehicles and barrier systems; economy in construction, installation, and maintenance; enhancement of highway aesthetics; and performance as headlight glare screens or highway delineators. But although these last functions are of importance, they cannot be used to justify a design modification wherein the crash injury reduction capabilities of a system are compromised.

In the following sections, certain results obtained during the research are combined with those of a comparable nature from other investigations. The intent is to identify certain salient aspects which, in combination, define the governing guidelines for guardrails and median barriers as a technology, and form the basis for rational approach to the effective use of such systems by highway designers.

BASIC CONFIGURATIONS

Center Sections *

Guardrail and median barrier systems, generally tailored for specific highway requirements at a given site, are commonly classified according to lateral stiffness (see Table 1). *Rigid barriers* are normally used where lateral deflections are not permitted; such locations as narrow medians are examples. Because these systems must be essentially unyielding, they are almost exclusively constructed of massive sections of concrete. The State of New Jersey has had satisfactory service with its standard rigid barrier (Fig. 1A); California has performed three crash tests on the New Jersey design and reported good results (*75*). General Motors Proving Ground modified the New Jersey barrier profile (Fig. 1B) and crash-tested the device; improved barrier performance was reported (*48*).

Most foreign countries have experienced dissatisfaction with their current rigid barriers, and one country (Germany) has discontinued the use of its standard rigid barrier (Fig. 1C). The Trief barrier (Fig. 1F) has been proven to be unsatisfactory by tests conducted by the United Kingdom and the Netherlands. Tests conducted by the United Kingdom and the Netherlands also indicate that the Dansk Auto Vaern (Fig. 1E) conceived by Denmark is unsatisfactory. The Trief and D.A.V. barriers were judged to be too low in relation to a vehicle's center of gravity.

Depending on structural behavior, *semirigid barriers* can be classed into two groups: (1) strong beam/strong post, or a balanced design, and (2) strong beam/weak post. Semirigid guardrails and median barriers are shown in Figures 2 and 3, respectively.

The most common barrier/guardrail system in use is a strong beam/strong post design consisting of a corrugated steel beam mounted on various types of posts. Some of the current steel beams are described in Figure 4. Strong posts are generally 6B8.5 and 6WF15.5 steel and 6 × 8-in., 8 × 8-in., or 8-in.-diameter timber. Post embedment length varies with type of soil, but is normally between 36 and 48 in. Although the practice is not universal, the beam is frequently blocked-out from the posts to minimize vehicle snagging and to lessen the tendency for the vehicle to ride over the barrier. Strong beam/strong post systems react to the vehicle collisions by a combination of flexure and tensile forces. The mounting height of the top of the guardrail generally varies between 24 and 27 in. above grade; although post spacing is most commonly found to be 12.5 ft, crash tests have demonstrated that a 6.25-ft spacing is more effective. For median barriers, beam mounting height should be 30 in. with 6.25-ft post spacing; a rubbing rail is required to prevent vehicle snagging (see Fig. 3F).

A recent innovation is the strong beam/weak post concept, in which the posts near the point of impact are purposely designed to break away so that the force of impact is distributed by beam action to a relatively larger number of posts. Attributes of this system are: (1) barrier performance is independent of impact point at or between posts and of soil properties, and (2) vehicle snagging on a post is virtually eliminated. Examples of the strong beam/weak post concept are the box beam guardrail and median barrier (Figs. 2C and 3D). The beam is a 6 × 6 × 3/16-in. steel tube for guardrail installations and 8 × 6 × 1/4-in. steel tube for median barriers; in both cases, the weak posts are 3I5.7 steel members spaced at 6-ft intervals. To fully develop the yield strength of the posts in a wide range of soils, a reaction plate is attached to the post and the post is embedded a minimum of 36 in. The top of the box beam is normally 30 in. above grade (33 in. on outside of superelevated

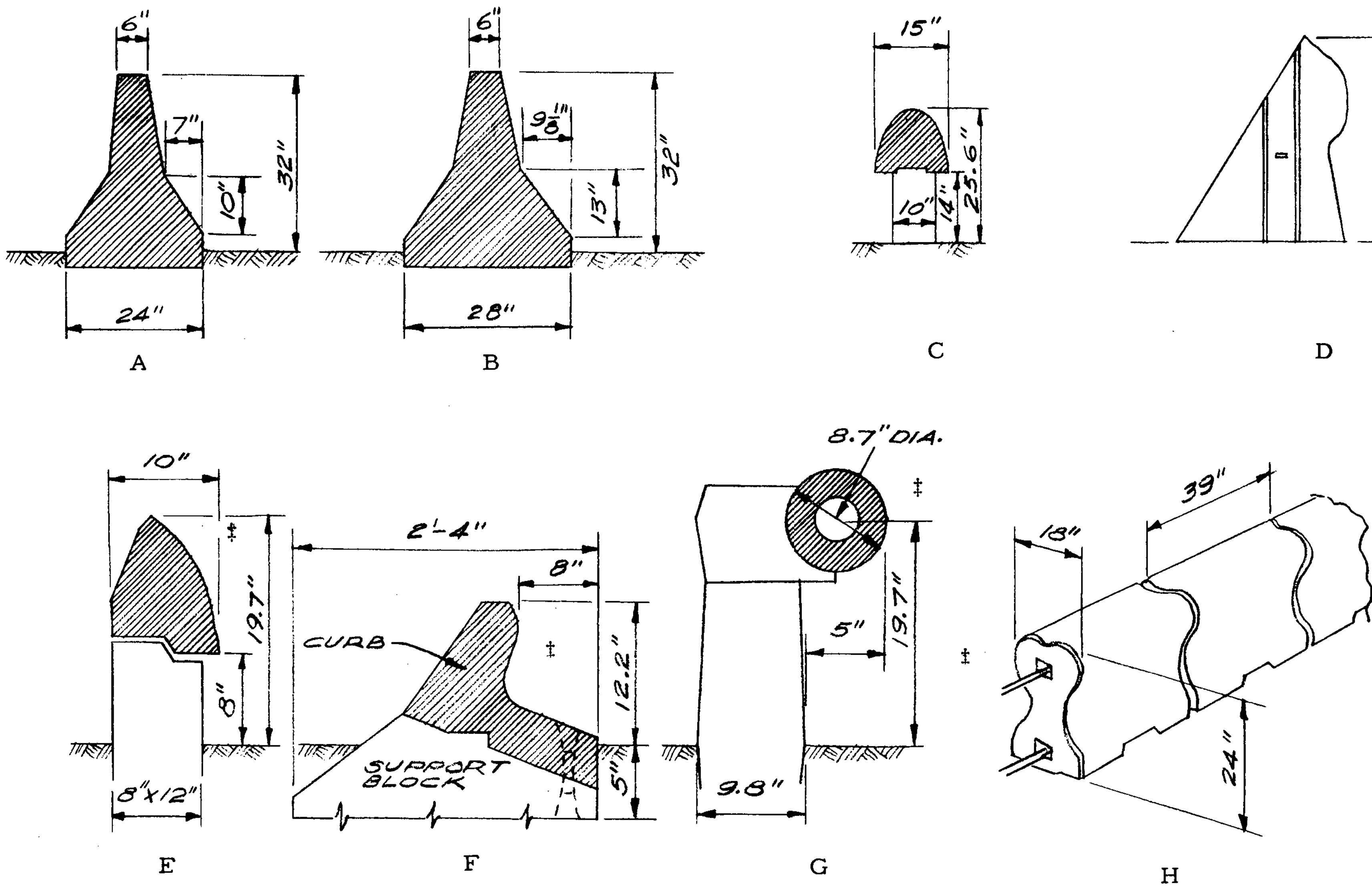
* That portion of an installation exclusive of upstream and downstream terminals.

TABLE 1

CATEGORIES OF U.S. GUARDRAIL SYSTEMS

Stiffness Classification	Typical Systems	Application
A. Rigid	New Jersey, General Motors concrete barrier	Used where no lateral deflection is acceptable
B. Semi-Rigid		
1. Strong Post/Strong Beam	Blocked-out W-section beam on 8 × 8-in. timber post	Used where small lateral deflection is acceptable
2. Weak Post/Strong Beam	Box-beam; W-beam on 3I5.7 posts	Used where moderate lateral deflection is acceptable
C. Flexible		
1. Strong Post/Weak Beam*	Multiple cables on 7-in.-diameter timber post	Used where large lateral deflection is allowed
2. Weak Post/Weak Beam	Cable on 3I5.7 post	Used where large lateral deflection is allowed

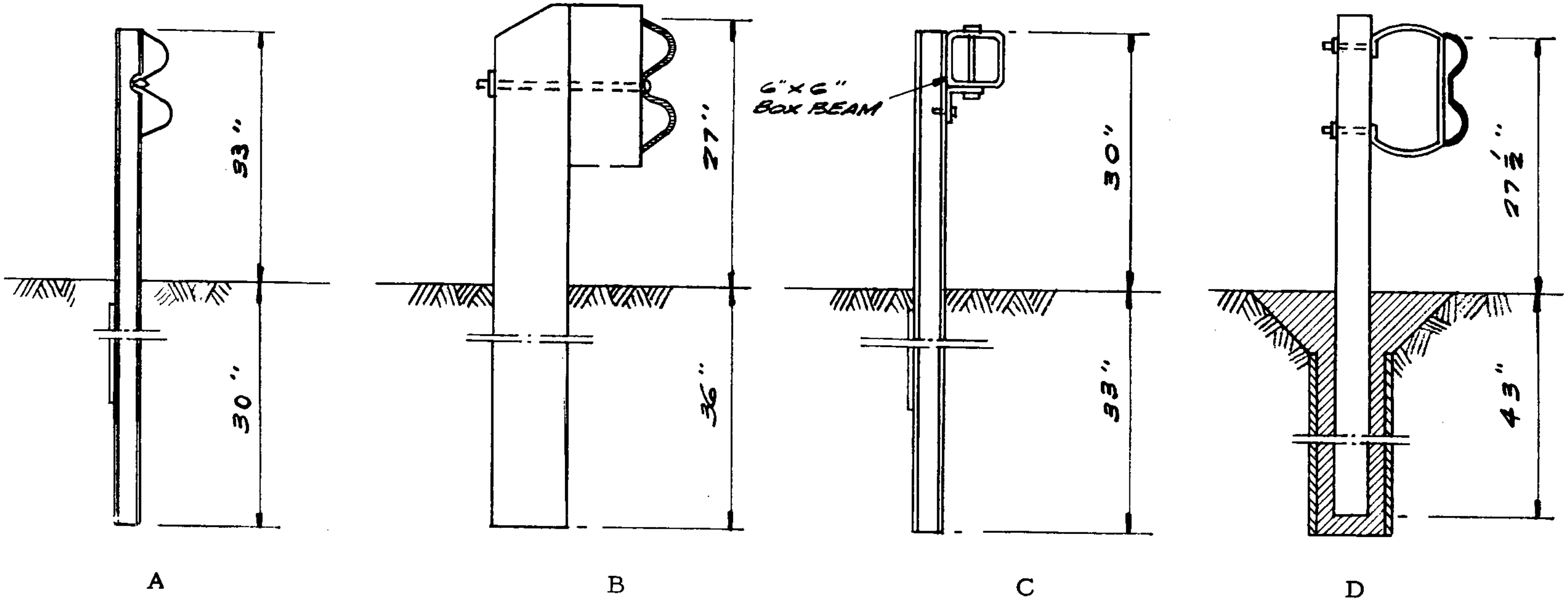
*This system is not recommended because of a tendency to pocket and snag vehicles.



A. New Jersey concrete median barrier.
B. General Motor concrete median barrier.
*C. German DAV concrete median barrier.
D. Sabla concrete kerb guardrail (France).
†E. Denmark, DAV, concrete guardrail used in Europe and Japan.
†F. Belgium, Trief, concrete guardrail used in Europe.
G. Italy, Sergad, concrete guardrail used in Italy.
H. Italy, Vianini–Autostrade, concrete median barrier.

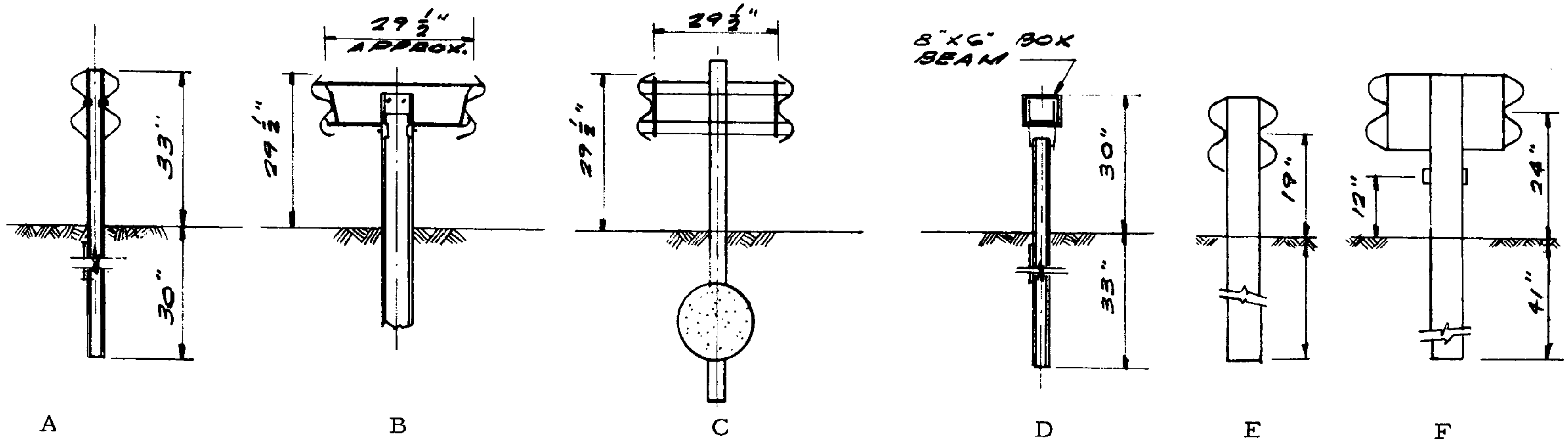
*No longer considered a satisfactory design.
†Proved unsatisfactory by tests.
‡Traffic side.

Figure 1. Rigid guardrails and median barriers.



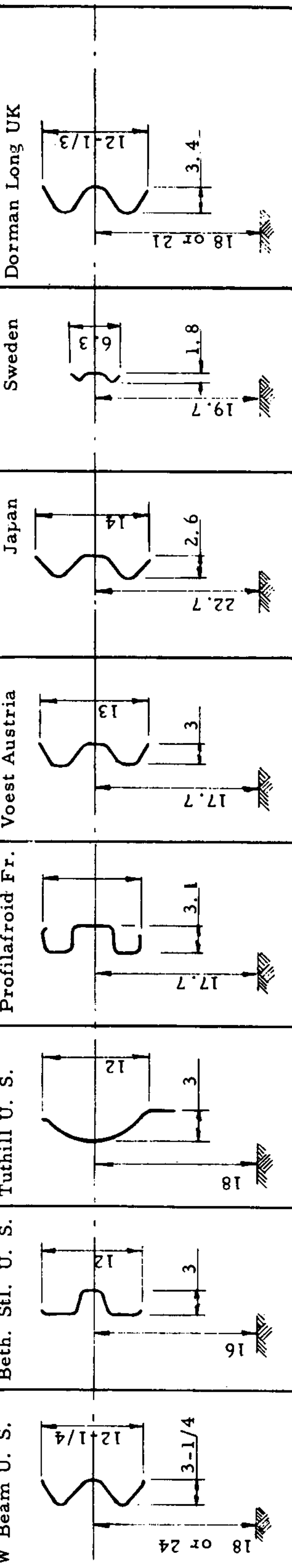
A. W-beam on weak post (New York, 1/70).
B. Blocked-out W-beam guardrail (California).
C. Box-beam guardrail (New York, 1/70)
D. Spring bracket blocked-out W-beam guardrail (Switzerland).

Figure 2. Semirigid guardrail systems.



A. W-beam on weak post (New York, 1/70).
B. German Baden Wurtemberg.
C. Netherlands.
D. Box-beam median barrier (New York, 1/70).
E. Double W-beam barrier, strong post (United States and Europe).
F. Double blocked-out W-beam median barrier (California).

Figure 3. Semirigid median barrier systems.



Type	W Beam U. S.	Beth. Stl. U. S.	Tuthill U. S.	Profilafroid Fr.	Voest Austria	Japan	Sweden	Dorman Long UK
Dimensions (in.)								
Section Length (ft. -in.)	12-6 or 25-0	12-6	11-2	13-0	13-4	13-9		11-5
Mounting Centers (ft. -in.)	12-6 or 6-3	12-6 or 6-3	10-0 or 5-0	13-0	12-6	13-0	9-0	10-6
Material:-								
Specification	S. A. E. 1010			St 37	St 70	JISG 3101	St 37	B. S. S. 15
Thickness (in.)	.105 .135	.105 .135	.135	.12	.12	.08	.24	.11
Weight (lb/ft)	6.75 8.88	6.5 8.5	7.4	8.1	7.95	---	7.8	8.0
Section Modulus (in.^{3})	1.37 1.53	1.21 1.54	1.82	1.89	1.84	---	0.67	1.24

Figure 4. Present steel beam profile (66).

curves) and is attached to the posts in such a fashion that it is readily pulled away under vehicle impact.

Flexible barriers of either the weak beam/strong post or weak beam/weak post types generally consist of posts connected by steel cables. Barrier action relies on large dynamic deflections to redirect errant vehicles gradually, thereby subjecting the occupants to tolerable lateral decelerations.

An example of the weak beam/strong post system is the multiple wire rope beam mounted via offset brackets to posts. Between two and four cables (¾-in.-diameter with minimum 25,000-lb tensile strength) are generally attached to posts spaced from 10 to 16 ft. Full-scale crash tests (*22*) of this system have indicated hazardous performance characteristics. The tests showed that vehicles become pocketed or snagged, except for very shallow angle impacts (*60*).

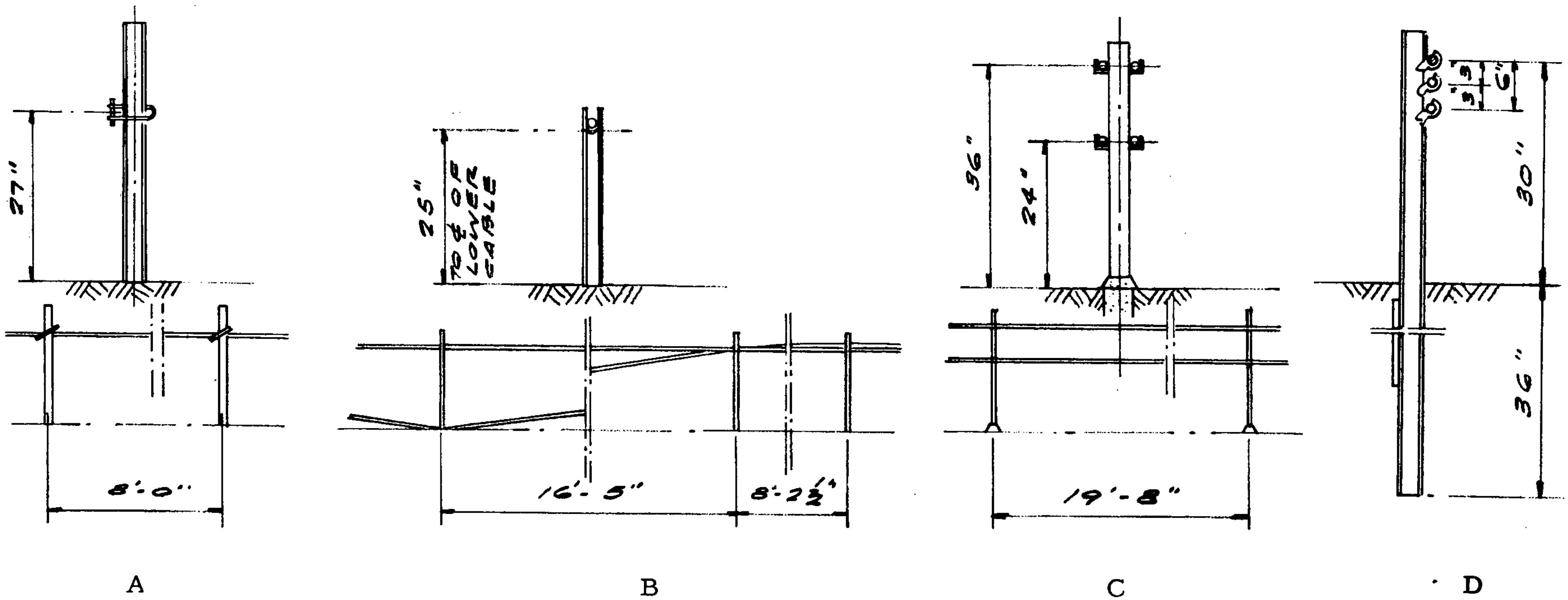
Flexible barriers with weak posts exhibit large lateral deflection of 10 ft or more; the cables are readily stripped from the weak posts, which are easily bent, thereby preventing vehicle snagging. The California Division of Highways (*9, 23, 36, 45*) investigated cable-chain link fence median barrier. Two ¾-in.-diameter wire rope cables are fastened by U-bolts to 2.25H4.1 steel posts; a 48-in. chain-link fence is attached to the posts by wire ties. Presently, California is using an expanded-metal glare screen because chain-link fabrics exhibit a tendency to gather rapidly in front of the errant vehicle and to cause snagging and violent spin-out. New York uses three cables spaced 3 in. apart (top cable at 30 in. above grade) attached with J-bolts to 3I5.7 steel posts spaced at 16-ft centers (Fig. 5). One of the principal attributes of these flexible systems is their relatively low installation cost; however, this initial cost is somewhat offset by higher maintenance expense (*40*).

Terminal Sections

Regardless of the type of barrier system employed, a typical installation is composed of three components: (1) upstream terminal section, (2) center section of "length-of-need," and (3) downstream terminal section; these elements are defined in Figure 6. To prevent an errant vehicle from striking the warranting feature, the installation must be extended a considerable distance upstream (i.e., length-of-need) to accommodate critical combinations of vehicle departure angles and speeds. Furthermore, terminal sections must be added to both ends to anchor the system in order that redirecting tensile and/or flexure forces can develop in the rail.

A widely accepted requirement by any guardrail installation is the ability to sustain the full impact force of a 4,000-lb vehicle traveling at 60 mph striking the guardrail at a 25-degree angle without penetration. However, for the terminal section, penetration may be acceptable; a vehicle breaking through a terminal section would not be endangered by the warranting roadside feature because penetration would occur outside the "length-of-need." By permitting penetration, highway designers are given more flexibility in evolving safer terminal treatments.

There are three general types of guardrail terminal treatments: (1) flares, (2) ramps, and (3) straight extensions. Many variations of these types exist. Flared terminals



A. California cable median barrier.
B. United Kingdom cable median barrier.
C. German Baden Wurtemberg cable median barrier.
D. New York cable guardrail on weak post (1/70).

Figure 5. Flexible guardrail and median barriers.

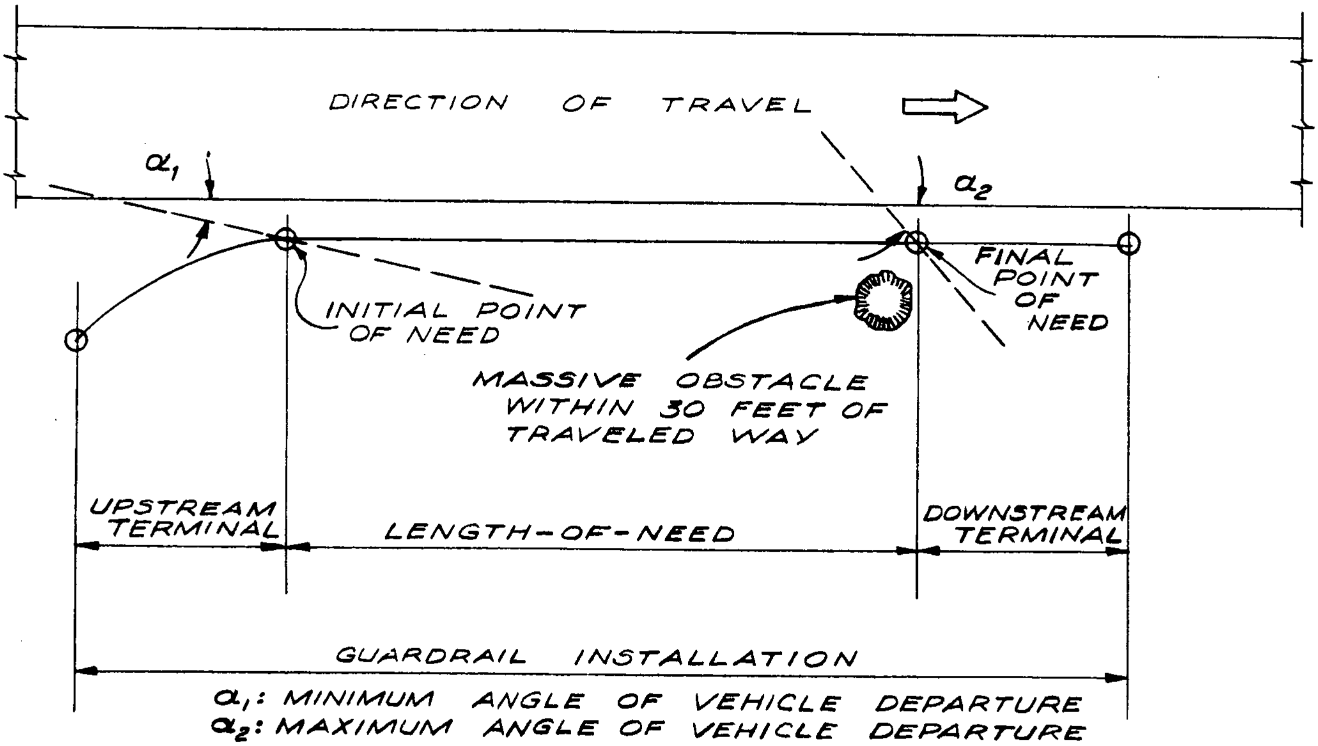


Figure 6. Definition of guardrail elements.

(Fig. 7) swing away from the pavement edge either in a straight or parabolic manner; height of rail with respect to local grade is held constant. Ramped terminals (Fig. 8) provide a gradual slope to the beam from effective rail height to grade level; the beam may be twisted 90 degrees within the ramped section and is generally anchored at grade intersection to a concrete footing. Straight extensions (Fig. 9) are additional lengths of the typical guardrail system, generally with a standard end-wing added to the beam end.

Unless adequate restraint at the ends is provided, certain guardrail and median barrier systems will deflect excessively and permit vehicle pocketing and/or penetration. California tests (*93*) showed that unanchored terminal sections for strong post systems must be greater than 30 ft in length in order to develop the necessary structural and dynamic effectiveness. Although experimental evidence is unavailable, weak post guardrail systems would be expected to require either an anchor footing or a very long terminal section (i.e., possibly 100 ft or more).

Improperly designed end treatments present a hazard to traffic. Fatal accidents have been documented where errant vehicles have struck the ends of straight terminal sections, resulting in spin-outs or abrupt deceleration. In some instances, the guardrail beam has penetrated the passenger compartment. To remove this danger, highway engineers have resorted to the ramped and flared terminals so that the beam end is no longer exposed to oncoming traffic. Both of these treatments have obvious drawbacks; the ramp tends to launch an errant vehicle and the flare increases the angle of impingement.

FUNCTIONAL CHARACTERISTICS

Warranting Criteria

A basic aspect of the guardrail and median barrier technology is identification of locations along highways where protective installations are needed. Specific decision criteria to use a guardrail or median barrier in a given location are referred to as warrants. An ideal guardrail system—that is, one that safely redirects errant vehicles without endangering other traffic and without causing injuries or fatalities among the occupants—would improve safety at most highway sites, with the possible exception of those with flat embankments that are clear of obstacles. However, such ideal systems do not exist; guardrail and median barrier systems are intrinsic roadside hazards and provide the errant vehicles with only a *relative degree of protection.*

Many existing installations are more hazardous than the roadside condition and may increase rather than reduce severity of ran-off-the-road accidents at a given site. For the period 1965-67, the California Highway Traffic Department (*95*) has shown that in 33.8 percent of freeway fatal accidents involving single vehicles, the vehicles hit off-road fixed objects (Tables 2 and 3). Furthermore, 34.6 percent of these off-road fixed-object fatal accidents involved a highway guardrail; therefore, it can be concluded that 11.7

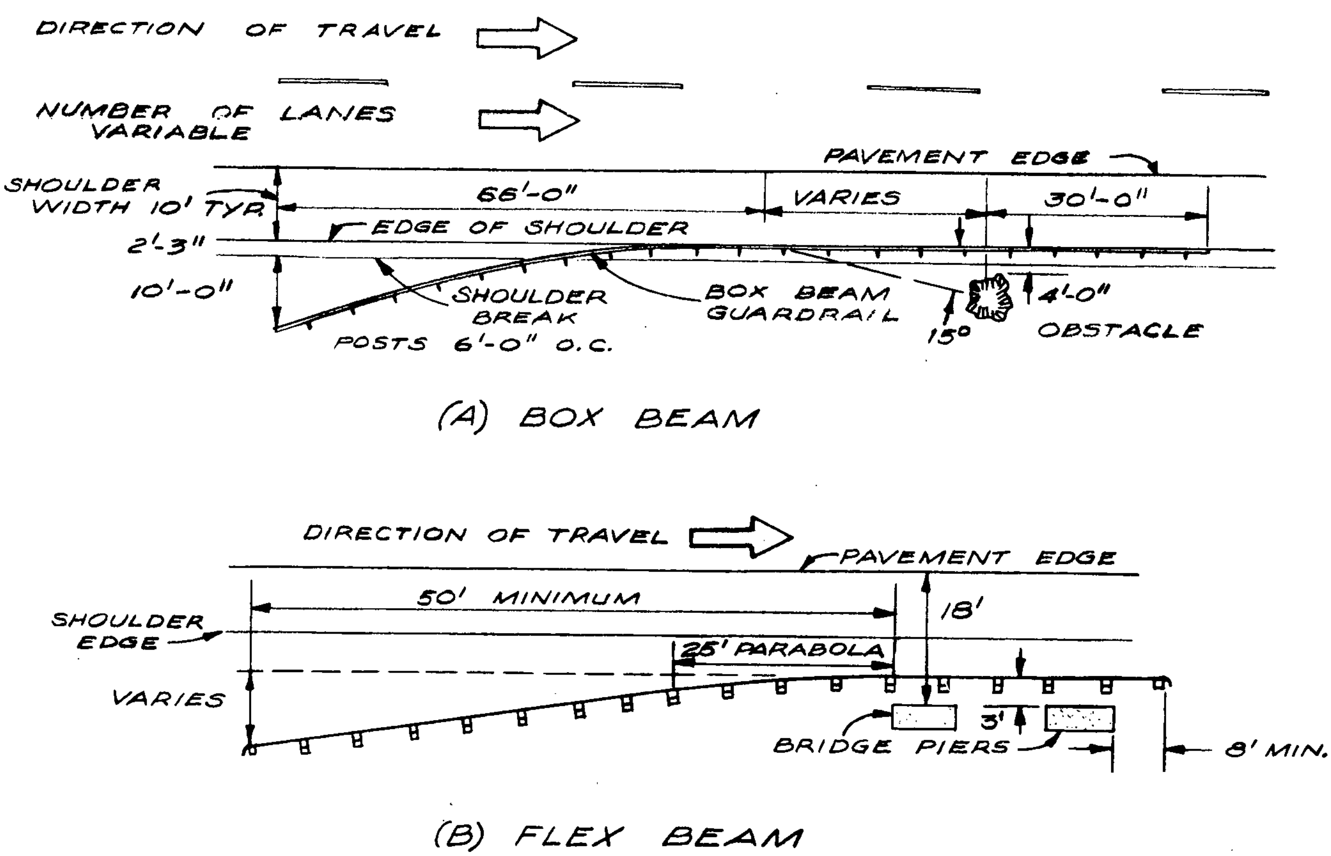


Figure 7. Flared terminal treatments.

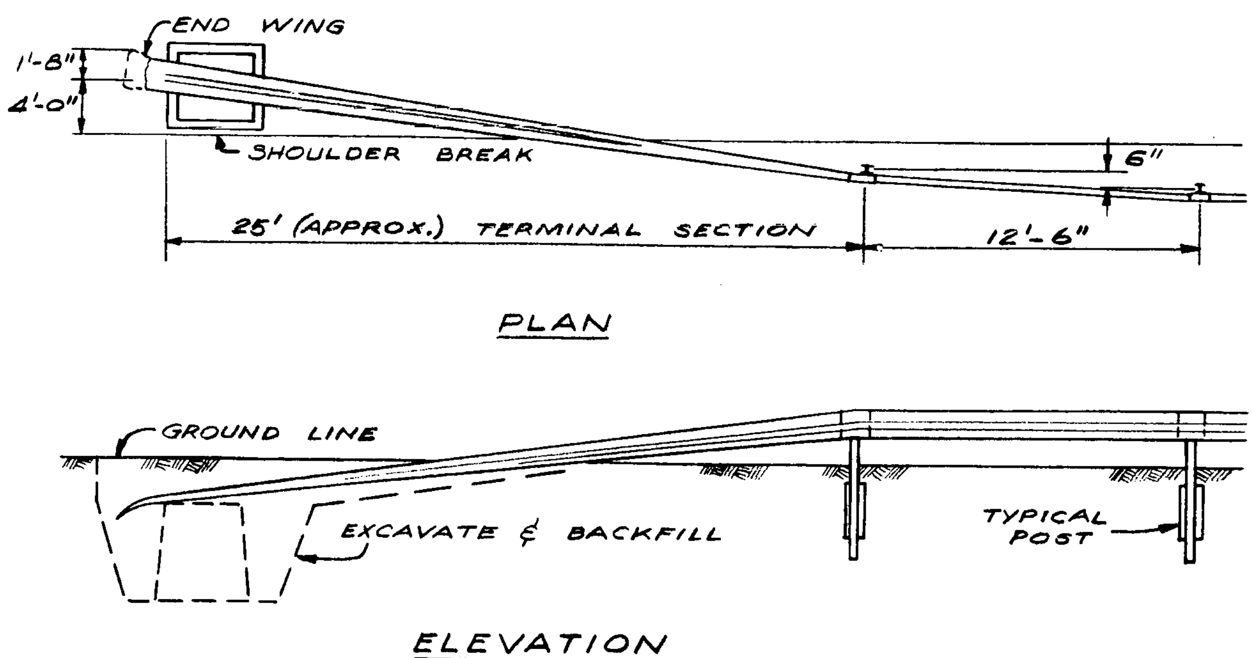


Figure 8. Ramped terminal treatment.

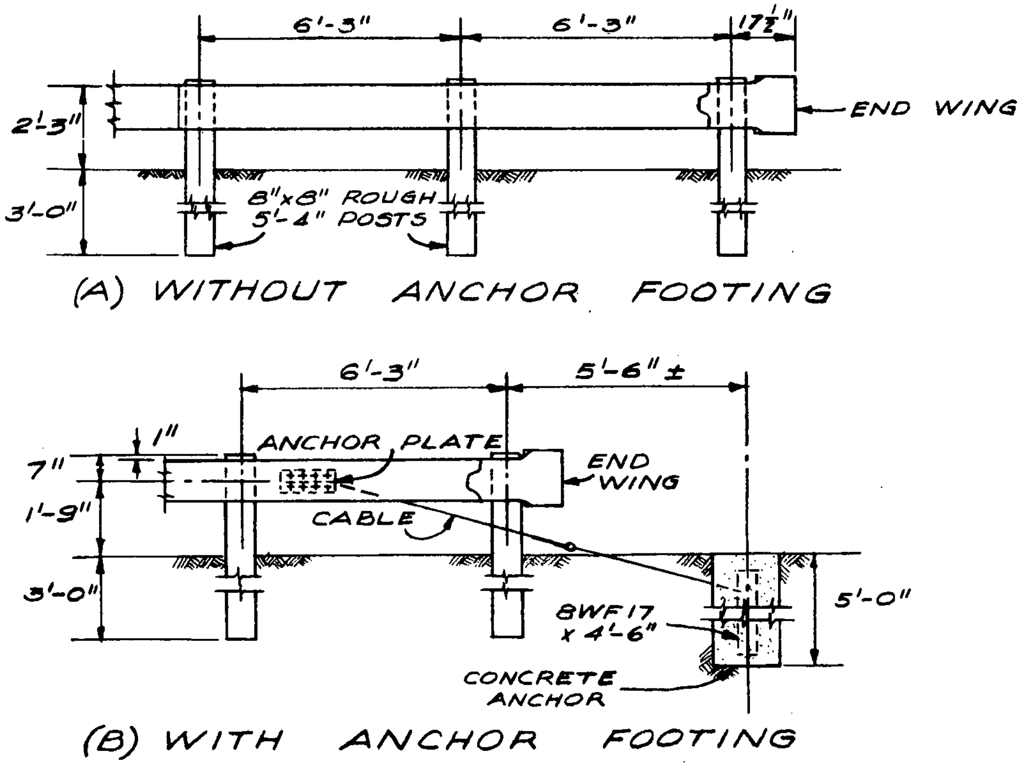


Figure 9. Straight extension terminal treatment.

