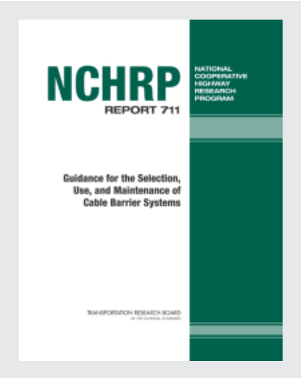

Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 711

Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems

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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.

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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.

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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FOREWORD

By Mark S. Bush
Staff Officer
Transportation Research Board

This report provides guidance for the selection, use, and maintenance of cable barrier systems. While cable barrier systems have been in use for more than 70 years, their use has been on the rise and is expected to continue in the future. The increase in use of cable barrier systems has been attributed to the success rate in keeping vehicles from crossing the median, reducing roadway departures, and decreasing impact severity. Due to advancements in cable barrier system technology, installation and repair costs are lower and cable barrier use has increased in varying roadway environments. Safety studies, although limited, have shown that cable barriers help reduce those median cross-over collisions that lead to some of the most severe head-on type crashes. This document will be of particular interest to design, maintenance, traffic, and safety engineering professionals.

Cable barriers installed in the United States prior to 2000 were primarily low-tension, non-proprietary systems. With the first new generation high-tension cable barrier system installed in 2000 on an experimental basis, the proprietary product performed well, which led DOTs and manufacturers to have an increased interest in high-tension cable barriers. Since 2000, the use of both low- and high-tension cable barriers has expanded. In recent years, the popularity and rate of deployment of cable barrier systems along roadsides and in medians of the nation's roads and highways has significantly increased. As the use of these products has increased, so has knowledge about critical placement issues and the need for guidance relative to the design, selection, and maintenance to achieve the highest level of performance in various environments. Research, testing, and experience with these systems has revealed that the location and placement of the system has a significant influence on system performance.

The available generic and proprietary systems have performance differences and commonalities. Agencies have deployed the available generic and proprietary cable barrier systems based on limited performance information available from crash tests. Although there is general agreement that cable barriers are highly effective in reducing median cross-over accidents, there have not been sufficient analyses to establish reliable crash reduction factors. Cable barriers as a roadside device are most suited in locations with sufficient space to accommodate the lateral deflections that may occur during crashes, but lateral deflection information is not available for all barrier and roadside conditions. Cable barriers have been noted to function for a wide range of vehicle and limited truck types; however, various problems have also been reported. Further, design guidance currently available is dated and does not reflect the capabilities of the current generation of cable barrier systems. These issues prompted research to better understand cable-barrier effectiveness and the influence of factors related to design, median configurations, roadway geometrics, and impact conditions. Given the results of previous research, the variety of cable barrier systems available, and the inadequacy of past deployment practices for new systems, there was a need to establish better guidance for highway engineers.

George Washington University completed this research under NCHRP Project 22-25. The research involved (1) efforts to determine agency experiences with cable barrier systems and their practices for design, selection, and maintenance and (2) the identification of cable barrier system features available. Research focused on issues related to lateral placement, system length, anchorage requirements, transitions, and cost and maintenance. Computer simulation was used extensively to investigate key factors on performance with varied design parameters, installation configurations, road median geometrics, and impact conditions to isolate the effects of these parameters on barrier response. The research results coupled with the findings of previous studies provided the basis for developing the recommended guidelines. This report consists of Chapters 1 through 7, a glossary, and Appendix E (which summarizes the guidance recommended in the report). The entire contractor's report is available on the TRB website and includes several appendices to provide details relative to the cable barrier systems studied, the approaches employed, the detailed results, and related materials. The information included in this report will help highway agencies use better design and appropriate placement of cable barrier systems to reduce serious injuries and fatalities as well as operational costs.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains color versions if supplied.

CHAPTER 1

Introduction

Cable barriers are longitudinal roadside devices used to contain and/or redirect errant vehicles that depart the roadways. These barriers gradually redirect or arrest an impacting vehicle by stretching of the cables, minimizing forces on the vehicle and its occupants. While cable barriers have been used on U.S. highways for more than 60 years, their use has been on the rise and is expected to increase in the future. This increase in use is attributed to cable barriers' success rate in keeping vehicles from crossing the median or leaving the roadway, reduced impact severity, availability of new cable barrier technologies, low initial installation cost, and suitability for various median and roadside environments.

Cable barriers as a roadside device are most suited in locations where there is sufficient space to accommodate the lateral deflections that may occur during crashes. Figure 1.1 shows a generic 3-cable low-tension barrier installed on a divided highway with narrow median and relatively flat side slopes. Such low-tension systems are still in use and continue to be used, but new technologies have led to the development of a host of proprietary cable barrier systems. Figure 1.2 depicts some of these systems. Differences in the number, heights, and arrangement of cables, post types, cable connectors, embedment, and other features are obvious in these pictures. Not so obvious is the difference between the high-tension and low-tension cable systems. Although these systems have been tested to current standards and have been "accepted" for use on U.S. highways, the differences complicate efforts to select a system for a particular application. More specifically, high-tension cable systems, when compared to low-tension systems, have the advantage of lower deflection during impacts and supposedly reduced maintenance costs. These have seen increased usage in many states and hundreds of miles of new installations are added yearly.

Several studies have shown that cable barriers reduce median crossover accidents that could lead to some of the most severe head-on crashes, which are often fatal. Although there is general agreement that cable median barriers are "highly effective" with some reporting success rates higher than 90 percent, there have not been sufficient analyses to establish reliable crash reduction factors. Cable barriers have been noted to function for a wide range of vehicles, including tractor-trailer trucks. There have, however, been problems reported. These have included overrides, underrides, shearing vehicle roof pillars, post fracture, and anchorage failures. The frequency and causes of these occurrences, however, is not fully understood.

The noted occurrence of vehicles underriding the barrier, crossing the median, and penetrating into the opposite traffic lanes has been the impetus for research to identify the cause of the problems and find means to mitigate them. This prompted FHWA to initiate research studies on cable median barriers to identify some of the reasons for median crossovers and to develop design guidelines to optimize the safety performance of cable barriers. In these studies, finite element analyses, vehicle dynamics analyses, and full-scale crash tests were used to assess factors that could influence the effectiveness of cable barriers in redirecting or arresting errant vehicles. These

Figure 1.1. Typical generic, 3-cable, low-tension median cable barrier installation.

Figure 1.2. Typical new proprietary cable barrier systems available.

factors included the terrain geometry and shape, speeds and angles of the vehicles as they leave the road, lateral placement of the barrier, barrier system configuration (heights of cables), vehicle type (front geometry and mass), post spacing, and barrier lengths. These efforts provided an explanation for the occurrence of underrides and revealed a much stronger relationship between barrier placement and median configuration on barrier effectiveness than had been assumed.

The need to better understand the effectiveness of cable barriers and the influence of factors related to the design of cable barrier systems, the configuration of medians, and the nature of impact conditions prompted an interest in further research. The variety of cable barrier systems available, the inadequacy of past deployment practices for new systems, and the need to establish better guidance to highway engineers provided further stimulus for this research.

1.1 Project Objectives and Scope

The objective of this NCHRP project was to develop guidelines for the selection, use, and maintenance of cable barrier systems. The first part of the study involved conducting a comprehensive literature search to collect all studies, state guidelines, in-service evaluations, design drawings, installation manuals, and maintenance documentation related to cable barrier systems. Based on the findings from the literature search, different cable barrier issues were investigated to develop a better understanding of the effects of key factors on the performance of cable barrier systems. The investigation consisted of conducting computer simulations with varied design parameters, installation configurations, and impact conditions to identify the effects of these parameters on the barrier response. These investigation results, coupled with the findings from previous studies, were analyzed and used to develop the guidelines.

The request for proposals for this project outlined eight tasks to achieve these objectives, namely:

- Task 1: Conduct a literature review of recent studies, including international studies, relating to cable barrier systems.
- Task 2: Identify, collect, and review state guidelines and in-service evaluations for cable barrier systems. Additionally, collect and review manufacturers' design, installation, and maintenance documentation for all proprietary cable barrier systems.
- Task 3: Prepare an interim report that summarizes Tasks 1 and 2, identifies additional information needed to develop the guidelines, provides a revised work plan detailing the scope of Phase II, and includes a detailed outline of the proposed guidelines.
- Task 4: Meet with the NCHRP Project Panel to review the Task 3 interim report and submit a revised interim report addressing the panel's review comments.
- Task 5: Execute the approved Phase II work plan using quarterly progress reports to incrementally share research findings.
- Task 6: Prepare draft guidelines detailing the entire range of typical installations for cable barrier systems.
- Task 7: Formulate and execute a plan to solicit feedback on the draft guidelines, incorporating review by state agencies and industry representatives. Synthesize the comments received in the external review and recommend revisions to the guidelines for NCHRP approval.
- Task 8: Submit a final report documenting the entire research effort including the revised guidelines as an appendix. The final report should document limitations on analysis and sources of the material presented and cite needs for future research.

These tasks were embodied in the project research plan that led to this report.

The first interim meeting with the NCHRP Project Panel held in September 2009 further focused the research efforts. Based upon the initial efforts, 13 subtasks were proposed to the panel as possible topics for more detailed study. The findings of the research completed under Tasks 1 and 2 and the recommendations for more detailed research were summarized in the interim report. Based upon the discussions with the panel and the proposed efforts, the panel directed the research team to undertake in Task 5 the seven critical research areas summarized in Table 1.1. Other proposed topics are described in future research needs in Chapter 7.

Table 1.1. Proposed subtasks to be performed under Task 5.

Subtask	Description
5.1	**Title:** Cable Barrier Lateral Placement **Objective:** Assess barrier performance when placed at different positions across the median. **Approach:** Conduct vehicle dynamics simulations to compute vehicle trajectory as it crosses the median and assess vehicle/barrier engagements. **Varied Factors:** • Vehicle type (820C, 1100C, 2000P, 2270P, Crown Victoria, single-unit truck) • Median profiles (v-shaped, flat bottom, rounded bottom, non-symmetric) • Median slopes (10H:1V, 8H:1V, 6H:1V, and 4H:1V) • Median widths (5 to 17 m, 16 to 56 ft) • Approach speed (50 to 100 km/h, 31 to 62 mph) • Approach angle (5 to 25°) (Note: This supplements work already conducted under FHWA projects. The tools used to carry out this task have been previously developed.)
5.2	**Title:** Barrier Deflection **Objective:** Study effect of end-anchor spacing on barrier deflection. **Approach:** Conduct finite element simulations to study the effects of different design parameters on barrier deflection. **Varied Factors:** • Barrier designs (generic, Brifen, Gibraltar, Nucor, Safence, and Trinity) • Installation length (100 to 1,000 m, 330 to 3,300 ft) • Post spacings (1.5 to 6 m, 5 to 20 ft) • Cable tensions (15 to 24 kN, 3.4 to 5.4 kips) • Impact location (at post and in between posts)
5.3	**Title:** Post-Anchoring and End-Anchoring Systems **Objective:** Evaluate post foundation and end-anchor movement, failure, and pull-out. **Approach:** Conduct finite element computer analyses to investigate post and end-anchor movement/pull-out/failure. **Varied Factors:** For line post anchoring systems • Soil strength (weak and strong) • Embedment (post driven in soil, socket driven in soil, socket in concrete) • Footing size For end-anchoring systems • Soil strength (weak and strong) • End-anchor size • Anchoring type (single-cable and multi-cable)
5.4	**Title:** Interconnection with Other Systems **Objective:** Evaluate safety performance of cable barrier transitions and end terminals. **Approach:** Use existing practices for connecting cable barriers to adjacent semi-rigid barriers and finite element computer analyses. **Varied Factors:** • Cable barrier systems (generic, Brifen, Gibraltar, Nucor, Safence, and Trinity) • Connecting barrier (W-beam and Three-beam) • Transition designs (two to three common designs) • Test level (TL3 and TL4)
5.5	**Title:** Construction and Maintenance Tolerances **Objective:** Assess effect of construction tolerance on barrier performance. **Approach:** Use computer simulation, literature findings, and survey results to establish acceptable tolerances on different design and installation parameters. **Varied Factors:** • Tolerance on cable heights (settlement) • Tolerance on changes in median width • Tolerance on median slope • Tolerance on post spacings • Soil tolerances • Effect of other objects in median

Table 1.1. (Continued).

Subtask	Description
5.6	**Title:** Guidance on Placement Relative to Horizontal Curvatures **Objective:** Assess barrier performance when placed on roads with horizontal curvatures. **Approach:** Use finite element and vehicle dynamics computer analyses to study the effects of horizontal curvature on barrier performance (vehicle engagement and barrier deflection). **Factors to Vary:** For vehicle dynamics simulations • Curvature radius (75 to 300 m, 250 to 1,000 ft) • Vehicle types (820C, 1100C, 2000P, 2270P, Crown Victoria) • Speed and angle • Median width For finite element analyses • Curvature radii (75 to 300 m, 250 to 1,000 ft) • Post spacings (1.5 to 6 m, 5 to 20 ft) • Cable barrier length (100 m and 500 m, 330 and 3,300 ft)
5.7	**Title:** Installation and Maintenance Costs **Objective:** Approximate overall cable barrier installation and maintenance costs. **Approach:** Use data from the literature and State DOT survey to estimate overall costs of CMB and benefits/cost tradeoff between different options. **Factors to Consider:** • Installation costs • Maintenance and repair costs • Post embedment (driven/socket/mow strip) • Barrier placement (affect maintenance and number of cable barrier hits) • Environment condition (temperature/soil condition) • Average daily traffic

1.2 Report Organization

This report is organized into seven chapters as follows:

- Chapter 1—Introduction
- Chapter 2—Literature Review
- Chapter 3—Cable Barrier Current Practices
- Chapter 4—Descriptions of Available Cable Barriers
- Chapter 5—Analyses and Results
- Chapter 6—Guidelines for Cable Barriers
- Chapter 7—Summary and Conclusions

The contractors' final report also includes several appendices to provide details relative to the cable median barrier systems studied, approaches employed, detailed results, and similar materials. Appendix E is included in this report. Appendixes A through D *are not* published herein but are available on the TRB website by searching on *NCHRP Report 711*.

CHAPTER 2

Literature Review

At the outset of the project a detailed literature review was performed to gather information related to cable barriers with a focus on the design, performance, evaluation, maintenance, and application of cable barrier systems. Many types of documents were collected, organized, and reviewed including cable barrier research papers and reports, presentations, DOT guidelines, in-service evaluations, international studies, usage and safety performance statistics, and success stories. A synthesis of the collected information is presented in the following sections and the documents are available at http://crash.ncac.gwu.edu/dmarzoug/CableBarrierLiterature/.

2.1 History and Usage

Cable barriers have been used in the United States for more than 60 years. New York DOT played an important role in the development and refinement of the cable barrier. Early use of cable barriers was concentrated in the northern states because of the openness of the barrier, which allows snow to pass through rather than pile up in front of the barrier as is the case with beam and concrete barriers. A 1982 study by Post and Chastain showed that cable guardrails were more cost-effective than (strong-post) W-beam guardrails for certain types of installations [1]. In 1997, it was reported that 18 states had 3-cable low-tension barriers in use; however, only 4 states were still installing cable barriers [2].

Until 2000, all cable barriers in the United States were low-tension, non-proprietary systems. In 2000, the first high-tension proprietary cable barrier system was installed in Oklahoma City, OK. A safety barrier, developed by Brifen in the United Kingdom in the 1980s and used in over 30 countries, was installed first on an experimental basis on a 305 m (1,000 ft) section of the Lake Hefner Parkway in Oklahoma City in August 2000. Shortly thereafter it was installed along 11 km (7 miles) of the parkway. The Brifen system performed well, which led other states and other manufacturers to get interested in high-tension cable barriers.

Since 2000, the use of high-tension cable barriers has expanded rapidly in the United States. Table 2.1 shows cable median barrier usage in the United States for 1997, 2004, and 2006 as reported by Ray in a report for Washington State DOT [3]. This table is based on several surveys of state DOTs, and it is not believed to give a complete picture of usage. For example, Oklahoma, which started the movement toward high-tension cable barriers, is not shown as a user of median barriers in the 2004 surveys even though it had been using cable barriers since 2000. Several states shown to be using cable barriers in 2004 are not included in the 2006 survey. From 2000, when Oklahoma installed its experimental section of Brifen cable median barriers, usage of high-tension cable barriers had spread to at least 30 states by 2006.

Table 2.2 gives Ray's estimate of the number of miles of cable median barrier in use at the end of 2006 by state in the United States.

Table 2.1. States using cable median barriers [3].

Year	No.	States Reporting Cable Median Barrier Use
1997	4	North Carolina, Washington, South Dakota, Missouri
2004	12	Alabama, Arizona, Iowa, Mississippi, Missouri, Nebraska, Nevada, New York, North Carolina, South Carolina, Washington, Wisconsin
2004	14	Alabama, Arizona, Iowa, Minnesota, Mississippi, Missouri, Nebraska, Nevada, New Jersey, New York, North Carolina, South Carolina, Washington, Wisconsin
2006	25	Alabama, Arkansas, Arizona, Colorado, Florida, Georgia, Idaho, Illinois, Indiana, Iowa, Maine, Missouri, Montana, Nevada, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, Wisconsin

Table 2.2. Cable median barrier mileage estimate [3].