TABLE 2

640 SINGLE-VEHICLE FATAL ACCIDENTS COMPILED BY CALIFORNIA HIGHWAY TRAFFIC DEPARTMENT (*95*), 1965–1967

Accident Type	Number of Fatal Accidents						Number of Persons Killed					
	1965		1966		1967		1965		1966		1967	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Ran-Off-Road, Hit Fixed Object	197	33.6	240	37.6	204	30.3	221	31.6	274	37.8	235	28.5
Ran-Off-Road, Did Not Hit Fixed Object	113	19.3	163	25.6	167	24.8	124	17.7	172	23.8	189	22.9
Rear-End	98	16.7	80	12.5	107	15.9	111	15.8	90	12.4	124	15.0
Wrong-Way	35	6.0	23	3.6	32	4.7	69	9.9	31	4.3	58	7.0
X-Median	33	5.6	35	5.5	43	6.4	51	7.3	54	7.5	85	10.3
Pedestrian	69	11.7	78	12.2	74	11.0	72	10.3	80	11.0	79	9.6
Sideswipe	17	2.9	2	0.3	27	4.0	21	3.0	2	0.3	28	3.4
Construction Zone	19	3.2	8	1.3	1	0.1	25	3.6	11	1.5	1	0.1
Miscellaneous	6	1.0	9	1.4	19	2.8	6	0.8	10	1.4	26	3.2
Totals	587	100.0	638	100.0	674	100.0	700	100.0	724	100.0	825	100.0

	1965	1966	1967
Travel (MVM)	23,000	25,970	28,870
Fatality Rates (per 100 MVM)	3.04	2.79	2.86
Fatality Accident Rates (per 100 MVM)	(2.55)	(2.46)	(2.33)

TABLE 3

640 SINGLE-VEHICLE FIXED-OBJECT FATAL ACCIDENTS (%) COMPILED BY CALIFORNIA HIGHWAY TRAFFIC DEPARTMENT (*95*), 1965–1967

Vehicle Type	Object													
	Abutments/ Piers	Guardrail at Fixed Objects	Bridge Rails	Steel Sign Poles	Light Poles	Cable Barrier	Other Guardrail	Right-Of-Way-Fence	Beam Barrier	Trees	Bridge End-Post at Gore	Wall	Miscellaneous	Subtotals
Standard Cars	15.2	11.1	7.5	3.9	3.9	4.4	2.2	1.7	1.6	1.6	1.6	0.8	3.4	58.9
Intermediate Cars	0.2	0.6	0	0.2	0	0	0	0	0	0.2	0.2	0	0.2	1.6
Compacts and Foreign Cars	3.1	3.0	2.7	2.2	3.1	3.6	1.6	0.5	0.3	0.8	0.6	0.2	1.9	23.6
Station Wagons and Vans	1.4	0.9	0.6	0.3	0.6	0.5	0.3	0.3	0	0.3	0.3	0	0.8	6.3
Pickups	0.8	0.9	0.3	0.1	0.5	0	0.5	0	0.3	0	0.1	0.1	0	3.6
Trucks	0.6	0.6	0.8	0.5	0.1	0.5	0	0.3	0	0.3	0	0	0.1	3.8
Motorcycles	0.1	0.5	0.3	0.1	0	0.3	0.8	0	0.1	0	0	0	0	2.2
Grand Totals	21.4	17.6	12.2	7.3	8.2	9.3	5.4	2.8	2.3	3.2	2.8	1.1	6.4	100.0
Guardrail Fatal Accidents		17.6				9.3	5.4		2.3					34.6

percent* of single-vehicle fatal accidents involved a barrier. From statistics compiled by Hosea (*87*) on completed sections of the Interstate System for 1968 and given in Tables 4, 5, and 6, the percentage of single-vehicle fatal accidents involving guardrail and median divider—364 and 71 accidents, respectively (Table 6)—is determined to be 23.6 percent* (i.e., 435 out of 1,842 single-vehicle accidents). Although these accident statistics reflect performance of adequate as well as unsatisfactory barrier designs, the fact remains that highway barrier installations constitute a major roadside hazard. For this reason, highways should be designed with the specific intent of eliminating, or at least minimizing, the use of barrier systems, and at the same time upgrading the performance and functional capabilities of existing installations.

At some locations, guardrails and median barriers may decrease accident severity, but accident frequencies actually increase because these systems usually constitute larger targets and are located closer to traffic than a roadside hazard. This aspect adds to the basic concept that guardrails and median barriers should be kept to a minimum. Accordingly, highway designers are well advised to examine the feasibility of adjusting site features (e.g., flattening an embankment slope or removing a tree) so that such installations will not be required.

The Idaho Formula and the procedure presented in *HRB Special Report 81* (*38*) are considered to be of questionable value as guardrail warranting criteria. In both criteria, the *combined* effect of accident *frequency* and accident *severity* is used. Based on the premise that a guardrail installation should be placed only where the severity of potential accidents will be reduced, it follows that accident frequency* should not enter into guardrail warranting criteria. Embankment geometry (height and slope) and roadside conditions (i.e., permanent bodies of water) are valid hazard considerations; however, shoulder width, horizontal curvature, downgrade, and climatic conditions generally relate to accident frequency and fail to influence the response to the question, "Would it be less hazardous for errant vehicles, regardless of number, to strike a guardrail or be permitted access to the roadside?" If it is judged that a guardrail installation is not necessary at a particular embankment (that is, the vehicle occupants would be less endangered by permitting the vehicle access to the embankment), such a decision remains valid whether one or one thousand vehicles run off the road at that point.

Warranting criteria for roadside obstacles are based on the relative hazard of striking various objects or the guardrail. From data generated at General Motors Proving Ground (*76*), one can conclude that of the vehicles that inadvertently left the roadway, only approximately 20 percent went beyond 30 ft from the pavement edge; the total traversable distance free of objects was 70 ft or more (Fig. 10). A 30-ft wide cleared zone has been adopted by several highway agencies; where a wider zone can be effected within practical and economical limits, the highway designer is encouraged to enlarge the traversable distance to 50 ft or more.

Guardrail warranting criteria for embankments are based on a study performed by Glennon (*57*). After determining

* Discrepancy between these figures (i.e., 11.7 versus 23.6 percent) is attributed in large part to definition of single- and multivehicle accidents.

* Although accident frequency factors are not used in determining guardrail installation warrants; the factors are used in establishing priority of construction of two or more warranted installations; see *NCHRP Report 54*, Appendix D.

TABLE 4

FATAL ACCIDENTS ON COMPLETED SECTION OF THE INTERSTATE SYSTEM (*87*), 1968

Type of Accident	Accidents			Fatalities		Injuries		Property Damage	
	No.	Total	% Subgroup	Total	Per Accident	Total	Per Accident	Total ($1000)	Per Accident ($)
Total Accidents, All Types	2754	100	–	3326	1.21	3067	1.14	7783.9	2826
Single Vehicle:									
Run-off-Road	1462	53.1	79.4	1685	1.16	1223	0.84	3281.3	2244
Overturned on Road	31	1.1	1.7	37	1.19	36	1.16	35.6	1148
Collision with Parked Car	96	3.5	5.2	114	1.19	111	1.16	440.2	4585
Pedestrian:									
Person Outside Their Vehicle	61	2.2	3.3	65	1.07	11	0.18	15.3	251
Trespassers	153	5.6	8.3	154	1.01	12	0.08	40.0	261
Total Pedestrian	214	7.8	11.6	219	1.02	23	0.11	55.3	258
Other	39*	1.4	2.1	42	1.08	30	0.77	75.2	1928
TOTAL SINGLE VEHICLE	1842	66.9	100.0	2097	1.14	1423	0.77	3887.6	2111
Multiple Vehicle:									
Rear-End Collision	411	14.9	45.1	504	1.23	667	1.62	2006.6	4882
Head-On Collision:									
Wrong-Way Driver	131	4.8	14.4	230	1.76	222	1.69	416.6	3180
Vehicle from Opposing Lanes	164	5.9	18.0	243	1.48	417	2.54	783.3	4776
Other	14	0.5	1.5	22	1.57	25	1.79	57.5	4107
Total Head-On Collision	309	11.2	33.9	495	1.61	664	2.15	1257.4	4069
Broadside Collision	65	2.4	7.1	81	1.25	129	1.98	197.8	3043
Sideswipe	127	4.6	13.9	149	1.17	184	1.45	434.5	3421
TOTAL MULTIPLE VEHICLE	912	33.1	100.0	1229	1.35	1644	1.80	3896.3	4272

*Primarily, vehicles that struck other objects or nonmotor vehicles on the road and accidents in which occupants fell from vehicle.

the severity indices* for 1,000 ran-down-embankment accidents, a prediction equation was established by multiple regression using embankment height and slope to predict accident severity. The equation developed was

$$\log \mathrm{SI} = 0.566 + 0.160 \log h + 0.324 \log s \qquad (1)$$

in which

SI = severity index;
h = height of embankment, in ft; and
s = slope of embankment.

Glennon then determined the severity index for 331 em-

* Severity Index $= (24F + 6I + P)/N$, in which
F is the number of fatal accidents for the condition,
I is the number of injury accidents for the condition, and
P is the number of PDO accidents for the condition.

TABLE 5

CHARACTERISTICS OF SINGLE-VEHICLE OFF-THE-ROAD FATAL ACCIDENTS ON COMPLETED SECTIONS OF THE INTERSTATE SYSTEM, 1968 (*87*)

Type of Accident	Total		Vehicles Leaving the Road: Left Side of Road		Right Side of Road	
	No.	%	No.	%	No.	%
Total Accidents, All Types	1462	100.0	695	100.0	767	100.0
Struck Fixed Object:						
Total	1208	82.6	540	77.7	668	87.1
Overturned	480	32.8	230	33.1	250	32.6
Overturned Only	245	16.8	152	21.9	93	12.1
All Overturns	725	49.6	282	55.0	343	44.7
Off-the-Road Only	9	0.6	3	0.4	6	0.8

TABLE 6

FIXED OBJECTS STRUCK FIRST IN SINGLE-VEHICLE OFF-THE-ROAD FATAL ACCIDENTS ON COMPLETED SECTIONS OF THE INTERSTATE SYSTEM, 1968 (*87*)

First Object Struck	No.		%
Total, All Objects	1208		100.0
Guardrail[(a)]	364		30.1
Bridge or Overpass	217		18.0
Sign	97		8.0
Embankment	86		7.1
Curb	72		6.0
Divider[(b)]	71		5.9
Pole[(c)]	63		5.2
Ditch or Drain	57		4.7
Culvert	51		4.2
Fence[(d)]	28		2.3
Tree	26		2.2
Other	76		6.3

NOTES: (a) Includes cable type.
(b) Includes rail, concrete, and chainlink.
(c) Principally light poles.
(d) Principally right-of-way-fences.

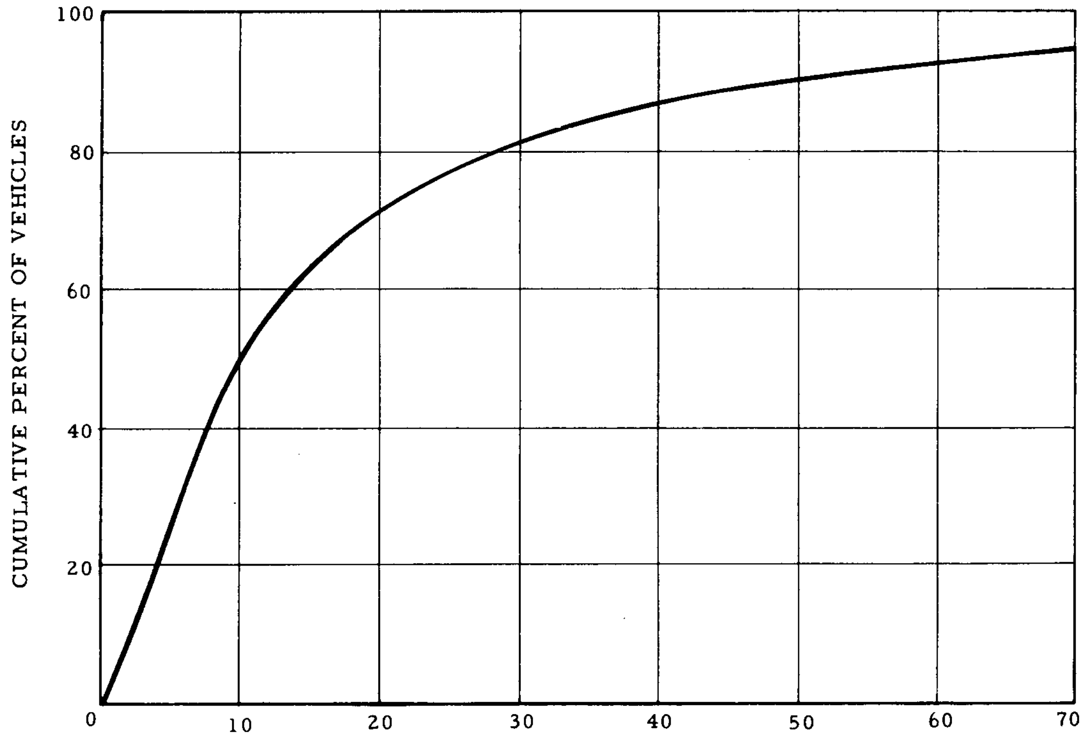


Figure 10. Distribution of off-the-road incidents, General Motors Proving Ground study (76).

bankment guardrail accidents to be 4.24 and concluded that any combination of embankment height and slope yielding a severity index greater than 4.24 needs guardrail to minimize the severity. A plot of the equal severity curve is shown in Figure 11. Also shown in Figure 11 is the recommendation of *HRB Special Report 81*. It is to be noted that, according to Glennon, *Report 81* provides for excessive use of guardrail for embankment heights greater than 10 ft.

Warranting criteria for median barriers have, to a large extent, been dictated by adverse accident experience along divided highways. Recently, California (*114*) developed a warranting criterion based on analysis of across-the-median type accidents. The unpublished report presented average daily traffic (ADT) and median width as significant warranting factors (Fig. 12). Median barriers are warranted for highways only where traffic volume exceeds 20,000 ADT and where the median width is less than 46 ft. New York State generally disregards traffic volume as a factor and does not specify median barriers for median widths greater than 36 ft.

Performance Criteria

For evaluating the effectiveness of various barrier systems, the most significant performance criteria are those related to the:

- The structural integrity of guardrails and median barriers.
- The occupant and/or vehicle accelerations.
- The post-impact trajectory of the errant vehicle.

From the viewpoint of order of consideration, the initial requirement is quite obviously the structural integrity of a guardrail or median barrier as determined by its ability to sustain an impact without permitting an errant vehicle to vault over, break through, or wedge under the installation. Only those systems that can redirect the vehicle need be considered further as worthwhile candidates.

After structural integrity, a second, but most important, consideration is the protection of the vehicle occupants. Human tolerance to a crash environment is related to accelerations (*22*). As accelerations increase in intensity, so do the number of injuries and fatalities; hence, the most effective barrier systems are those that maintain their structural integrity but also simultaneously minimize the intensities of acceleration experienced by the occupants. Basically, occupant accelerations during impact are functions of: (1) vehicle dynamics (i.e., vehicle weight, speed, angle of approach, etc.), (2) vehicle crashworthiness (i.e., energy dissipated by primary and secondary structures and passenger compartment appurtenances), (3) occupant restraint systems (including the attachment components and structural elements), as well as (4) the structural dynamic properties of the barrier system.

In order to assess and compare various system designs, it is expedient to standardize as much as possible the first three (vehicle-related) factors; that is, test controls frequently involve the use of a dummy restrained by lap belt

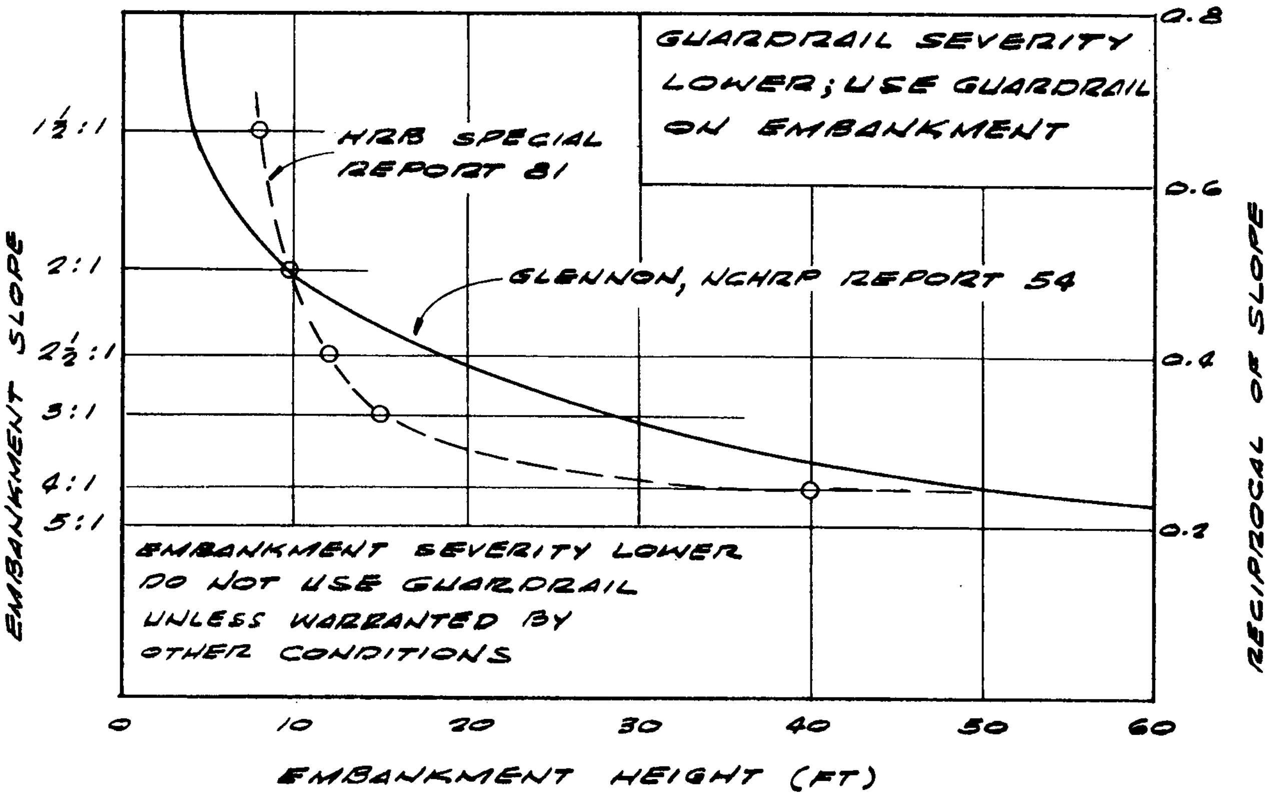


Figure 11. Severity comparison of embankments versus guardrail (57).

and chest harness, an automobile that weighs 4,000 lb, and impact conditions such that the vehicle strikes the test installation at 60 mph and a 25-degree angle. Because of the highly transient, interacting phenomena produced during a vehicle-barrier crash environment, it is apparent that accelerations (as criteria for assessing guardrail or median barrier effectiveness) are neither straightforward nor singularly unique. For purposes of simplification, attempts have been made to concentrate on the accelerations experienced by the vehicle rather than those sustained by the passengers.

TABLE 7

MAXIMUM VEHICLE ACCELERATIONS FOR HUMAN TOLERANCE (*22*)

Restraint	Maximum Acceleration (g's)*		
	Lateral	Longitudinal	Total
Unrestrained occupant	3	5	6
Occupant restrained by lap belt	5	10	12
Occupant restrained by lap belt and shoulder harness	15	25	25

*Maximum onset rate of 500 g's per sec; acceleration duration not to exceed 200 msec.

But even this approach does not appreciably alleviate the complexity of delineating the significant accelerations. For a given set of impact conditions, vehicle accelerations at a precise instant in time differ, depending on spatial location of the point of measurement. As an example, longitudinal accelerations at the vehicle center of gravity may be less than 30 percent of those at the front bumper. Accordingly, the vehicle center of gravity has been arbitrarily selected as the point of measurement to facilitate correlation and comparison of test results.

But regardless of how thoroughly vehicle accelerations are measured and defined, their value in formulating performance criteria is marginal unless they can be used to establish the dynamic forces experienced by the passengers. Accelerations sustained by occupants are not directly relatable to those experienced by the vehicle unless the occupants are extremely well restrained. For example, accelerations measured in the chest cavity of dummies restrained in the driver's seat by both a lap belt and chest harness appear to have some relation to the accelerations measured near the vehicle's center of gravity. Maximum permissible vehicle accelerations which are within the limits of human tolerance have been suggested (*22*). As presented in Table 7, such vehicle accelerations are classified according to direction and degree of occupant restraint. Note that the vehicle occupants are more vulnerable to lateral accelerations regardless of restraint. These values should be considered upper limits; obviously, a guardrail system that redirects errant vehicles with lower acceleration intensities is preferred.

With regard to lateral acceleration, one aspect of significance has evolved from certain rigid barrier tests. Although such barriers are unyielding, occupant lateral accelerations measured in shallow-angle (less than 15 degrees) crash tests have been found to be moderate, and to compare favorably with those generated during tests involving semirigid systems. This phenomenon may be explained by the fact that as the vehicle contacts the rigid barrier the inside front wheel "rides up" the sloped barrier surface and the driver becomes inclined to the vertical plane. In so doing, the lateral force imposed on the driver is reduced. From General Motors Proving Ground tests, it was found (*48*) that when test vehicles impacted a GM concrete barrier at a speed of 50 mph and 12-degree angle, the lateral acceleration to a simulated human occupant did not exceed 3g. In tests where the barrier was repeatedly struck at 50 mph from an 8-degree angle by operator-driven cars, no vehicle damage or driver injuries were observed. Hence, for *shallow* angle impacts, the New Jersey and General Motors concrete barriers are notable exceptions to the rule that "the more a system deflects laterally, the less intense will be the vehicle lateral accelerations." On the other hand, vehicle redirection is abrupt for large (20 degrees or more) angle impacts. In these collisions, the vehicle structure comes in contact with the upper part of the barrier before the front wheel reaches and "rides up" the sloped surface. Hence, the sloped surface is ineffective during the redirection.

In addition to magnitudes and direction, two other characteristics of accelerations—rate of onset and duration—are significant in determining human tolerance. It has been suggested (*22*) that the values presented in Table 7 are applicable where the duration does not exceed 200 msec and the rate of onset does not exceed 500 g's per sec. Vehicle lateral accelerations from five guardrail crash tests are shown in Figure 13; rate of onset for these typical curves is less than 100 g's per sec and duration at peak acceleration is less than 100 msec. The importance of acceleration duration is shown in Figure 14.

At this stage in the technology, it would appear that if specific characteristics of the various accelerations were to be used to measure a system's effectiveness, these would be the peak accelerations of the vehicle in the lateral and longitudinal direction. As determined by microanalysis of high-speed motion pictures, these were selected as the principal indicators of guardrail capabilities in the study reported herein.

To minimize the possibility of involving other traffic, the third performance requirement for a barrier system is that the errant vehicle be redirected in a trajectory parallel to and near the installation. However, it must be recognized that accidents where a vehicle is abruptly redirected back into a traffic lane and becomes involved in a multicar collision are problematical and are believed to be few in number. Such a sequence of events is assumed to be peculiar to those highway sites where traffic is extremely dense, or where sight distances or traffic densities preclude the ability of other vehicles to undertake evasive action. Accident statistics are unavailable to confirm or deny these conjectures. For these reasons, post-impact vehicle trajectory is a performance consideration that should be reserved in making a selection among systems that are comparable with regard to structural integrity characteristics and accelerations produced during vehicle redirection.

In reporting results of full-scale crash tests, it has been customary to define the exit angle of the vehicle as the parameter to measure barrier effectiveness in terms of post-impact trajectory. However, the instant in time in which to measure such an angle during the sequence of events has not been firmly established. More important is the fact that any angle, regardless of its spatial and temporal definition, is not sufficient to describe whether or not the vehicle post-impact trajectory is indeed adequate in terms of the requirement to avoid the involvement of other traffic. A more meaningful and readily discernible trajectory parameter is the *rebound distance,* defined as distance from the original guardrail line to the maximum outermost point on the vehicle during the post-impact trajectory (Fig. 15). Rebound distance is the vehicle trajectory property selected in this study to quantitatively characterize the third guardrail and median barrier performance requirement.

DEVELOPMENT PROCEDURES

Design and Analysis Methods

Structural analysis methods for depicting the dynamic response of semirigid and flexible guardrail systems have been developed and used with some degree of success. Such methods are the result of a combination of theoretical studies, laboratory experiments, and full-scale crash tests. Attempts have been made to predict a vehicle's dynamic behavior during impact and its subsequent trajectory on an analytical basis. Until recently, only gross properties could be projected from even the simplest impact conditions. Laboratory experiments have been used to develop fundamental material and structural properties, and some subscale modeling of the guardrail-vehicle interaction has been performed. Full-scale crash tests have been conducted by several organizations in the United States and in some foreign countries. As a result of these efforts, a better understanding of guardrail dynamic behavior has begun to evolve; however, a need still exists for verified analytical methods by which barrier and vehicle parameters can be used to predict the performance characteristics of guardrail systems. A methodology based on full-scale crash tests has been used by some states to develop acceptable guardrails and median barriers, but because of the expense only a limited number of tests have been conducted on any one system.

For the present, the highway designer's efforts are basically restricted to selecting the most appropriate system from a group of four or five proven guardrail configurations. The structural criteria available to the designer are intended

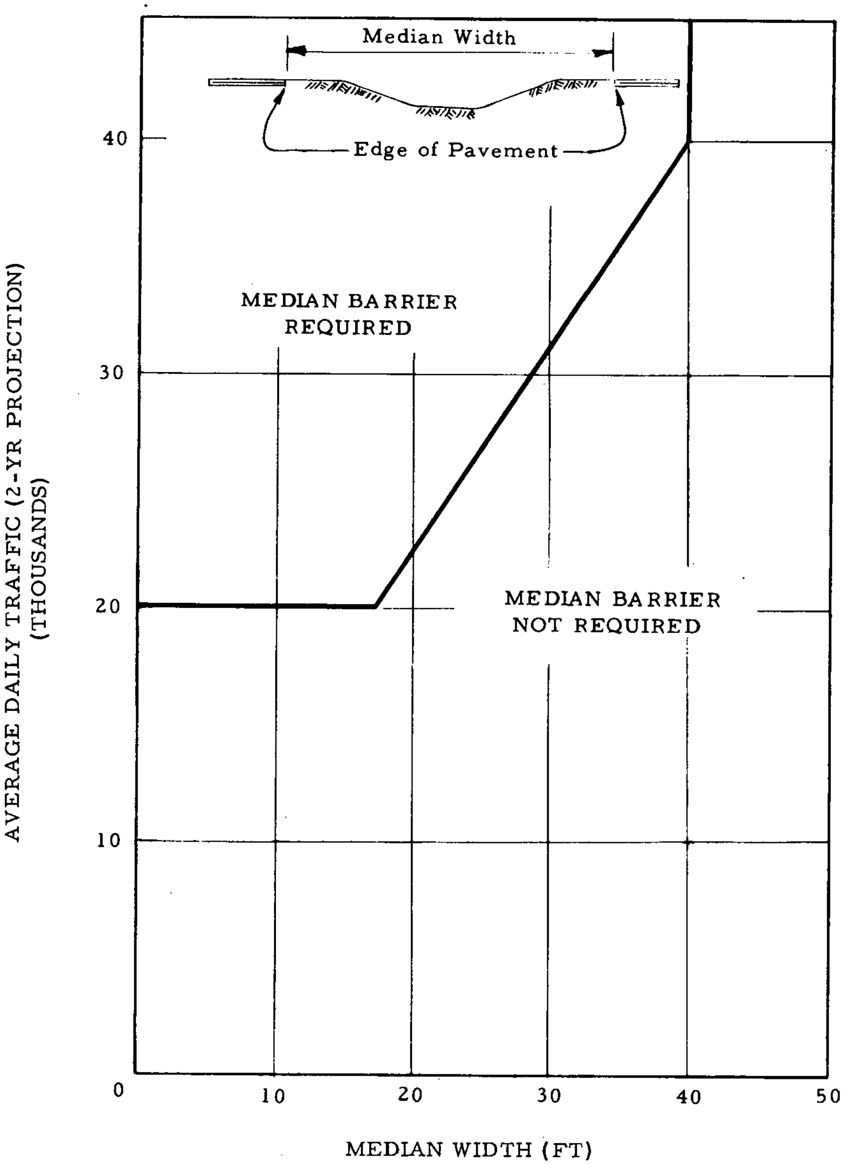


Figure 12. Median barrier warrant criterion (72).

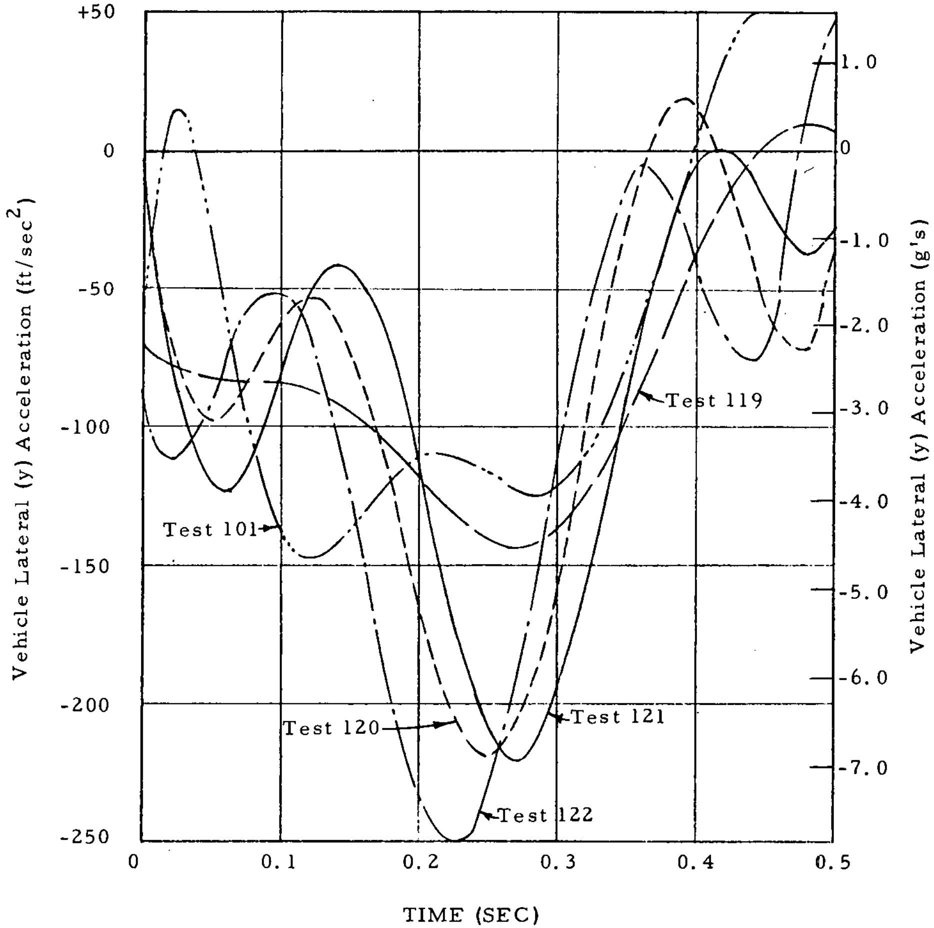


Figure 13. Vehicle lateral accelerations for five full-scale crash tests.

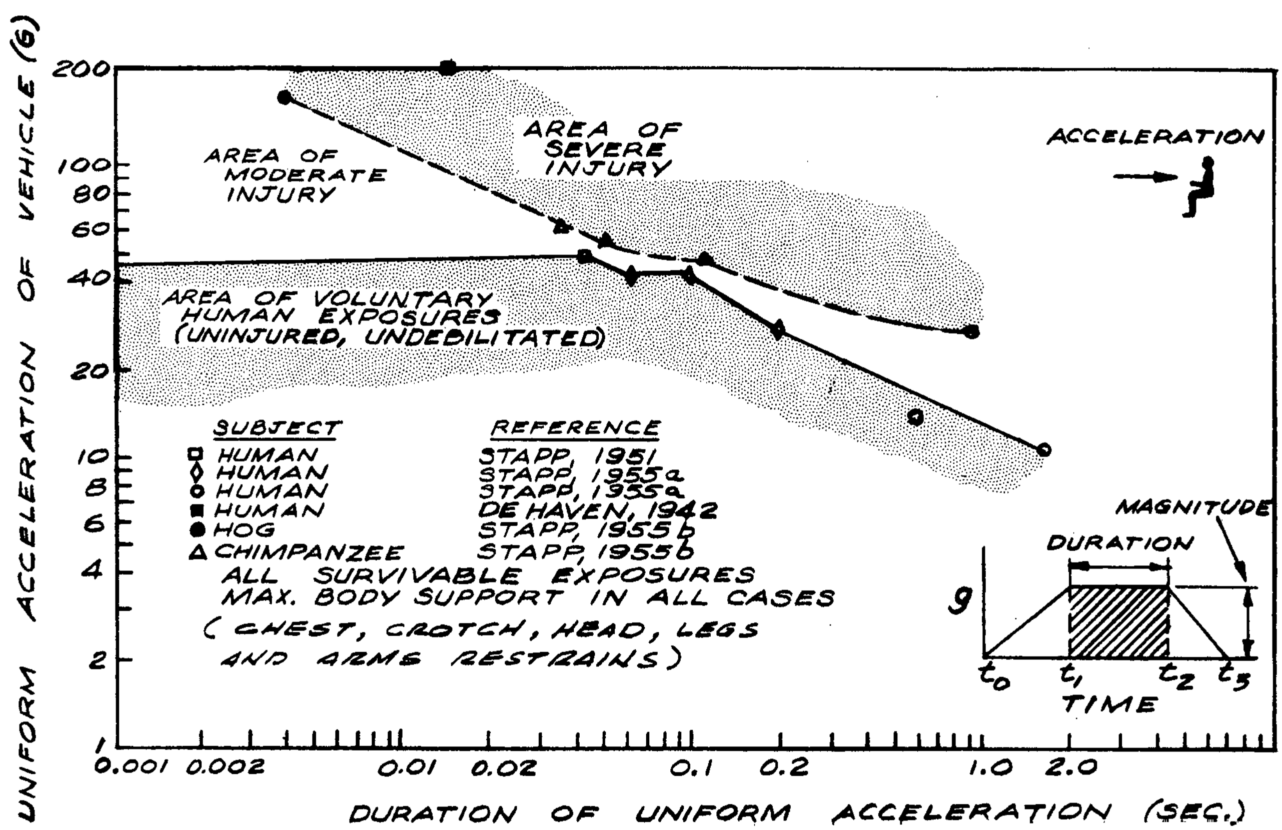


Figure 14. Maximum tolerance limits to longitudinal acceleration (sternumward g).

primarily for the purpose of insuring that the maximum dynamic deflection of a system is compatible to that space available at the highway site. From crash testing experience, it has been determined that small changes in barrier construction can have unpredictable and quite significant effects on guardrail performance; thus, the highway designer is also limited as to the type of adjustments that can be made to a guardrail for adaptation to local conditions.

A basic ingredient to developing and advancing any technology are the theoretical principles that ultimately define the design and analysis procedures, and form the basis for productive experimental and testing programs.

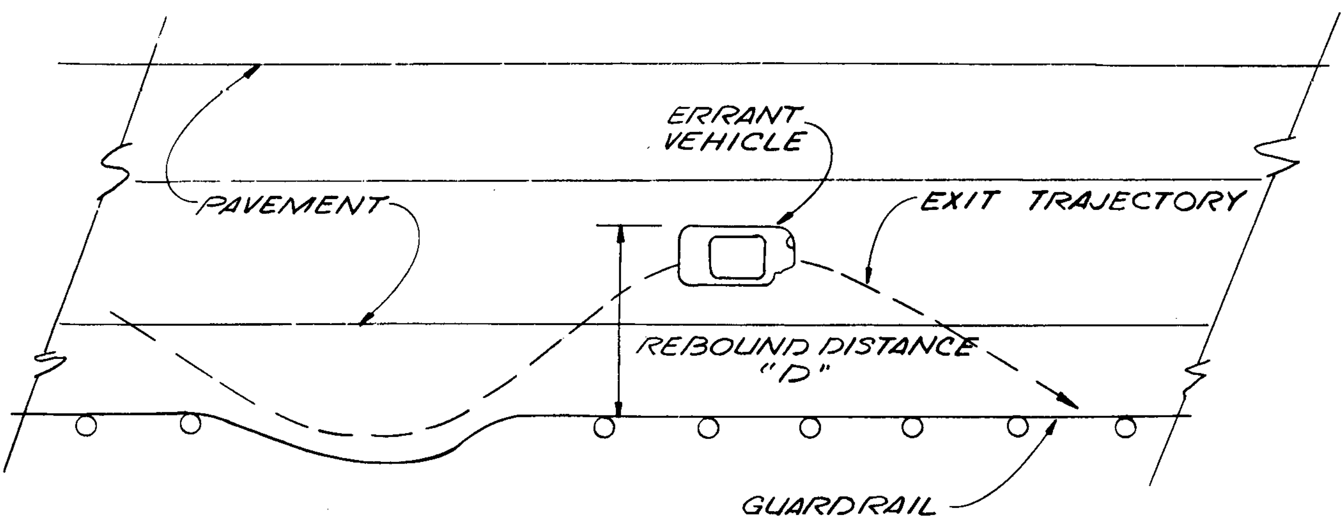


Figure 15. Definition of vehicle post-impact rebound distance.

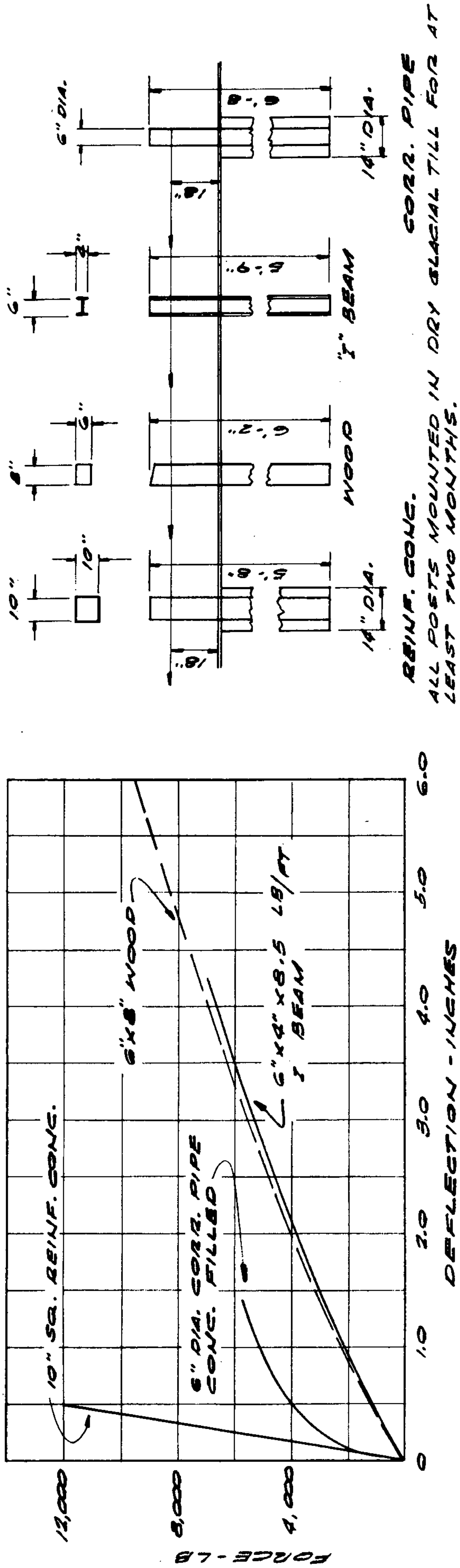


Figure 16. Static pull test, guardrail posts (16).

Traffic barrier systems are no exception. A number of groups have attempted to characterize mathematically the vehicle-guardrail impact dynamics. It has been reasoned that until this crash situation can be defined analytically the importance of various guardrail parameters (i.e., post spacing, beam strength, etc.) cannot be properly evaluated. The task has proven most difficult. Early theoretical attempts relied on simplified conditions and gross assumptions regarding the guardrail and vehicle behavioral phenomena. Not too surprisingly, correlations between predicted and actual results obtained during crash tests were nonexistent. Recently, more refined theoretical approaches have been developed that use third-generation digital computers. Under contract with the New York State Department of Public Works, Cornell Aeronautical Laboratory (*50*) developed a computer program to describe vehicle motion in terms of longitudinal and lateral translation, and yaw rotation. The barrier system involves three force deflection characteristics: (1) tension only, (2) bending only, and (3) combined bending and tension. Under contract with the Bureau of Public Roads, Cornell Aeronautical Laboratory also developed an eleven degree-of-freedom model for collision simulation; the barrier portion of the program is the same as above. In this program, a six degree-of-freedom model of the vehicle was developed in conjunction with an improved mathematical model capable of accommodating combined bending and tension in a guardrail system. After verification using results obtained from the full-scale crash tests, the models were used to conduct parameters sensitivity analyses to identify the more significant performance-related variables. Also, response characteristics of typical guardrail systems were computed for impacts with vehicles at other than the customarily used test conditions.* Results of these studies are discussed in Chapter Three.