State	Miles	Year	State	Miles	Year	State	Miles	Year
Alabama	118	2006	Maine	1.5	2006	Oregon	23	2005
Arizona	89	2006	Minnesota	6.3	2003	Rhode Island	1.4	2005
Colorado	40	2005	Missouri	250	2006	S. Carolina	470	2005
Florida	187	2005	N. Carolina	600	2007	Texas	500	2006
Iowa	64	2007	New York	5	1989	Utah	16.4	2003
Illinois	70	2005	Ohio	27.5	2006	Washington	135	2006
Kentucky	13	2006	Oklahoma	23	2005	Total	2,640	

Table 2.3. Approximate miles of installed high-tension cable barriers [4].

Manufacturer	April 2006	September 2006	January 2008	April 2008
Safence	4	17	110	185
Brifen	287	323	405	440
Gibraltar	195	395	540	685
Nucor Steel Marion	221	340	403	453
Trinity Industries	341	570	825	912
Total Miles Installed	1,048	1,645	2,283	2,675

Table 2.3 gives an estimate of installed miles of cable barrier for four different points in time, April 2006, September 2006, January 2008, and April 2008. These data gathered by the Texas Transportation Institute (TTI) show the rapid rate of installation of high-tension proprietary cable barriers that has occurred since 2006. Between September 2006 and April 2008, over 1,000 miles of cable barrier were installed. The growth in use of high-tension cable barriers from 7 miles in 2001 to almost 2,700 miles in 2008 is remarkable. Also, it should be noted that the TTI numbers do not consider low-tension, non-proprietary cable barriers. The difference between Ray's estimate of 2,600 miles at the end of 2006 and TTI's estimate of 1,645 miles can be explained in large part by TTI's exclusion of low-tension barriers. For example, North Carolina is reported by Ray to have 600 miles of barriers installed, and most of these miles were low-tension barriers.

2.2 Cable Barrier Designs

Cable barriers are categorized as weak-post barriers since their posts are designed to fail in a crash to allow the longitudinal structural element (cable) to absorb energy from the impact through elongation (stretching). The elongation of the cable causes the barrier to deflect laterally in a parabolic form that assists in redirecting the impacting vehicle in a smooth and "forgiving" manner. The elastic nature of the barrier reduces the severity of the impact but causes larger dynamic deflections than would be experienced with a semi-rigid or rigid barrier under similar impact conditions. Thus weak-post barriers can be used safely only when adequate clear area exists behind the barrier to accommodate the dynamic deflection.

The development of weak-post barriers is described in a 1967 publication by Graham et al. [5]. The article describes the theory behind weak-post barriers as well as crash tests conducted on the standard 3-cable barrier, the weak-post W-beam guardrail, and the box-beam median barrier. A summary of available cable barrier systems is presented in Chapter 4 of this report.

2.3 Performance of Cable Barriers

Low-tension cable barrier systems have been in use for at least 60 years, and their performance has been studied extensively. Many of the earliest studies were done in New York because New York DOT was the main developer of the 3-cable low-tension barrier. Gabler et al. describe these early studies and later studies of 3-cable low-tension barrier performance. Findings of these studies are summarized in Table 2.4, and more details on these studies are provided in Gabler's *Evaluation of Cross Median Crashes* [6].

North Carolina has been the leading user of low-tension cable barriers, having 966 km (600 miles) installed as of 2007 [3]. In 1998, North Carolina began a program to prevent and reduce the severity of cross-median crashes. The program is being carried out in the following three phases:

Phase I: Add median protection to freeways with historical crash problems;
Phase II: Systematically protect all freeways with median widths of 21 m (70 ft) or less; and
Phase III: Revise design policy to protect future freeways with median widths of 21 m (70 ft).

Between 2000 and 2006 in North Carolina, approximately 1,600 km (1,000 miles) of freeways were enhanced at a cost of over $120 million. The number of crossover fatal crashes decreased from 33 crashes in 1998 to 4 crashes in 2005 (from 16.7 percent of all fatal crashes to 2.8 percent). Similarly, the number of cross-median fatalities was reduced from 47 fatalities in 1998 to 6 fatalities in 2005 (from 20.5 percent of all fatalities to 3.6 percent). It is estimated that 110 fatal cross-median crashes have been avoided and 177 lives saved from January 1999 to September 2006, resulting in crash cost savings of more than $385 million in fatal crash cost alone (using 2001 dollars). Table 2.5 shows North Carolina's fatal crash data for 1990 to 2006 [7].

A long-term median barrier evaluation in North Carolina investigated 689 km (428 miles) of new median barrier installations (203 miles of low-tension cable barrier, 132 miles of W-beam

Table 2.4. Previous studies of performance of low-tension, 3-cable barriers [6].

State	Researchers	Date	No. of Crashes	Findings
NY	Van Zweden, Bryden	1967-1969	375 RS	20% penetrations, 4 fatalities, 15 injuries, 356 no injuries
NY	Carlson, Allison, Bryden	1977	23 RS (12 LON, 11 term)	33% penetrations, 2 minor injuries, 21 no injuries
IA	Schneider	1979	31 RS	23% penetrations, 1 fatality, 4 injuries
NY	Tyrell, Bryden	1989	99 Median	4% penetrations, 24 injuries, 75 PDO
NY	Hiss, Bryden	1992	427 RS	20% penetrations, 38 major injuries, 178 minor injuries, 211 PDO
NY	Hiss, Bryden	1992	16 Median	6% penetrations, 1 major injury, 10 minor injuries, 5 PDO
NC	Mustafa	1997	125 Median	11 major injuries, 28 minor injuries, 88 PDO
OR	Sposito, Johnson	1999	53 Median	6% penetrations, 5 major injuries
WA	McClanahan, Albin, Milton	2004	59 Median per year	No fatalities, 10 penetrations, 5 heavy vehicle containments

RS – Roadside, PDO – Property Damage Only

Table 2.5. North Carolina fatal crashes from 1990 to 2006 [7].

PHASE I AND PHASE II MEDIAN BARRIER PROJECT LOCATIONS

Year	Fatal Crashes	Across Median Fatal Crashes	Percent of Total	Fatalities	Across Median Fatalities	Percent of Total
1990	145	33	22.8	177	47	26.6
1991	144	26	18.1	188	44	23.4
1992	128	22	17.2	147	31	21.1
1993	158	20	12.7	196	38	19.4
1994	146	23	15.8	179	36	20.1
1995	150	18	12.0	177	28	15.8
1996	159	26	16.4	189	40	21.2
1997	147	33	22.4	194	47	24.2
1998	198	33	16.7	229	47	20.5
1999	178	24	13.5	207	30	14.5
2000	191	23	12.0	226	36	15.9
2001	160	7	4.4	183	11	6.0
2002	152	13	8.6	173	14	8.1
2003	129	12	9.3	146	13	8.9
2004	146	8	5.5	179	13	7.3
2005	144	4	2.8	165	6	3.6
2006 (Sept)	100	4	4.0	111	4	3.6

Median Barrier Projects Started Here

guardrail, 43 miles of W-beam/cable mix, 31 miles of weak post W-beam, and 18 miles of W-beam/weak post W-beam mix). An analysis of before and after crash data showed that the added median barriers reduced fatal and severe injury crashes and cross-median crashes. For freeways with cable barriers, fatal and severe injury crashes overall were reduced 13 percent while fatal and severe injury cross-median crashes were reduced 74 percent. The data also showed that the added median barriers increased the number of total crashes, the number of minor injury crashes, and the number of property-damage-only crashes. For freeways with cable barriers, the total number of crashes increased 113 percent from 793 to 1,688. Of the 895 additional crashes, only 568 (63 percent) were crashes involving the median barrier. The other 37 percent of the additional crashes may have been a result of the 34 percent increase in ADT between the before period and the after period. The summary data are presented in Table 2.6 [7].

The other state that has installed a lot of low-tension cable barriers is Missouri. As part of Missouri's Blueprint for Safer Roads Program, approximately 800 km (500 miles) of cable barrier, both low- and high-tension, had been installed as of 2007. These cable barriers have been found to be about 95 percent effective in preventing vehicles from entering opposing lanes. Figure 2.1 shows that statewide cross-median fatalities have dropped from an average of about 50 per year to fewer than 10 per year after installation of the cable median barriers [8].

Figure 2.2 shows the relationship between the installation of cable barriers and the reduction in cross-median fatalities on I-70 in Missouri. In 2003, when Missouri began its major program to install median barriers, I-70 had 23 fatalities from cross-median crashes. In 2007, when Missouri had in place 290 km (180 miles) of median barrier on I-70, fatalities from cross-median crashes had dropped 83 percent to 4 cross-median fatalities [8].