Laboratory and Full-Scale Test Methods

The dynamic response of guardrails involves several complex structural mechanisms, including:

- Strength and behavior of the embedded posts when subjected to a dynamic lateral load.
- Energy dissipation characteristics of the vehicle and the guardrail during impact.
- Guardrail structural properties that affect the vehicle trajectory.

Various laboratory tools and techniques have been used to acquire an understanding of these mechanisms. Knowledge of the basic characteristics of each element of an assembly is necessary as input to theoretical as well as component improvement investigations. An example of this was in the development testing of the standard post (*62*). When a vehicle impacts a barrier rail at 60 mph and at an angle of 20 degrees, posts located at or near the point

* Standard vehicle conditions: 4,000 lb, 60 mph, and 25 degrees.

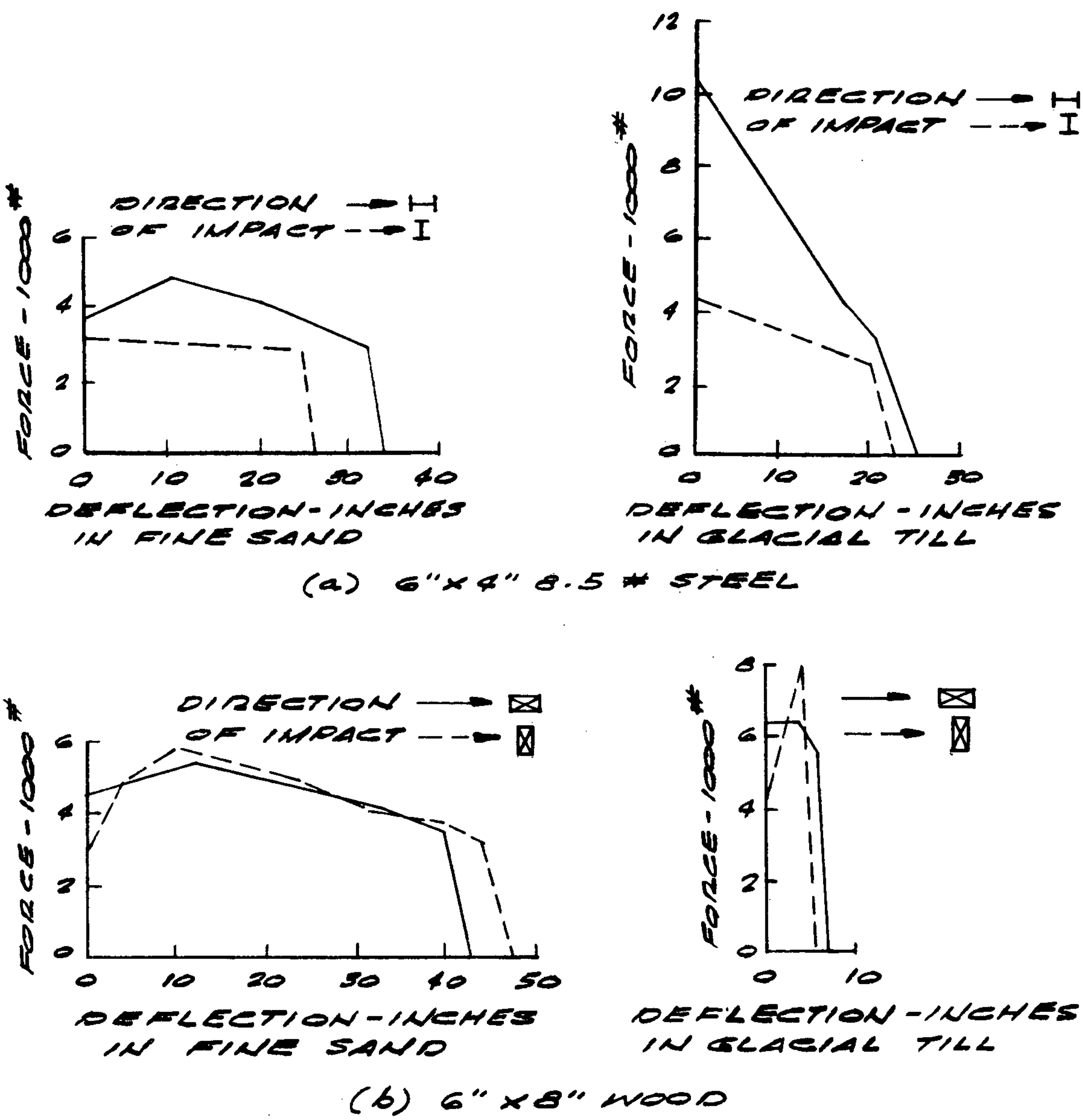


Figure 17. Dynamic force-deflection characteristics of posts in soils (60).

of initial contact will be moved laterally at a speed of about 20 mph. New York employed a truck with a special bumper and impacted test posts at 10 to 20 mph; the resulting loads and displacements were measured. From this study evolved the standard New York post that utilizes a steel plate welded to the post within the embedment length to achieve adequate soil bearing load. This eliminates costly concrete footings and reduces the assembly cost of driving posts at the installation site. General Motors (*16*) investigated the relative merit of steel, concrete, and timber posts and found that reinforced concrete has undesirable performance characteristics, but both timber and steel materials could be used for strong as well as weak post designs. Properties of some of the typical and more common guardrail elements are given in Figures 16 through 18. It should be stressed that laboratory tests have been used to develop elements of systems, but full-scale crash testing is required for a complete assembly evaluation.

Use of subscale modeling to investigate the vehicle/guardrail interaction is attractive when compared to full-scale testing because (1) the experiments can be controlled to a finer degree in the laboratory, (2) the parameters can be more easily varied, (3) the rate of unit testing can be accelerated, and (4) the costs of experimentation are reduced. On the other hand, in scaling size some parameters (mass, stiffness, moment of inertia, etc.) may be distorted, introducing uncertainties in the experimental results. For this reason, subscale model testing of guardrail has been done only on a limited basis by Johns Hopkins University (*5*) and Stevens Institute of Technology (*67*). The Johns Hopkins tests were conducted on energy-absorbing cable-

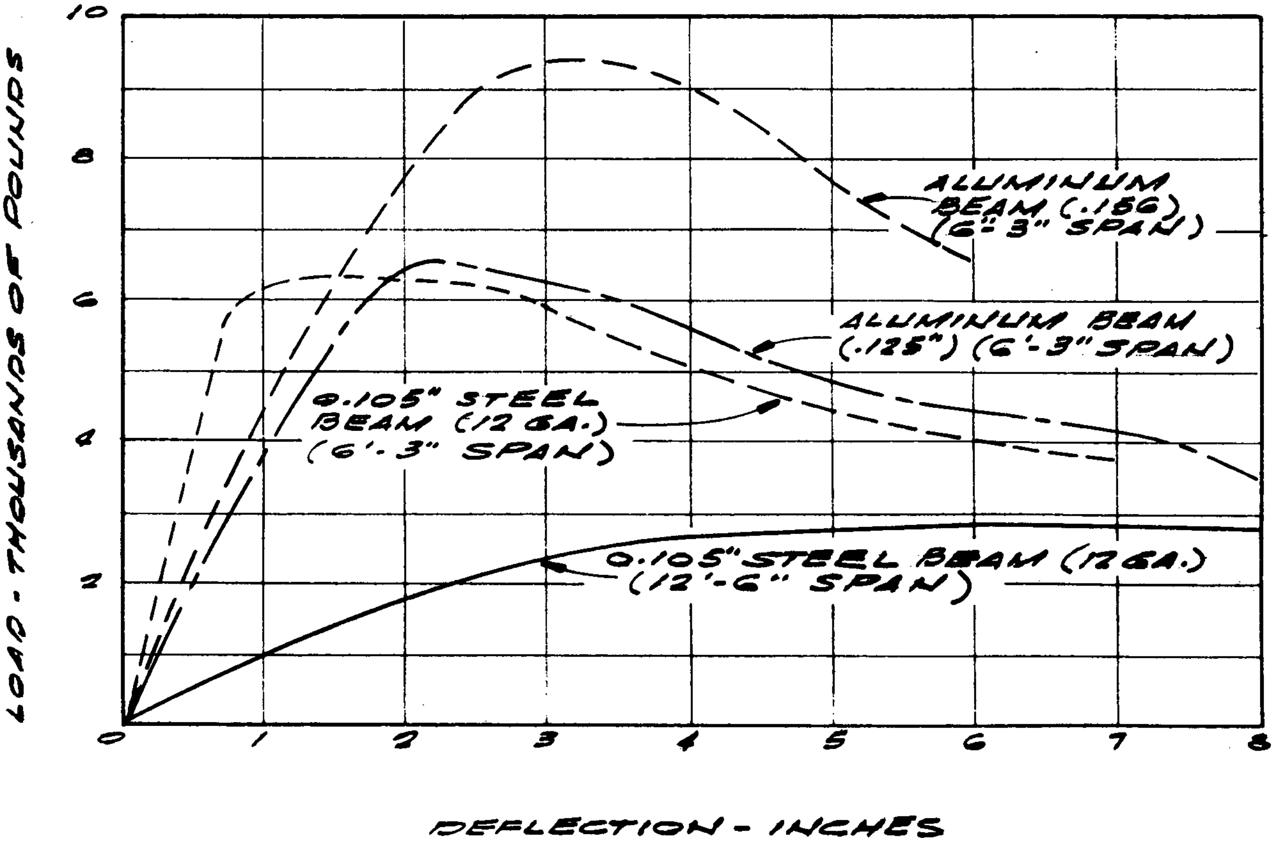


Figure 18. Standard W-beam deflection curves (16); *static loading of beam sections, concentrated load at center.*

TABLE 8

SUMMARY OF GUARDRAIL FULL-SCALE TESTS, UNITED STATES

FLEXIBLE GUARDRAIL

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rails (in.)	Vehicle Weight (lb)	Vehicle Speed (mph)	Impact Angle (deg)	Total Momentum (lb-sec)	Lateral Momentum (lb-sec)	Vehicle Decel. Long./Lat. (g)	Max. Dyn. Defl. (ft)	Max. Perm. Defl.	Guardrail Performance or Vehicle Reaction
1	62	4 cables[b]	6 X 4-in. 8.5 steel	10-0	39	26, 22, 18, 14	3,800	41	34	7,100	3,980	–	12.0	–	Poor, violent reaction
2	62	3 cables	2-1/4 X 2 X 4.1 steel[c]	8,0	30	30, 24, 18	3,900	62	32	11,000	5,830	–	11.0	–	Car redirected
3	62	3 cables	315.7 steel[d]	8-0	39	30, 24, 18	3,500	55	25	8,800	3,720	–	11.0	–	Car rolled over
4	62	3 cables	315.7 steel[d]	8-0	39	30, 24, 18	3,500	53	25	8,400	3,550	–	8.5	–	Large redirection angle
5	62	3 cables	315.7 steel[d]	12-0	39	30, 24, 18	3,500	54	25	8,600	3,640	–	8.7	–	Car redirected 12 deg, nearly rolled over
6	62	3 cables	315.7 steel[d]	12-0	42	27, 21, 15	3,500	43	35	6,800	3,900	–	9.3	–	Front end snagged on cables
7	62	3 cables	315.7 steel[d]	12-0	37	30, 24, 18	3,500	53	5	8,400	730	–	1.0	–	Good
8	62	3 cables	315.7 steel[d]	16-0	45	27, 24, 21	3,500	44	25	7,000	2,960	–	11.0	–	Good (exit angle 15 deg)

(a) Cables are 3/4-in.-dia. steel with 25,000 lb breaking strength.
(b) Spring offset.
(c) A frame footing.
(d) 1/4-in. steel plate footing.

SEMIRIGID GUARDRAIL

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rails (in.)	Vehicle Weight (lb)	Vehicle Speed (mph)	Impact Angle (deg)	Total Momentum (lb-sec)	Lateral Momentum (lb-sec)	Vehicle Decel. Long./Lat. (g)	Max. Dyn. Defl. (ft)	Max. Perm. Defl.	Guardrail Performance or Vehicle Reaction
1	16	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	43	24[a]	4,163	37	20	7,010	2,410	7.5 / 6	–	1.3	Good
2	16	Steel W-Beam (12 ga)	6 X 4 in. 8.5 steel	12-6	43	24[a]	4,163	35	33	6,630	3,620	–	–	7.8	Pocketed, short instal.
3	16	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	43	24[a]	4,163	30	33	5,690	3,100	–	–	3.0	Good
4	16	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	43	24[a]	4,033	35	20	6,410	2,200	–	–	0.5	Good, large exit angle
5	16	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	43	24[a]	4,030	35	33	6,600	3,500	5.6 / 3.6	–	2.0	Penetrated, vaulted over beam
6	30	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	39	27[a]	3,800	54	19	9,350	3,040	9.2 / 3	–	–	Pocketed (short end anchor)
7	113	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,215	54	15	7,910	2,050	–	–	0.9	High exit angle
8	113	Steel W-Beam (12 ga.)	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,200	60	25	11,720	2,260	10.1 / 8	–	3.2	Large defl. and spin
9	62	Steel W-Beam (10 ga.)	6 X 4 in. 8.5 steel	12-6	39	27[a]	3,800	54	19	9,300	3,020	–	6.0	–	Poor, post too strong, beam too weak
10	62	Steel W-Beam (12 ga.)	315.7 steel[b]	12-0	39	30[a]	3,500	51	25	8,100	3,430	–	10.7	8.0	Faulty end anchor failed, car retained
11	62	Steel W-Beam (12 ga.)	315.7 steel[b]	12-0	39	30[a]	3,500	54	25	8,600	3,640	–	6.8	4.0	Redirected, large exit angle
12	62	Steel W-Beam (12 ga.)	315.7 steel[b]	12-0	39	30[a]	3,500	35	35	5,600	3,220	–	9.0	4.0	Vehicle retained, rail snagged vehicle
13	62	Steel W-Beam (12 ga.)	315.7 steel[b]	12-0	39	30[a]	3,500	57	6	9,100	950	–	0	0	Excellent
14	16	Steel W-Beam (12 ga.)	6 X 8-in. wood	12-6	48	24[a]	4,163	60	24.8	11,400	4,800	–	–	3.1	Good
15	16	Steel W-Beam (12 ga.)	6 X 8-in. wood	12-6	48	24[a]	3,963	65	25	11,720	4,950	10.1 / 8	–	–	Penetrated (short instal.)
16	16	Steel W-Beam (12 ga.)	6 X 8-in. wood	12-6	48	24[a]	4,029	37	20	6,780	2,320	6.8 / 5.8	–	1.3	Good
17	16	Steel W-Beam (12 ga.)[c]	6 X 8-in. wood	12-6	48	24[a]	4,150	68	18.5	12,920	4,100	16.4 / 13.1	–	4.4	Good, high deflection
18	16	Steel W-Beam (12 ga.)	6 X 8-in. wood	10-10	50	24[a]	4,033	35	18.5	6,440	2,040	–	–	0.2	Good
19	9	Steel W-Beam (12 ga.)	8 X 8-in. wood	12-6	30	25[a]	3,980	60	27	10,880	4,950	–	4.0	–	Pocketed and roll over
20	16	Steel W-Beam (12 ga.)[c]	6 X 8-in. concrete	12-6	48	24[a]	4,085	65	20.5	12,020	4,200	9.3 / 6.4	–	6.3	Pocketed, beam torn loose
21	16	Steel W-Beam (12 ga.)	6 X 8-in. concrete	12-6	47	24[a]	4,033	35	20	6,410	2,200	2 / 3.5	–	0.5	Good
22	16	Steel W-Beam (12 ga.)	6 X 8-in. concrete	12-6	47	24[a]	4,058	39	20.4	7,200	2,460	5.1 / 6.8	–	1.3	Good, high exit angle
23	16	Steel W-Beam (12 ga.)	10 X 10-in. concrete	12-6	42	24[a]	4,033	34	20	6,140	2,100	8.1 / 5.9	–	1.5	Good
24	113	Alum. W-Beam (0.125 in.)	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,465	56	15	8,840	2,290	–	–	1.4	Good
25	113	Alum. W-Beam (0.125 in.)	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,140	60	15	8,600	2,220	–	–	1.9	Good
26	113	Alum. W-Beam (0.125 in.)[d]	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,225	60	15	8,820	2,290	–	–	1.9	Good
27	113	Alum. W-Beam (0.125 in.)[d]	6 X 4 in. 8.5 steel	12-6	–	27[a]	3,210	54	15	7,900	2,040	–	–	0.8	Good
28	113	Alum. W-Beam (0.125 in.)	6 X 4 in. X 0.188 Alum. Z	12-6	63	27[a]	3,210	63	15	9,210	2,390	–	–	1.9	Poor, vehicle mounted rail
29	46	Steel blocked-out W-Beam	8 X 8-in. wood	12-6	41	24[a]	4,570	58	25	12,100	5,120	–	–	0.4	Penetrated
30	46	Alum. (0.156) blocked-out W-Beam	8 X 8-in. wood	6-3	35	24[a]	4,570	60	25	12,500	5,290	–	Failed		Beam failed and snag
31	46	Steel blocked-out W-Beam	8 X 8-in. wood	6-3	35	24[a]	4,570	59	25	12,300	5,200	–	–	1.5	Good (exit angle 19 deg)
32	46	Steel blocked-out W-Beam	8 X 8-in. wood	6-3	35	27[a]	4,570	60	25	12,500	5,290	–	–	1.5	Good (exit angle 17 deg)
33	46	Steel blocked-out W-Beam[c]	8 X 8-in. wood	6-3	41	30[a]	4,570	60	25	12,500	5,290	–	–	1.8	Good (exit angle 13 deg)
34	32	Steel blocked-out W-Beam[f]	6 X 4 in. 8.5 steel	6-3	38	27[a]	3,900	59	25	10,400	4,400	–	Failed		Beam failed, vehicle rolled over
35	62	Steel blocked-out W-Beam[f]	6 X 4 in. 8.5 steel	6-3	38	28[a]	3,900	59	25	10,400	4,400	–	Failed		Rail tore and separated
36	16	Steel W-Beam[c]	6 X 8-in. concrete	6-3	48	24[a]	4,210	67	18	12,800	3,960	12.9 / 11.5	–	1.7	Good
37	16	Steel W-Beam[c]	6 X 8-in. concrete	6-3	48	24[a]	23,590	27	15	29,000	7,520	–	–	1.7	Good
38	16	Steel W-Beam[c]	6 X 8-in. concrete	6-3	48	24[a]	23,590	40	15	42,900	11,100	8.8 / 5	–	1.8	Good
39	62	Steel 6X 6 X 3/16 box beam	315.7 steel[b]	6-0	39	27[a]	3,500	50	25	8,000	3,390	–	3.0	1.0	Good redirection
40	62	Steel 6 X 6 X 3/16 box beam	315.7 steel[b]	6-0	39	27[a]	3,500	49	35	7,800	4,470	–	5.1	–	Excellent
41	16	Steel std. Tuthill beam[c]	6 X 8-in. wood	10-10	48	24[a]	4,033	35	18.1	6,420	1,990	–	–	0.9	Vehicle mounted rail
42	16	Steel std. Tuthill beam	6 X 8-in. concrete	5-0	46	24[a]	4,058	35	20	6,450	2,210	7.1 / 4.0	–	1.0	Good
43	16	Steel std. Tuthill beam	6 X 8-in. concrete	5-0	46	24[a]	4,317	32	20	6,280	2,150	16.5 / 11.7	–	1.1	Good redirection
44	16	Standard 4 cable	6 X 4 in. 8.5 steel	12-2-1/2	40	27[h]	4,137	41	20	7,700	2,640	– / 5.8	–	2.0	Good
45	16	Standard 4 cable	6 X 4 in. 8.5 steel	12-6	40	27[h]	4,500	61.5	20	12,600	–	–7 / 6	Failure		Cables failed
46	30	Standard 4 cable	6 X 4 in. 8.5 steel	10-0	39	26[h]	3,800	41	34	7,100	–	3.7 / 4.3	–	–	Pocketed and spinout
47	82	Alum. extruded beam 4-3/4 in. offset	5-1/2 in. WF alum.	8-0	–	27[a]	4,000	56	25	10,200	4,320	– /10.4	1.2	0.4	Good (exit angle 20 deg)
48	82	Alum. extruded beam 4-3/4 in. offset	5-1/2 in. WF alum.	13-4	–	27[a]	4,000	59	15	10,700	2,780	– / 5.3	–	0.3	Good (exit angle 10 deg)

(a) Top of rail.
(b) With 1/4-in. plate footing.
(c) With spring bracket.
(d) Modified W section.
(e) Plus steel 6, 8.2 rubbing rail.
(f) Steel section block-out bracket.
(h) Height of top cable.

TABLE 9

SUMMARY OF MEDIAN BARRIER FULL-SCALE TESTS, UNITED STATES

FLEXIBLE MEDIAN BARRIERS

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rails (in.)	Vehicle Weight (lb)	Vehicle Speed (mph)	Vehicle Angle (deg)	Total Momentum (lb-sec)	Lateral Momentum (lb-sec)	Vehicle Decel. Long./Lat. (g)	Barrier Defl. (ft-in.)	Barrier Performance or Vehicle Reaction
1	9	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	1 at 27[b]	4,000	56	27	10,200	4,680	69 / 154	7-2	Spinout
2	9	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	4,000	61	31	11,100	5,700	–	8-6	Good
3	9	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	3,700	41	15	6,900	1,790	55 / 22	3-4	Good
4	9	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	3,700	52	32	8,750	4,630	53 / 34	9-0	Snag on intermed. anchor
5	9	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	3,850	60	31	10,500	5,400	–	8-0	Good
6	9	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	17,500	42	34	33,450	18,700	–	12-0	Good
7	23	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	4,300	78	7	15,250	1,860	6.5 / –	5-6	Violent spinout
8	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30	4,300	84	7	16,430	2,000	2.4 / –	5-6	Violent spinout
9	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30	4,300	86	7	16,830	2,060	4 / –	6-0	Violent spinout
10	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30	4,300	76	10	14,850	2,570	3.6 / –	6-0	Violent spinout
11	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30	4,300	84	7	16,430	2,010	4.8 / –	7-0	Violent spinout; anchor failed
12	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30	4,300	75	7	14,700	1,800	3 / –	6.0	Spinout
13	23	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	1 at 20, 32, 44	4,300	77	7	15,080	1,840	6.8 / –	5-6	Rollover
14	23	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30	2 at 30[c]	4,300	74	22	14,450	5,430	–	–	Vaulted barrier
15	23	1 cable and fence[d]	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	1 at 30[c]	4,300	82	20	16,000	5,470	–	12-0	Pitch down and spinout
16	36	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 30	4,300	90	25	17,600	7,450	–	17-0	Good; slight spinout
17	36	2 cables	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 30	4,300	83	25	16,250	6,880	–	–	Penetrated; anchor failed
18	36	2 cables	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 30	4,300	84	25	16,450	6,960	–	17-0	Good; spinout
19	36	2 cables	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 27	4,300	87	25	17,000	7,200	–	17-0	Good; spinout
20	45	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 26[f]	4,138	67	7	12,640	1,540	–	3-8	Good; spinout, nearly vaulted
2[illegible]	45	2 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 26[f]	2,540	67	25	7,750	3,280	–	7-6	Good (small car)
[illegible]	45	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 26[g]	4,138	65	7	12,250	1,500	–	4-6	Snag; violent pitch and rollover
23	45	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 27[g]	4,138	60	7	11,300	1,380	–	3-6	Violent spinout
24	45	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 27[g,h]	2,540	65	25	7,520	3,180	–	–	Pen: cable splice failed (small car)
25	45	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[e]	2 at 27[g,h]	2,540	63	25	7,300	3,090	–	–	Penetrated (small car)
26	16	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	4,190	65	16.7	12,400	3,560	4.5 / 5	8-0	Good
27	16	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 30[b]	4,992	65	8	14,580	2,030	34 / 4.5	3-8	Snag; violent spin
28	16	3 cables and fence	2-1/4 X 2-1/4 in. 4.1 steel	8	30[a]	2 at 34[i]	3,870	35	8.5	6,160	914	3.8 / 2.6	3-2	Good
29	41	2 cables and fence	–	–	–	–	–	60	10	8,200	1,450	–	–	Rollover
30	32	3 cables	2-1/4 X 2-1/4 in. 4.1 steel	8	30[j]	1 at 18, 24, 30	3,900	58	29	10,300	5,000	–	11-0	Good (exit angle 8 deg)
31	20	3 cables	Light pipe A frame[k]	35	36[e]	1 at 15, 22, 29	4,060	38	15	7,030	1,810	–	–	Good
32	20	3 cables	Light pipe A frame[k]	35	36[e]	1 at 15, 22, 29	4,060	40	12-15	7,400	1,670	–	–	Good
33	20	3 cables	Light pipe A frame[k]	35	36[e]	1 at 15, 22, 29	3,500	56	20	8,920	3,050	–	–	Climbed cables; 3 wheels crossed bar
34	20	3 cables	Light pipe A frame[k]	35	36[e]	1 at 15, 22, 29	3,500	43	25	6,850	2,900	–	–	Rollover

(a) 8-in.-dia. concrete footing.
(b) Plus 1 at 9 in.
(c) 8% ramp.
(d) Envelop barrier.
(e) 10-in.-dia. concrete footing.
(f) On 6-in. raised median.
(g) Plus 1 at 18 in.
(h) Above 15-in. sloped median.
(i) Plus 1 at 12 in.

SEMIRIGID MEDIAN BARRIERS

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rails (in.)	Vehicle Weight (lb)	Vehicle Speed (mph)	Vehicle Angle (deg)	Total Momentum (lb-sec)	Lateral Momentum (lb-sec)	Vehicle Decel. Long./Lat. (g)	Max. Dyn. Defl. (ft)	Max. Perm. Defl.	Barrier Performance or Vehicle Reaction
1	9	Dbl steel W-Beam	8 X 8 in. wood	12-6	30	25	3,980	59	31	10,690	5,500	–	5.0	4.6	Vehicle roll over
2	9	Dbl steel W-Beam	8 X 8 in. wood	6-3	30	25	3,980	58	31	10,500	5,400	–	3.4	2.5	High exit, vehicle roll over
3	9	Dbl steel W-Beam	8 X 6 in. 15.5 steel[a]	6-3	30[a]	30[a]	4,000	58	30	10,550	5,270	–	3.0	2.3	Poor, snag
4	9	Dbl steel W-Beam	8 X 8 in. wood	6-3	42	30	4,050	59	26	10,870	5,770	–	3.3	2.3	Snag and vehicle roll over
5	9	Dbl blkd-out steel W-Beam[c]	8 X 8 in. wood	6-3	41	30	4,000	60	32	10,900	5,770	–	3.1	2.0	Good, high exit angle
6	9	Dbl blkd-out steel W-Beam[c]	8 X 8 in. wood	6-3	41	30	17,500	41	36	32,600	19,200	–	4.8	4.3	Good, high exit angle
7	46	Dbl blkd-out steel W-Beam[c]	8 X 8 in. wood	6-3	41	30	4,570	69	25	14,400	6,100	–	–	1.3	Good (exit angle 15 deg)
8	46	Dbl blkd-out steel W-Beam[d]	8 X 8 in. wood	6-3	41	30	4,570	68	25	14,200	6,000	–	–	1.0	Good (exit angle 14 deg)
9	46	Dbl blkd-out alum. (0.125) W-Beam[c]	8 X 8 in. wood	6-3	41	30	4,570	67	25	14,000	5,920	–	Failed		Vehicle penetrated, rolled over
10	46	Dbl blkd-out alum. (0.156) W-Beam[e]	8 X 8 in. wood	6-3	41	30	4,570	67	25	14,000	5,920	–	–	1.8	Good (exit angle 14 deg)
11	30	Dbl blkd-out steel W-Beam[f]	6 X 4 in. 8.5 steel.	6-3	39	27	3,800	67	16	11,580	3,190	2.8 / 5.3	–	–	Good (exit angle 9 deg)
12	30	Steel box beam 5-1/4 X 10 in.	2-1/4 H 4.1 steel	4-0	39[g]	26	3,600	58	18	9,510	2,940	4 / 6.2	1.1	0.2	Good (exit angle 7 deg)
13	30	Steel box beam 5-1/4 X 10 in.	2-1/4 H 4.1 steel	4-0	39[g]	26	3,600	52	24	8,520	3,460	6 / 6	0.8	0.2	Good (exit angle 7 deg)
14	30	Steel box beam 2-1/4 X 10 in.	2-1/4 H 4.1 steel	4-0	39[g]	26	3,600	60	25	9,840	4,160	–	–	–	Pocketed, anchor failed
15	30	Steel box beam 2-1/4 X 10 in.	2-1/4 H 4.1 steel	4-0	39[g]	26	3,600	55	20	9,020	3,090	4.3 / 2.8	–	–	Good (exit angle 9 deg)
16	62	Steel box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	36[h]	27	3,500	56	25	8,900	–	–	5.5	3.0	Good
17	62	Steel box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	36[h]	27	3,500	43	35	6,800	–	–	5.6	7.5	Good
18	62	Alum. box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	36[h]	27	3,500	50	25	8,000	–	–	3.0	2.0	Good
19	75	Steel box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	16.3[j]	27	4,540	71	25	14,700	–	–	Failed		Rail torn free from posts, vehicle penetrated
20	75	Steel box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	16.5[j]	27	4,540	64	25	13,200	–	–	4.1	2.4	Exit angle 6 deg, vehicle rolled 18 deg
21	75	Steel box beam 8 X 6 X 1/4 in.	315.7 steel	6-0	16.5[j]	27	4,540	49	10	10,100	–	–	0.8	0.3	Good (exit angle 3 deg)
22	82	Alum. box beam 8 X 6 in.	315.7 steel	6-0	–	27	4,000	–	–	–	–	6.2 / 2.0	6.0	3.0	Vehicle redirected parallel to rail
23	82	Alum. extrusion 2-1/2 in. offset	6 X 4 M 8.5 steel	6-3	–	27-1/2	4,000	–	–	–	–	12+ /	–	–	Vehicle penetrated
24	82	Alum. extrusion 2-1/2 in. offset	6 X 4 M 8.5 steel	6-3	–	24-1/2	4,000	–	–	–	–	11.4 / 12.0	–	–	Vehicle penetrated
25	82	Alum. extrusion 4-3/4 in. offset	5-1/2 WF alum.	10-0	–	27	4,000	–	–	–	–	6.8 / 9.3	1.2	0.3	Good (exit angle 15 deg)
26	82	Alum. extrusion Figure 6	315.7 steel	6-3	–	27-1/2	4,000	–	–	–	–	–	Failure		Vehicle penetrated barrier
27	82	Alum. extrusion Figure 8	315.7 steel	6-3	–	24-1/2	4,000	–	–	–	–	8.2 / 9.2	–	–	Vehicle snagged, spun out
28	82	Alum. extrusion Figure 11	315.7 steel	6-3	–	27-1/2	4,000	–	–	–	–	–	5.0	–	Fair
29	82	Alum. extrusion Figure 13	315.7 steel	6-3	–	27-1/2	4,000	65	25	11,600	4,700	4.0 / 1.4	3.0	1.0	Good
30	82	Alum. extrusion Figure 16	315.7 steel	6-3	–	27-1/2	4,000	53	15	9,650	2,500	–	1.5	0.7	Good
31 to 35	82*	Alum. extrusion Figure 16	315.7 steel	6-3	–	27-1/2	4,000	60	25	10,900	4,630	3.5 /	3.0	1.5	Good

*Based on average of 5 tests of identical systems.
(a) 12-in.-dia. concrete footing.
(b) 6-in. curb in front of rail.
(c) Plus 6, 8.2-lb steel rubbing rail.
(d) Plus steel "Hat" section rubbing rail.
(e) Plus 6, 3.0-lb aluminum rubbing rail.
(f) Steel block-out bracket.
(g) 8-in.-dia. concrete footing.
(h) 1/4-in. steel plate footing.
(j) 16-in.-dia. concrete footing.

RIGID MEDIAN BARRIERS

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rails (in.)	Vehicle Weight (lb)	Vehicle Speed (mph)	Vehicle Angle (deg)	Total Momentum (lb-sec)	Lateral Momentum (lb-sec)	Barrier Performance or Vehicle Reaction
1	75	New Jersey Conc. Median Barrier	–	–	–	32	4,540	38	7	7,800	952	Vehicle redirected with no rebound and max. roll of 2 deg away from barrier
2	75	New Jersey Conc. Median Barrier	–	–	–	32	4,540	65	7	13,400	1,640	Vehicle redirected with max. rebound 1.4 ft and max. roll of 14 deg away from barrier
3	75	New Jersey Conc. Median Barrier	–	–	–	32	4,540	63	25	13,000	5,500	Vehicle redirected exit angle 12 deg, max. roll 25 deg away from barrier airborne for 20 ft.

and-post-type guardrails using a rigid car (no suspension or turning capability). The Stevens Institute tests were conducted using an articulated model vehicle and a rigid barrier. The lack of scale model testing to date is probably indicative of the feeling that this method is less productive than full-scale testing.

Full-scale crash tests represent a most important evaluation phase in developing guardrails. Presently, theoretical studies and laboratory experiments are most useful when the results are applied to define full-scale test requirements. Experience has shown that small details in construction, which cannot be studied in the laboratory, significantly affect a particular system's performance. Because of this and the complexities of the vehicle-barrier crash phenomenon, full-scale tests continue to be essential to the development and evaluation of effective systems. Since 1952, the California Division of Highways, the New York State Department of Public Works, General Motors Corporation, University of Miami, Cornell Aeronautical Laboratory, and Lehigh University have conducted and reported results of full-scale crash tests. In Europe and Japan, testing has been in progress since 1954. A summary of full-scale testing activity is given in Tables 8, 9, and 10.

New York State recently completed a two-year crash

TABLE 10

SUMMARY OF GUARDRAIL/BARRIER FULL-SCALE TESTS, FOREIGN

No.	Ref.	Rail	Post	Post Spacing (ft-in.)	Post Depth in Soil (in.)	Height of Rail[(a)] (in.)	Vehicle Wt (lb)	Vehicle Speed (mph)	Impact Angle (deg)	Total Momentum (lb-sec)	Vehicle Decel. Long./Lat. (g)	Guardrail/Barrier Performance or Vehicle Reaction
1	20	DAV conc. g.r.	Concrete	–	–	20	3,750	34	20	5,800	–	Good
2	20	DAV Dywidag g.r.	Concrete	–	–	22	3,000	46	20	6,290	–	Vehicle rolled over
3	35	DAV Dywidag med.	Concrete	13-1	–	25.6	2,800	61	15	7,780	–	Good
4	35	DAV Dywidag med.	Concrete	13-1	–	25.6	2,800	61	30	7,720	–	Vehicle thrown violently; rollover
5	35	DAV Dywidag med.	Concrete	13-1	–	25.6	25,000	46	15	51,800	–	Penetrated and/or vehicle rollover
6	35	DAV conc. g.r.	Concrete	13-1	–	25.6	25,000	47	15	53,500	–	Penetrated and/or vehicle rollover
7	35	DAV conc. g.r.	Concrete	13-1	–	–	25,000	46	15	52,400	–	Penetrated and/or vehicle rollover
8	6	DAV conc. g.r.	9.5 X 10-in. conc.	6-6	35.5	21	20,900	24	26.5	22,500	–	Penetrated
9	6	DAV conc. g.r.	10 X 10-in. conc.	13-1	39	19.7	19,800	31	25	27,500	–	Penetrated
10	121	Corr. steel beam g.r.	3-in. steel pipe	12-6	39.5	26	13,250	30	8	18,000	–	Good (exit angle 5 to 10 deg)
11	121	Corr. steel beam g.r.	3-in. steel pipe	12-6	39.5	26	13,700	35	15	21,700	–	Good (exit angle 5 to 10 deg)
12	121	Corr. steel beam g.r.	3-in. steel pipe	12-6	39.5	26	15,500	44	15	30,900	–	Vehicle rollover on rail
13	121	Corr. steel beam g.r.	4-in. steel pipe	12-6	59	37.5	15,900	38	15	27,500	–	Good
14	121	Corr. steel beam g.r.	4-in. steel pipe	12-6	59	31.5	15,800	35	15	25,200	–	Good
15	121	Corr. steel beam g.r.	4-in. steel pipe	12-6	59	37.5	15,850	45	15	32,500	–	Vehicle rollover on rail
16	121	Corr. steel beam g.r.	4-in. steel pipe	12-6	59	31.5	15,850	41	15	29,200	–	Good
17	121	Corr. steel beam g.r.	44 steel V	12-6	59	37.5	16,150	42	15	30,900	–	Good
18	121	Corr. steel beam g.r.	44 steel V	12-6	59	37.5	22,100	35	15	35,200	–	Good
19	121	Corr. steel beam g.r.	44 steel V	12-6	59	37.5	31,000	47	15	65,600	–	Vehicle rollover on rail
20	6	Swed. profile steel beam g.r.	8 X 10-in. conc.	9-10	44	23	20,900	28	22.5	26,700	–	Large deflection; good
21	6	Swed. profile steel beam g.r.	8 X 10-in. conc.	9-10	47	19	19,600	28	27.5	25,000	–	Penetrated; rail failed
22	6	Swed. profile steel beam g.r.	8 X 10-in. conc.	9-10	47	19	19,800	29	28	25,800	–	Penetrated
23	6	Swed. profile steel beam g.r.	27.6 railroad rail	9-10	44	23	20,000	28	24	25,500	–	Rail knocked over; vehicle redirected
24	6	Swed. profile steel beam g.r.	8 X 10-in. conc.	9-10	41.5	25.5	20,000	28	26	25,500	–	Rail knocked over; vehicle redirected
25	6	UNP 14 steel channel g.r.	8 X 10-in. conc.	9-10	44	23	20,000	20	27.5	18,100	–	Good
26	35	Dbl steel beam median	–	13-1	–	25.6	2,800	38	5	4,850	–	Good
27	35	Dbl steel beam median	–	13-1	–	25.6	2,800	60	15	7,650	–	Good (exit angle 10 to 12 deg)
28	35	Dbl steel beam median	–	13-1	–	25.6	2,800	60	30	7,650	–	Snagged
29	35	Dbl steel beam median	–	13-1	–	25.6	25,000	42	15	48,000	–	Knocked down; vehicle straddled rail
30	35	Dbl steel beam median	–	6-6	–	25.6	2,800	61	30	7,800	–	Snagged; vehicle rollover
31	35	Dbl alum. beam median	–	6-6	–	25.6	2,800	53	30	6,760	–	Rail failed
32	35	Dbl blkd-out steel median	–	6-6	–	25.6	2,800	65	30	8,240	–	Vehicle rollover
33	35	Dbl blkd-out steel median	–	13-1	–	25.6	2,800	48	30	6,120	–	Snagged and penetrated
34	35	Dbl blkd-out steel median[(a)]	–	13-1	–	29.5	25,000	48	15	54,600	–	Vehicle rollover on rail
35	35	Dbl blkd-out steel median[(a)]	NP 12 I	13-1	–	29.5	25,000	44	15	50,100	–	Good
36	35	Dbl blkd-out steel median[(a)]	NP 12 I	13-1	–	29.5	2,800	69	20	8,800	–	Good
37	35	Dbl blkd-out steel median[(a)]	NP 12 I	13-1	–	29.5	2,800	64	20	8,100	–	Good
38	35	Dbl blkd-out steel median[(a)]	NP 12 I	13-1	–	29.5	2,800	55	20	7,000	–	Good
39	35	Dbl blkd-out steel median[(a)]	NP 12 I	13-1	–	29.5	25,000	41	20	46,100	–	Good
40	54	Conc. inertia median barrier	None	–	–	23.5	1,985	47	20	4,220	–	Good
41	58	Conc. inertia median barrier	None	–	–	23.5	2,640	51	30	6,160	–	Good (exit angle 12 deg)
42	35	Slibar metal mesh fence	Lt wt tripod	26-2	–	–	2,800	67	15	8,500	–	Penetrated
43	35	Slibar metal mesh fence	Lt wt tripod	26-2	–	–	25,000	46	15	52,400	–	Penetrated
44	35	Stuttgart median[(b)]	Lt steel tube[(c)]	6-6	39	–	2,800	67	15	8,500	–	Good
45	35	Stuttgart median[(b)]	Lt steel tube[(c)]	6-6	39	–	25,000	47	15	53,500	–	Vehicle rollover on barrier
46	65	Four cables, chain link fence	3 X 1-1/2-in. I steel	8-0	–	2 at 27,19	3,000	44	20	5,600	–	Good (exit angle 12 deg)
47	65	Four cables, chain link fence	2-1/4 X 1-in. I steel	8-0	–	2 at 27,19	3,000	42	19	5,730	–	Good (exit angle 18 deg)
48	65	Two cables, chain link fence	2-1/4 X 1-in. I steel	8-0	–	2 at 27	3,000	46	20	6,280	–	Good (exit angle 13 deg)
49	65	Two cables, chain link fence	3 X 1-1/2-in. I steel	8-0	–	2 at 24-1/2	3,000	41	20	5,600	–	Good (exit angle 17 deg)
50	65	Two cables, chain link fence	3 X 1-1/2-in. I steel	8-0	–	2 at 24-1/2	1,560	52	20	3,690	–	Exit angle 15 deg, vehicle rolled
51	65	Two cables	3 X 1-1/2-in. I steel	8-0	–	2 at 24-1/2	1,950	62	19	5,506	–	Spinout
52	65	Two cables, chain link fence	3 X 1-1/2-in. I steel	8-0	–	2 at 24-1/2	3,000	48	8	6,550	–	Good (exit angle 10 deg)
53	65	Two cables, chain link fence	3 X 1-1/2-in. I steel	8-0	–	2 at 24-1/2	3,000	58	10.5	7,920	–	Spinout, rollover
54	65	Two cables, chain link fence	1-7/8 OD steel tube 3/16-in. t	8-0	–	2 at 24-1/2	3,000	57	5	7,780	–	Exit angle 5 deg, vehicle partially climbed barrier
55	65	Two cables, chain link fence	2-1/4 X 1-in. I steel	8-0	–	2 at 24-1/2	3,000	60	10	8,200	–	Spinout, rollover

(a) Top of rail.
(b) With hydraulic cylinder.
(c) Weak at base.