In 2006, Missouri used accident data from 1999 to 2005 to evaluate the performance of its low-tension cable barrier on medians with slopes steeper than 6H:1V. Many of these slopes were 5H:1V, but some were steeper. Of the 1,402 accidents investigated, 67 (5 percent) were marked as a "failure," meaning that a crossover was not prevented [1].

In 2004, Washington DOT studied the in-service performance of its low-tension cable barriers. Before and after accident data showed that the average number of crashes per year increased from

Table 2.6. Median barrier before and after crash data at select locations in North Carolina [7].

	All Barrier Types			Cable			W-Beam			W-Beam / Cable Mix		
	Before	After	Percent Change	Before	After	Percent Change	Before	After	Percent Change	Before	After	Percent Change
Mileage	428			203			132			43		
Average ADT	26,600	34,300	29%	22,000	29,400	34%	28,800	36,700	27%	32,800	42,500	30%
Total Crashes	2,048	3,718	82%	793	1,688	113%	695	1,044	50%	251	507	102%
Severe Injury (K & A) Crashes	120	98	-18%	47	41	-13%	38	28	-25%	15	13	-9%
Moderate / Minor Injury (B & C) Crashes	696	1,103	58%	267	448	68%	242	347	43%	83	154	86%
Property Damage	1,232	2,517	104%	479	1,199	150%	414	668	61%	153	340	122%
Across Median Crashes	152	30	-80%	60	23	-62%	41	3	-94%	18	3	-84%
Fatal Across Median Crashes	13	2	-80%	4	2	-56%	3	1	-82%	2	0	-100%
Severe Injury (K & A) Across Median Crashes	20	3	-87%	7	2	-74%	7	1	-91%	2	0	-100%
Crashes Involving Median Barrier	--	1,218	--	--	568	--	--	309	--	--	165	--
Percent of Crashes Involving Median Barrier	--	33%	--	--	34%	--	--	30%	--	--	33%	--
Breach Rate	--	2.4%	--	--	4.0%	--	--	0.9%	--	--	1.6%	--
* All Crash Numbers are Crashes / Per Year												

49 to 100; however, the average annual rate of fatal crashes dropped 89 percent from 3.00 to 0.33. Likewise, the average annual rate of disabling crashes dropped 51 percent from 3.60 to 1.76. Washington DOT estimates that the societal costs due to such crashes were reduced 76 percent from $13.58 million to $3.32 million [1].

Ray has summarized the data from several states on reductions in cross-median crashes [3]. These data (shown in Table 2.7) are for installations of both low- and high-tension cable barrier systems. Some of the data is based on small sample sizes, which implies that some of the results

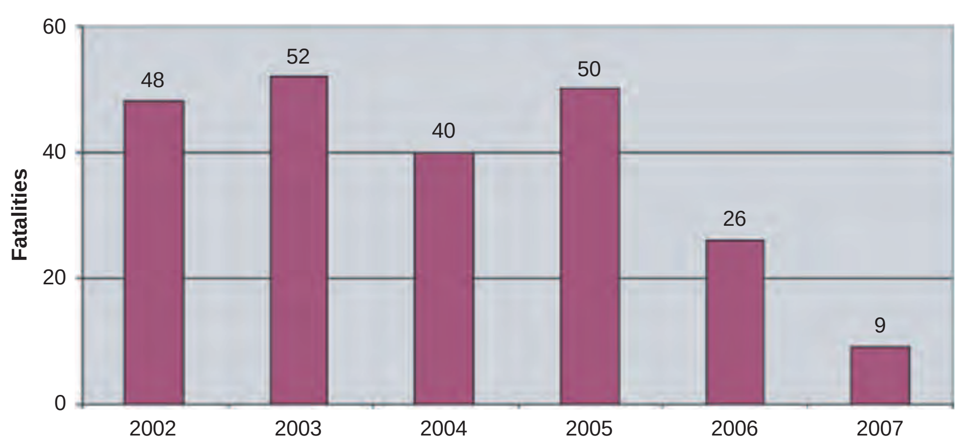


Figure 2.1. Missouri interstate cross-median fatalities [8].

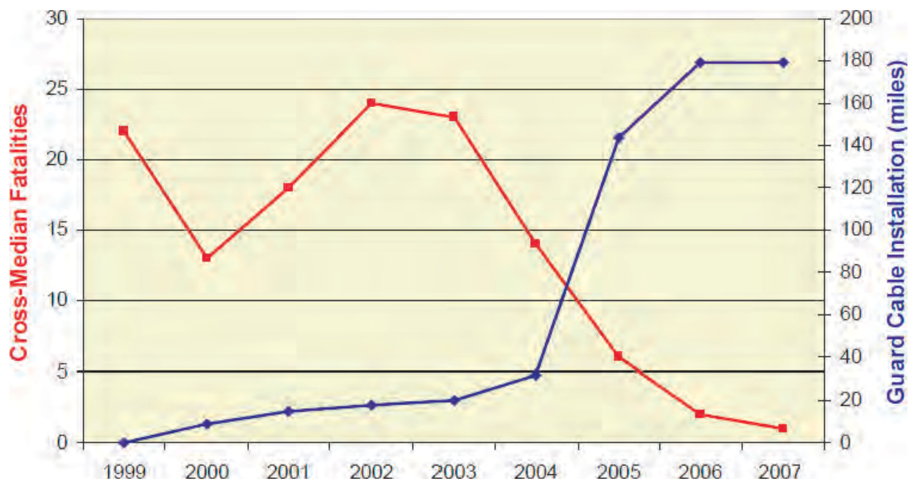


Figure 2.2. Cable installations vs. cross median fatalities—I-70 in Missouri [8].

shown have wide statistical confidence intervals. Table 2.8 shows the effectiveness of cable barriers in preventing cross-median penetrations. All but one state reported 93 percent effectiveness or better. Utah's 88.9 percent effectiveness is based on only 18 crashes. The two states reporting 100 percent effectiveness, Iowa and Rhode Island, also are based on small sample sizes. From these data, the average effectiveness of cable barriers in preventing median barrier penetrations (including or excluding the three states with small sample sizes) is 98.0 percent [3].

A number of states have performed in-service evaluations of high-tension cable barriers since these systems were new to the DOTs. Summaries of these studies are given in Table 2.9. All reports indicate that the high-tension cable barrier systems are effective in reducing cross-median crashes.

Table 2.7. Performance of cable median barriers in various states: reduction in cross-median crashes [3].

State	Annual "Before" (Number)	Annual "After" (Number)	Reduction (percent)
Fatal Cross-Median Crashes			
Alabama	47.5	27	43
Arizona	1.7	0.7	59
Missouri	24	2	92
North Carolina	2.1	0	100
Ohio	40	0	100
Oklahoma	0.5	0	100
Oregon	0.6	0	100
Texas	30	1	97
Utah	15	0	100
Washington	4.4	0.4	91
Cross-Median Crashes			
Florida	---	---	70
North Carolina	25.4	1	96
Ohio	371	27.5	93
Utah	114	55	52
Washington	42.4	11.2	74

Table 2.8. Performance of cable median barriers in various states: effectiveness [3].

State	Collisions (Number)	Penetrations (Number)	Effectiveness (percent)
Arkansas	490	25	94.9
Louisiana	20	0	100
North Carolina	71	5	93.0
New York	99	4	96.0
Ohio	372	4	98.9
Oklahoma	400	1	99.8
Oregon	53	3	94.3
Rhode Island	22	0	100
South Carolina	2,500	10	99.6
Utah	18	2	88.9
Washington	774	41	94.7

Table 2.9. Performance of high-tension cable barriers in various states.

State	System	Miles	Time	Crashes	Fatal	Serious Injury	Minor Injury	Heavy Vehicle	Pene-tration	Ref
AR	Brifen		1 yr	44	0	0	0	1	0	[9]
AZ	Brifen	40	30 mo	104	1[a]	0	4	8	0	[10]
CO	Brifen	2.3	18 mo	9	0	0	0		1[b]	[11]
IN	Brifen	13	1 yr	70	0	0	0	1	4[c]	[12]
IO	Brifen	3.5	21 mo	20	0	1[d]	0	0	0	[13]
OH	Brifen	14.5	3 yr	452	0	0	39		13	[14]
OK	Brifen	7	1 yr	128	0	0	1		0	[15]
RI	CASS	1.4	1 yr	20	0	0	0		0	[3]
TX	Brifen		13 mo	65						[16]
TX	Nucor		6 mo	6						
TX	CASS		13 mo	76						
UT	CASS	8	16 mo	74	0	2			3	[1]
UT	Brifen	2	18 mo	11	0	1			3	

[a] Fatality unrelated to barrier, [b] penetration occurred at a drainage inlet where the cables were higher than specified, [c] no cross-median crashes, [d] injury occurred during impact with tractor-trailer before impact with barrier.

2.4 Placement of Barriers

The TTI report entitled "Guidelines for the Selection of Cable Barrier Systems (Generic Design vs. High Tension)" discusses the tradeoffs involved in the lateral placement of cable barriers. To reduce the number of impacts, the barriers should be placed as far away from the travel lane as possible. To achieve the highest level of performance, the barrier should be placed on near-level terrain, which usually is found close to the travel lanes. Also, adequate clear space behind the barrier must be maintained to allow for dynamic deflection of the barrier during impacts [1].

Cable barriers are typically placed on medians with slopes of 6H:1V or flatter. However, several of the high-tension barrier systems have been crash-tested successfully on 4H:1V median slopes. To reduce the chance of barrier penetration from reverse hits on medians with 6H:1V slopes, barriers should not be placed from 1 ft to 8 ft from the ditch centerline [1, 17]. Barriers placed along the centerline of median ditches have experienced problems from poor and saturated soil conditions and drainage inlets. The poor soil conditions can cause foundation and anchor failures, and the drainage inlets have been found to allow vehicles to penetrate the barrier because of the increased height of the cables at the inlet.

Table 2.10. Cable barrier installation guidelines [3].

State	Installation Guidelines: Median Width Min.	Median Width Max.	Min. Traffic Volume	Crash Rate	Max. Slope	Cable Barrier Type	Location
	(ft)	(ft)	(veh/day)		(H:V)		
AZ	30	75	All Urban		6:1	LT33	CM
DE	50	–					
VA	–	40					
OH	–	76	36,000		6:1	HT	GT8BD
NC	36	70			6:1	LT	SDR/SSR/CM
OR	30	–					
MO	36	60	20,000	0.8 cross-median crashes /100MVMT	6:1	LT30 HT	CM/GT14S/ SDR
NY	36	72	20,000		6:1	LT30	CM/SSR/SDR
NY	36	72	20,000		10:1	HT	CM
KY				0.12 fatal crashes/mi/yr			
WA	30	50			6:1	LT30 HT	CM/GT8BD

CM = Center of median
GT8BD = Greater than 8 feet from the bottom of the ditch
HT = High-tension cable median barrier
LT = Low-tension cable median barrier
LT30 = 30-inch low-tension cable barrier
LT33 = 33-inch low-tension cable barrier
SDR = Shoulder double run
SSR = Shoulder single run
GT14S = Greater than 14 feet from the edge of the nearest shoulder

Ray's cable barrier summary [3] contains a table with data from ten states on their guidelines for installing cable median barriers. His table has been reproduced as Table 2.10. The most common recommendations are "center of median" and/or "greater than 8 ft from the bottom of the ditch," which is consistent with the TTI report and the AASHTO *Roadside Design Guide.*

Missouri recommends for medians at least 9 m (30 ft) wide, to place the cable barrier 1.22 m (4 ft) down slope of the edge of median (hinge point). For medians narrower than 9 m (30 ft), the cable barrier should be installed at the vertex of the V or flat-bottomed ditch [18].

FHWA-sponsored research at the National Crash Analysis Center of the George Washington University has investigated the issue of median crossovers by conducting full-scale crash tests of a large sedan impacting a cable barrier placed at a 1.22 m (4 ft) offset from the center of V-shaped 6H:1V sloped median [19]. In addition, vehicle dynamics simulations were used to evaluate and optimize cable barrier performance on sloped medians under different impact conditions.

Vehicle dynamics simulations were conducted to compute vehicle trajectories as they cross or traverse a median on a diagonal path. A commercially available software package was used to undertake the computations and generate an animation showing what happens. In these studies, the vehicle trajectory as it crosses the sloped median was computed and used to determine if the barrier would engage and redirect the vehicle. Simulations with varied vehicle types (small car, large sedan, and pickup truck), impact speeds (50 to 100 km/h, 31 to 62 mph), approach angles (5 to 25 degrees), median profiles (V-shaped and flat bottom), median slope (8H:1V, 6H:1V, and 4H:1V), and median widths (5 to 17 m, 16 to 56 ft), were conducted to assess barrier performance. The vehicle's relative height was compared to vertical locations of the cables to assess vehicle-to-barrier interaction.

The analysis was used to investigate individual cases (i.e., one vehicle, one speed, one angle, and one median profile) as shown in Figure 2.3. The figure shows a trace envelope for the vehicle moving left to right relative to the cross-section of the median and six possible placement locations for this 3-cable barrier design. Interface with all cables is clearly good (Good oval) and missing all cables is bad (Bad oval). Interfacing with only one or two of the cables is considered acceptable.

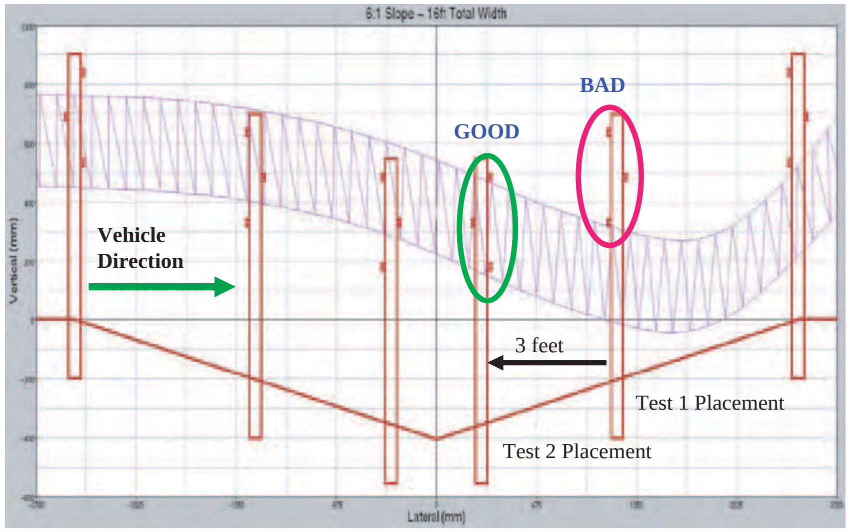


Figure 2.3. Sample trace envelope of vehicle crossing a sloped median.

Additionally, trace envelopes from several cases (varied vehicle types, speeds, and angles) were combined to study optimum placement of cable barriers.

Figure 2.4 shows sample plots highlighting a region in the median between 1 ft and 8 ft where significant variations in vehicle vertical position are observed. Similar variation for this critical region was noticed for different median widths (5 to 15 m, 16 to 48 ft), as indicated by the pattern of "bulges." This plot indicates that barrier placement in this region should be avoided or additional cables are needed [19].

2.5 Cable Heights

Cable heights are important in determining cable barrier effectiveness. Existing cable barriers have either three or four cables (19 mm, ¾ in, 3 × 7 strand galvanized wire ropes). Most high-tension cable barriers use prestretched cables to reduce post-construction tension loss caused by construction stretch (the seating of wire strands during loading). Although cable heights vary among barrier systems, in most systems, the bottom cable is between 432 and 533 mm (17 and 21 in.) high. The top cable height for most systems is between 762 and 1,067 mm (30 and 42 in.). Figure 2.5 shows cable heights for some of the available cable barrier systems. A more complete list of available systems and their cable heights is included in Appendix B of the contractors' final report.

Cable barriers need to accommodate a wide range of vehicle types, from low-profile sports cars to high-center-of-gravity trucks. If the bottom cable is too high, then low-profile vehicles can potentially penetrate under the cables. If the top cable is too low, large vehicles can potentially override the barrier. If the cables are too far apart, vehicles could penetrate between the cables. The 4-cable systems provide for a wider coverage of vehicles (such as TL4 vehicles) than do 3-cable systems, but they are marginally more expensive because of the additional cable. The cable heights for existing barriers work well for impacts on level terrain. However, these heights may not work well when cable barriers are placed on slopes and optimum lateral placement becomes critical to ensure adequate performance.