TABLE 11

SUMMARY OF NEW YORK STATE IMPACT TESTS, 1968–1969

Test No.	Feature	Weight (lb)	Speed (mph)	Angle (deg)	Results	
61	New cable to post fasteners	4,000	55	30	Car redirected and stopped 50 ft from impact	Problem Area No. 1. Evaluation of modified cable guiderail mounted on wood posts
62	New cable to post fasteners	4,000	55	27	Car redirected and stopped 50 ft from impact	
63	New cable to post fasteners and weakened wood posts	4,000	55	27	Car redirected and stopped 100 ft from impact	
74	Cable guiderail with 50-ft radius	3,100	30	90	Posts on curves were not disturbed	Problem Area No. 2. Determine if decreased post spacing on sharp curves is sufficient to carry cable tension during collision on tangent portion or rail
76	Cable guiderail with 50-ft radius	3,100	35	90	Posts on curves were not disturbed	
34	"W" median	3,680	56	25	Car redirected even though it was yawing badly at impact due to partial loss of control during test	Problem Area No. 3. Check performance of "W" median barrier
65	"W" guiderail, mounting height 27 in.	3,000	55	25	Car redirected	Problem Area No. 4. Find out how vehicles get over "W" rail and how to prevent it
66	"W" guiderail, mounting height 24 in.	3,000	57	25	Car redirected	
119	"W" guiderail, mounting height 33 in.	3,800	62	25	33-in. mounting height appears satisfactory	
120	"W" guiderail, mounting height 33 in.	2,000	65	25	33-in. mounting height appears satisfactory	
36	"W" median, no bumper on truck	15,000 Dumptruck	40	25	Over barrier	
37	"W" median, no bumper on truck	15,000 Dumptruck	26	25	Over barrier	
38	"W" median, modified bumper used	15,000 Dumptruck	30	25	Truck redirected	
33	6 X 8 median, modified paddles	2,000	51	25	Not analyzed	Problem Area No. 5. Improve box beam median barrier performance
40	6 X 8 median, modified paddles	3,680	65	25	Not analyzed	
42	6 X 8 median, modified paddles	3,680	60	25	Not analyzed	
79	6 X 8 box beam, no slots in rail 6-ft 0-in. post spacing	3,100	30	25	Not analyzed	Problem Area No. 6. Control box beam deflection through rail strength and post spacing
80	6 X 8 box beam, no slots in rail 6-ft 0-in. post spacing	4,000	45	25	Not analyzed	
86	6 X 8 box beam, no slots in rail 6-ft 0-in. post spacing	2,600	60	25	Not analyzed	
94	6 X 8 box beam, no slots in rail 3-ft 0-in. post spacing	3,500	62	25	Not analyzed	
95	6 X 12 box beam, no slots in rail 6-ft 0-in. post spacing	3,100	60	25	Not analyzed	
48	Double 6 X 6 box beam	3,680	58	25	Vehicle redirected. No snagging, little deflection	Problem Area No. 7. Development of stiff box beam median barrier
49	Double 6 X 6 box beam	15,000 Dumptruck modified bumper	50	25	Vehicle redirected. No snagging, little deflection	
50	Double 6 X 6 box beam	15,000 Dumptruck no bumper	45	25	Vehicle redirected. No snagging, little deflection	
73	6 X 8 median with ditch slopes 1 on 4 and 1 on 4	3,000	50	25	Car partly nosed under barrier and was not redirected	Problem Area No. 8. Check performance of box beam median barrier located on side of depressed median
74	Cable guiderail	3,100	30	90	Results not analyzed	Problem Area No. 9. Measurement of dynamic force-deflection characteristics to verify calculated deflections
76	Cable guiderail	3,100	35	90	Results not analyzed	
78	Cable guiderail	3,100	30	90	Results not analyzed	
75	6 X 6 guiderail	3,100	32	90	Results not analyzed	
77	6 X 6 guiderail	3,100	30	90	Results not analyzed	
64	Cable guiderail	2,000	60	25	Car redirected	Problem Area No. 10. Determine effect of vehicle size on NYS barriers
39	Cable guiderail, special bumper on truck	15,000 Dumptruck	36	25	Truck redirected	
35	"W" median	2,000	58	25	Post contact seriously damaged front suspension and caused car to spin out	
36	"W" median, no bumper on truck	15,000	40	25	Truck went over rail	
37	"W" median, no bumper on truck	15,000	26	25	Truck went over rail	
38	"W" median, modified bumper on truck	15,000	30	25	Truck redirected	
45	6 X 6 guiderail	2,000	62	25	Steering damaged, but car was nicely redirected	
46	6 X 6 guiderail, special bumper on truck	15,000	45	25	Truck rolled over. Rail end gave way	
33	6 X 8 median	2,000	51	25	Car redirected with moderage damage	
43	6 X 8 median, special bumper on truck	15,000 Dumptruck	40	25	Truck appeared close to tipping over but was redirected	
41	6 X 8 median, 15-ft ramped end, ¾ of car on rail	2,700	62	0	Car remained upright	Problem Area No. 11. Determine seriousness of snagging and vaulting of car on barrier end treatments
53	6 X 8 median, 15-ft ramped end, ¾ of car on rail	3,680	60	0	Car remained upright	
54	6 X 8 median, 15-ft ramped end, side wheels on rail	3,680	74	0	Car remained upright	
97	6 X 6 guiderail drop end	3,100	52	0	Guiderail end did not penetrate vehicle. Vertical acceleration was excessive	
51	"W" guiderail approach	2,700	51	21	No indications of ramping or snagging problems	
56	"W" guiderail departure	3,680	25	25	No indications of ramping or snagging problems	
98	"W" guiderail, newly designed driveway end	3,100	50	0	No indications of ramping or snagging problems	
44	Cable guiderail departure	3,680	52	25	Car broke fittings at cable end as expected. No snagging occurred. Vehicle continued on path	
99	Cable guiderail, newly designed drive-way end	3,100	50	0	No indication of ramping or snagging problems	
47	Cable guiderail to 6 X 6 guiderail (current design)	3,680	60	25	Car redirected, rails badly damaged	Problem Area No. 12. Develop transitions
52	Cable guiderail to 6 X 6 guiderail	2,700	60	25	Severe rail damage	
59	Cable guiderail to 6 X 6 guiderail	3 000	50	25	Car snagged	
60	Cable guiderail to 6 X 6 guiderail	4,000	55	25	Car redirected	
71	Cable guiderail to 6 X 6 guiderail	3,100	60	25	Car snagged	
117	Cable guiderail to 6 X 6 guiderail	4,000	45	25	Car redirected smoothly	
118	Cable guiderail to 6 X 6 guiderail	3,000	62	25	Car redirected smoothly	
55	Cable guiderail ("W" guiderail)	3,680	60	25	Car snagged on "W" end broke two cable splices–penetrated barrier	
57	"W" guiderail to 6 X 6 guiderail current design	3,000	64	25	Car redirected, no snagging. High lateral accelerations	
58	"W" guiderail to 6 X 6 guiderail	3,680	54	25	Car redirected, no snagging, moderate lateral acceleration	
72	"W" median to 6 X 8 median	3,680	60	25	Car redirected, no snagging	

TABLE 12

SUMMARY OF RECENT SwRI CRASH TESTS

Test No.	Post	Post Area (in²)	Post Bolt	Vehicle Weight (lb)	Vehicle Speed (mph)	Impact Angle (deg)	Max Dyn Defl (ft)	Max Perm Defl (ft)	Guardrail Performance or Vehicle Reaction	Ref
ODH-1	4 X 4-in. wood	16	5/16-in.-dia steel	4589	67.0	25.0	13+	10.0	Vehicle straddled rail, rolled 3-1/2 times	108
ODH-2	4 X 6-in. wood	24	5/16-in.-dia steel	4404	62	25.3	6.9	5.7	Vehicle straddled rail, good redirection	108
ODH-3	7-in.-dia wood	38.4	5/16-in.-dia steel w/pipe insert	4445	62.5	28.7	4.3	2.2	Vehicle pocketed, rolled over	108
ODH-4	6-in.-dia wood	28.2	5/16-in.-dia steel w/pipe insert	4242	63.1	28.3	6.5	5.2	Good redirection, vehicle rolled 15 deg but remained upright	108
ODH-5	6 X 6-in. (notched) wood	36 (30)	1/4-in.-dia steel w/pipe insert	4407	70.8	26.7	7.2	2.9	Good redirection	108
ODH-7	*	*	*	4292	58.2	26.3	6.8	2.7	Some tendency to pocket, but overall good performance	108
AA-1	3-in. I Al	N/A	N/A	4057	62.7	26.6	7.2	3.1	Good redirection, vehicle came to rest in contact with rail	110

*Transition test, see Figure C.1 of Appendix C, Ref. 108.

test program in which 12 problem areas were investigated. Preliminary results of these tests are summarized in Table 11.

Table 12 gives recent full-scale crash test results of barrier systems conducted at SwRI for the State of Ohio and The Aluminum Association. A wood alternate to the 3I5.7 steel post (Standard G2, *NCHRP Report 54*) was investigated for Ohio. The "strong beam" median barrier was evaluated for the Aluminum Association; the barrier system was similar to the one evaluted in Test 110 (Appendix B) with the exception that Test AA-1 beam splices were extruded from alloy 6351 instead of 6005.

CHAPTER THREE

RESEARCH RESULTS

DATA FROM FULL-SCALE CRASH TESTS

Twenty-five full-scale crash tests were performed. A summary of the results is presented in Table 13; individual tests are described in Appendix A. The tests were grouped according to three general categories. A general performance category included those tests in which the vehicle impacted near the center of a relatively long installation. This category can be further delineated according to tests concerned with (1) the designs presented in *NCHRP Report 54*, (2) other designs that are in use, and (3) the variation in post spacing or blockouts for standard systems. The second category involved transition sections used to investigate dynamic performance of the approach-guardrail-to-rigid-bridge-rail connection. The third category included the end treatment tests selected to examine dynamic performance of the upstream terminal features of guardrail installations; with exception of two tests, the end treatments were those whose designs are presented in *NCHRP Report 54.*

General Performance Tests

The basic purpose of the 14 general performance tests was to examine the dynamic behavior and to appraise the performance of several guardrails and median barriers cur-

TABLE 13

SUMMARY OF GUARDRAIL FULL-SCALE CRASH TESTS

SwRI Test	Purpose	Rail	Post	Blockout	Post Spacing (ft-in.)	Post Embedment (in.)	Rail Height (in.)	Vehicle Test Conditions			Vehicle Redirection				Maximum Guardrail Deflection (ft)		Damage Repair Cost ($)		Guardrail Performance
								Weight (lb)	Speed (mph)	Impact Angle (deg)	Peak Accelerations (g's)(a) Long.	Lat.	Exit Angle (deg)	Rebound(c) Distance (ft)	Dynamic	Permanent	Barrier	Vehicle	
101	General performance	Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	4042	55.3	30.5	-4.7	-4.7	-11.7	36	4.25	2.60	230	1274	Large exit angle (18 deg)
102		Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	3856	54.7	25.2			-12.5	20	2.40	1.50	158	961	Good; exit angle 12.5 deg, and vehicle turned back to rail
103		Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	4123	60.1	22.2	-3.2	-6.5	-15.0	15	2.84	2.40	230	990	Good; exit angle 15 deg, and vehicle turned back to rail
105		Steel W-Beam	315.7	None	12-6	33	30	4051	59.2	27.8	-3.1	-3.8	-9.0	18	7.30	5.30	163	751	Good; vehicle was airborne for 50 ft
123		Steel W-Beam	315.7	None	6-3	33	30	3883	64.3	27.1	-3.1	-5.6	(d)	22(d)	5.80	3.50	262	792	Vehicle spun out
124		Steel W-Beam	315.7	None	9-4-1/2	33	30	3904	60.7	26.4	-4.1	-4.1	-6.0	24	6.75	5.60	180	738	Good; vehicle was airborne for 50 ft
109		Alum. extrusion(b)	31 Alum.	N/A	6-3	36	27.5	4078	41.3	25.0			0	7	1.60	0.80	113	720	Good; vehicle stopped parallel to rail
110		Alum. extrusion(b)	31 Alum.	N/A	6-3	36	27.5	4550	56.5	25.0							575	1349	Vehicle penetrated barrier when splice failed
112		Steel box 8 X 6 X 1/4 in.	315.7	N/A	6-0	37	27	3761	51.0	26.9	-3.4	-5.6	0	7	4.60	2.80	288	761	Good; vehicle stopped parallel to rail
114		Steel box 6 X 6 X 3/16 in.	315.7	N/A	6-0	36	27	4031	57.7	26.0	-3.5	-6.7	0	7	4.80	2.90	247	902	Good; vehicle stopped parallel to rail
119		Steel W-Beam	6B8.5	None	6-3	41.5	27	4169	53.4	30.2	-4.6	-4.4	-19.8	38	2.74	2.67	136	872	Vehicle exit angle large; rail partially severed
120		Steel W-Beam	6B8.5	1-6B8.5	6-3	41.5	27	3813	56.8	28.4	-4.0	-6.8	-8.0	22	4.05	2.90	150	1179	Good
121		Steel W-Beam	6B8.5	2-6B8.5	6-3	41.5	27	4478	56.2	27.4	-3.7	-6.8	-9.3	11	3.10	2.10	236	706	Good
122		Steel W-Beam	6B8.5	2-6B8.5	6-3	41.5	27	4570	62.9	25.3	-3.9	-7.8	-9.0	22	4.95	2.90	248	803	Good
				Reference															
104	Transition to concrete Bridge parapet	Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4129	54.0	29.6				7	1.00	0.96		1196	Severe vehicle damage
117		Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4297	58.8	25.0				14	N/A	N/A		1314	Severe vehicle damage
118		Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4297	58.8	28.0				7	–	–		1884	Severe vehicle damage. concrete failed
				Terminal	Reference														
106	End treatment	Steel W-Beam	315.7	Ramp/Flare	Std G2, NCHRP Report 54			3869	51.3	15.0				N/A	N/A	N/A		2363	Vehicle rolled over
107		Steel W-Beam	315.7	Ramp	Std MB2, NCHRP Report 54			4390	61.3	25.0				N/A	N/A	N/A		3358	Vehicle rolled over
108		Steel W-Beam	7-in.-dia. wood	Ramp	Texas Hwy Dept., "Texas Twist"			4397	58.0	15.0				40	1.25	0.8		871	Vehicle redirected; impact was at first post
111		Steel W-Beam	7-in.-dia. wood	Ramp	Texas Hwy Dept., "Texas Twist"			4061	71.0	15.0				N/A	N/A	N/A		3673	Vehicle rolled over
113		Steel box 8 X 6 X 1/4 in.	315.7	Ramp	Std MB3, NCHRP Report 54			3761	52.0	25.0				N/A	N/A	N/A		3644	Vehicle rolled over
115		Steel box 6 X 6 X 3/16 in.	315.7	Ramp/Flare	Std G3, NCHRP Report 54			4031	65.5	25.0				N/A	N/A	N/A		1075	Vehicle penetrated end; good performance
116		Steel box 8 X 6 X 1/4 in.	315.7	Ramp	Std MB3, NCHRP Report 54			3761	60.8	0				N/A	N/A	N/A		3067	Vehicle rolled over
125		Steel W-Beam	8 X 8-in. wood	Blunt End	Std G4, NCHRP Report 54			4500	63.5	0				N/A	N/A	N/A		2039	Severe vehicle damage; high dummy accelerations

(a) Vehicle acceleration determined from analysis of high-speed film.
(b) Aluminum Association strong beam design.
(c) Distance from original guardrail line to maximum outermost point on vehicle during post impact trajectory.
(d) Vehicle spun out.

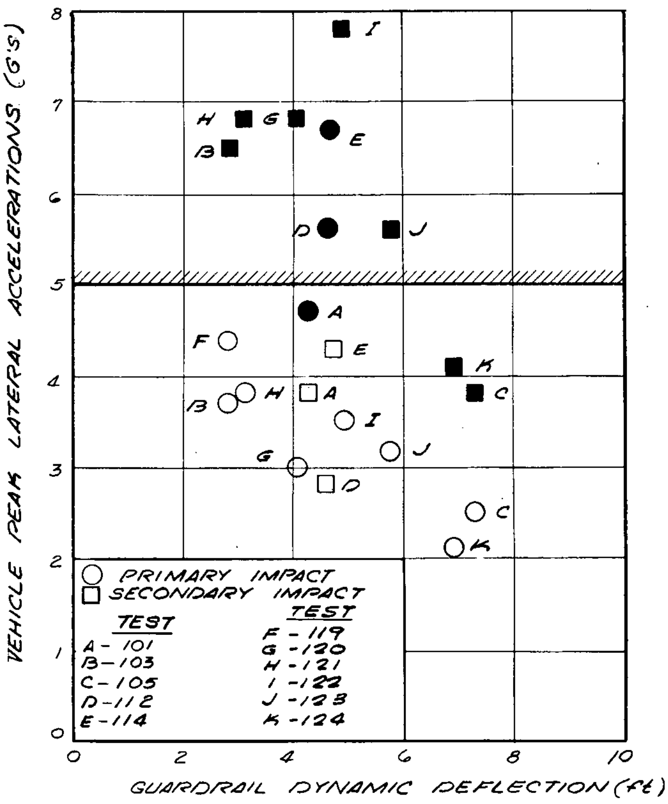


Figure 19. Vehicle lateral acceleration as a function of guardrail dynamic deflection.

rently in use. With the exception of one test, all of the guardrail systems contained and redirected the impacting vehicle, thereby demonstrating an ability to comply with the structural integrity criteria (Table 13). In Test 110, an aluminum strong beam median barrier was penetrated when a beam splice failed; a metallurgical and chemical analysis of the splice by the Aluminum Association revealed that the splice was fabricated from a 6005 rather than a 6351 alloy. In Test 119, a steel W-beam was partially sheared within the impact zone and appeared to be near complete failure.

TABLE 14

SUMMARY OF TRANSITION-TO-BRIDGE-PARAPET TESTS

	Vehicle			Impact Point		Max Accelerations (G's)*	
Test	Weight (lb)	Speed (mph)	Impact Angle (deg)	Post No.	Dist from Parapet (ft)	Longitudinal	Lateral
104	4129	54.0	29.6	8	12.60	7.0†	11.6†
117	4297	58.8	25.0	10	6.25	–8.8	19.0
118	4297	58.8	28.0	7/8	13.75	–28.0	–8.8

*Data from accelerometers mounted in dummy chest cavity; dummy was restrained by both lap belt and shoulder harness.
†Concrete parapet was displaced laterally 8 in. by vehicle impact.

With regard to vehicle peak longitudinal accelerations as determined from film data analysis (Table 13), the most significant point is that all values are less than the recommended tolerable limit of 5 g's (Table 7) for either restrained or unrestrained occupants. In addition to data derived from analysis of high-speed movie film, vehicle accelerations were also acquired from accelerometers located in a dummy's chest cavity and from "G" meters positioned in the car. These data are presented in Appendix A.

In only four tests (101, 105, 119, and 124) was the vehicle subjected to levels of lateral accelerations that would be tolerable (Table 7) to occupants restrained by only a lap belt. In all other tests vehicle occupants would require both lap belt and shoulder harness in order to escape major injuries.

Vehicle lateral accelerations are plotted against guardrail dynamic deflection in Figure 19. Two points are plotted for each test: a primary impact when the left or right vehicle front strikes the installation, and a secondary impact when the rear of the vehicle swings around and hits the guardrail. In a majority of cases, the secondary impact produced the higher level of lateral acceleration; however, both experimental and analytical results indicate that maximum lateral accelerations may also occur during primary impact. For delineation, the points representing the maximum of each test set are darkened.

Transition to Bridge Parapets

Three tests were performed on the G4 guardrail transition to concrete bridge parapet; installation details are included in Appendix A in *NCHRP Report 54.* A summary of the test results is given in Table 14. Tests 104 and 117 were similar except for the point of impact. Test 118 was a repeat of Test 104. To be noted is the fact that the accelerations given in Table 14 were measured on the dummy. These values should not be related to tolerable limits suggested in Table 7 because acceptable accelerations as measured on a dummy would probably be somewhat higher than for vehicle accelerations (see Fig. 14).

In Test 104, dummy accelerations were generally lower than those measured in the other transition tests; however, movement of the concrete parapet is considered to have affected the impact forces and vehicle redirection significantly. In Test 117, the impact point was in the strong section of the transition, and the vehicle was abruptly redirected. The peak lateral acceleration of the dummy was extremely high (10.0 g). Test 118 illustrates the importance of an adequate guardrail-to-brige-parapet connection. Failure of the connection exposed the concrete parapet end, thereby causing a most severe collision.

Guardrail Terminal Design Tests

Eight full-scale crash tests were performed on terminal designs. Of these, six involved various ramped designs (Tests 106, 107, 108, 111, 113, and 116). One test was

TABLE 15

SUMMARY OF GUARDRAIL TERMINAL ENDS FULL-SCALE CRASH TEST RESULTS

SwRI Test No.	NCHRP* System	Installation Description			Vehicle Properties			Vehicle Response		
		Basic System		Terminal* Type	Weight (lb)	Speed (mph)	Impact Angle (deg)	Damage‡	Distance Traveled (ft)	Remarks
		Beam	Post							
106	G2	W	3I5.7	Ramp/Flare	3869	51.3	15	Total loss	160	Vehicle rolled and tumbled
107	MB2	W	3I5.7	Ramp	4390	61.3	25	Total loss	125	Vehicle rolled and tumbled
111	†	W	7-in.-dia wood	Ramp†	4061	71.0	15	Total loss	200	Vehicle rolled and tumbled
113	MB3	Box	3I5.7	Ramp	3761	52.0	25	Total loss	225	Vehicle rolled and tumbled
115	G3	Box	3I5.7	Flare	4031	65.5	25	Severe	350	Vehicle did not roll; decelerated gradually
116	MB3	Box	3I5.7	Ramp	3761	60.8	0	Total loss	280	Vehicle rolled and tumbled
108	†	W	7-in.-dia wood	Ramp†	4397	58.0	15	Severe left front	135	Vehicle redirected at 10-deg exit angle
125		W	8 X 8 wood	Blunt end	4500	63.5	0	Total loss	10	High longitudinal acceleration

*See NCHRP Report 54.
†"Texas Twist."
‡See Appendix B, vehicle damage appraisal.

performed on a flare (Test 115) and one on a blunt-end terminal (Test 125). A summary of test data is presented in Table 15; the tests are described in detail in Appendix A.

With the exception of Test 108, the test vehicles were launched, rolled, and tumbled in the ramp terminal tests; all were damaged beyond repair. For Test 108, the test vehicle impacted at Post 1 and was redirected. In the flare terminal test (Test 115), the vehicle penetrated the rail and decelerated in a stable and acceptable manner. In Test 125, the test vehicle impacted the blunt terminal, sustained major front end damage, was launched, and landed astride the installations.

VERIFICATION OF ANALYTICAL PREDICTIVE PROCEDURES

Efforts were directed to formulating methods for characterizing vehicle-guardrail interactions. The methods were verified by correlating analytically predicted guardrail and

TABLE 16

SUMMARY OF GUARDRAIL COMPUTER PROGRAMS

Program	Developed by	Calculates	Limitations	Control Data Corporation Computer	Run Time*	
					Minutes	Seconds
SPRING	SwRI	Post spring constant	Post does not pull out of ground	6600	0	6
LDN3	CAL	Barrier force/deflection characteristics	Beam tension only, normal applied load	6600	0	10
FDN1	CAL	Barrier force/deflection characteristics	Beam bending only, normal applied load	6600	0	10
FDBCWT	CAL	Barrier force/deflection characteristics	Long installations only, normal applied load	6600	0	15
BARRES I	SwRI	Barrier force/deflection characteristics	Elastic beam only	6600	0	40
BARRES II	SwRI	Barrier force/deflection characteristics	None	3600	2	38
GRDRAIL	SwRI	Barrier force/deflection characteristics	Constant axial load, normal applied load	6600	0	6
POLYNOM	SwRI	Barrier response polynomial coefficients	Exact only at sampling points	3600	0	30
CAL3DOF	CAL	Vehicle trajectory	Three degrees-of-freedom only, flat surfaces	3600	1	45
CAL11DOF	CAL	Vehicle trajectory	None	3600	31	22
TIGER	SwRI	Vehicle trajectory	Six degrees-of-freedom only, flat surfaces	6600	0	36

*Approximate values for comparative purposes only; the 6600 is approximately six times faster than the 3600.

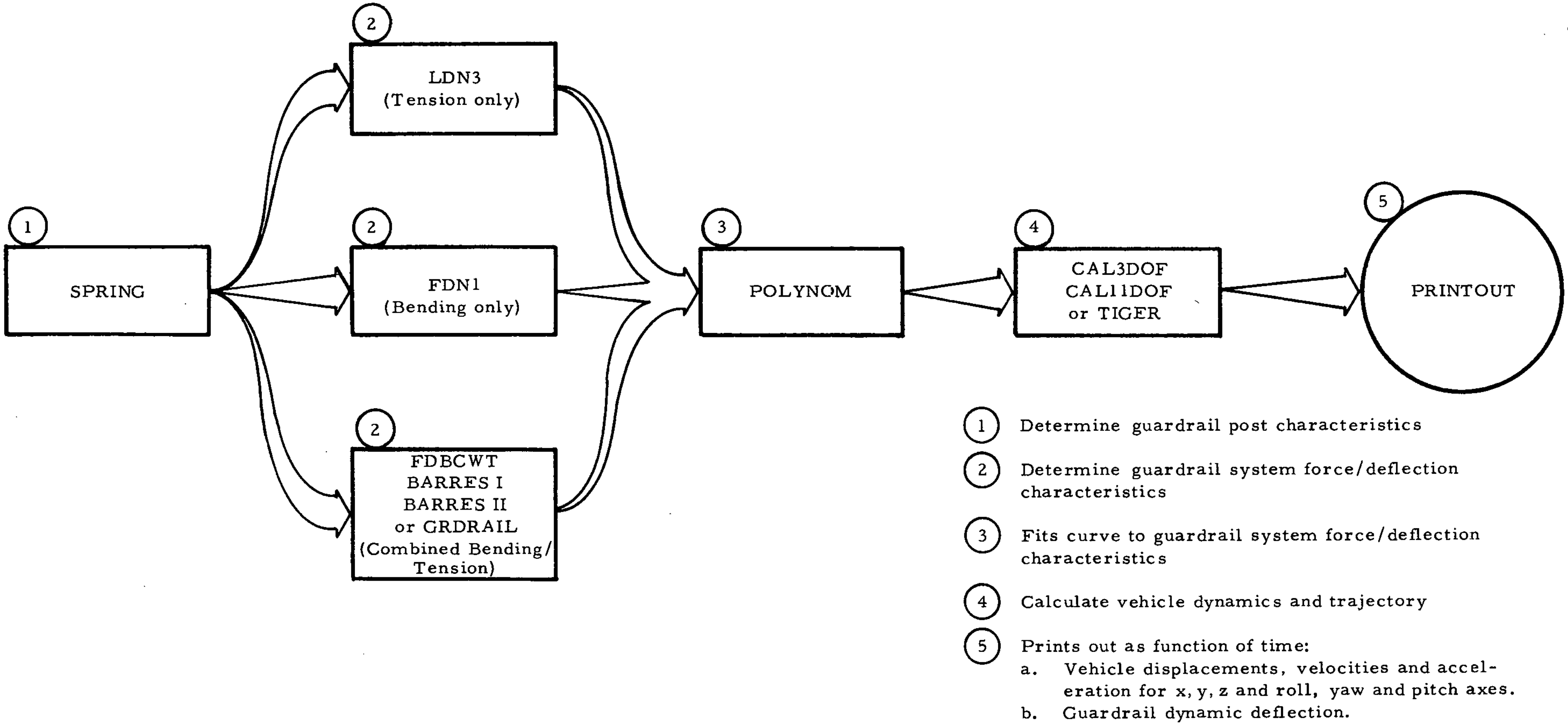


Figure 20. Relationship and operational sequence of computer programs.

vehicle response parameters with those experimentally determined by full-scale crash tests.

The eleven computer programs are given in Table 16 with their functions and limitations. For evaluating any guardrail system, four of the eleven programs are required (Fig. 20). The force/deflection spring constant of a guardpost/soil system is calculated by SPRING. This constant is combined with guardrail beam properties, and an over-all guardrail system force/deflection characteristic is produced by LDN3, FDNI1 or FDBCWT, BARRES I, BARRES II, or GRDRAIL. Inasmuch as this force/deflection characterization usually consists of several discontinuous curves, the POLYNOM program is used to create a single response curve for a guardrail system. In the last step, using either the CAL 3 DOF, CAL 11 DOF, or TIGER program, the vehicle interacts with the barrier and the guardrail system response and the vehicle trajectory are computed. Vehicle and guardrail properties, printed every 5 msec, are the following:

- Barrier deflection
- Vehicle dynamics:
  - Heading angle
  - Velocity angle
  - Coordinates (longitudinal and transverse)
  - Velocity (longitudinal, transverse, and yaw)
  - Accelerations (longitudinal, transverse, and yaw)

Other properties, such as instantaneous barrier force, are calculated but not printed. Typical vehicle/guardrail collision and redirection occur within 0.5 sec; however, the vehicle trajectory is usually calculated for a duration of 0.7 sec to assure that the car is free from the guardrail.

The ability of the aforementioned program to describe a process or event is dependent on three factors. First, analytical comprehensiveness must provide for all parameters with engineering significance. Second, the range of the variables or parameters must be known beforehand or approximated. Third, the material constants must be known. Limitations in any one or all three factors can adversely affect the validity of the results.

Verifications are performed by comparing predictions with experimental results. It is to be noted that the experimental results are subject to error; hence, they cannot be assumed to be accurate. For example, inadequate test controls or a lack of proper sensitivity in the dynamic response instrumentation system may inaccurately describe the event. Accordingly, both analytical and experimental results need to be assessed closely to reconcile any differences.

Correlations between predicted and measured results for Test 121 are presented in Figures 21 through 26. The guardrail installation for this test consisted of a standard 12-gauge W-beam mounted on and offset 6 in. from 6B8.5 posts spaced at 6 ft 3 in. centers. Movement of the vehicle's center of gravity is shown in Figure 21 for the first 0.5 sec of the redirection stage. The point of initial contact between rail and vehicle was used to establish the origin of the reference axes. The correlation is satisfactory; the maximum lateral variation is less than 6 in. at any point.

Vehicle heading angles during the same 0.5-sec interval are shown in Figure 22. For the first 0.3 sec after impact, the maximum variation is about 2 degrees. Although the deviation increases to 7 degrees at 0.4 sec, it decreases to 3 degrees at 0.5 sec.

In Figure 23, vehicle longitudinal (x) and lateral (y) velocities are compared. The maximum variation in longitudinal velocity is approximately 5 mph; for lateral vehicle velocity, the difference approaches 10 mph. The predicted lateral velocity lags by about 0.1 sec at the peak positive magnitudes.

Figure 24 shows a comparison of vehicle longitudinal accelerations plotted as a function of time. The experimental values appear to be damped, which seems reasonable because the experimental data reflect the vehicle dynamics

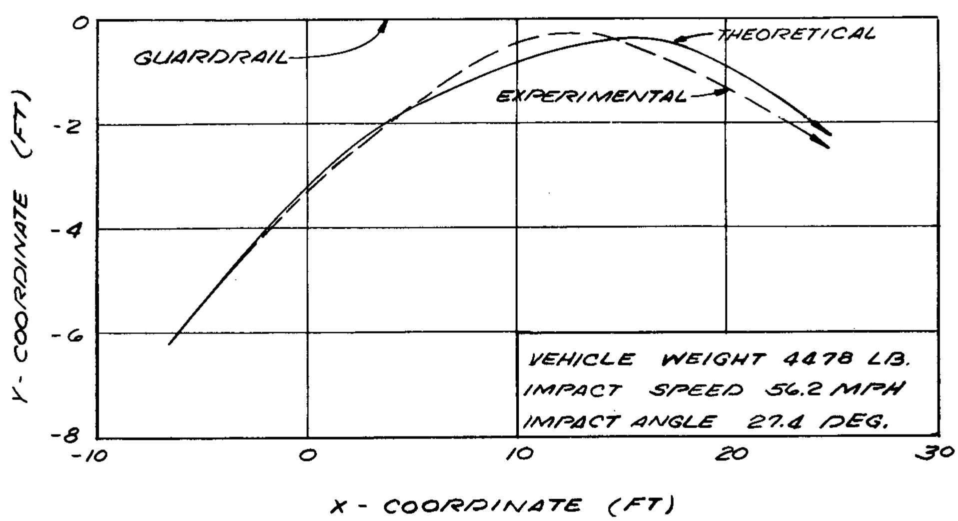


Figure 21. Comparison of theoretical and experimental vehicle (center of gravity) trajectories for Test 121.

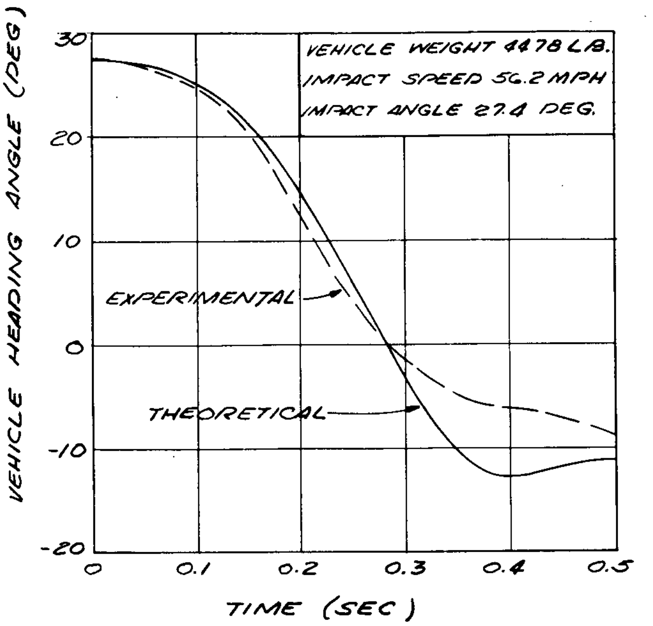


Figure 22. Comparison of theoretical and experimental vehicle heading angles for Test 121.

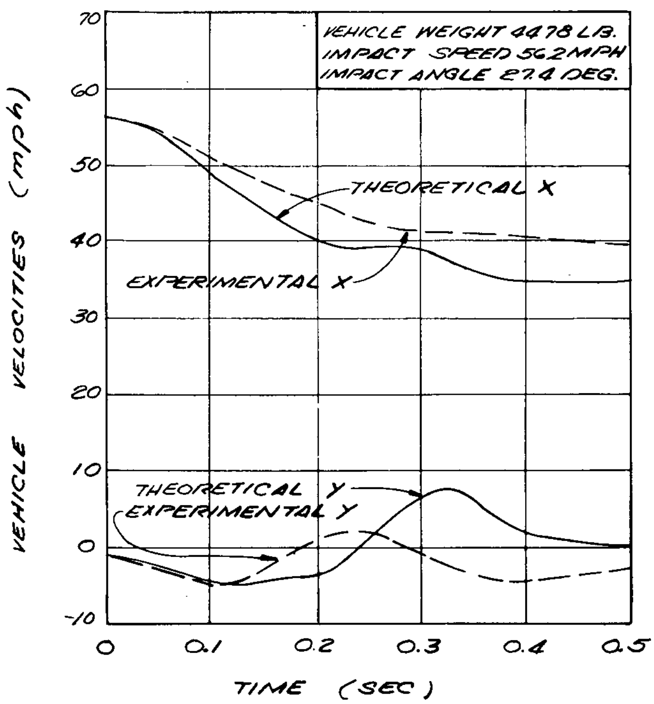


Figure 23. Comparison of theoretical and experimental vehicle velocities (x, y) *for Test 121.*

as measured on the roof structure whereas analytical predictions are expressed in terms of vehicle center of gravity.

In Figure 25, vehicle lateral accelerations are compared. A 0.1-sec time lag exists; however, both curves clearly indicate primary and secondary impacts (i.e., the first and second negative peaks), and the magnitudes of the negative peaks are in close agreement.