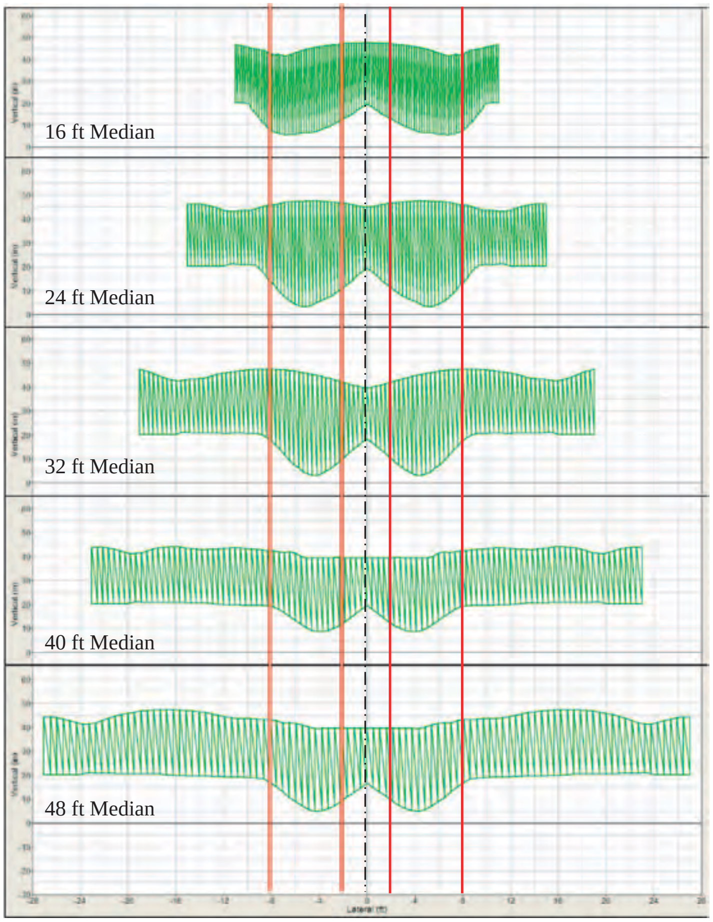


Figure 2.4. Vehicle trajectories from computer simulations of a pickup truck traversing a V-shaped 6:1 sloped median at different impact speeds and angles [19].

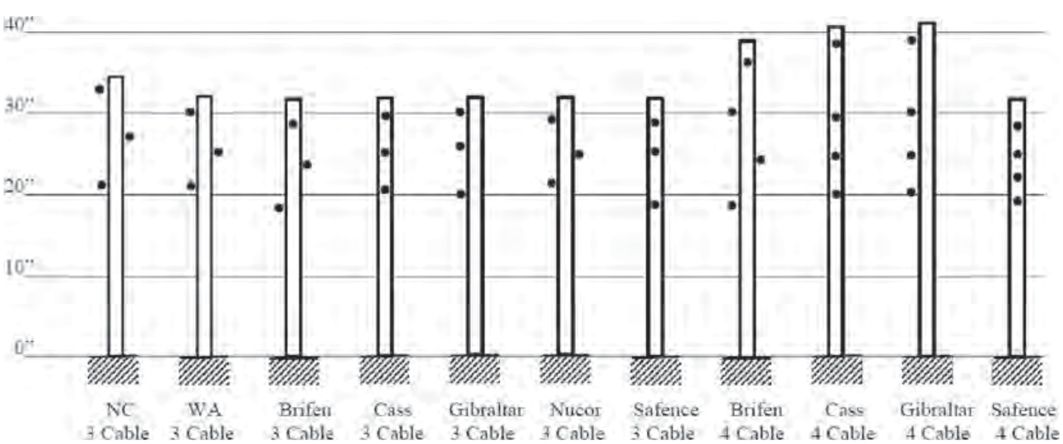


Figure 2.5. Sample cable barrier design variations [19].

2.6 Deflection, Post Spacing, and Anchor Spacing

The dynamic deflection of a cable barrier during impact is an important characteristic for many reasons. Compared to semi-rigid W-beam barriers and rigid concrete barriers, cable barriers have much greater deflections, which is the reason that cable barriers typically are more forgiving to the impacting vehicle's occupants.

However, for the barrier to be safe, adequate space behind the barrier that is clear of hazards must be provided. If deflections are too large, the impacting vehicle could crash into rigid objects behind the barrier or worse yet, collide with a vehicle in the opposing lane of traffic on a divided highway.

The dynamic deflection in a particular crash depends on many factors including impact conditions (vehicle speed, impact angle, and mass), barrier design (post spacing, post cross-section, post foundation/embedment, anchor spacing, cable-post interface/connection, number of cables restraining the vehicle, cable tension, cable modulus of elasticity), and environmental conditions (coefficient of friction of ground, soil strength, terrain slope). Because of these many factors, it is not possible to predict exact deflections that will occur in the field.

Cable barriers were crash-tested according to guidelines contained in *NCHRP Report 350* [20]. Systems developed after 15 October 2009 must be tested according to the procedures described in the *Manual for Assessing Safety Hardware (MASH)* [21]. One of the reported outcomes of crash tests is the maximum dynamic deflection that occurred during the test. Since the NCHRP Report 350 crash tests are conducted under standardized conditions, the reported dynamic deflection may provide a basis for comparing different barrier system designs if similar installation length, post spacing, and initial tension are used. The dynamic deflection, which occurs in the field under conditions that differ from the standard test conditions, will be different from the deflection reported during the crash test.

An FHWA memorandum dated 20 July 2007, and sent to FHWA division administrators, provided detailed information on a number of cable barrier considerations [22], as follows:

- In general, deflection distance is known to increase with longer spacing between posts.
- What is not known, but strongly suspected, is that longer post spacing may also affect the propensity for vehicles to penetrate the cable barrier, i.e., by underride or by traveling between cables.
- The FHWA recommends that the highway agencies specify the post spacing when cable barriers are bid. The conventional range for cable post spacing is 2 to 4.6 m (6.5 to 15 ft).
- Prestretched cables have advantages including reduced dynamic deflection by reducing the "play" between the individual wire strands in the bundle that forms the cable prior to installation.
- The "design deflection" noted in each FHWA acceptance letter is the *minimum* deflection distance that should be provided to fixed object hazards and is based on NCHRP Report 350 Test 3-11 using the 2000P (2,000 kg, 4,400 lb) pickup truck.
- The deflection distance recorded in FHWA letters is also related to the length of the test installation. For example, if a 91 m (300 ft) long barrier is tested and the "design deflection" recorded, the actual deflection under similar conditions will be greater if the barrier length between tie-downs exceeds 91 m (300 ft). Future crash test criteria will specify a minimum installation length for test sections on the order of 183 m (600 ft) to better determine the deflection that can normally be expected.

The National Crash Analysis Center (NCAC) at George Washington University performed a number of simulations on two different types of cable barrier systems for two different initial cable tensions and for three different anchor spacings [23]. Finite element models of an interwoven (weaved) 4-cable barrier and a non-woven (parallel) 4-cable barrier were developed and validated. Post spacings were 3.2 m (10.5 ft) for the weaved system and 3.0 m (10 ft) for the parallel system. Two cable tensions, 15 kN (3.2 kips) and 24 kN (5.2 kips), were used for the initial tension in the system before impact. These tensions approximately represent typical "hot weather" (100°F) and "average weather" (50°F) conditions respectively for high-tension cable barriers. Anchor spacings of 100 m to 1,000 m (3,300 ft) were used in the simulations. The 100 m (330 ft) length is the typical spacing used for NCHRP Report 350 crash tests. The results of the simulations are shown in Figure 2.6.

As expected, the deflections increase for lower cable tensions. The very small change (<5 percent) in deflection for the 38 percent decrease in cable tension is explained by the very large change in cable tension that occurs during an impact. Increases in cable tensions at the anchors during impact are 4 to 5 times as large as the before-impact tension. This finding indicates that for high-tension cable barriers, dynamic deflections from crashes occurring during hot weather when cable tensions are lower should not be much greater than what would occur during average weather.