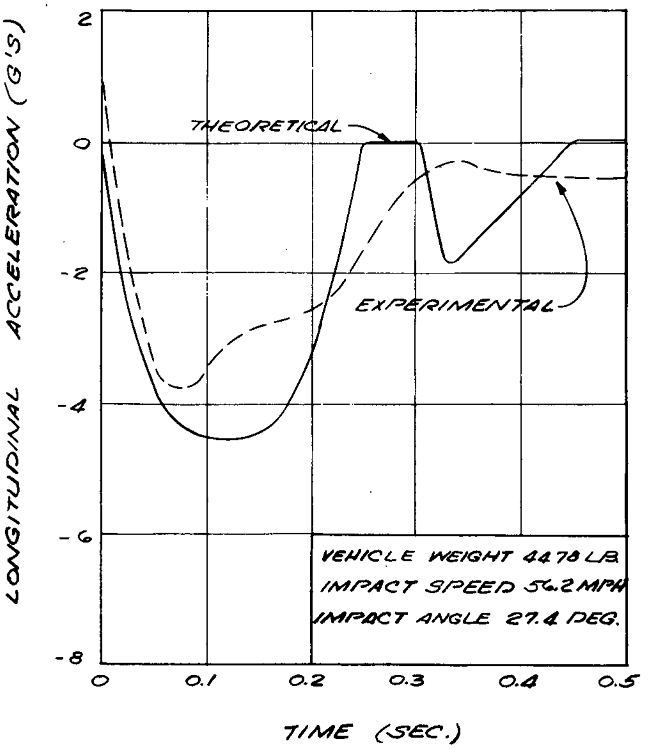


Figure 24. Comparison of theoretical and experimental vehicle longitudinal accelerations.

Vehicle yaw acceleration data are shown in Figure 26; both curves depict primary and secondary vehicle impacts. The analytical curve lags the experimental curve by approximately 0.1 sec; and although the peak magnitudes differ, the correlation is such as to indicate that the predictive capability for this parameter is adequate for engineering purposes.

Vehicle peak longitudinal accelerations determined from film data analysis for eleven performance tests are presented in Figure 27. A significant point is that all the experimental values are less than the recommended tolerable limit of 5 g's (Table 7) for either restrained or unrestrained occupants. The predicted accelerations are within a ±20 percent deviation and are generally to the right of the 1:1 correlation line. The latter is of importance, because if it is assumed that the experimental data are valid and that a lack of correlation is intrinsic in the analytical procedure, the errors are conservative; that is, the predicted values indicate conditions that are more severe than those actually encountered, thereby obviating a sense of false security with an ineffective system.

Peak vehicle lateral acceleration information for the same tests is shown in Figure 28. In comparing the experimental data with the three upper limits of human tolerance, it is of interest to note that in only four tests (101, 105, 119, and 124) were the vehicles subjected to lateral accelerations acceptable for occupants restrained only by lap belts. By

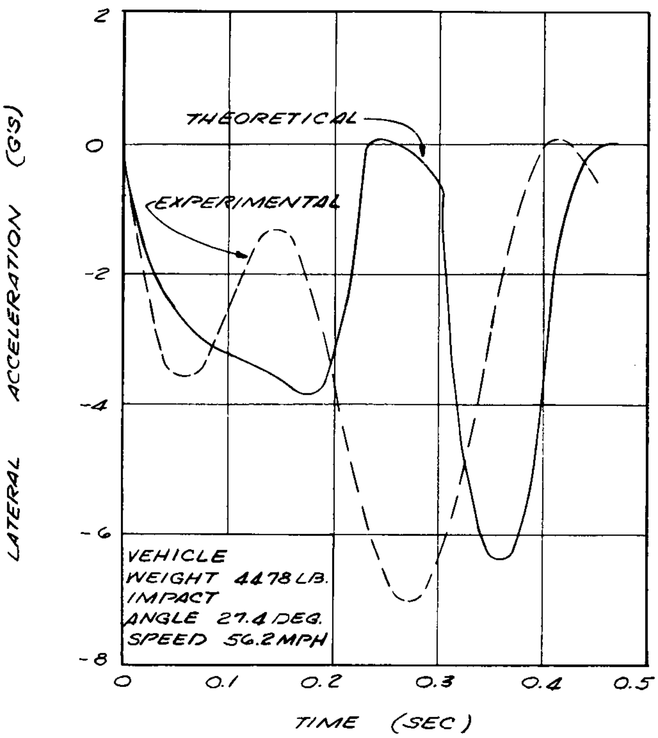


Figure 25. Comparison of theoretical and experimental vehicle lateral accelerations.

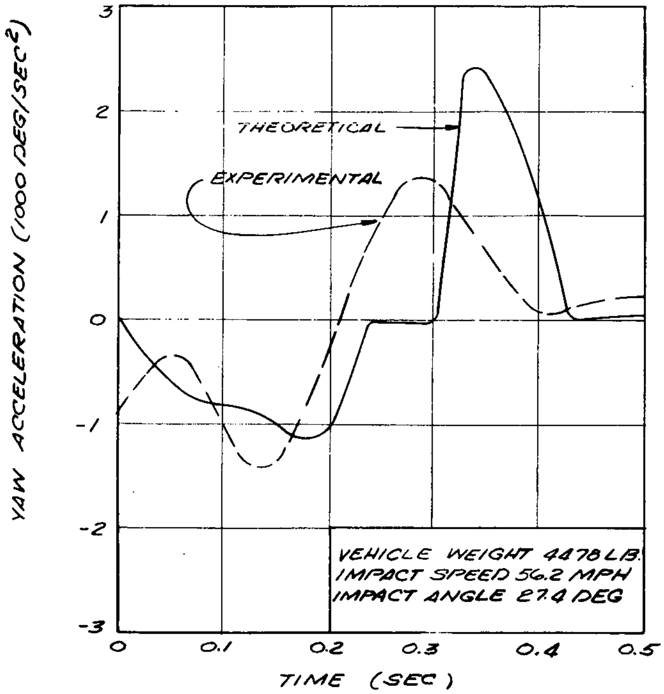


Figure 26. Comparison of theoretical and experimental vehicle yaw accelerations.

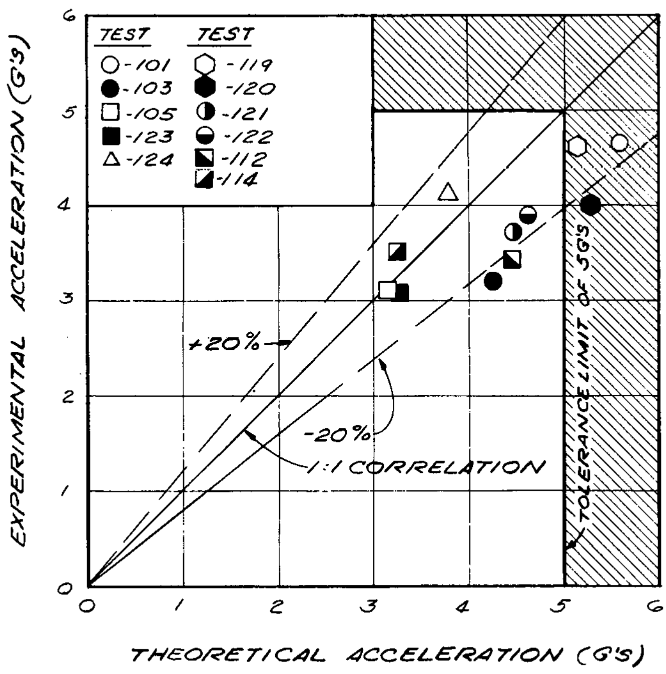


Figure 27. Comparison of theoretical and experimental peak longitudinal vehicle accelerations.

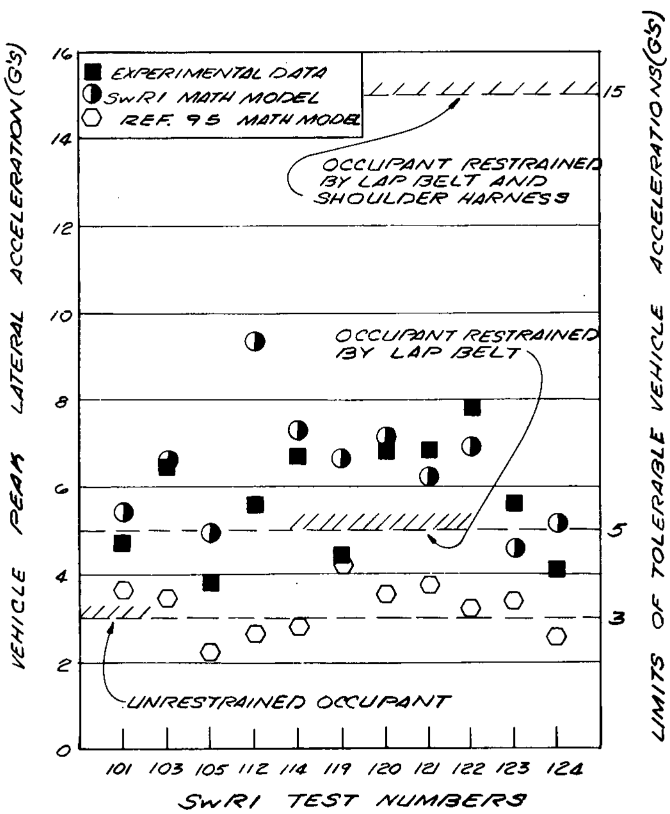


Figure 28. Comparison of theoretical and experimental peak lateral vehicle accelerations.

comparing results for all other tests with the criteria presented in Table 7, one can conclude that the occupants would have to use both a shoulder harness and a lap belt to escape major injuries. In evaluating the predictive ability of the research agency's analytical procedure, it is noteworthy that with the exception of Tests 121, 122 and 123 all the deviations were such as to indicate accelerations in excess of those measured. For these three tests, the unconservative error was not more than 1 g.

Olson (*95*) developed a simple algebraic expression for predicting average "lateral" vehicle decelerations during redirection using inputs of vehicle geometry, impact velocity, and impact angle, and the lateral barrier deflection:

$$G_{\text{lat}} = \frac{V_I^2 \sin^2 \theta}{2g\,AL \sin \theta - B\,(1 - \cos \theta) + D} \qquad (2)$$

in which

L = vehicle length, in ft;
$2B$ = vehicle width, in ft;
D = lateral displacement of barrier, in ft;
AL = distance from vehicle front end to center of mass, in ft;
V_I = vehicle impact velocity, in fps;
θ = vehicle impact angle, in deg; and
g = acceleration due to gravity, in ft/sec^2.

Lateral direction in this formula is normal to the original barrier line and is independent of the vehicle coordinate system, whereas the vehicle acceleration results predicted by the research agency's mathematical model are referenced to the vehicle lateral and longitudinal axes. Although Olson makes several assumptions in deriving Eq. 2, the most significant one assumes that lateral and longitudinal vehicle decelerations are constant during the time interval required for the vehicle to become parallel to the undeformed barrier. After viewing the vehicle lateral acceleration data in Figure 25, one would certainly question the validity of this assumption. Accordingly, predictions resulting from Eq. 2 appear to consistently yield lateral accelerations that are lower than those obtained experimentally. Although the procedure is straightforward and requires a minimum of computer capability, it must be used with a high degree of caution because, based on test conditions presented herein (Fig. 28), one can erroneously conclude that all the barrier systems are adequate provided the car occupant is restrained with a lap belt.

Correlations between predicted and experimental results for three guardrail systems are summarized in Table 17. The three systems evaluated are the W-beam strong post, W-beam weak post, and box beam. The predicted vehicle data were determined for the vehicle center of gravity. Experimental results were derived from analysis of high-speed moving pictures of targets attached to the vehicle roof. It is expected that the roof accelerations would lag the center of gravity accelerations and be slightly damped; this is generally the case.

PARAMETRIC STUDIES

After it had been experimentally established that the analytical methods were capable of predicting certain dynamic response events with an acceptable degree of accuracy, a study was conducted to determine the sensitivity of certain variables. By varying one parameter independently over an expected range of its value, the effect on the calculated performance factors of the guardrail or vehicle was determined. In these studies the selected performance factors were guardrail maximum deflection, and vehicle peak lateral, longitudinal, and yaw accelerations.

There were several objectives in performing parametric examination of the vehicle-guardrail interactions. For example, those parameters which were found to have negligible influence on the performance indicators could be eliminated or treated as constants, thereby simplifying complex formulas and eliminating the need to acquire unnecessary test data. Secondly, the studies provided guidelines to the experimentalist in that the importance and control criticality of certain parameters were identified. Finally, the results of these investigations could be made useful in determining those modifications which were most

TABLE 17

CORRELATION OF THEORETICAL PREDICTIONS TO EXPERIMENTAL RESULTS

Semirigid Guardrail System	Maximum Guardrail Deflection	Vehicle Trajectory and Dynamics						
		Displacements			Velocity		Acceleration	
		Heading Angle	X Coordinate	Y Coordinate	Longitudinal	Transverse	Longitudinal	Transverse
Strong Post W-Beam	G	G	E	E	G	F	G	E
Weak Post W-Beam	G	G	G	G	E	F	F	G
Box Beam	P	G	G	G	G	G	G	E

Legend: Correlation is based on maximum (or minimum) value of experimental parameter during first 0.5 sec after impact.

Deviation	Correlation
0%-10%	E (excellent)
10%-30%	G (good)
30%-50%	F (fair)
>50%	P (poor)

TABLE 18

VEHICLE PARAMETERS IN THE MATHEMATICAL MODEL

Computer Notation	Parameter Description	Typical Values Test 101	Test 102	Test 103	Test 105
WT	Weight (lb)	4,043	3,856	4,123	4,051
IX	Moment of inertia (X-X) in.-lb-sec^2	6,400	10,680	8,500	11,520
IY	Moment of inertia (Y-Y) in.-lb-sec^2	38,000	29,400	39,450	33,600
IZ	Moment of inertia (Z-Z) in.-lb-sec^2	46,000	32,200	46,600	37,200
LF	Distance; center of gravity to front axle (in.)	61.5	55	62	52.5
LR	Distance; center of gravity to rear axle (in.)	57.5	60	57	64.5
KF	Spring constant, front wheel (lb/in.)	270	270	270	270
KR	Spring constant, rear wheel (lb/in.)	215	215	215	215
H	Height of center of gravity, (in.)	22.5	23.5	23.5	21.3
S	Wheel span (in.)	59.5	58.4	61	59.5
D	Wheel diameter (in.)	27.5	27.5	27	27
SKV	Deformation constant (lb/in^3)	4,000	4,000	4,000	4,000
DO	Wheel spring movement (in.)	3	3	3	5
W	Tire width (in.)	8	8	8	8
P	Tire pressure (psi)	35	35	35	30

conducive to upgrading existing guardrail systems.

It should be noted that data presented in this section are analytical; only a portion have been verified by actual tests. Although the analytical procedure was verified for specific test conditions, the values of parameters in the sensitivity study were permitted to vary over a larger range.

Vehicle Properties

Table 18 lists 15 vehicle parameters used in the analytical method, together with typical values for actual test cars. Each property was incrementally varied initially to 70 percent and then to 130 percent of the vehicle values used in Test 101 while the remaining 14 properties were held constant.

The vehicle dynamic performance factors used were maximum guardrail deflection, and the peak lateral, longitudinal, and yaw accelerations at the vehicle's center of gravity. The variations of these factors for a plus and minus 30 percent change indicated that the major vehicle parameters were weight, mass moment of inertia about the z-axis, height of the center of gravity, and deformation constant; these results are summarized in Table 19. Parameters

TABLE 19

SIGNIFICANCE OF VEHICLE PARAMETERS ON DYNAMIC PERFORMANCE

Vehicle Parameter	Notation	Nominal Value	Percentage Variation from Nominal Vehicle Performance(1): 70% of Nominal Vehicle Value: Maximum Guardrail Deflection	70%: Vehicle Peak Accelerations X	70%: Y	70%: Yaw	130% of Nominal Vehicle Value: Maximum Guardrail Deflection	130%: Vehicle Peak Accelerations X	130%: Y	130%: Yaw
Weight	W	4,043	−21%	+33%	−27%(2)	−20%(2)	+27%	−24%	−19%	+1%
Mass Moment of Inertia										
About X-axis	I_x	6,400	*	*	*	*	*	*	*	*
About Y-axis	I_y	38,000	*	*	−1%	−1%	*	*	+1%	*
About Z-axis	I_z	46,000	−8%	−3%	*	+43%	*	+1%	−24%	−44%
Spring Constant										
Front Wheel	KF	270	*	*	*	*	*	*	*	*
Rear Wheel	KR	215	*	*	*	*	*	*	*	*
Height of Center of Gravity	H	22.5	*	*	*	+2%	*	*	−21%	−10%
Wheel Span	S	59.5	*	*	−1%	*	*	*	−3%	*
Deformation Constant	SKV	4,000	−6%	*	−9%	−11%	+4%	+1%	+2%	+3%
Tire Pressure	P	35	*	*	*	*	*	*	*	*

*Less than 1% difference.

(1)Parametric analysis performed on strong post guardrail system: blocket-out W-beam mounted on 8 X 8-in. timber posts spaced at 6-ft 3-in. centers. Rail tension was 10,000 lb, soil modulus 50 psi/in., coefficient of friction of rail to vehicle 0.5. Vehicle weighs 4043 lb, impacts guardrail at 55.3 mph and 30.5 deg angle. Nominal vehicle performance results are the following:

(a) Maximum guardrail deflection: 37 in.

(b) Vehicle peak accelerations

x direction: 5.75 g's

y direction: 7.15 g's

yaw: 4,000 deg/sec^2

(2)Vehicle did not experience secondary impact.

TABLE 20

EFFECT OF STEER ANGLE ON VEHICLE TRAJECTORY

Time (seconds)	X-Coordinate (ft) Steer Angle		Y-Coordinate (ft) Steer Angle		Heading Angle (deg) Steer Angle	
	0 deg	30 deg	0 deg	30 deg	0 deg	30 deg
0.000	−5.1450	−5.1450	−6.4573	−6.4573	28.90	28.90
0.100	2.4090	2.3823	−3.3283	−3.3264	20.10	20.26
0.200	9.2661	9.1710	−3.3502	−3.3641	−12.31	−12.18
0.300	15.6227	15.4304	−5.8451	−5.7878	−13.99	−13.98
0.400	21.9075	21.5730	−8.7297	−8.6064	−7.30	−7.11
0.500	28.2125	27.6940	−11.4571	−11.2752	−0.62	−0.27
0.600	34.5187	33.7578	−13.9946	−13.7716	6.40	6.62
0.700	40.8107	39.7604	−16.3884	−16.1249	13.50	13.44

Performance Factor	Percentage Variation with 30 deg Left Steer
Maximum Guardrail Deflection	+2%
Vehicle Peak Accelerations	
Lateral	+2%
Longitudinal	−4%
Yaw	<1%

of secondary importance on performance factors are the mass moment of inertia about the y-axis, and the wheel span. Those parameters that appear to have a negligible effect on the performance factors were (1) mass moment of inertia about the x-axis, (2) front wheel spring constant, (3) rear wheel spring constant, and (4) tire pressure. However, it is possible that selection of other performance factors and/or guardrail systems may alter the results given in Table 19.

To evaluate the influence that a driver could possibly have on vehicle redirection and trajectory, two cases were examined where the steer angle was set at 0 and 30 degrees. The results (Table 20) indicate that the steer angle has an insignificant effect on vehicle trajectory or guardrail deflection. This is probably due to the fact that the redirection force of the front wheels is in the magnitude of 1,000 lb or less whereas the barrier exerts a force of 20,000 to 30,000 lb.

Performance of G4 Strong Post System

Results of parametric analysis for the G4 guardrail system are shown in Figures 29, 30, and 31. In Figure 29, peak longitudinal acceleration is shown as functions of vehicle speed and approach angle. It would be expected intuitively that longitudinal peak acceleration would vary as the sine of the impact angle, and it does. It is to be noted that acceleration values are only mildly sensitive to vehicle speed.

Peak lateral accelerations are shown in Figure 30 as functions of vehicle velocity and impact angle. Of interest

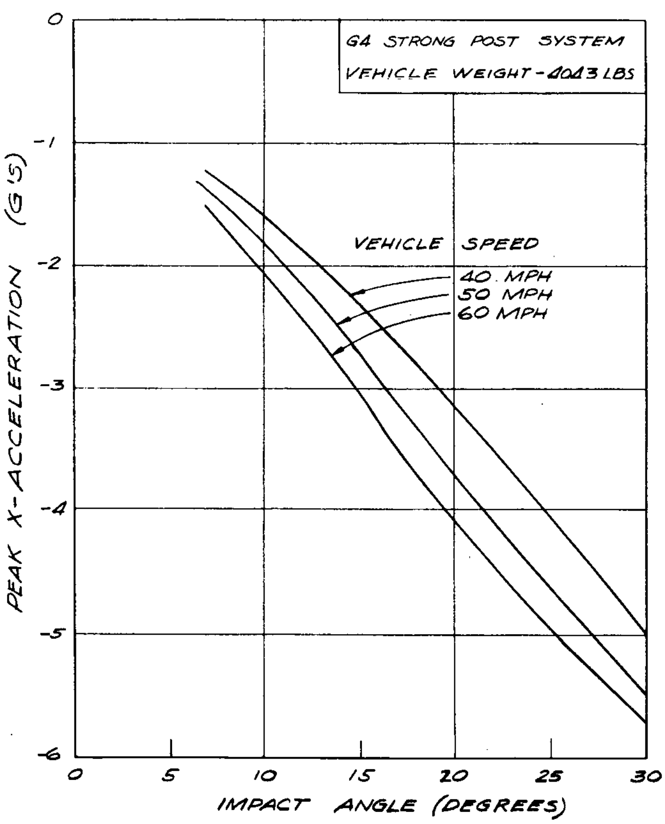


Figure 29. Vehicle peak longitudinal acceleration as functions of impact speed and angle for G4 system.

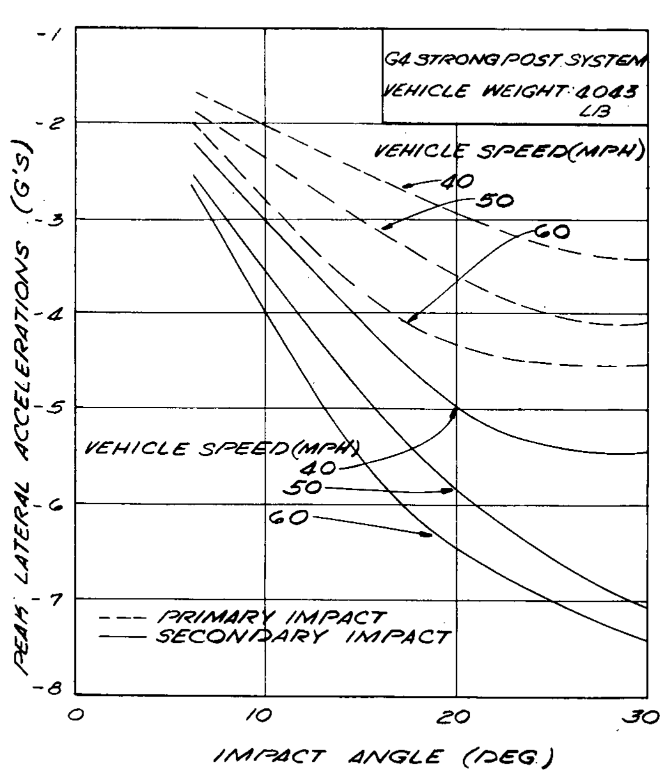


Figure 30. Vehicle peak lateral accelerations as functions of impact speed and angle for G4 system.

is the fact that lateral (y) acceleration for primary impact attains its critical value near the vehicle impact angle of 20 degrees. Maximum lateral acceleration actually occurs during the secondary impact for all cases investigated. A 5-g lateral acceleration would be induced in a 4,000-lb vehicle striking the G4 system at 13 degrees and 60 mph, 15 degrees and 50 mph, or 20 degrees and 40 mph.

Peak yaw acceleration (Fig. 31) appears to attain its critical value between 20- and 25-degree impact angle, regardless of vehicle speed. Peak lateral and yaw acceleration occur during secondary vehicle impact (about 0.4 sec after impact), whereas peak longitudinal and maximum barrier deflection occur shortly after primary impact (about 0.2 sec).

Performance of G2 Weak Post System

Similar to the G4 system, the G2 guardrail system was evaluated according to peak accelerations induced in the vehicle during redirection. In Figure 32, peak longitudinal accelerations for three vehicle speeds are plotted against impact angle. These curves are akin, in shape, to those for the G-4 system, except the magnitude is significantly less. It is of interest that these magnitudes are within the human tolerance range regardless of type of occupant restraint (Table 7).

Peak lateral accelerations are plotted against impact angle in Figure 33; maximum lateral acceleration occurs during secondary impact. Comparing results with the G4 system, acceleration values are generally 40 to 50 percent less for the G2 system for those cases investigated.

Peak yaw acceleration plots shown in Figure 34 do not reach maximum values as they did for the G4 system for

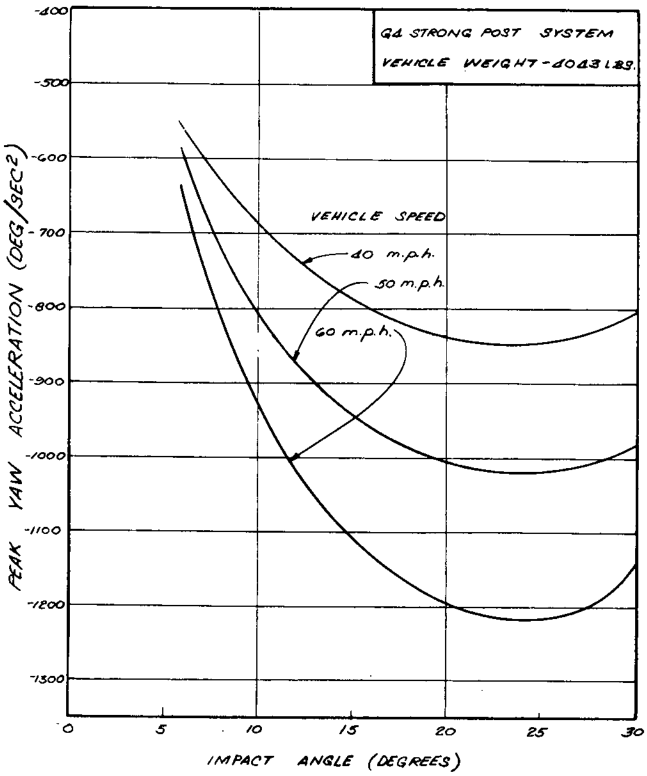


Figure 31. Vehicle peak yaw acceleration as functions of impact speed and angle for G4 system.

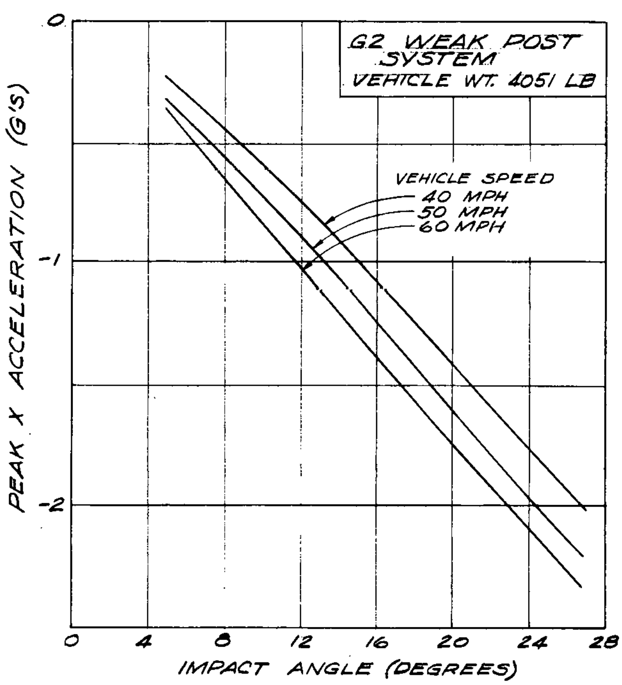


Figure 32. Vehicle peak longitudinal acceleration as functions of impact speed and angle for G2 system.

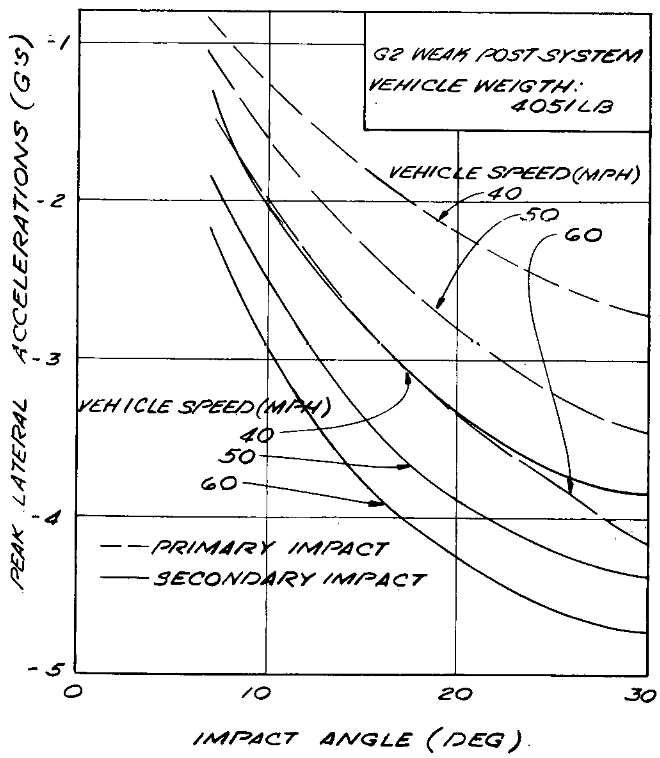


Figure 33. Vehicle peak lateral accelerations as functions of impact speed and angle for G2 system.

the range of impact angles explored. Also, magnitudes for G2 and G4 accelerations are in the same range.

In Figure 35, both peak lateral and longitudinal vehicle accelerations are shown as a function of vehicle weight. From these curves, it is seen that vehicle weight is a most important parameter. These plots portray graphically the more severe conditions associated with redirection for lighter vehicles.

Guardrail Properties

To investigate significance of guardrail system components in regard to over-all system performance, the value of each parameter was varied discretely over a practical range and the vehicle dynamics were determined. In the G4 strong post system, parameters that were examined are (1) rail tension, (2) soil modulus, (3) post strength, and (4) rail-vehicle coefficient of friction. Results of this investigation are summarized in Table 21.

Rail tension, as idealized, is independent of both time and location along the rail system. In actual experimental tests, rail tension has been determined to vary with time and with distance from the contact point, especially for the G4 system. Performance of the guardrail system is changed by increasing the rail tension from 10,000 to 15,000 lb; however, no change in vehicle accelerations was noted when the rail tension was increased from 15,000 to 20,000 lb.

The soil modulus was examined for a range of 40 to 50 psi/in.; only vehicle peak lateral acceleration was affected with a variation from 7.8 to 7.5 g's. Noteworthy is the fact that lateral acceleration decreased with an increase in soil modulus.

Post strength was varied in 1,000-lb increments from 3,000 to 6,000 lb. Vehicle peak accelerations, both lateral and longitudinal, appear to be sensitive to and vary directly with post strength.

The coefficient of friction between the vehicle and the rail was examined for values of 0.2 and 0.5. Vehicle peak longitudinal acceleration increased from 4.4 to 6.2 g's, a 40 percent change. On the other hand, maximum peak lateral accelerations, which occurred during the secondary impact, were unaffected.

Because the G2 guardrail system is practically independent of soil conditions, the influence of soil modulus and post strength were not examined. Primary attention of the G2 system parametric study was directed toward the type of post and the post spacing. In Table 22, the performance of a 2-in.-diameter pipe and a 4I7.7 post are compared with the standard 3I5.7 post. Dynamic deflections and vehicle accelerations are similar for the 4I7.7 and 3I5.7

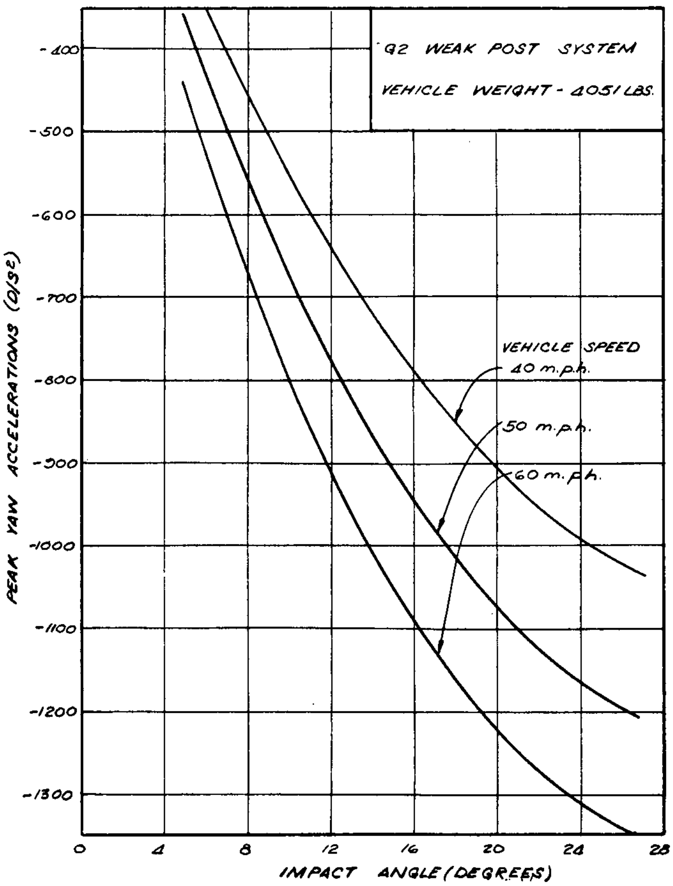


Figure 34. Vehicle peak yaw acceleration as functions of impact speed and angle for G2 system.

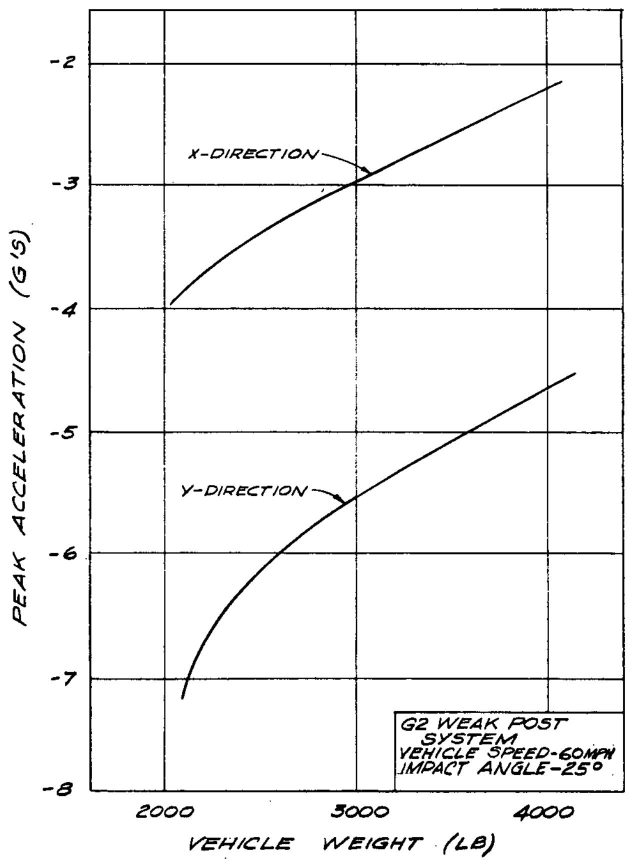


Figure 35. Vehicle peak accelerations as a function of vehicle weight for G2 system.

TABLE 21

EFFECT OF G4 BARRIER PARAMETERS ON PEAK ACCELERATIONS OF VEHICLE

Parameter Varied	Rail Tension (lb)	Soil Modulus (psi/in.)	Post Strength (lb)	Rebound* Modulus	Rail-Vehicle Friction Factor	Peak Accelerations (g's)		
						X	Y† First	Y† Second
Rail Tension	10,000	50	5000	S	0.2	3.7	5.0	5.9
	15,000	50	5000	S	0.2	4.3	6.5	8.7
	20,000	50	5000	S	0.2	4.3	6.5	8.7
Soil Modulus	10,000	50	6000	D	0.2	4.3	5.9	7.5
	10,000	40	6000	D	0.2	4.3	5.9	7.8
Post Strength	10,000	50	6000	D	0.5	6.2	4.7	7.8
	10,000	50	5000	D	0.5	6.0	4.4	7.0
	10,000	50	4000	D	0.5	5.4	4.0	7.1
	10,000	50	3000	D	0.5	4.8	3.7	6.4
Rail-Vehicle Friction	10,000	50	6000	D	0.5	6.2	4.7	7.8
	10,000	50	6000	D	0.2	4.4	5.9	7.8

*S-Barrier unload modulus equals load modulus. D-Barrier unload modulus equals twice load modulus.
†First peak occurs at initial vehicle impact; second peak occurs when rear of vehicle spins into barrier.

TABLE 22

G2 GUARDRAIL POST STUDY

Parameter	Post Type 2-In. Pipe	Post Type 315.7*	Post Type 417.7
Post Spacing	12 ft 6 in.	12 ft 6 in.	12 ft 6 in.
Post Strength (lb)	1533	3940	4100
Dynamic Deflection (ft)	8.3	5.9	5.8
Peak Vehicle Acceleration			
Longitudinal (g's)	6.2	2.2	2.2
Lateral (g's)	3.2	4.6	4.7
Yaw (deg/sec^2)	1800	2700	2650

*Standard G2 guardrail system post.

TABLE 23

POST SPACING EFFECTS ON G2 SYSTEM PERFORMANCE

Post	Spacing	Barrier Deflection (ft)	Peak Acceleration* (g's) x	Peak Acceleration* (g's) y
315.7	16 ft 0 in.	7.1	−1.9	−4.0
315.7	12 ft 6 in.†	5.9	−2.2	−4.7
315.7	8 ft 4 in.	4.6	−2.8	−5.3
315.7	6 ft 3 in.	3.6	−3.4	−6.2
315.7	3 ft 1-1/2 in.	2.3	−4.3	−7.8

*At vehicle center of gravity; 4051-lb vehicle striking guardrail system at 60 mph and 25-deg angle.
†Standard post spacing for G2 system.

posts. However, the guardrail system using 2-in.-diameter pipe posts is more flexible (dynamic deflection of 8.3 ft compared to 5.9 ft for the standard), produces higher longitudinal accelerations (6.2 g's in contrast to 2.2 g's), and subjects the vehicle to less lateral peak accelerations (3.2 g's compared to 4.6 g's).

As a means for controlling dynamic deflection for the

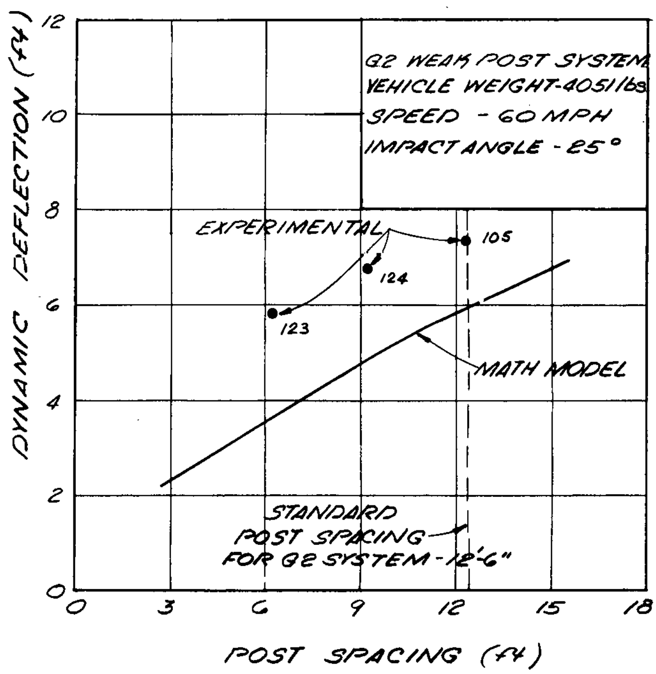


Figure 36. G2 system dynamic deflection as a function of post spacing.

G2 weak post system, post spacing was varied from 3 ft 1½ in. to 16.0 ft. As shown in Figure 36, dynamic deflection varies from 2.3 ft for the close post spacing to 7.0 ft for the 16-ft spacing. Experimental results from Tests 105, 123, and 124 are plotted for comparison. The discrepancy can be attributed to the analytical assumptions that the rail is continuous, whereas it is actually composed of short sections spliced together. During the first phase of impact, slack is taken out of spliced joints and a deflection is induced in the system without a corresponding buildup of barrier force. Peak accelerations are given in Table 23 for several post spacings.

CHAPTER FOUR

APPRAISAL AND APPLICATION OF RESULTS

APPRAISAL

In appraising the significance and validity of findings of Chapters Two and Three, it is appropriate to examine these data according to four aspects: (1) state-of-the-art investigation, (2) theoretical developments, (3) experimental procedures, and (4) current and upgraded guardrail systems.

State-of-the-Art Investigations

Findings particularly applicable to dynamic performance of highway guardrail and median barriers were acquired from the literature and in discussions with highway engineers. Two important aspects were appraised during the program to have a most significant effect on guardrail design technology. The first recognizes that guardrail installations are roadside hazards and may cause fatalities and injuries. Hence, their use should be limited to those highway sites where a need has been clearly indicated and cannot be eliminated by other means (*16*). Furthermore, justifications or warrants for a guardrail installation should be based on minimum relative crash severity by comparing collision severity of a vehicle striking the guardrail to that of striking a roadside obstacle (*57*). For example, vehicle occupants may have a better chance for survival if the vehicle is permitted access to a steep embankment slope * rather than the vehicle being redirected by a guardrail installation. This is true regardless of whether the accident frequency is ten cars per year or ten cars per hour. Hence, accident frequency is not a factor in guardrail-warranting considerations.

The second aspect of guardrail state-of-the-art to evolve in the program has been the recognition of an order of consideration for guardrail performance requirements. Although peformance factors have been identified by others, these requirements were ordered according to their importance to dynamic performance of an installation and to their contribution to over-all effectiveness of a system. Dynamic performance requirements, in order of priority, are:

1. Structural integrity of guardrail.
2. Vehicle peak accelerations.
3. Vehicle post-impact trajectory.

With this arrangement, researchers and engineers have clearly defined evaluation criteria whereby two or more guardrail systems can be appraised according to dynamic performance and the better system identified and selected.

Results of full-scale crash tests reported in the literature were summarized in Chapter Two. Care should be exercised in comparing results among test series and among testing agencies as test procedures, controls, and data acquisition and processing techniques varied extensively. Only in the past seven years has full-scale crash testing approached a standard procedure. Hence, results from earlier tests should be viewed only for gross characteristics and historical value.

Theoretical Developments

Appraisal of the mathematical model is determined on the basis of validity, capabilities/limitations, and usefulness. Selection of a six degree-of-freedom idealized vehicle instead of an eleven degree-of-freedom car appears to be justified by good correlation of results between theoretical prediction and experimental data and from findings from parametric studies. However, use of the agency's 6-DOF model was directed to case conditions where the pavement surface was flat and free of irregularities. On the other hand, for the cases examined in the Project, the 6-DOF model appeared to possess unneeded articulation. For example, variations in spring constants for front and rear wheels, mass moments of inertia about the pitch and roll axes, and tire properties, were found to have little if any influence on vehicle trajectory. For this reason, the 3-DOF model of a vehicle may be adequate to predict basic behavior of guardrail systems.

It should be noted that the mathematical models used in this program have useful ranges and limitations. They can be upgraded to handle unique and more sophisticated conditions when the need is demonstrated. Presently, the vehicle-guardrail interaction model cannot predict either

* This, of course, depends on height of embankment and steepness of slope.

vehicle snagging or penetration. Also, it can accommodate only constant-height systems; ramped end treatments are beyond the model's scope.

Findings of parametric studies should be considered as tentative until verified by full-scale tests. Nevertheless, several significant and interesting results were developed which should be considered in the design and testing of guardrail installations. For it was shown in Table 19 that the yaw mass moment of inertia has a significant effect on guardrail performance, whereas the roll and pitch mass moments of inertia have negligible influence. Steer angle of the vehicle front wheels during redirection has an insignificant effect on vehicle trajectory as shown in Table 20.

The fact that guardrail performance can be changed by varying components or parameters of the guardrail installation is demonstrated by the findings. The relatively low magnitude of change which was effected by significant variation in barrier parameters as shown in Table 21 is somewhat disappointing. Post spacing and post type for the G2 weak post system developed by New York appear to give optimum performance.

Experimental Procedures

Procedures used in performing full-scale vehicle-to-guardrail impact tests are described in Appendix A. Several other agencies have performed full-scale crash testing; each has used its own unique methods and procedures for controlling the test and acquiring experimental data. Costs of test facilities and equipment, as well as unit cost for performing tests, varied over a wide range among the agencies; and the test control precision and quality of acquired data were not necessarily proportional to these costs. Because vehicle crash testing is a most expensive research operation, the SwRI test facility and experimental procedures were developed on a cost-effectiveness basis; that is, they would provide the lowest cost test (and therefore more tests for a level of funding) that would produce significant and meaningful data and results.

Vehicle speed and impact angle were not controlled within the precision expected; vehicle speed for Test 106 (terminal treatment) was 8.3 mph below the desired 60 mph, and impact angle for Test 119 was 5.2 degrees above the desired 25-degree approach. A large part of this error can be attributed to the unpredictable performance of the high-mileage cars used. Speed control was improved late in the program (i.e., last four tests) witth the use of a speed limiting device inserted in the vehicle's ignition circuit. It is to be noted that vehicle impact conditions (i.e., speed, angle) do not affect the quality of the guardrail response data acquired, but only the momentum and energy level at which the system is evaluated.

High-speed motion picture photography was the primary data acquisition system employed. This photography not only recorded vehicle and guardrail interaction mechanisms, but it also established the precise value of pre-impact vehicle speed and angle. A method of film analysis and data processing provided vehicle displacements, velocities, and accelerations at any instant during the redirection trajectory. Also, the use of an instrumented anthropometric dummy generated data relevant to forces that vehicle occupants would be subjected to during impact and redirection. A recommended procedure for conducting full-scale crash tests was developed and is presented in Appendix B.

In summary of the experimental procedures, vehicle controls are considered to have been adequate; however, the data acquisition instrumentation and processing are considered quite good.

Current, Modified, and New Barrier Systems

There are no perfect or universally applicable guardrail or median barrier systems. Each system is best suited for a limited range of application. For example, a cable barrier should not be used in medians too narrow to accommodate system deflection. On the other hand a concrete barrier that has excellent performance capabilities for vehicles impacting at small (i.e., less than 15 degrees) impact angles may be a poor selection for a wide median site where probability of large angle hits increases. Hence, selection of an appropriate system should be based on highway site conditions.

General Performance

General performance of G2, G3, G4 guardrail and MB3 median barrier systems was evaluated by crash tests in this program; the remainder of the systems recommended in *NCHRP Report 54* (i.e., G1, MB1, MB2, MB5, and MB6) had been evaluated by others. In addition, the Aluminum Association strong beam median barrier and a system composed of a W-beam mounted on 6B8.5 post were investigated. Findings of these tests are given in Table 13 and discussed in Chapter Three. An appraisal of these data is presented in Table 24. Each test installation is appraised according to (1) dynamic performance, (2) property damage, and (3) over-all performance. Dynamic performance factors are barrier structural integrity, vehicle peak lateral and longitudinal accelerations, and vehicle rebound trajectory. Property damage to barrier and vehicle are considered separately. Over-all barrier appraisal is a composite of dynamic performance factors and property damage factors with the dynamic behavior factors emphasized. Performance rating factors, given in the lower part of Table 24, were established somewhat arbitrarily, to some degree; however, the vehicle acceleration ranges correspond to those presented in Table 7.

Appraisals of the systems recommended in *NCHRP Report 54* (i.e., G2, G3, G4, and MB3) ranged from fair to excellent. As might be expected, the more rigid system, G4, generally caused the most property damage. The G2 system with reduced post spacing (Test 123) caused slightly higher vehicle lateral acceleration and more barrier damage than the other two G2 tests (Tests 105 and 124).

Tests 109 and 110 performed on the Aluminum Association strong beam median barrier are considered inconclusive; Test 109 was performed at a planned speed of 41.3 mph, which is less than the nominal 60 mph for the general performance tests, and the installation was penetrated in Test 110. The Aluminum Association performed a metallurgical analysis of Test 110 beam and reported that

TABLE 24

GENERAL PERFORMANCE APPRAISAL OF BARRIER INSTALLATIONS*

SwRI Test	NCHRP Report 54 System	Beam	Member	Post Offset (in.)	Spacing (ft)	Dynamic Performance Evaluation					Property Barrier	Damage Vehicle	Overall Barrier Appraisal
						Barrier Structural Adequacy	Vehicle Peak Acceleration Longitudinal	Vehicle Peak Acceleration Lateral	Vehicle Rebound Distance	Composite Rating			
101	G4	W	8 X 8 wood	8	6.25	S	A	B	D	C	B	D	Fair
102	G4	W	8 X 8 wood	8	6.25	S	–	–	C	C	A	C	Fair
103	G4	W	8 X 8 wood	8	6.25	S	A	C	B	B	B	C	Good
105	G2	W	3I5.7	None	12.5	S	A	B	B	B	A	B	Good
123	G2-A	W	3I5.7	None	6.25	S	A	C	C	B	B	B	Good
124	G2-B	W	3I5.7	None	9.3	S	A	B	C	B	A	B	Good
109	–	Alum.	3IA1	N/A	6.25	S†	–	–	A	–	A	B	Good
110	–	Alum.	3IA1	N/A	6.25	U	–	–	–	U	C	D	Unsatisfactory
112	MB3	8 X 6 X 1/4 box	3I5.7	N/A	6.0	S	A	C	A	A	B	B	Excellent
114	G3	6 X 6 X 3/16 box	3I5.7	N/A	6.0	S	A	C	A	A	B	C	Excellent
119	–	W	6B8.5	None	6.25	S‡	A	B	D	B	A	C	Good
120	–	W	6B8.5	6	6.25	S	A	C	C	B	A	C	Good
121	–	W	6B8.5	12	6.25	S	A	C	A	A	B	B	Excellent
122	–	W	6B8.5	12	6.25	S	A	C	C	B	B	C	Good
Performance Appraisal			Factor				Range (g's)	Range (g's)	Range (ft)		Range ($100)	Range ($100)	
Excellent			A				0 to 5	0 to 3	0 to 12		0 to 2	0 to 4	
Good			B				5 to 10	3 to 5	12 to 18		2 to 4	4 to 8	
Fair			C				10 to 25	5 to 15	18 to 24		4 to 6	8 to 12	
Poor			D				>25	>15	>24		>6	>12	
Satisfactory			S Redirected										
Unsatisfactory			U Penetrated										

*See Table 13 for test results.
†Test speed was 41.3 mph.
‡W-beam was partially severed in impact area.

the beam splice was fabricated from an incorrect alloy (6005 instead of 6351).

Four crash tests conducted on a W-beam/6B8.5 post system indicated good to excellent results (Tests 119, 120, 121, and 122). A 6-in. offset is considered the better design selection when compared to the 0- or 12-in. offset based on low impact angle crashes and current practice considerations.

End Treatment Designs

As demonstrated by six of eight full-scale crash tests performed on barrier upstream terminal treatments, present designs are hazardous. In particular, ramped terminals for box beam and W-beam barrier systems can cause impacting vehicles to launch, roll, and tumble. One horizontal flare terminal, a box beam, performed in an acceptable manner by allowing the vehicle to penetrate; the one test is certainly not conclusive, but it definitely shows promise. Development of safer end treatment designs is considered the highest priority item for subsequent research.

Transition Design

Only the G4 guardrail-to-concrete bridge rail transition design was investigated in the program. Although the G4 transition will redirect vehicles, the redirection is surmised to be more severe (i.e., vehicle accelerations) in some cases than a collision with either the guardrail or the bridge rail. This is due to the fact that the two systems function quite differently. For example, the guardrail performs by deflecting laterally, whereas a concrete bridge rail with a New Jersey profile performs by lifting and banking the vehicle. The transition between the systems exhibits decreased deflection and minimum "lifting" capabilities; hence, the transition section is a poor compromise of two systems. As the guardrail and bridge rails have the same function, the transition between two barriers that perform differently should be eliminated by continuing the bridge rail system to the point-of-need established for the approach guardrail.

APPLICATION

NCHRP Report 54 was published in the early phase of the program and represented guardrail and median barrier technology of early 1968. Although most of the designs and recommendations in that report had been tested and thoroughly evaluated by others, there were some aspects, notably end treatments and transitions to bridge rail, that lacked full-scale test verification. Nevertheless, these aspects were included in order to provide a more complete treatment of guardrail technology. In the full-scale testing phase of this program, emphasis was directed to those areas of *Report 54* that had not been extensively investigated. Results of the program, and in particular the test phase, that have immediate and direct application are summarized.

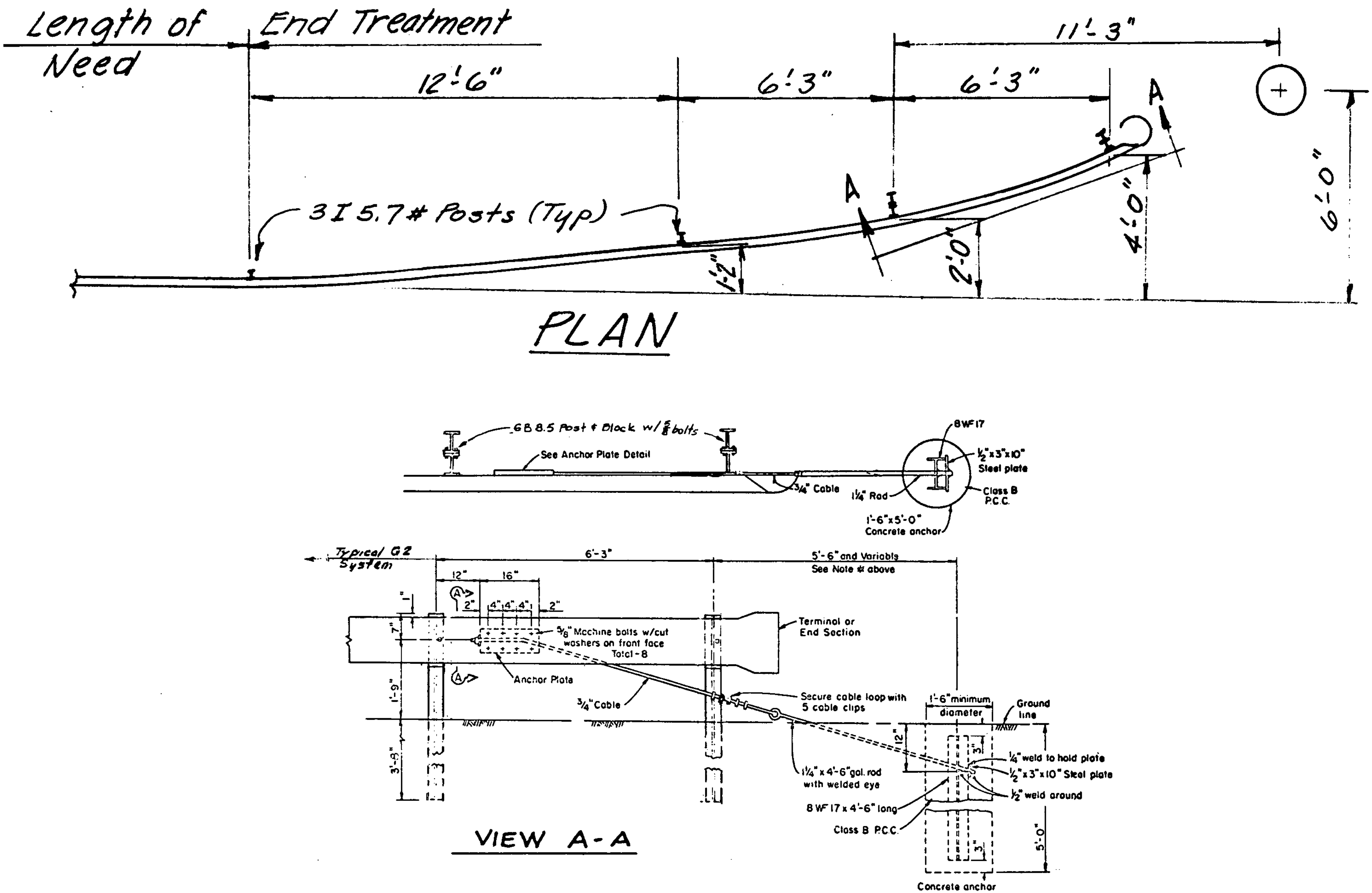


Figure 37. Recommended end treatment, G2 standard.

TABLE 25

INTERIM RECOMMENDATIONS FOR BARRIER TERMINALS

Barrier System	Terminal	SwRI Test	Performance	Interim Recommendation
G1 (Cables, 3I5.7 post)	Ramp	None	–	NCHRP Report 54 G1 terminal
G2 (W-Beam, 3I5.7 posts)	Ramp/Flare	106	Vehicle rolled	See Figure 37
G3 (6 X 6 Box, 3I5.7 posts)	Ramp/Flare	115	Vehicle penetrated; good	NCHRP Report 54 G3 terminal
G4 (W-Beam, 8 X 8-in. wood post)	Flare	125	Severe vehicle damage	NCHRP Report 54 G4 terminal
MB1 (Cables, 3I5.7 post)	Ramp	None	–	NCHRP Report 54 MB1 terminal
MB2 (W-Beam, 3I5.7 post)	Ramp	107	Vehicle rolled	See Figure 37
MB3 (8 X 6 Box, 3I5.7 post)	Ramp Ramp	113 116	Vehicle rolled Vehicle rolled	NCHRP Report 54 G3 terminal type where possible; otherwise MB3 terminal
MB4 (W-Beam, 8 X 8-in. wood post)	Blunt End	125	–	NCHRP Report 54 MB4 terminal
MB5 (New Jersey concrete)	Ramp	None	–	NCHRP Report 54 MB5 terminal
MB6 (General Motors concrete)	Ramp	None	–	NCHRP Report 54 MB6 terminal
Texas (W-Beam, 7-in.-dia wood post)	Texas Twist	108 111	Inconclusive; Vehicle rolled	NCHRP Report 54 G4 terminal

Recommended Barrier Systems

NCHRP Report 54 Systems

Guardrail and median barrier systems recommended in *NCHRP Report 54* have been further validated for dynamic performance. In particular, the G2, G3, and G4 guardrail and MB3 median barrier systems demonstrated capabilities of redirecting impacting vehicles in such a manner that properly restrained (i.e., with seat belt and chest harness) occupants would probably have survived the crash without serious injuries.

Additional System

A system consisting of a standard W-beam rail mounted at 27-in. height and offset 6 in. from 6B8.5 steel posts spaced at 6-ft 3-in. centers is recommended for use at sites where moderate deflection (i.e., 4 ft) is acceptable.

Strong Timber Posts

Southern yellow pine is recommended as an acceptable substitute for Douglas fir for the 8 × 8-in. post in the G4 system.

Spacing of Weak Posts

Spacing of the 3I5.7 steel posts for the G2 system may be decreased from the standard 12-ft 6-in. centers to 6-ft 3-in. centers in order to decrease lateral dynamic deflection about 20 percent. This has applications in effecting a lateral stiffness transition from a weak-post to a strong-post system and at highway sites where an obstacle encroaches within the standard system lateral deflection zone.

Barrier Terminal Treatments

To provide design guidelines until research is accomplished, some interim recommendations are presented in Table 25. For the most part these recommendations suggest designs included in *NCHRP Report 54*. However, in the case of G2 and MB2 barriers, a new design is presented in Figure 37. Principal attributes of this new design are that the ramped end has been eliminated and the exposed end has been flared to minimize the "spearing" tendency.

Transitions to Bridge Rails

Lateral stiffness transition detail for the G4 approach-guardrail-to-concrete-parapet connection presented in *NCHRP Report 54* is adequate for redirecting vehicles. However, the redirection may be abrupt, with accompanying intense vehicle accelerations. The most important features of the transition design are that (1) the approach beam must be adequately anchored to the bridge rail and (2) the lateral stiffness of the approach barrier must be gradually increased toward the bridge rail by employing larger size posts and a smaller post spacing. These features will decrease the tendency for vehicle pocketing in the transition zone.

Warrants and Design Selection Procedures

Guardrail and median barrier warranting and design selection procedures as presented in *NCHRP Report 54* are recommended for general use by highway engineers.

CHAPTER FIVE

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

From the findings and results of the investigation, several conclusions concerning design and performance of highway guardrail systems are made.

State of the Art

Three of the most important highway safety considerations with regard to barrier technology and design approach are:

1. Guardrail installations are roadside hazards. Therefore, their use must be kept to an absolute minimum. Highway designers should explore all feasible means of flattening steep embankments and eliminating other guardrail-warranting factors.

2. Guardrails are warranted only at locations where the severity of potential vehicle collision with the guardrail is less than the collision with the screened object. Accident frequency is not a warranting factor although it may be used to establish priority or the *sequence* in which two or more warranted installations are built (see Appendix D, *NCHRP Report 54*).

3. Guardrail system dynamic performance is evaluated according to the following priority sequence:
   (a) Structural integrity (vehicle will not vault over, break through, or wedge under system).
   (b) Vehicle peak acceleration (measured near center of gravity).
   (c) Vehicle post-impact trajectory.

Barrier Performance

1. Guardrail systems presented in *NCHRP Report 54* demonstrated fair to excellent dynamic performance. Vehicle acceleration and vehicle damage were somewhat higher for the relatively rigid G4 system than for the G2, G3, and MB3 systems. Barrier damage repair cost was slightly higher for the box beam systems (average $268) than for the G4 (average $206) or G2 (average $202) systems. In all these tests the vehicle was smoothly redirected; it is conjectured that properly restrained passengers would have sustained the redirection without fatality or serious injury.

2. A guardrail system composed of W-beam mounted on 6B8.5 steel posts set at 6.25-ft intervals demonstrated good to excellent dynamic and property damage performance. In four tests, the vehicle was redirected by the installation with moderately induced vehicle accelerations. Barrier damage ($192) and vehicle damage ($890) were lower than the averages ($230 and $915, respectively) for all 14 general performance crash tests.

3. The Aluminum Association strong beam median barrier was penetrated; however, metallurgical analysis of the failed beam splice by the Aluminum Association indicated that the splice was fabricated from an incorrect 6005 alloy instead of 6351 alloy. Results of a subsequent full-scale crash test (conducted outside the scope of this study) performed by the research agency on the aluminum barrier system indicated acceptable barrier performance.

4. Southern yellow pine is a suitable wood species alternate for Douglas fir in the G4 and MB4 barrier systems.

5. Post spacing in the G2 system may be reduced to 6 ft to facilitate a 20 percent decrease in system lateral deflection.

End Treatments

Terminal details or end treatments for guardrail installations presented in *NCHRP Report 54* and tested in this program are significantly more hazardous than the remainder of the guardrail installation. In particular, the ramped terminal causes an impacting vehicle to launch, roll, and tumble. Flared treatments increase vehicle impact angles and exhibit a tendency to pocket the vehicle. Anchored straight extensions are hazardous when struck end-on, due to tendencies for the beam to penetrate the passenger compartment and for the vehicle to be stopped abruptly; however, the length-of-hazard is a minimum for this design.

Approach Guardrail-to-Bridge Rail Transition

The G4 guardrail-to-concrete bridge parapet transition redirects impacting vehicles, although this redirection is abrupt and results in moderately high vehicle accelerations. Attributes of this transition are that the approach beam is securely anchored to the concrete parapet and is laterally stiffened near the parapet. A preferred transition design approach that would minimize inherent difficulties of current transitions would be to extend, if feasible, the bridge rail system to replace the approach guardrail installation.

SUGGESTED RESEARCH

In the past decade, considerable research has been performed in the area of guardrail design and performance. Need of this research is evidenced by the fact that more than 11.7 percent of all single-vehicle fatal accidents involve a guardrail. Advances have been made in the understanding of guardrail dynamic behavior during vehicle impact. Several guardrail systems have evolved by means of trial and error to a point where their performance is both predictable and acceptable. Nevertheless, there are still unsolved problems plaguing even the better-designed systems.

Several areas of future research in highway guardrail technology are recommended and discussed briefly in the following.

Guardrail Terminal Treatments

From test results in this investigation and from experience by others, upstream terminal treatments have been demonstrated to be the most hazardous part of a guardrail installation. In particular, designs with ramped beams cause impacting vehicles to launch, roll, and tumble; treatments with horizontally flared beams increase the vehicle impact angle (and therefore increase the collision severity). Although a cable-anchored straight terminal does not eliminate the possibility of the beam penetrating the passenger compartment of a vehicle striking the installation end-on, it does reduce the length of the terminal and hence the length-of-hazard to a near minimum. Accordingly, new concepts for anchoring guardrail installations should be formulated and evaluated. This is probably the most pressing problem at hand and should receive the highest priority of attention. Ideas that should be examined include earth mounds, oil drums, water tubes, frangible concrete, and flares.

Approach Guardrail to Bridge Rail Transition

The G4 approach guardrail-to-concrete bridge wall transition redirected the vehicle in two of three crash tests; concrete parapet failure in Test 118 permitted the vehicle to snag on the bridge wall. Vehicle redirection for Tests 104 and 117 was successful but abrupt. Although this transition detail is recommended for the interim, research effort to develop improved transitions is indicated; a suggested approach to this problem is to develop an integrated approach-rail-bridge-rail barrier system with both segments of the barrier having approximately the same lateral rigidity. The critical area of this approach is to produce a system with a certain lateral stiffness with posts embedded in soil or attached to the bridge deck.

Strong Post Investigation

Dynamic performance of a strong post guardrail system (i.e., G4 system), unlike the weak post system (i.e., G2 system), depends on soil properties. No provision is made in current guardrail design to account for variation in soil conditions. This can be attributed to the lack of understanding of a post-soil system subjected to a dynamically applied horizontal force. It is suggested that laboratory tests be conducted to establish embedment depth for the more common guardrail posts, using soils ranging from loose sand to frozen clay.

Investigate Field Performance of Barriers

Highway accident studies, at best, have indicated only when (or if) a barrier was involved. Little information has been collected to help highway engineers and researchers to evaluate how well a particular barrier system has performed in service. Examples of desired information would include:

1. Specific barrier type (i.e., W-beam on timber posts spaced at 6-ft 3-in. centers, etc.)
2. Location of impact along installation (i.e., near terminal or in center portion).
3. Condition of barrier prior to crash (i.e., correct layout, proper rail height, soil condition, etc.)
4. Barrier damage.

This information is needed both for severe accidents where injuries and fatalities occur and for minor impingement incidents that are normally unreported. Data from a research program could be used to identify such items as barrier performance in terms of fatality and injury rate per barrier impact and property damage repair cost per impact. Ultimately, two or more barrier sytems could be evaluated on these demonstrated service factors.

Theoretical Investigations

Mathematical models as developed and used in this investigation have demonstrated value and merit in providing a fundamental understanding of the dynamic interaction of vehicle-guardrail impacts. Several phases of the mathematical model have indicated variance from the corresponding physical phenomenon and need to be refined; an example of this is the post-soil behavior for strong post guardrail systems. Experimental work should precede this effort. Also, the model should be refined to more realistically reflect rail tension and initial slack in the installation and incorporate capabilities to predict vehicle snagging and penetration.

Guardrail Warrants

Guardrail and median barrier warrants as presented in *NCHRP Report 54* represent the current state of the art. These warrants are applicable to only the more common roadside conditions and give little assistance to designers facing unusual situations. Suggested research in this area would be concerned with ran-off-the-road accident studies comparing relative severity of guardrail impacts with other roadside hazards. Attention should also be directed to the more uncommon roadside hazards. Information should be collected and synthesized that will permit cost-effectiveness social judgment decisions. For example, accident frequency generally increases when a barrier is installed in narrow medians; the question to be considered on both cost and moral basis is: "How many median barrier impacts, some involving serious injuries, are acceptable for the reduction of one fatality?"

NCHRP Report 54

NCHRP Report 54 was published in August 1968 and reflected then current state-of-the-art information on guardrail design, location, and maintenance. Research performed in the past 18 months has shown that some of the recommended design details should be improved. An addendum to *NCHRP Report 54* should be prepared as soon as feasible to include the following changes:

1. Add a guardrail system consisting of W-beam mounted on and offset 6 in. from 6B8.5 steel posts spaced at 6.25-ft centers.

2. Revise the rail height of previously recommended guardrail and median barrier systems to reflect recent crash tests by New York State, as follows:

SYSTEM	RAIL HEIGHT (IN.) OLD	NEW
G1	27	30
G2	30	33
G3	27	30
MB1	27	30
MB2	30	33
MB3	27	30

3. Add a statement to alert highway designers of the merits and drawbacks of various terminal treatments.

APPENDIX A

FULL-SCALE TESTING

Twenty-five full-scale guardrail and median barrier crash tests were conducted between November 11, 1968, and October 15, 1969. The test program included three basic test groups: (1) general performance, (2) transition to bridge parapet, and (3) end treatments. Vehicles under power were guided into test installations at various speeds and angles to determine the performance and the behavior of the various systems. Data from an anthropometric dummy were recorded and high-speed motion picture cameras provided time/displacement records of the crash events.

TEST PROCEDURES AND INSTRUMENTATION

Facility Description

The tests were conducted at the main campus of Southwest Research Institute in San Antonio, Tex. A 12-ft wide, 1,500-ft-long asphalt-paved run-up strip provided adequate acceleration distance for standard cars with six-cylinder engines to attain speeds of 60 mph; cars with eight-cylinder engines required less distance. At the end of the run-up strip a 22-ft-wide by 200-ft-long paved area provided a recovery space for test vehicles. Features of the facility are shown in Figure A-1. A control building located adjacent to the run-up strip housed the data recording and vehicle control instrumentation.

Test Vehicles

Self-powered, full-size, four-door sedans were used as test vehicles. With the exception of two 1957 Chevrolets, the vehicles were of model years 1961 through 1963. Vehicle guidance was provided by a guide bracket attached to the left front wheel spindle as shown in Figure A-2. Threaded through this bracket and running the full run-up strip length was a ¼-in.-dia. steel guide cable pretensioned to 2,000 lb. Just prior to impact this guide bracket was stripped from the car; hence, the car was essentially free of steering control at impact. Vehicle brakes and ignition were controlled before and after impact by means of signals transmitted through a tether line trailing the vehicle. Braking of the vehicle was performed by remotely actuating a solenoid valve that permitted air from a pressurized accumulator to enter the brake lines. This package, mounted in the trunk, permitted the engineer to pulse or lock the brakes. The brakes and ignition were incorporated with a "fail-safe" provision; tether line severance automatically produced braking and loss of ignition.

Anthropometric Dummy

The test subject was a 50th percentile Model 182 anthropometric dummy (Fig. A-3) manufactured by the Sierra Engineering Company. The dummy weighs 157.5 lb, has a standing height of 68.3 in., and a sitting height of approximately 34.1 in. The joints are articulated to simulate human motions, and the friction joint resistances can be varied from loose to tight. It is discontinuous at the joints to allow freedom of motion. The dummy has a resilient flesh covering over-all with the exception of the head. The head is an

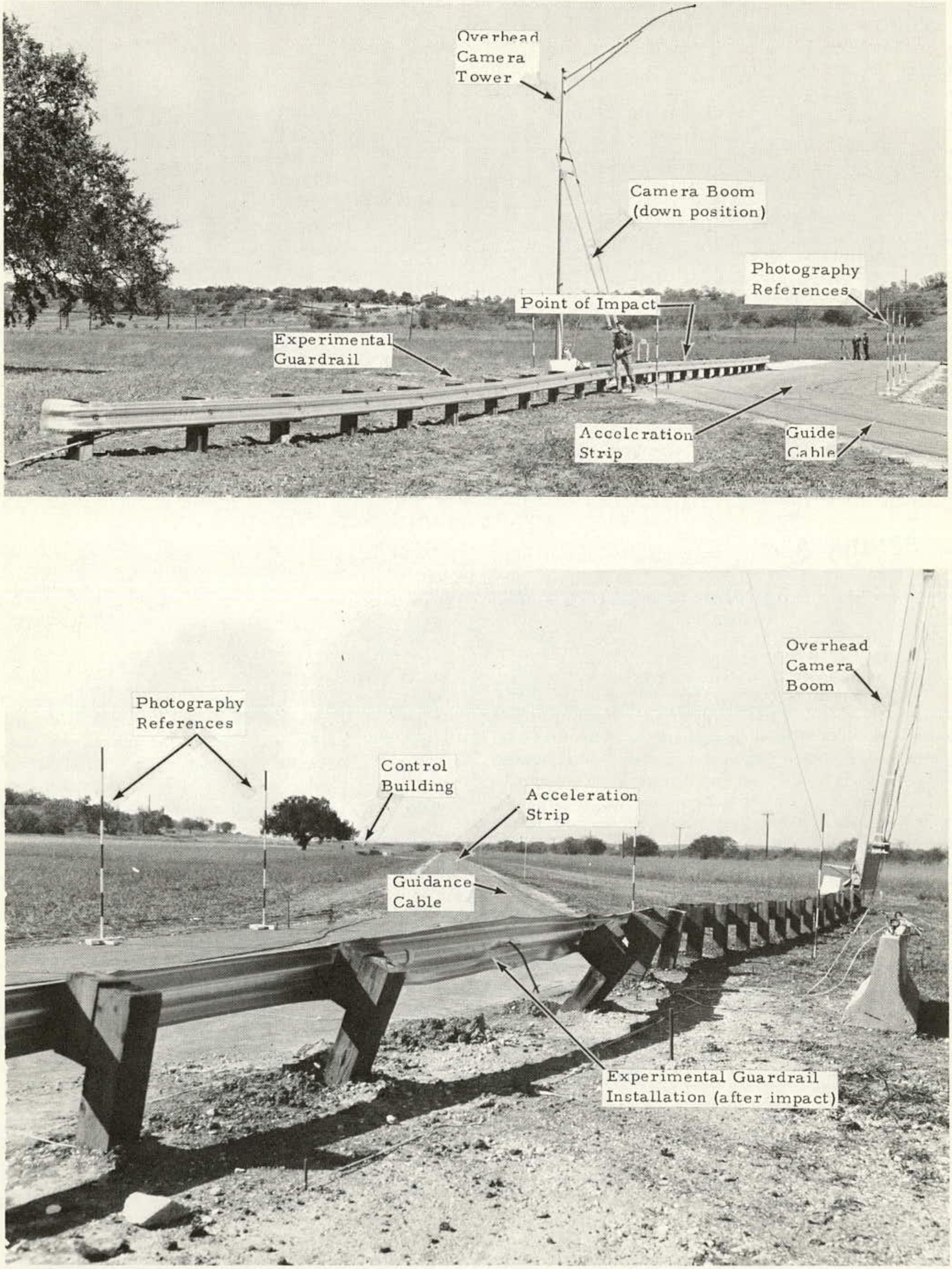


Figure A-1. Features of the vehicle-guardrail crash facility.

Figure A-2. Guide bracket on typical test vehicle.

aluminum casting covered with a rigid foam outer layer. The head and chest cavities are accessible for installation of instrumentation.

During tests the dummy was secured in the driver's position with lap belt and shoulder harness. The dummy's hands were adjusted near, but not touching, the steering wheel in order to avoid interfering with the vehicle guidance system.

Instrumentation

Mounted in the dummy's chest cavity were three strain-gauge-type accelerometers oriented in the longitudinal (vehicle fore and aft), lateral (left to right), and vertical (or spineward) directions. The range for the longitudinal and lateral transducers was ±25g; the vertical gauge range was ±10g. Dynamic forces in the occupant restraint belts were measured using specially designed load cells, shown installed in Figure A-3. The restraint belt slips over the center cylinder, on which strain gauges are mounted as shown in Figure A-4. Pertinent information on the load cells, as well as the accelerometers, is given in Table A-1.

Signals from on-board transducers were conditioned by on-board multichannel solid-state amplifiers and transmitted via the tether line to a high-speed magnetic tape recorder located in the control building. Data acquisition equipment is shown in Figure A-5. Lateral, longitudinal, and vertical aircraft-type peak "g" meters were attached to the floor pan in the right-front passenger compartment. The meter readings from these devices are used primarily as relative indicators and no significance is placed on the absolute magnitudes.

Camera Coverage

Camera coverage varied among tests; however, general camera placement is shown in Figure A-6. Impact events were recorded by high-speed data cameras from three viewpoints: parallel to the guardrail, normal to the guardrail, and overhead. Real-time documentary movie coverage, as well as pertinent still photographs, were provided for the tests.

A medium-speed (200 fps) movie camera with a 142°, wide-angle, "fisheye" lens was installed inside the vehicle to record dummy reaction during crash events. A typical on-board camera installation is shown in Figure A-7.

Data were taken from high-speed movies by means of a motion analyzer and processed according to a computer program designed for the purpose.

Figure A-3. Anthropometric test dummy.

Film for the high-speed data was Ektachrome EF; Kodachrome II was used for the standard-speed documentary coverage.

VEHICLE DAMAGE APPRAISAL

Vehicle deformation indices were developed to provide a common basis for describing the severity of deformation to vehicles involved in highway collisions. In 1968 the National Safety Council published a seven-point scale to aid accident investigators in assessing damage sustained by motor vehicles in traffic accidents. This TAD Vehicle Damage Rating scale was a relatively simple compilation that identified the direction of the principal impact force and the relative severity of damage to vehicles. In subsequent field test evaluations of the TAD scale, the accuracies of rating speed, cost, damage, and injuries were studied, and a "new scale" was recommended.

In order to expand and improve on the methods of rating vehicle damage, a separate international ad hoc committee formed in January 1968 undertook to develop a comprehensive medical injury index and vehicle deformation index. The deformation index developed by this committee has maintained the simplicity of the vehicle damage and severity reporting according to four components, as follows:

1. Direction of the principal force at the impact point.
2. Vehicle deformation location.
3. General type of collision.
4. Damage severity scale.