Anchor spacing was found to have a significant impact on deflection. For both systems, parallel and weaved, the increase in deflection resulting from an increase in anchor spacing from 100 m (330 ft) to 300 m (990 ft) was about 25 percent. However, for anchor spacings greater than 300 m (990 ft), the two systems behave differently. The simulations indicate that the weaved system reaches a maximum deflection at an anchor spacing of approximately 300 m (990 ft), and for anchor spacings greater than 300 m (990 ft) the deflection remains constant. This phenomenon is explained by the very high frictional force exerted on the posts by the interwoven cables, which causes each post to act somewhat like a mini-anchor. With non-woven parallel cable systems, the frictional force exerted on the posts is low, and deflection continues to increase with larger anchor

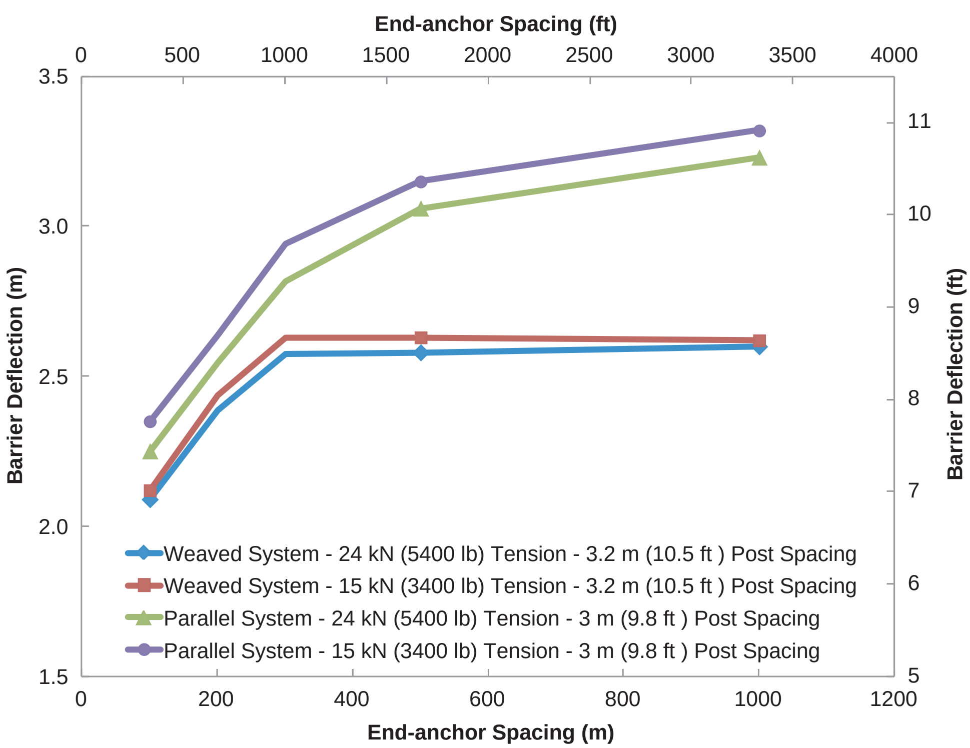


Figure 2.6. Effects of pre-impact cable tension and anchor spacing on deflection [23].

spacings. Simulations were not conducted on anchor spacings longer than 1,000 m (3,300 ft) because of the very long computation time required. Also, simulations were not conducted on other post spacings to determine the impact of post spacing on deflection. These findings are very important, since some highway agencies expect that the deflections reported with crash tests will be what will occur in the field.

2.7 Horizontal Curves

Horizontal curves affect cable barrier performance and must be considered when deciding where to place the cable barriers. Tension in the cables is what allows cable barriers to redirect vehicles. Impacts on the concave side of a curved cable barrier are not a problem; however, impacts on the convex side of a curved cable barrier will result in significantly higher deflections because of the slackening of the cables that occurs. The increase in deflection is a function of the sharpness of the curve and the anchor separation.

Alberson et al. determined deflection magnification factors by using Barrier7 software to conduct a parametric analysis of concave impacts [1, page 46]. This study examined low-tension cable barriers with a 5 m (16 ft) post spacing using as the base a 90 m (295 ft) anchor spacing and a straight section. The analysis gives magnification factors of 1.39 for a 4° curve with 90 m (295 ft) anchor spacing, 1.19 for a 0° curve (straight section) with 450 m (1,500 ft) anchor spacing, and 2.54 for a 4° curve with 450 m (1,500 ft) anchor spacing. These values are not applicable to high-tension cable barriers.

Since roadside encroachments are more common on the outside of a curve, TTI recommends that median cable barriers on horizontal curves be placed on the far side of the centerline ditch away from the outside of the highway curve. Placing the barrier farther away from the more likely encroachment provides more space for the driver to avoid the barrier, and any errant vehicles that hit the barrier will hit it on the concave side. However, this positioning puts the barrier closer to the opposing lanes where an encroaching vehicle will hit the barrier on the more vulnerable convex side [1].

2.8 Maintenance Issues

Cable barrier maintenance can be divided into two areas: repairs after crashes and on-going maintenance. Since cable barriers are used primarily in medians of heavily traveled highways, they tend to get hit quite often. For example, the first high-tension cable barrier installed in the United States on the Lake Hefner Parkway in Oklahoma has been hit over 500 times in 7 years of operation, which is an average of approximately 10 hits per mile per year over the 7-mile-long installation [24]. Therefore, cost of repair can be a major component of the life-cycle cost of cable barriers.

Repairs after Crashes

All current cable barriers have "weak" posts that are sacrificed in a crash and must subsequently be replaced. These posts are typically driven in soil, placed in sockets embedded in concrete foundations, or placed in driven sockets. Damaged driven posts may require special equipment for replacement. Socketed posts, on the other hand, can usually be replaced without specialized equipment, which reduces the repair cost. Post extraction problems can occur during subfreezing weather because the posts are often frozen in their sockets. Extraction problems also can occur when posts are sheared off at ground level rather than being bent over.

Figure 2.7. Cable barrier systems after crash [25].

Low-tension cable barrier systems lose their effectiveness after a crash because of the lack of tension in the cables, which causes the cables to droop, or even lie, on the ground. On the other hand, high-tension systems maintain their effectiveness after crashes as long as the anchors remain in place and a limited number of posts is destroyed. Figure 2.7a shows a low-tension 3-cable barrier after five posts were destroyed in a crash. Figure 2.7b shows a high-tension 3-cable barrier after four posts were destroyed in a crash.

The number of posts damaged in a crash varies depending on the crash conditions. For high-tension systems most states report an average around seven posts that have to be replaced after a crash. Table 2.11 presents data on post replacements from seven states.

Highway agencies report that repair times for high-tension systems typically range from 30 minutes to 2 hours except for crashes involving long sections of barrier. Arkansas recorded the repair time and cost for each crash that occurred during its first year of operation of the Brifen high-tension system. An average crash involved the replacement of 7.6 posts in 73 minutes at a cost of $302 [26]. Texas reported an average crash involved the replacement of 7.8 posts in 75 minutes [16]. Costs of repair reported by other states vary widely, partly depending on who does the repairs: DOT personnel or private contractors.

Table 2.11. Average number of posts destroyed per crash—high-tension barriers.

<table>
<tr><th>State</th><th>No. of Crashes</th><th>Ave No. Posts Damaged</th><th>Ref</th></tr>
<tr><td>Arkansas</td><td>44</td><td>7.6</td><td>[26]</td></tr>
<tr><td>Arizona</td><td>104</td><td>8</td><td>[10]</td></tr>
<tr><td>Colorado</td><td>19</td><td>4</td><td>[11]</td></tr>
<tr><td>Indiana</td><td></td><td>6</td><td>[12]</td></tr>
<tr><td>Iowa</td><td></td><td>4.2</td><td>[13]</td></tr>
<tr><td>Oklahoma – Hefner PW</td><td>508</td><td>6.6</td><td rowspan="2">[27]</td></tr>
<tr><td>Oklahoma – I-35</td><td>244</td><td>6.2</td></tr>
<tr><td>Texas – Brifen</td><td>65</td><td>6.6</td><td rowspan="3">[16]</td></tr>
<tr><td>Texas – Trinity CASS</td><td>76</td><td>8.6</td></tr>
<tr><td>Texas – Nucor</td><td>6</td><td>9.5</td></tr>
</table>

On-Going Maintenance

Most of the reported non-crash-related maintenance issues have involved soil conditions, post foundations, and/or anchors. Some barriers located along the median centerline have experienced problems with weak, saturated soils. The problems include anchor movement and post foundation failures. However, these same problems have been reported in higher areas where soils are not saturated. In many of these cases, the problem was due to an undersized anchor that was not able to resist the ambient tension in the cables. Figure 2.8 shows examples of anchor failures in Ohio and Texas. Figure 2.9 shows what happens when an anchor is destroyed in a crash. Anchors are critical to the performance of high-tension cable barriers, thus extra care needs to be taken to ensure that they are designed properly and located in areas least likely to be hit. Because of the large number of anchor failures, states are beginning to require greater monitoring of soil conditions and more detailed designs of anchors.

Failure of concrete post foundations also has been a problem as shown in Figure 2.10. Lack of proper reinforcing steel and undersized designs for prevailing soil conditions appear to be the main causes for these failures. Frost heaving also could be associated with concrete footing failure in the northern states.

All of the problems experienced with anchors and post foundations can be fixed by better engineering design, more carefully written specifications, and better oversight of construction.