The first two characters of the index describe the direction of the principal force at the point of impact. It is assumed that a clock can be superposed on top of the vehicle with 12:00 o'clock representing the front of the

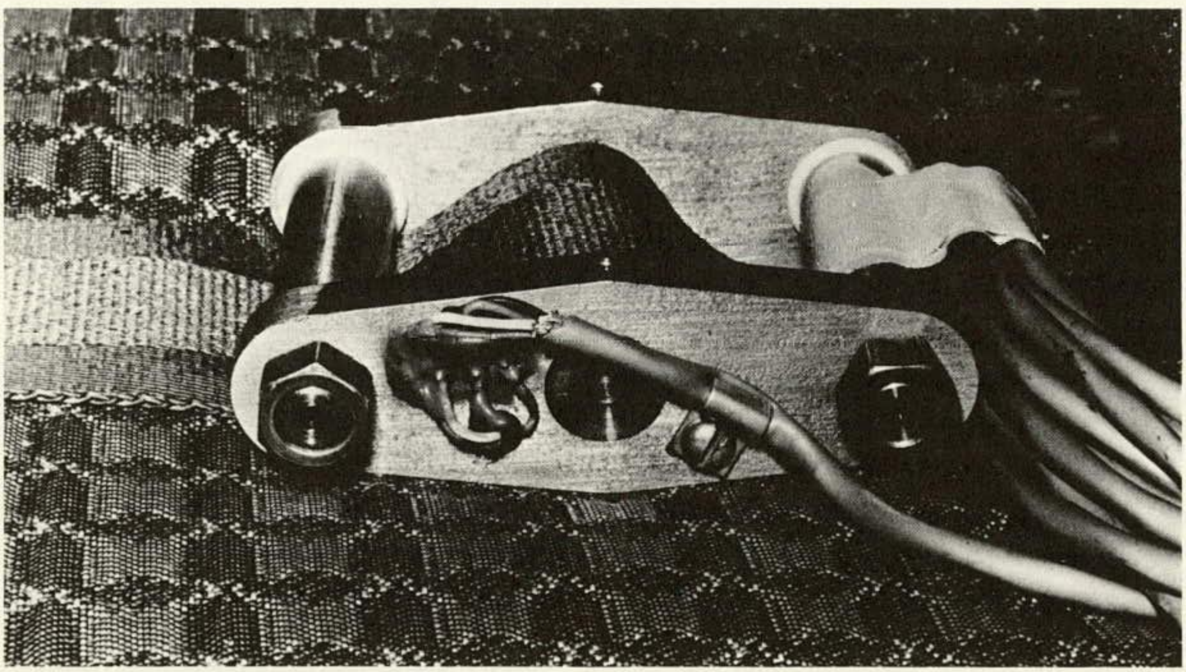
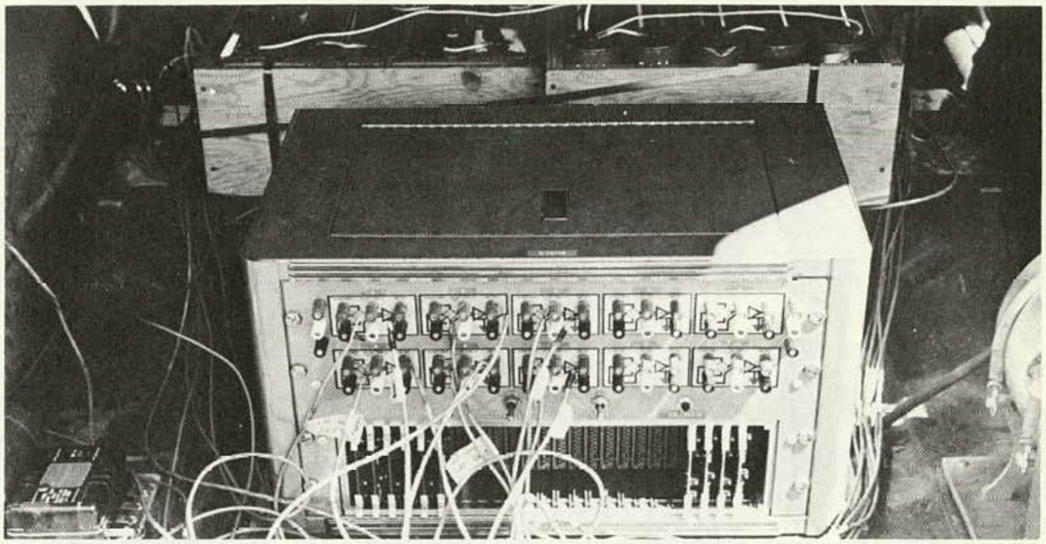


Figure A-4. Seat belt load cell assembly.



car. Then the numbers 01 through 12 in the first two positions represent the direction of application of the impact force.

The third position identifies the principal part of the car affected, as follows: F, front; R, right side; B, back; L, left side; T, top; U, undercarriage; and X, unclassifiable.

The fourth position identifies the specific horizontal location of the damage, as follows: D, distributed; L, left (front or rear); C, center (front or rear); R, right (front or rear); F, side (left front or right front); P, passenger compartment

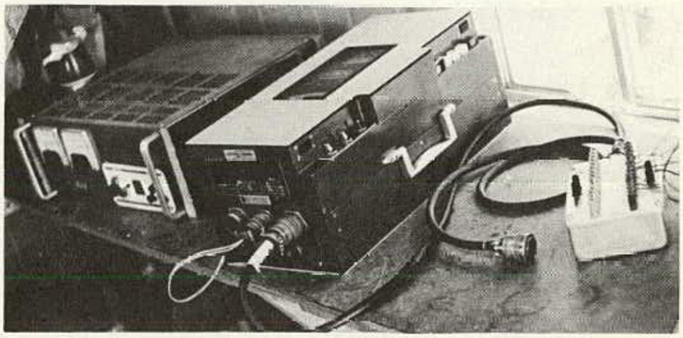


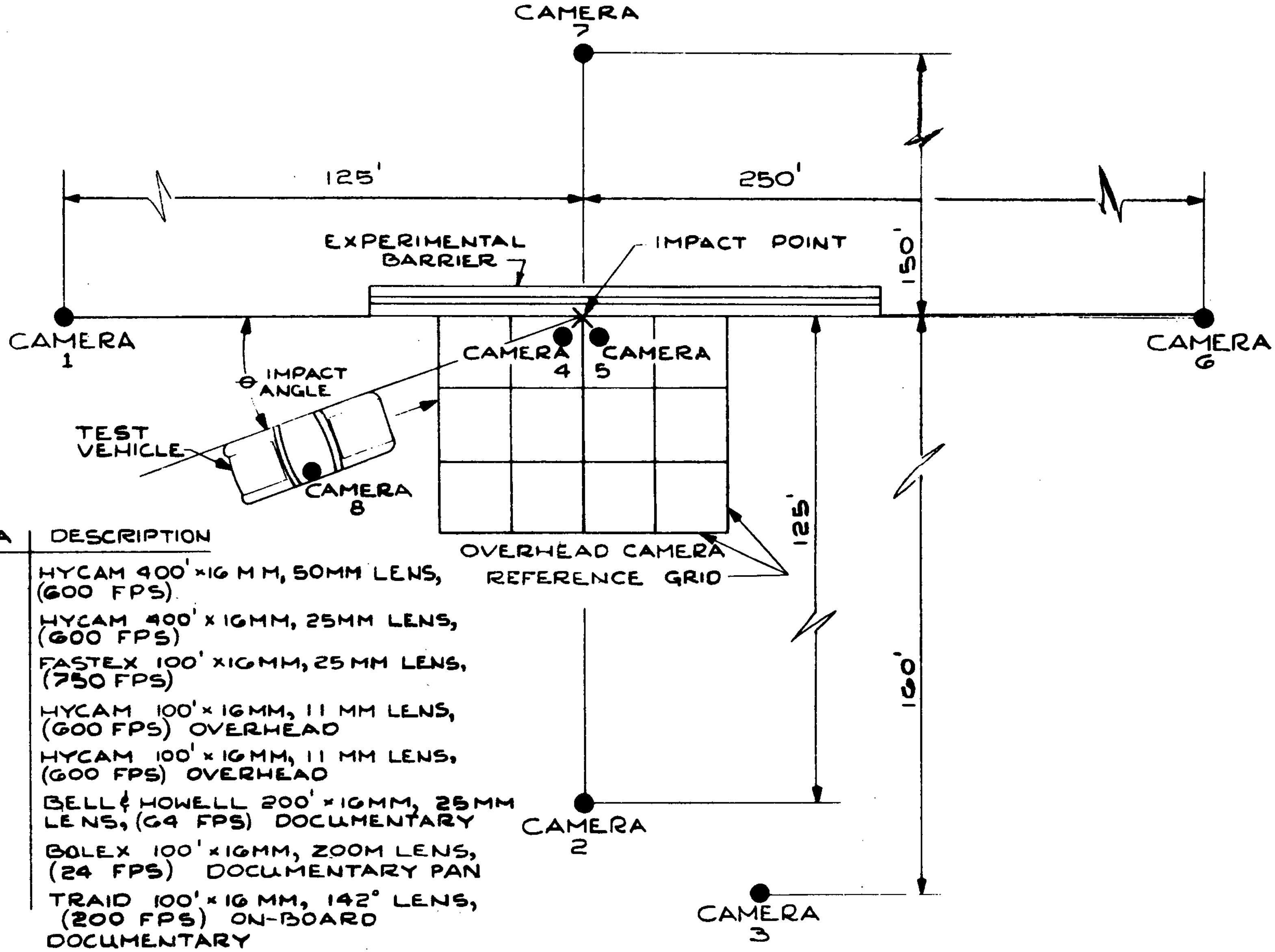
Figure A-5. Data acquisition equipment.

TABLE A-1

CHARACTERISTICS OF TRANSDUCERS USED WITH ANTHROPOMETRIC DUMMY

Ident. No.	Function	Effective Range (lb or g)	Nominal Bridge Resistance (ohms)	Transducer Voltage Sensitivity* (units/mv)
13804	Accelerometer Vertical	±10 g	350	0.540 g/mV
13882	Accelerometer Transverse Lateral	±25 g	350	1.052 g/mV
13883	Accelerometer Transverse A-P	±25 g	350	1.143 g/mV
B-7-9033-291-1	Load Cell Left Seat Belt	0-2000 lb†	120	516 lb/mV
B-7-9033-291-2	Load Cell Right Seat Belt	0-2000 lb†	120	488 lb/mV
B-7-9033-291-3	Load Cell Shoulder Strap	0-2750 lb†	120	490 lb/mV

Based on 3.55-V dc bridge supply voltage.
†Calibration range.



CAMERA	DESCRIPTION
1	HYCAM 400'×16 MM, 50MM LENS, (600 FPS)
2	HYCAM 400' x 16MM, 25MM LENS, (600 FPS)
3	FASTEX 100' x16MM, 25 MM LENS, (750 FPS)
4	HYCAM 100'× 16MM, 11 MM LENS, (600 FPS) OVERHEAD
5	HYCAM 100' × 16MM, 11 MM LENS, (600 FPS) OVERHEAD
6	BELL & HOWELL 200' × 16MM, 25MM LENS, (64 FPS) DOCUMENTARY
7	BOLEX 100' ×16MM, ZOOM LENS, (24 FPS) DOCUMENTARY PAN
8	TRAID 100'× 16 MM, 142° LENS, (200 FPS) ON-BOARD DOCUMENTARY

Figure A-6. Typical camera positions for crash test.

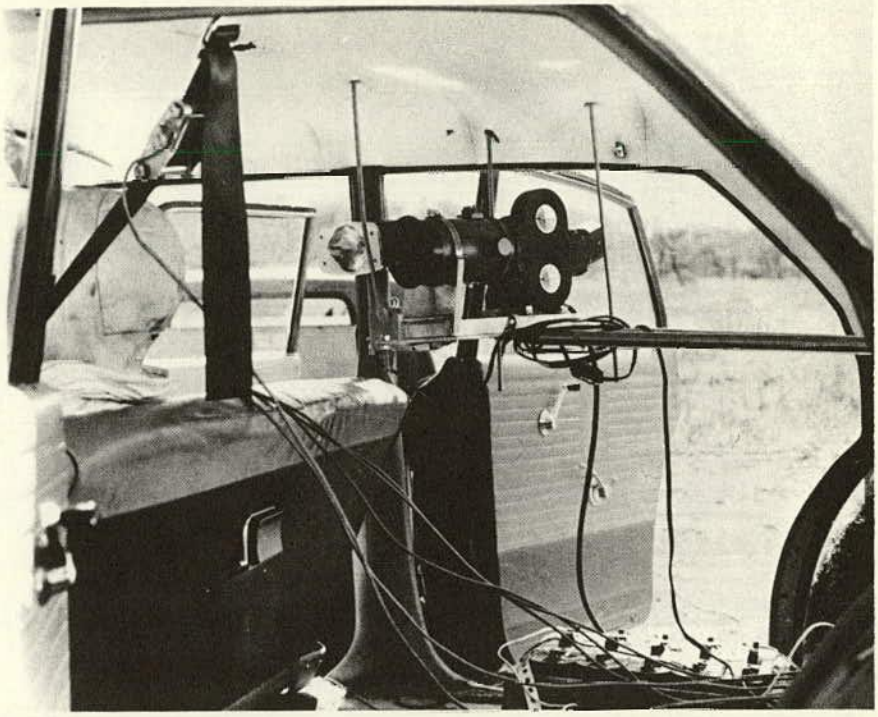


Figure A-7. Interior camera installation.

(left or right); B, side (left rear or right rear); Y, F + P or L + C (front or rear); and Z, B + P or R + C (front or rear).

The specific vertical location of the damage is represented by the character in the fifth position, as follows: A, all; H, top of frame to top; E, everything below belt line; G, belt line and above; M, middle (top of frame to belt line or hood); and L, low (below top of frame).

The general type of collision is specified in position six, as follows: W, wide object impact (greater than 16-in. diameter); N, narrow object impact (diameter of 16 in. or less); S, sideswipe; O, rollover (includes rolling onto side); F, fire only; Y, fire with impact; and Z, submersion (where water presents a hazard to the occupants).

The final position represents the damage severity to the vehicle on a relative basis. This is scaled from a minimum of 1 to a maximum of 9, with 9 representing the most severe class of deformation (almost total destruction to the occupant compartment).

TEST RESULTS

The results of the 25 tests are summarized in Table A-2 in three groups: (1) general performance of guardrails and median barriers, (2) bridge parapet transitions, and (3) end treatments. On-board G-meter readings are given in Table A-3, damage appraisal index values in Table A-4.

General Performance Tests

The purpose of the general performance tests was to evaluate each guardrail system with the initial impact point located approximately at the center of the installation. Although standard end treatments were used, end effects were not introduced into the performance other than the contribution of the end in developing the tension strength of the rail. Fourteen tests were conducted on nine basic systems, as outlined in Table A-5. For each test, a brief description and pertinent data and photographs were recorded. An example of such a compilation is given in the following for Crash Test 105. Comparable data and photographs for the other crash tests of the program are available to qualified researchers on written request to: Program Director, NCHRP, Highway Research Board, 2101 Constitution Avenue, Washington, D.C. 20418.

SwRI CRASH TEST 105

Test Installation

A galvanized 12-gauge standard steel W-beam was mounted to 3I5.7 steel posts spaced at 12.5-ft centers. Rail attachment to post was by means of a $\frac{5}{16}$-in.-diameter steel bolt with 4,000-lb minimum tensile strength specified. A special washer between the bolt head and the rail and a footing plate on the post were other design details to be noted. Top of rail height was set at 30 in. above the pavement. This system, referred to as the strong beam/weak post design, was developed by New York and is designated as standard G2 in *NCHRP Report 54*. The G2 installation is shown in Figure A-8.

Performance

The 4,051-lb vehicle impacted the rail between Posts 6 and 7 (approximately mid-length of the 161-ft installation) at

TABLE A-2

SUMMARY OF GUARDRAIL FULL-SCALE CRASH TESTS

SwRI Test	Purpose	Rail	Post	Blockout	Post Spacing (ft-in.)	Post Embedment (in.)	Rail Height (in.)	Vehicle Test Conditions: Weight (lb)	Vehicle Test Conditions: Speed (mph)	Vehicle Test Conditions: Impact Angle (deg)	Vehicle Redirection: Peak Accelerations (g's)[a] Long.	Vehicle Redirection: Peak Accelerations (g's)[a] Lat.	Vehicle Redirection: Exit Angle (deg)	Vehicle Redirection: Rebound[c] Distance (ft)	Maximum Guardrail Deflection (ft): Dynamic	Maximum Guardrail Deflection (ft): Permanent	Damage Repair Cost ($): Barrier	Damage Repair Cost ($): Vehicle	Guardrail Performance
101	General performance	Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	4042	55.3	30.5	−4.7	−4.7	−11.7	36	4.25	2.60	230	1274	Large exit angle (18 deg)
102		Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	3856	54.7	25.2			−12.5	20	2.40	1.50	158	961	Good; exit angle 12.5 deg, and vehicle turned back to rail
103		Steel W-Beam	8 X 8-in. wood	8-in. wood	6-3	36	27	4123	60.1	22.2	−3.2	−6.5	−15.0	15	2.84	2.40	230	990	Good; exit angle 15 deg, and vehicle turned back to rail
105		Steel W-Beam	3I5.7	None	12-6	33	30	4051	59.2	27.8	−3.1	−3.8	−9.0	18	7.30	5.30	163	751	Good; vehicle was airborne for 50 ft
123		Steel W-Beam	3I5.7	None	6-3	33	30	3883	64.3	27.1	−3.1	−5.6	(d)	22[d]	5.80	3.50	262	792	Vehicle spun out
124		Steel W-Beam	3I5.7	None	9-4-1/2	33	30	3904	60.7	26.4	−4.1	−4.1	−6.0	24	6.75	5.60	180	738	Good; vehicle was airborne for 50 ft
109		Alum. extrusion[b]	3I Alum.	N/A	6-3	36	27.5	4078	41.3	25.0			0	7	1.60	0.80	113	720	Good; vehicle stopped parallel to rail
110		Alum. extrusion[b]	3I Alum.	N/A	6-3	36	27.5	4550	56.5	25.0							575	1349	Vehicle penetrated barrier when splice failed
112		Steel box 8 X 6 X 1/4 in.	3I5.7	N/A	6-0	37	27	3761	51.0	26.9	−3.4	−5.6	0	7	4.60	2.80	288	761	Good; vehicle stopped parallel to rail
114		Steel box 6 X 6 X 3/16 in.	3I5.7	N/A	6-0	36	27	4031	57.7	26.0	−3.5	−6.7	0	7	4.80	2.90	247	902	Good; vehicle stopped parallel to rail
119		Steel W-Beam	6B8.5	None	6-3	41.5	27	4169	53.4	30.2	−4.6	−4.4	−19.8	38	2.74	2.67	136	872	Vehicle exit angle large; rail partially severed
120		Steel W-Beam	6B8.5	1-6B8.5	6-3	41.5	27	3813	56.8	28.4	−4.0	−6.8	−8.0	22	4.05	2.90	150	1179	Good
121		Steel W-Beam	6B8.5	2-6B8.5	6-3	41.5	27	4478	56.2	27.4	−3.7	−6.8	−9.3	11	3.10	2.10	236	706	Good
122		Steel W-Beam	6B8.5	2-6B8.5	6-3	41.5	27	4570	62.9	25.3	−3.9	−7.8	−9.0	22	4.95	2.90	248	803	Good
				Reference															
104	Transition to concrete Bridge parapet	Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4129	54.0	29.6				7	1.00	0.96		1196	Severe vehicle damage
117		Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4297	58.8	25.0				14	N/A	N/A		1314	Severe vehicle damage
118		Steel W-Beam	8 X 8, 10 X 10-in. wood	NCHRP Report 54		36	27	4297	58.8	28.0				7	–	–		1884	Severe vehicle damage; concrete failed
				Terminal	Reference														
106	End treatment	Steel W-Beam	3I5.7	Ramp/Flare	Std G2, NCHRP Report 54			3869	51.3	15.0				N/A	N/A	N/A		2363	Vehicle rolled over
107		Steel W-Beam	3I5.7	Ramp	Std MB2, NCHRP Report 54			4390	61.3	25.0				N/A	N/A	N/A		3358	Vehicle rolled over
108		Steel W-Beam	7-in.-dia. wood	Ramp	Texas Hwy Dept., "Texas Twist"			4397	58.0	15.0				40	1.25	0.8		871	Vehicle redirected; impact was at first post
111		Steel W-Beam	7-in.-dia. wood	Ramp	Texas Hwy Dept., "Texas Twist"			4061	71.0	15.0				N/A	N/A	N/A		3673	Vehicle rolled over
113		Steel box 8 X 6 X 1/4 in.	3I5.7	Ramp	Std MB3, NCHRP Report 54			3761	52.0	25.0				N/A	N/A	N/A		3644	Vehicle rolled over
115		Steel box 6 X 6 X 3/16 in.	3I5.7	Ramp/Flare	Std G3, NCHRP Report 54			4031	65.5	25.0				N/A	N/A	N/A		1075	Vehicle penetrated end; good performance
116		Steel box 8 X 6 X 1/4 in.	3I5.7	Ramp	Std MB3, NCHRP Report 54			3761	60.8	0				N/A	N/A	N/A		3067	Vehicle rolled over
125		Steel W-Beam	8 X 8-in. wood	Blunt End	Std G4, NCHRP Report 54			4500	63.5	0				N/A	N/A	N/A		2039	Severe vehicle damage; high dummy accelerations

(a) Vehicle acceleration determined from analysis of high-speed film.
(b) Aluminum Association strong beam design.
(c) Distance from original guardrail line to maximum outermost point on vehicle during post impact trajectory.
(d) Vehicle spun out.

TABLE A-3

ON-BOARD G-METER READINGS

Test No.	Long.	Lat.	Vert.
105	+4/−1.4	+6.4/−2.2	+7.2/−5(P)
106	+12(P)/−5(P)	+12(P)/−5(P)	+6/−5(P)
107	+12(P)/−5(P)	+10.5/−5(P)	+12(P)/−5(P)
108	+6/−0.8	+5.4/−1.0	+3.6/−5(P)
109	+4.5/−3.5	+3.5/−4.0	+0.2/−3.0
110	+8.0/−3.0	+10.0/−5(P)	+1/−5(P)
111	+11.2/−2.0	+8.0/−5(P)	+12(P)/−5(P)
112	+6.8/−3.0	+12.0(P)/−5(P)	+1.0/−4.0
113	–	–	–
114	+5.0/−2.3	+9.8/−5.0(P)	+0.8/−4.8
115	+12(P)/−5(P)	+8.8/−5(P)	+5.6/−5(P)
116	+7.4/−5(P)	+9/−5(P)	+8/−5(P)
117	+12(P)/−5(P)	+12(P)/−5(P)	+12(P)/−5(P)
118	+12(P)/−5(P)	+12(P)/−5(P)	+10.2/−5(P)
119	+8.3/−3.1	+10.1/−2.4	+2.0/−4.4
120	+9.5/−3.8	+5.4/−1.0	+4.2/−5(P)
121	+6.0/−2.8	+8.6/−5(P)	+3.0/−4.6
122	+10.9/−1.2	+12(P)/−4.4	+8.4/−5(P)
123	–	–	–
124	+7.0/−5(P)	+7.5/0	+4.6/-5(P)
125	+12(P)/−5(P)	+12(P)/−5(P)	+12(P)/−5(P)

(1) Meter pegged at this reading, (P).

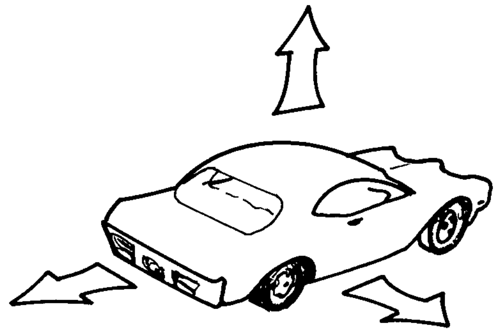


TABLE A-4

DEFORMATION INDEX VALUE FOR FULL-SCALE CRASH TEST VEHICLES

Test No.	Primary	Secondary
101	11LYEW3	
102	11LYEW3	
103	11LYEW4	
104	11LYEW5	
105	11LDMW2	
106	11LYM03	03RFM03 03TPG04
107	11LDA04	03RFH03 04RZH05
108	11LDEW3	
109	11LYEW3	
110	11LFEW4	02RZMN2
111	11LYEW3	02RYA05 08LZA04
112	11LDEW3	
113	09LDH03	01FRM04 12TPG04 04RZH03 08LBM03
114	11LYEW3	
115	11FYEW4	
116	01RYH04	
117	11LYAW5	
118	11LYAW6	
119	11LYEW3	
120	11LYEW5	
121	11LYEW3	
122	11LDEW4	
123	11LYEW2	
124	11LDHS2	
125	12FDEW6	

TABLE A-5

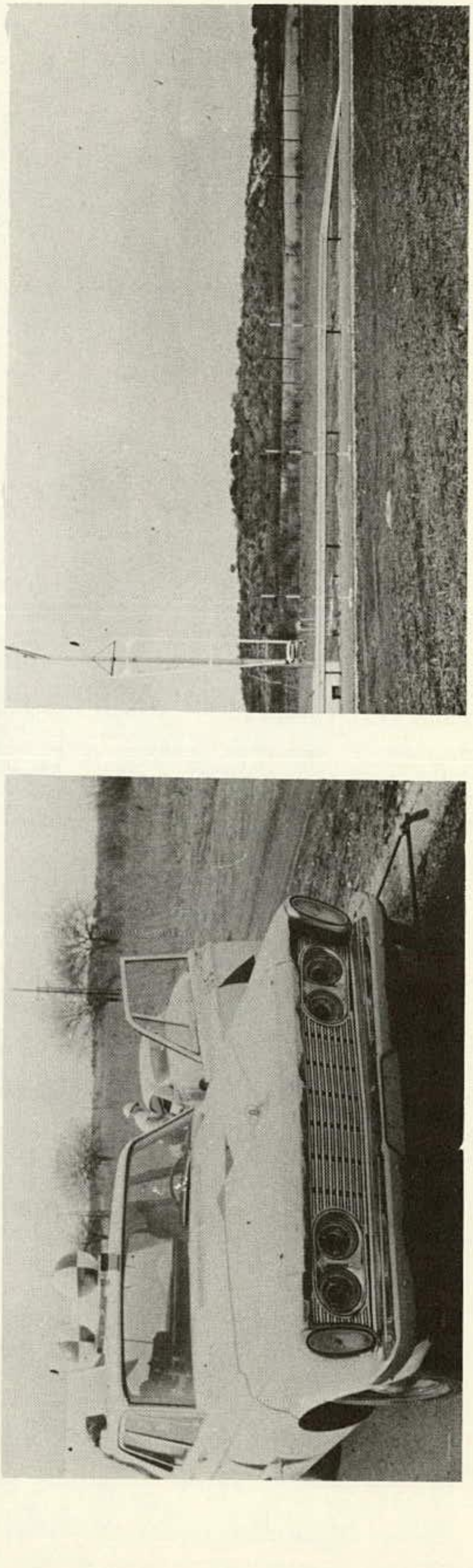
GENERAL PERFORMANCE TESTS ON GUARDRAIL SYSTEMS

Test No.	Guardrail System
101,102	Blocked-out steel W-beam on 8 × 8-in. timber posts
103	Short installation of blocked-out steel W-beam on 8 × 8-in. timber posts
105,123,124	Steel W-beam on 3I5.7 steel posts
109,110	Aluminum Association strong beam median barrier
112	Steel box beam median barrier
114	Steel box beam guardrail
119	Steel W-beam on 6B8.5 steel post
120	Steel W-beam on 6B8.5 steel post with 6-in. blockout
121,122	Steel W-beam on 6B8.5 steel post with 12-in. blockout

a speed of 59.2 mph and 27.8 deg angle to the rail. The vehicle was airborne for approximately 50 ft after leaving the rail, as shown in the film sequence of Figure A-9. Redirection was smooth at an exit angle of 9 deg, although there was a noticeable roll before the car "touched down." The brakes were applied about 150 ft from impact, and the car skidded and turned 270 deg before stopping 230 ft from the initial impact point (Fig. A-10). The maximum dynamic deflection of 7.25 ft occurred at Post 7. A summary of the test results is shown in Figure A-11. On-board instrumentation data are shown in Figure A-12. Experimental values for vehicle lateral, longitudinal, and yaw accelerations developed from film analysis are shown in Figures A-13, A-14, and A-15, respectively.

Installation Damage

Only two posts were damaged significantly, although one undamaged post was pulled out of the ground (Fig. A-16). Two rail sections were bent beyond repair. Although other



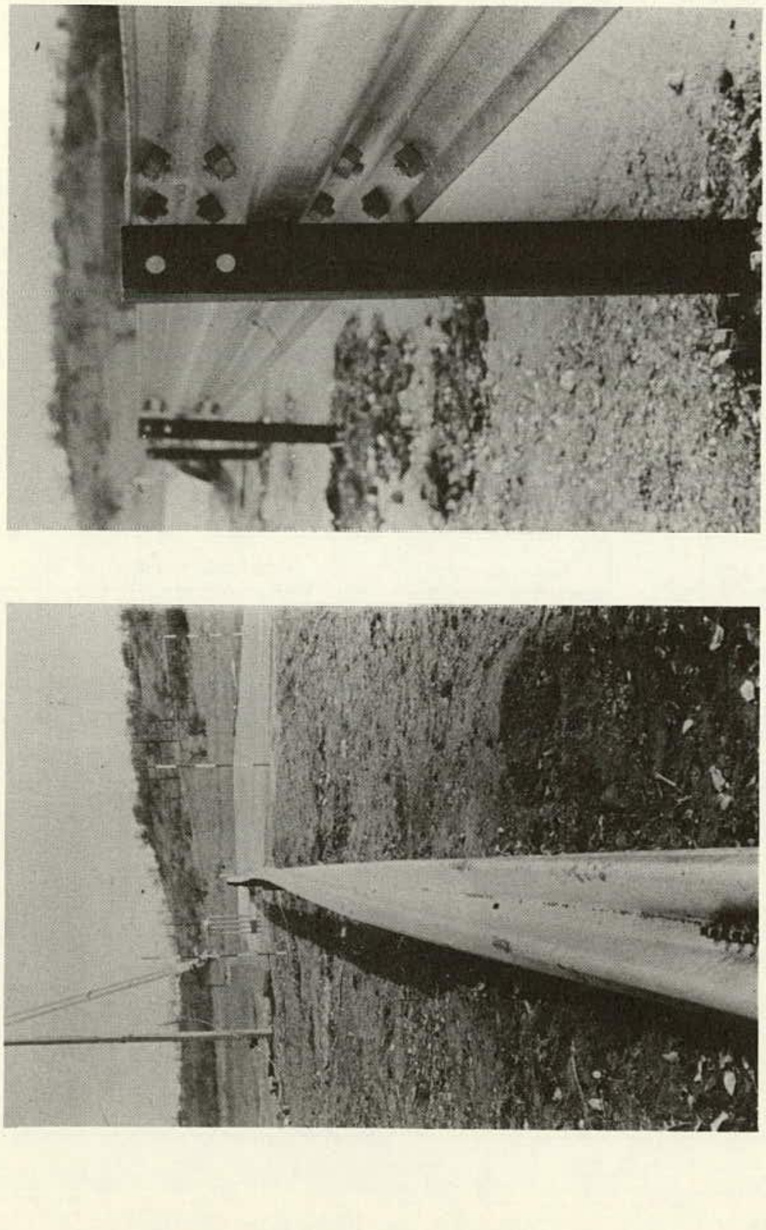


Figure A-8. Guardrail installation prior to Test 105.

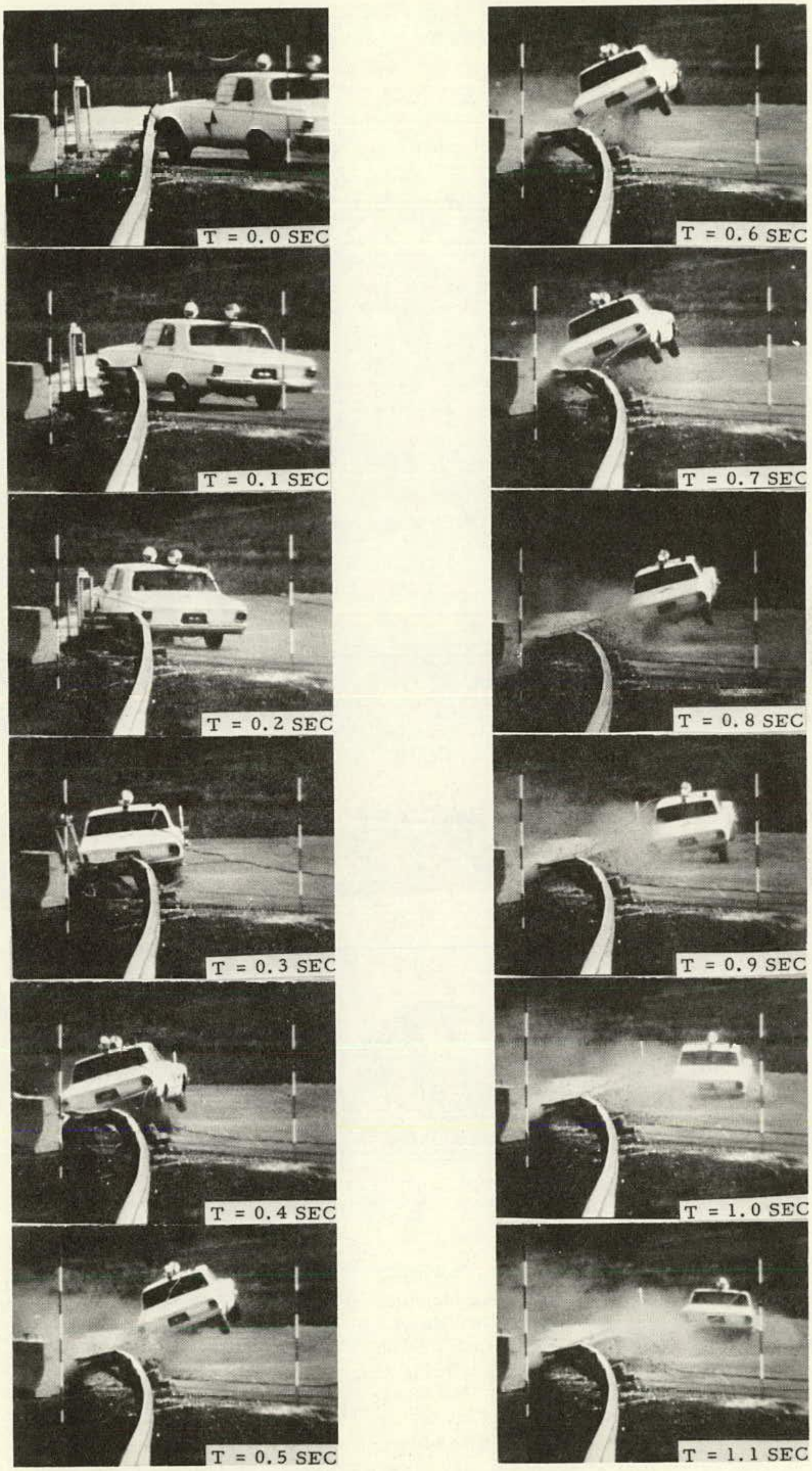


Figure A-9. Film sequence of Test 105.

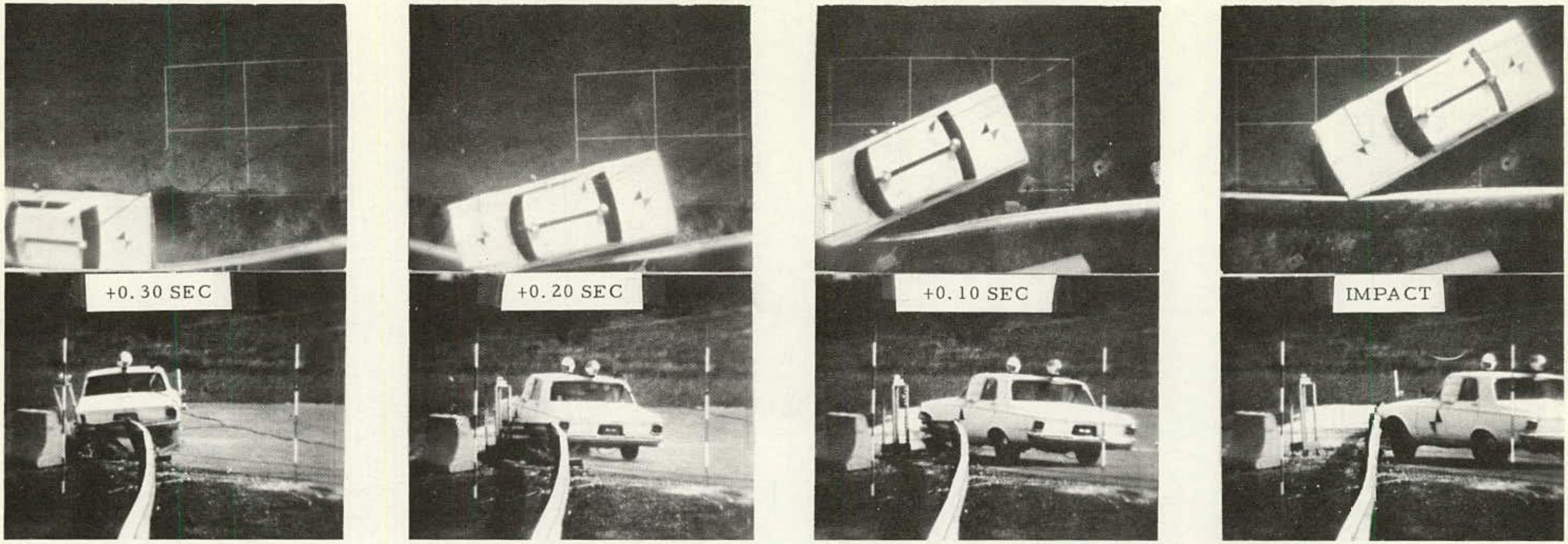
Figure A-10. Guardrail and vehicle damage, Test 105.

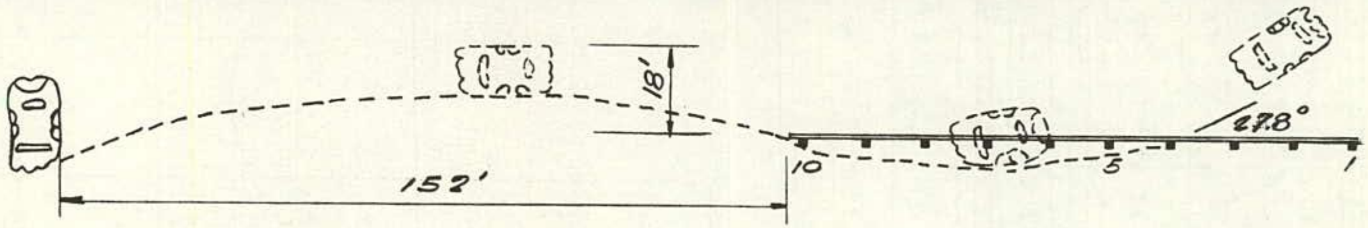
posts were displaced, only Posts 7, 8, and 9 showed evidence of damage. Post 7 was bent, twisted, and pulled out of the ground; the bolt attaching the rail to the post was sheared. Post 8 was unbent, but pulled out of the ground; the bolt head was pulled through the washer, as shown in Figure A-17, and the bolt was left intact in the post. Post 9 was bent and twisted at ground level; the bolt sheared, but the head was on the threshold of pulling through the washer, as shown in Figure A-17.

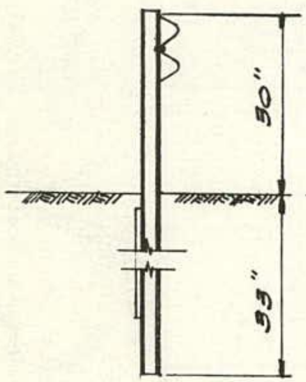
There was evidence of rail movement at the end anchorages, but no significant damage or impending failures were observed at these locations. Maximum permanent lateral deflection was 5.33 ft at Post 7. After the test, height of rail varied from 30 in. at Posts 1 through 5 to 17 in. at Posts 7 and 8.

Vehicle Damage

The test vehicle sustained relatively minor left front end damage, as shown in Figure A-10. The vehicle deformation index value was determined to be 11LDMW2.







New York
"W"-Beam

Beam Rail	12 ga. Galv. Steel x 12'-6"
Post	3I5.7 Steel x 5'-3"
Post Embedment	33"
Post Spacing	12'-6"
Length of Installation	161'
Ground Condition	Dry
Beam Rail Deflection - Max Permanent	5.33'
Beam Rail Deflection - Max Dynamic	7.30'
Vehicle Rebound Distance	18'
Vehicle Deformation Index	11DMW2

Test No.	105
Date	2/6/69
Vehicle	1963 Plymouth
Vehicle Weight (w/dummy & instrumentation)	4051 lb
Impact Speed	60.1 mph
Impact Angle	27.8 deg
Exit Angle	9 deg
Dummy Restraint	Lap Belt and Shoulder Harness

Figure A-11. Summary of results, full-scale crash Test 105.

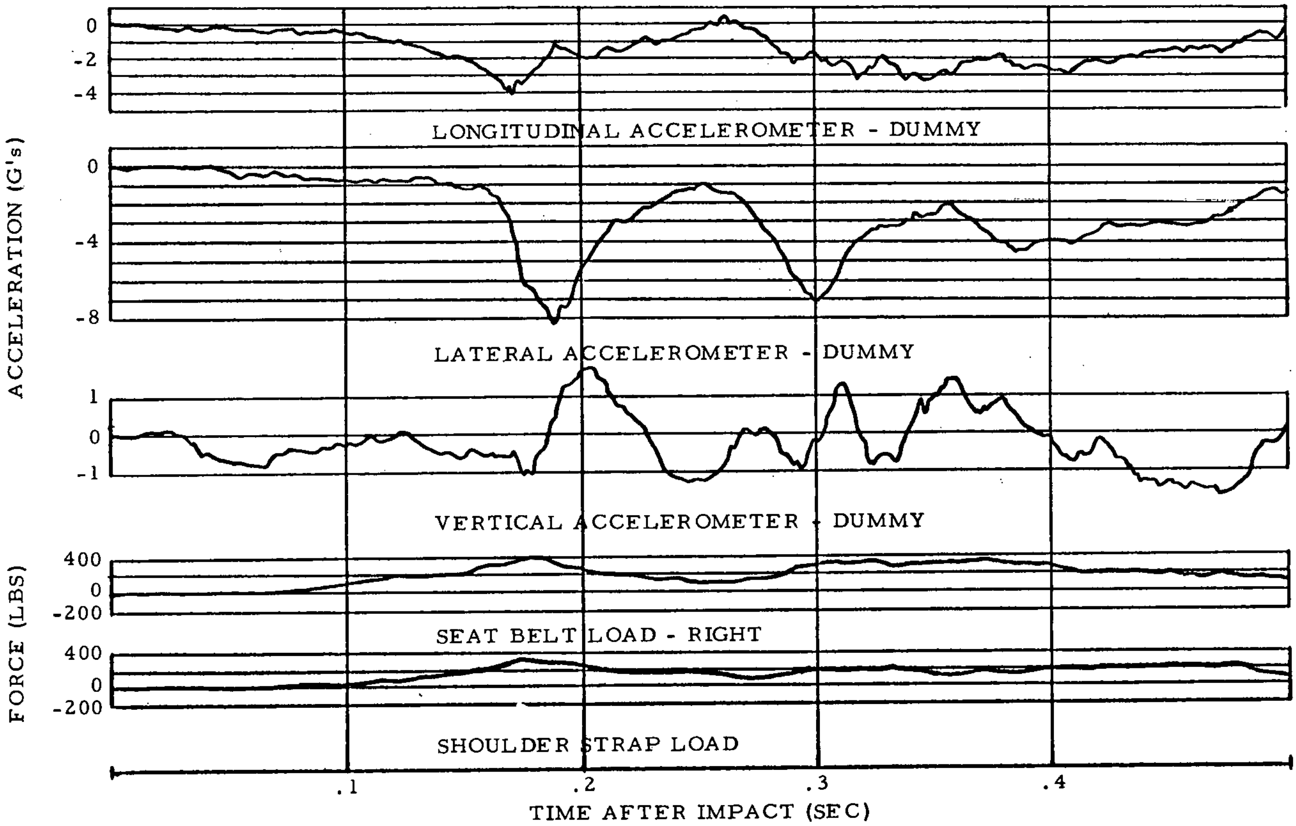


Figure A-12. On-board instrumentation data, Test 105.

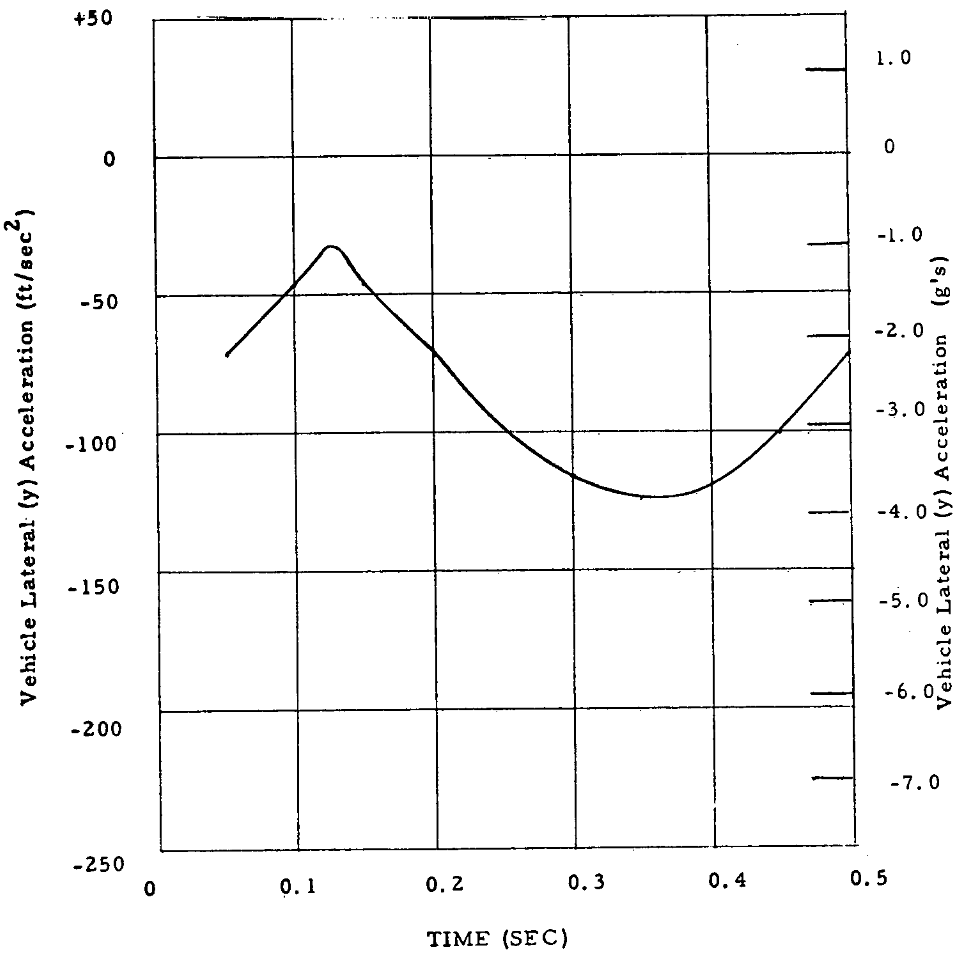


Figure A-13. Vehicle lateral acceleration, Test 105.

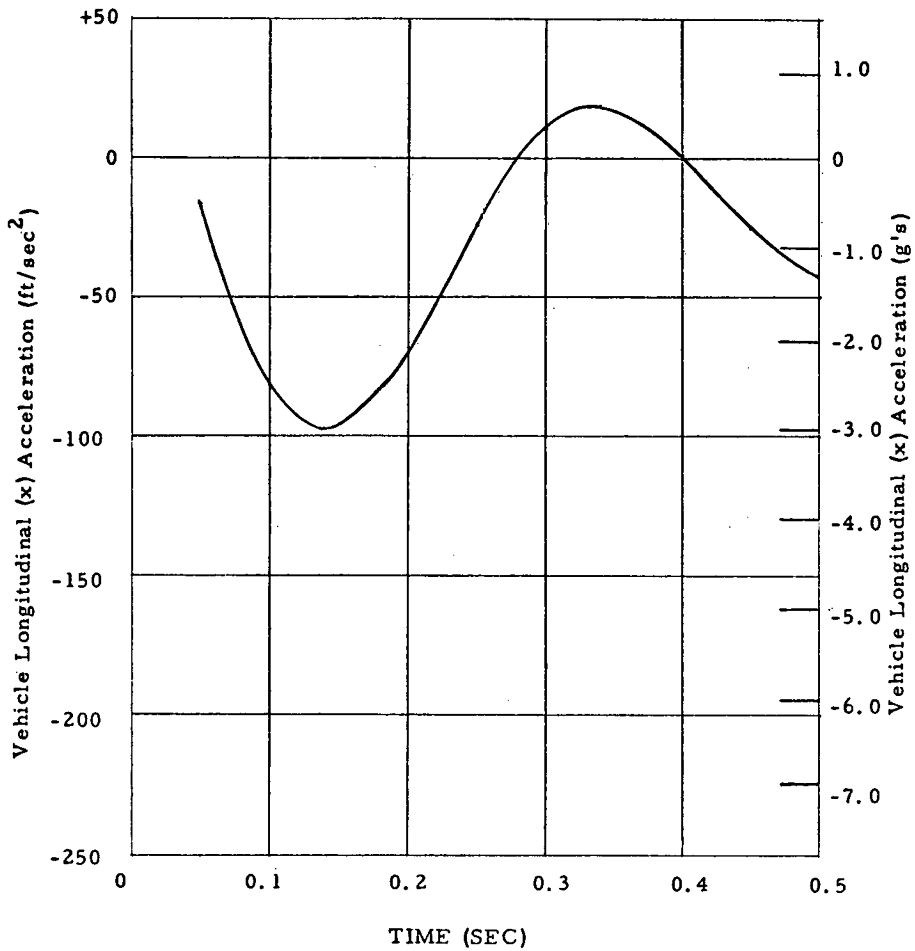


Figure A-14. Vehicle longitudinal acceleration, Test 105.

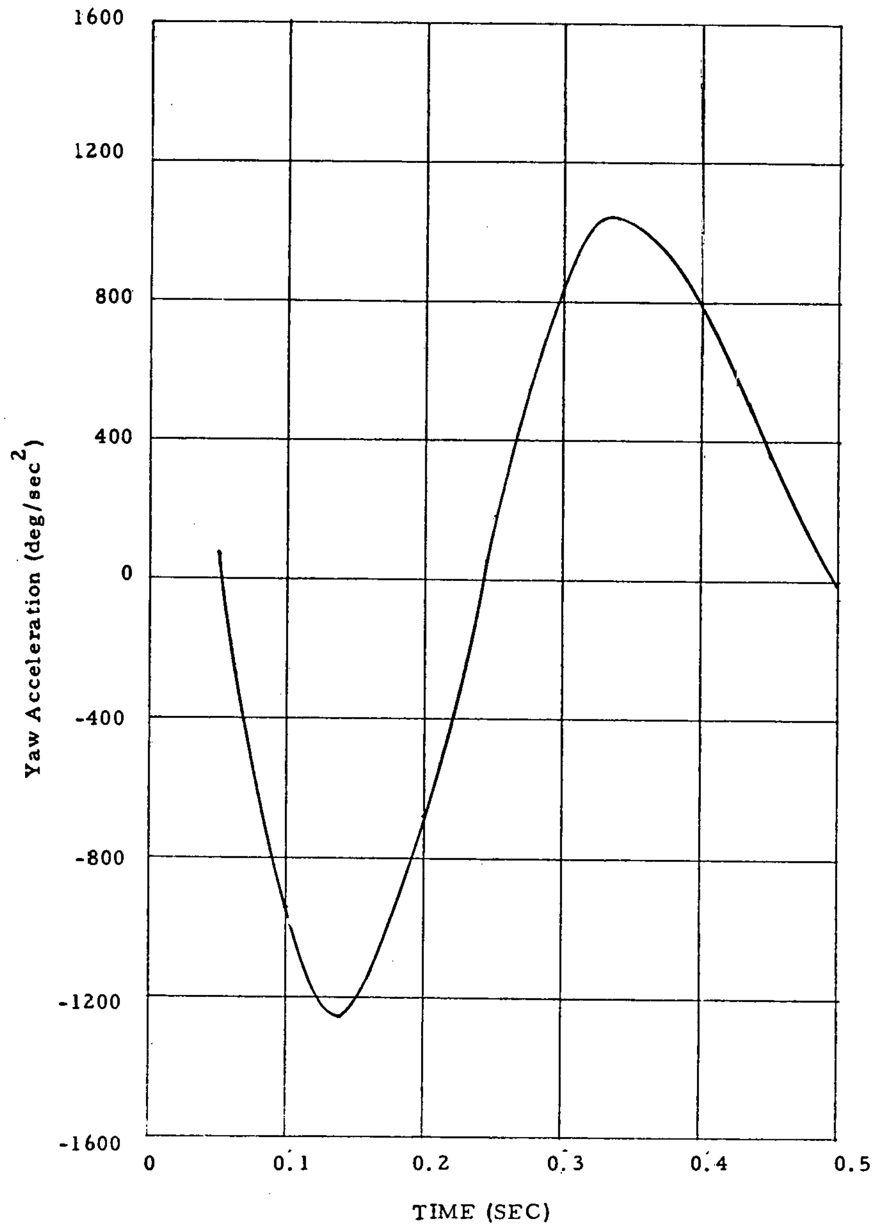


Figure A-15. Vehicle yaw acceleration, Test 105.

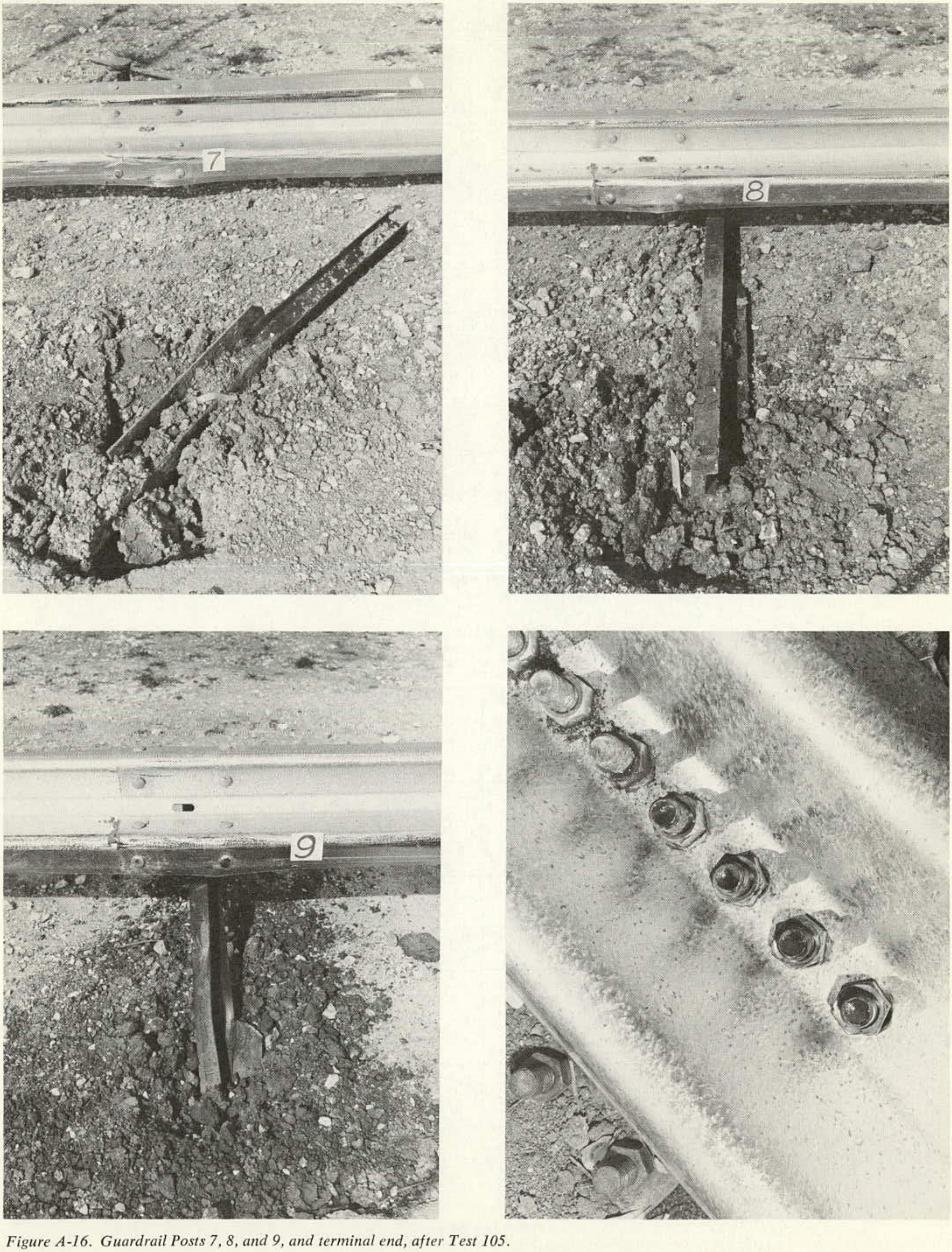


Figure A-16. Guardrail Posts 7, 8, and 9, and terminal end, after Test 105.

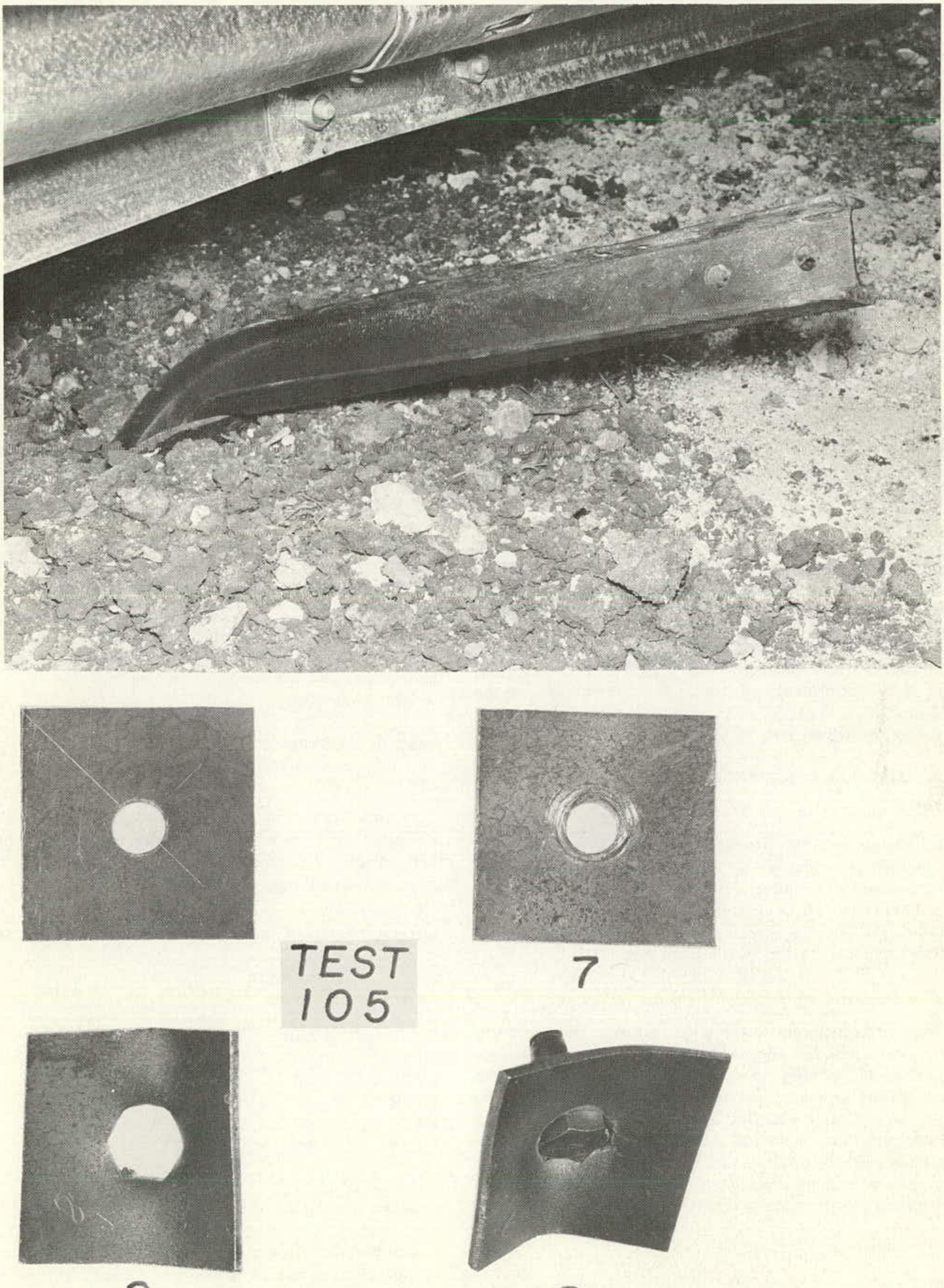


Figure A-17. Damage to Post 9 and damaged washers from Posts 7, 8, and 9, Test 105.

APPENDIX B

TENTATIVE METHOD OF TEST FOR DYNAMIC PERFORMANCE OF HIGHWAY GUARDRAIL AND MEDIAN BARRIER

The recommendations outlined in 1962 by the HRB Committee on Guardrails and Guideposts (*HRB Circ. 482*) did much to establish uniform testing criteria, but data reporting format and content are still determined by the individual testing agencies. A method similar to that outlined in the following would be a next step in advancing the state-of-the-art in full-scale crash testing criteria and procedures.

SCOPE

This method covers the testing of highway guardrails and median barriers for dynamic performance. Tests consist of impacting standard-size late-model passenger vehicles on full-scale guardrail and median barrier installations.

TESTING FACILITY

Institutions or organizations that perform the full-scale impact tests must be approved by ________________ prior to performance of tests. A representative of the ______________________________ shall be present during the actual test.

INSTALLATION DESCRIPTION

Guardrail/Median Barrier

Installation shall be constructed in a manner similar to the condition of actual service. Installation shall conform to recommended manufacturer's or designer's specifications and drawings. Minimum installation length; end anchorage; rail height; post type, spacing, and embedment; and installation alignment are the most critical parameters.

Test Surface

The surface adjacent to the test installation shall conform to either a paved or unpaved highway shoulder. The surface shall be flat, with no curbs, dikes, or ditches in front of the installation unless purposely specified otherwise. At the time of the test, the surface shall be dry and free of oil and loose materials. Sufficient area shall be available to allow the test vehicle to recover from the impact and decelerate to a stop without striking obstacles, etc., other than the extended guardrail or median barrier installation.

TEST VEHICLE

Model

The test vehicle shall be a standard-size passenger vehicle that is representative of the majority of the highway passenger vehicle population. The model age of the vehicle shall be no more than six years. The vehicle may contain any manufacturer-installed optional equipment (power brakes and steering, air conditioning, etc.) so long as the equipment is contained within the body shell. Type and size of engine or transmission are unspecified.

General Condition

The vehicle shall be in good condition and free of major dents and missing structural parts (i.e., doors, windshield, hood, etc). The test vehicle shall be painted white and marked with reference benchmarks to aid in analysis of high-speed photography.

Vehicle Weight

Vehicle weight shall not be less than 4,000 lb and not more than 5,000 lb. Not more than 500 lb of ballast shall be added to a test car to permit its meeting the minimum weight requirement.

TEST DESCRIPTION

Impact Conditions

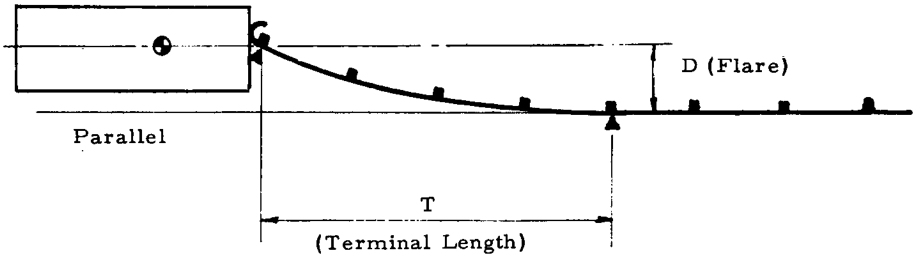
Test installations of guardrail/median barrier will be evaluated for general performance and end treatment performance. Accordingly, the following impact conditions describe the minimum test program:

GUARDRAIL/MEDIAN BARRIER IMPACT TEST CONDITIONS

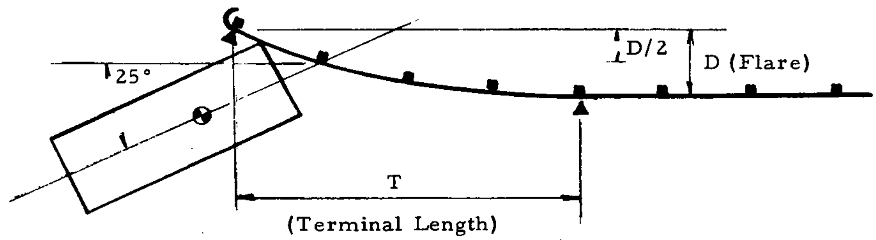
TEST NO.[a]	VEHICLE SPEED (MPH)	IMPACT ANGLE (DEG) 0	7½	25
GP1	60			X
GP2A	60		X	
GP2B [b]	40		X	
ET1 [c]	60			X
ET2 [c]	60	X		

[a] GP = general performance test; ET = end treatment test.
[b] If GP2A is successful, GP2B may be deleted.
[c] See Figure B-1(a) and (b).

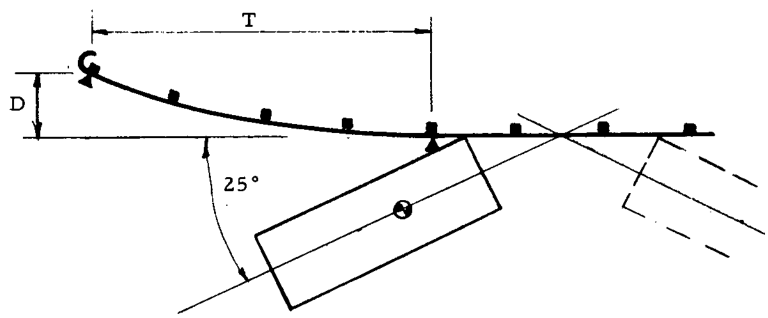
The purpose of general performance tests is to examine typical performance of a long installation. The point of impact for these tests should be located such that end treatment influence (other than anchorage) on the test is minimized. If Test GP2A is considered a success, it is suggested



(a) ET-1, 0° Impact



(b) ET-2, 25° Impact



(c) GP2B (Alternate)

Figure B-1. Impact test geometry.

that this test be changed to evaluate the performance for an impact immediately upstream or downstream of the terminal length (see Fig. B-1(c)). Impact conditions for this test would be the standard 60-mph, 25-deg test specified for GP1. If a new guardrail system incorporates a proven end treatment design, inclusion of Tests ET1 and ET2 is not recommended for the test program.

At the instant of impact, the test vehicle shall be under power and no brakes applied; steerage shall be at the normal position.

Data Acquisition Systems

The primary test data retrieval systems shall be high-speed movie photography. The camera positions and documentary camera positions should be adequate for data retrieval. Photography may be either black and white or color.

An anthropometric dummy with chest-mounted accelerometer shall be positioned in the driver's seat and secured with lap and shoulder straps (standard auto installation). Employment of an additional array of accelerometers in the dummy head should be considered for recording head impacts. Accelerometers for recording lateral and longitudinal vehicle accelerations should be mounted to the vehicle and provisions for removing the occurrence of high-frequency "noise" in the signal are necessary for obtaining meaningful data. The accelerometer monitoring equipment shall be capable of making continuous recordings of acceleration values during and after impact.

Vehicle Guidance

Guidance of the test vehicle may be by remote control (telemetry), by guide cable, or by guide rail system. No maneuvering of the vehicle shall be permitted within 1 sec of the impact and thereafter.

Vehicle Braking

The brakes shall not be applied until after the vehicle has cleared the test installation.

GUARDRAIL/MEDIAN BARRIER PERFORMANCE EVALUATION

Guardrail and median barriers will be evaluated according to the following three factors:

1. *Structural Integrity.* The test vehicle shall not penetrate, vault over, or wedge under the guardrail/median barrier installation. The installation shall maintain structural integrity during the impact (e.g., no broken rail, etc., that could penetrate the test vehicle passenger compartment).

2. *Vehicle Accelerations.* During the impact and redirection, vehicle accelerations measured near or at the center of gravity shall be less than the following values:

		ACCELERATION (±g)		
CLASS	OCCUPANT RESTRAINT	LATERAL	LONGITUDINAL	TOTAL
A	None	3	5	5
B	Lap belt only	5	10	12
C	Lap belt and shoulder harness	15	25	25

The guardrail system will be qualified according to one or more of the Classes A, B, and C.

3. *Vehicle Redirection.* The vehicle rebound distance, defined as the maximum distance measured from and normal to the guardrail line that any part of the vehicle attains during the rebound trajectory, will be determined for each guardrail installation and reported according to the following categories:

CATEGORY	REBOUND DISTANCE (FT)
I	Less than 12
II	12-24
III	More than 24

Each of the six tests that a guardrail or median barrier fails to pass (Item 1, Structural Integrity) shall be repeated twice, and the installation must perform successfully in both supplementary tests.

REPORT

A final report shall include but not be limited to the following:

1. *Test Procedures.* A complete description of the test facility and its associated equipment.

2. *Data.* The high-speed film analysis data shall include displacements vs time, heading angle vs time, vehicle velocities vs time, vehicle accelerations vs time, and maximum dynamic deflections. The on-board instrumentation data shall include vehicle accelerations and dummy response measurements. The gross vehicle weight and a complete vehicle description should be reported, as well as the vehicle damage incurred. The test installation damage and the maximum permanent displacements should be concisely summarized.

3. *Results.* The data should be reviewed and the performance of a guardrail system should be judged by the criteria outlined previously.

4. *Recommendations.* Recommendations shall be offered to improve qualifying systems and revisions for bringing substandard designs into conformance with performance criteria shall be offered.

APPENDIX C

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APPENDIX D

UNPUBLISHED MATERIAL

The contents of some of the appendices in the report as submitted by the research agency are not published herein. They are listed here, however, for the convenience of qualified researchers in the area of interest, who may obtain loan copies of any or all of the items by written request to: Program Director, NCHRP, Highway Research Board, 2101 Constitution Avenue, Washington, D. C. 20418. The items available are as follows:

THEORETICAL INVESTIGATIONS

This comprises theoretical characterizations of those phenomena involved in a guardrail-vehicle collision, including:

1. Development of the force/deflection properties of a guardrail post subjected to a horizontal force.
2. Development of the force/deflection characteristics for the integral guardrail system.
3. Discussion of the vehicle/barrier formulations.
4. Presentation of the pertinent computer program listings and sample inputs and outputs.

COMPUTER PROGRAM TO ANALYZE HIGH-SPEED MOVIE FILM

This is a brief discussion of the methods employed to analyze film from the high-speed cameras used to photograph the full-scale crash tests and thereby compute the position, velocity, and acceleration of the vehicle mass at succeeding increments of time. This procedure is applicable to a test setup where two or more cameras may be operating at unsynchronized and varying speeds.

FULL-SCALE TESTING

Of the 25 full-scale crash tests conducted during the course of this study, data and photographs for only one (Crash Test 105) are included in this report (Appendix A, pp. 53-63) as a typical example. Similar data and photographs for the other full-scale crash tests are available as noted above.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Rep. No.	*Title*
—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj. 4-3(2)), 81 p., $1.80
1	Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Proj. 6-8), 56 p., $2.80
2	An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1.80
2A	Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00
3	Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Proj. 3-5), 36 p., $1.60
4	Non-Chemical Methods of Snow and Ice Control on Highway Structures (Proj. 6-2), 74 p., $3.20
5	Effects of Different Methods of Stockpiling Aggregates—Interim Report (Proj. 10-3), 48 p., $2.00
6	Means of Locating and Communicating with Disabled Vehicles—Interim Report (Proj. 3-4), 56 p. $3.20
7	Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Proj. 1-2), 29 p., $1.80
8	Synthetic Aggregates for Highway Construction (Proj. 4-4), 13 p., $1.00
9	Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Proj. 3-2), 28 p., $1.60
10	Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Proj. 1-4), 31 p., $2.80
11	Effect of Control Devices on Traffic Operations—Interim Report (Proj. 3-6), 107 p., $5.80
12	Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Proj. 4-3(1)), 47 p., $3.00
13	Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Proj. 2-5), 43 p., $2.80
14	Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Proj. 10-5), 32 p., $3.00
15	Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Proj. 4-3(2)), 66 p., $4.00
16	Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Proj. 6-3), 21 p., $1.60
17	Development of Guidelines for Practical and Realistic Construction Specifications (Proj. 10-1), 109 p., $6.00
18	Community Consequences of Highway Improvement (Proj. 2-2), 37 p., $2.80
19	Economical and Effective Deicing Agents for Use on Highway Structures (Proj. 6-1), 19 p., $1.20
20	Economic Study of Roadway Lighting (Proj. 5-4), 77 p., $3.20
21	Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Proj. 1-5), 30 p., $1.40
22	Factors Influencing Flexible Pavement Performance (Proj. 1-3(2)), 69 p., $2.60
23	Methods for Reducing Corrosion of Reinforcing Steel (Proj. 6-4), 22 p., $1.40
24	Urban Travel Patterns for Airports, Shopping Centers, and Industrial Plants (Proj. 7-1), 116 p., $5.20
25	Potential Uses of Sonic and Ultrasonic Devices in Highway Construction (Proj. 10-7), 48 p., $2.00
26	Development of Uniform Procedures for Establishing Construction Equipment Rental Rates (Proj. 13-1), 33 p., $1.60
27	Physical Factors Influencing Resistance of Concrete to Deicing Agents (Proj. 6-5), 41 p., $2.00
28	Surveillance Methods and Ways and Means of Communicating with Drivers (Proj. 3-2), 66 p., $2.60
29	Digital-Computer-Controlled Traffic Signal System for a Small City (Proj. 3-2), 82 p., $4.00
30	Extension of AASHO Road Test Performance Concepts (Proj. 1-4(2)), 33 p., $1.60
31	A Review of Transportation Aspects of Land-Use Control (Proj. 8-5), 41 p., $2.00
32	Improved Criteria for Traffic Signals at Individual Intersections (Proj. 3-5), 134 p., $5.00
33	Values of Time Savings of Commercial Vehicles (Proj. 2-4), 74 p., $3.60
34	Evaluation of Construction Control Procedures—Interim Report (Proj. 10-2), 117 p., $5.00
35	Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests (Proj. 1-3(3)), 117 p., $5.00
36	Highway Guardrails—A Review of Current Practice (Proj. 15-1), 33 p., $1.60
37	Tentative Skid-Resistance Requirements for Main Rural Highways (Proj. 1-7), 80 p., $3.60
38	Evaluation of Pavement Joint and Crack Sealing Materials and Practices (Proj. 9-3), 40 p., $2.00
39	Factors Involved in the Design of Asphaltic Pavement Surfaces (Proj. 1-8), 112 p., $5.00
40	Means of Locating Disabled or Stopped Vehicles (Proj. 3-4(1)), 40 p., $2.00
41	Effect of Control Devices on Traffic Operations (Proj. 3-6), 83 p., $3.60
42	Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60
43	Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5), 38 p., $2.00
44	Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40
45	Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40
46	Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60
47	Accident Rates as Related to Design Elements of Rural Highways (Proj. 2-3), 173 p., $6.40
48	Factors and Trends in Trip Lengths (Proj. 7-4), 70 p., $3.20
49	National Survey of Transportation Attitudes and Behavior—Phase I Summary Report (Proj. 20-4), 71 p., $3.20

* Highway Research Board Special Report 80.

Rep. No.	Title
50	Factors Influencing Safety at Highway-Rail Grade Crossings (Proj. 3-8), 113 p., $5.20
51	Sensing and Communication Between Vehicles (Proj. 3-3), 105 p., $5.00
52	Measurement of Pavement Thickness by Rapid and Nondestructive Methods (Proj. 10-6), 82 p., $3.80
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60	Effects of Illumination on Operating Characteristics of Freeways (Proj. 5-2) 148 p., $6.00
61	Evaluation of Studded Tires—Performance Data and Pavement Wear Measurement (Proj. 1-9), 66 p., $3.00
62	Urban Travel Patterns for Hospitals, Universities, Office Buildings, and Capitols (Proj. 7-1), 144 p., $5.60
63	Economics of Design Standards for Low-Volume Rural Roads (Proj. 2-6), 93 p., $4.00
64	Motorists' Needs and Services on Interstate Highways (Proj. 7-7), 88 p., $3.60
65	One-Cycle Slow-Freeze Test for Evaluating Aggregate Performance in Frozen Concrete (Proj. 4-3(1)), 21 p., $1.40
66	Identification of Frost-Susceptible Particles in Concrete Aggregates (Proj. 4-3(2)), 62 p., $2.80
67	Relation of Asphalt Rheological Properties to Pavement Durability (Proj. 9-1), 45 p., $2.20
68	Application of Vehicle Operating Characteristics to Geometric Design and Traffic Operations (Proj. 3-10), 38 p., $2.00
69	Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects (Proj. 10-2A), 58 p., $2.80
70	Social and Economic Factors Affecting Intercity Travel (Proj. 8-1), 68 p., $3.00
71	Analytical Study of Weighing Methods for Highway Vehicles in Motion (Proj. 7-3), 63 p., $2.80
72	Theory and Practice in Inverse Condemnation for Five Representative States (Proj. 11-2), 44 p., $2.20
73	Improved Criteria for Traffic Signal Systems on Urban Arterials (Proj. 3-5/1), 55 p., $2.80
74	Protective Coatings for Highway Structural Steel (Proj. 4-6), 64 p., $2.80
74A	Protective Coatings for Highway Structural Steel—Literature Survey (Proj. 4-6), 275 p., $8.00
74B	Protective Coatings for Highway Structural Steel—Current Highway Practices (Proj. 4-6), 102 p., $4.00
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