Another issue that was observed in the field is failure of connectors used at the barrier end-anchoring points. A study conducted by TTI investigated the strength of different types of connectors (termination fittings) used in cable barrier systems [65]. The objective of the study was to develop a more reliable connection that would reduce the likelihood of cable release during impacts. Different connector types were tested under static and dynamic loading conditions. The connectors included Filed Swage, Epoxy Socket, Precision Sure Lock (prototype 2), and Nucor Steel Marion terminations. In all tests, the cable did not pull out from the connector but rather ruptured. The maximum load varied from 140.0 to 177.8 kN (31.5 to 40.0 kips) under static loading and varied from 149.3 to 208.0 kN (33.6 to 46.8 kips) for the dynamic cases. The

Figure 2.8. Examples of anchor failures in Ohio [28] and Texas [16].

Figure 2.9. High-tension cable barrier after its anchor failure due to crash [28].

Figure 2.10. Examples of post foundation failures in Ohio [28].

researchers recommended the use of Field Swage as a retrofit for low-tension systems because it is easier to install than the Epoxy Socket and has higher maximum strength than the other terminations. The importance of proper installation was also emphasized in the study to ensure that full strength is reached and premature cable pull-out is avoided. In addition to static and dynamic testing, full-scale crash tests were conducted using the Epoxy Socket and Field Swage terminations. The tests showed that both terminations meet the NCHRP Report 350 TL3 recommendation with the pickup truck test vehicle. It was noted, however, that due to its larger size in comparison to the Field Swage, the Epoxy Socket may affect the barrier performance when impacted with the small car test vehicle, therefore additional testing with this vehicle was recommended.

2.9 Review of Existing State DOT Guidelines

As part of this project, information from highway agencies having their own cable barrier guidelines was solicited. Eight state DOTs responded (Arizona, Florida, Georgia, Kentucky, Louisiana, Minnesota, Mississippi, and Oklahoma). The majority of these states developed Special Provisions for use on individual projects using cable barriers, but Florida and Minnesota developed guidelines apparently intended to be incorporated as Standard Specifications. The following paragraphs summarize the content common to most of the existing guidelines and highlight the unique aspects contained in some of them.

Although most of these states mandated the use of a 4-cable design tested and accepted as NCHRP Report 350 or MASH Test Level 4 (TL4) barriers, some accepted a 3-cable design at either TL3 or TL4. All states required that the line posts be set in sockets in concrete footings for ease of repair. Most specified a maximum allowed post spacing that ranged from 3 m (10 ft) to 5 m (16 ft). Again, most states specified post delineation (retro-reflective sheeting), ranging from 6 m (20 ft) along curves to 30 m (100 ft). An interval of about 15 m (50 ft) was most often specified.

A site-specific soil analysis was required in the majority of states to ensure adequate end anchorage and post foundation designs. Florida DOT in particular included very detailed requirements in its Standard Specification for Tension Cable Barrier System. Minnesota's Interim Design Guidelines for Tension Cable Guardrails was the only document received that included specific cable barrier design and layout information.

Virtually all the state guidelines required that the cable barrier installers be trained or certified for this type of barrier and most required that training be given to state DOT personnel, particularly to maintenance forces charged with repairing or replacing crash-damaged hardware.

A study undertaken by TTI attempted to formulate a comprehensive set of guidelines for the Texas DOT to provide for sound decision making for cable median barrier projects [29]. The recommendations are summarized in Table 2.12. They are categorized as guidelines for selection, design, placement, and general considerations. Commentary in the report provides the sources and the rationale for these guidelines. Much of the guidance is derived from current practices for other barriers, but the results of some of the analytic studies were incorporated.

A study for the Kansas DOT by the Midwest Roadside Safety Facility (MwRSF) entitled "Cable Median Barrier Guidelines," analyzed crash data to provide guidance for the determination of where cable median barriers would be warranted [30]. This effort considered crash histories and the associated influencing factors, such as weather, terrain, and traffic, in the formulation of guidance. The benefit-cost ratios were computed for typical situations where cable barriers were considered an option. Due to local conditions, it was noted that the warranting conditions for Kansas (as other Midwest states) were different from those in the Roadside Design Guide.

Table 2.12. Guidelines for the selection, design, placement, and use of cable median barriers recommended for Texas [29].

Area	#	Guidelines
Selection	**1**	Utilize the recommended guidelines for installing median barriers on high-speed roadways in Texas.
	2	Cable barrier is for use only in roadway medians in Texas.
	3	Cable barrier is for use only on medians greater than 25 feet in Texas. Median widths of 25 feet or less require the use of a more rigid barrier, such as a concrete median barrier.
	4	A 6:1 approach slope to the cable barrier system from both approach directions is required.
	5	Roadway facilities with truck percentages of 10% or more should receive greater consideration for the use of TL4 cable barrier systems instead of TL3.
	6	Cable barrier systems offer significant cost savings over other median barrier systems such as concrete, which allows for installation of a greater number of miles for the same funding level.
Design	**7**	Four-cable systems should use an end-anchor terminal that provides for a separate anchor connection for cable or that has been crash-tested at the trailing end.
	8	Post spacing for cable barrier systems should be specified when they are put out for bid.
	9	A minimum clear distance of 12 feet should be maintained from the edge of the cable barrier system.
	10	The posts for all cable barrier systems should be placed in concrete drill shafts with sockets.
	11	Use only prestretched cable.
	12	Cable barrier runs should be a minimum of 1,000 feet and a maximum of 10,000 feet in length.
	13	Parallel runs of cable barrier may be appropriate for situations such as differential profile grades, narrow medians, or when objects such as high-mast light poles are located in the middle of the roadway median.
	14	A minimum clear distance of 12 feet should be maintained between the cable barrier systems, and any obstruction should be maintained.
	15	Cable barrier systems should be placed such that there is a minimum of 2.5 feet (6 feet preferred) from the back of the metal beam guard fence posts to the barrier.
	16	Cable barrier systems should be a minimum of 6 feet behind guardrail extruder terminals to allow for extrusion and gating of the end treatment.
	17	Continue to monitor overall cable barrier performance statewide, and evaluate impacts from motorcycles and vehicles exceeding design loads.
Placement	**18**	As a general rule, a cable barrier system should be placed as far away from the travel lane as possible while maintaining proper orientations and performance of the systems.
	19	Cable barrier systems should be placed on relatively flat, unobstructed terrain if possible (10:1 or flatter) and may be placed on 6:1 maximum slopes if necessary.
	20	The preferred placement of the cable barrier within a v-ditch should not be in the area of 1 to 8 feet from the bottom of the ditch.
	21	The acceptable placement of cable barrier allows a maximum 4:1 slope if the cable barrier is placed on the 6:1 slope at a distance of 8 to 1 feet from the ditch bottom.
	22	Closer post spacing through horizontal curves is recommended based upon the radius of curvature.
	23	Placement of the cable barrier on the convex side (i.e., inside of the curve relative to near traffic) is recommended to allow maximum median space for vehicle recovery for leaving opposing travel lanes.
	24	Care should be exercised when placing cable barriers in superelevated sections.
	25	Placement of cable barrier systems on sag vertical alignments with a radius of less than a K-value of 11 should be avoided.
	26	Cross drainage structures with less than 36 inches of cover pose a challenge for placing cable barrier posts. Structures of less than 16 feet can be spanned in order to avoid post placement into the drainage structure.
	27	Designer should follow the Plans, Specifications and Estimates (PS&E) Preparation Manual guidance on identifying utilities with the project and the quality level of utility locates required.
General system considerations	**28**	Emergency response agencies should have educational materials to provide them with clear and concise guidance on when and how to safely cut cable when a vehicle is entangled after an impact.
	29	If the cable barrier is switched from one median side to the other and terminals are not protected, overlapping runs of cable barrier are recommended to provide adequate protection from possible crossovers.
	30	Footings for terminal anchors should be designed to keep static loads well below the ultimate strength.
	31	For future maintenance considerations, the use of mow strips is encouraged to reduce future hand mowing and herbicide operations.
	32	Distance between the edge of the travel lane and the cable barrier should consider mower widths.
	33	Anchor foundations and sockets should be designed for prevailing soil conditions at installation locations.
	34	Cable barrier system design should account for the potential of frost heave.
	35	Delineation of cable barrier should be at 100 foot spacing unless otherwise approved by the engineer.
	36	The maximum distance between breaks in the cable barrier system that allow emergency vehicle access should be 3 miles.

2.10 International Practices

The literature review included an attempt to determine the evolution of the technology and application of cable barriers in other parts of the world. These are summarized relative to use, evaluations, maintenance, and other concerns in the paragraphs below.

Usage

References were found to the use of safety fences, wire rope fences, and flexible barriers in Europe, Canada, Japan, Israel, Australia, and New Zealand. The use of modern cable barrier technology in some cases predates its use in the United States. A 1974 report entitled "Tensioned Cable Safety Barrier, M62," by F. R. Oliver examined a trial installation of tension cable in the "central reserve" or median on the M62 motorway in England [31]. It was noted that the cable barriers' smaller profiles nicely addressed the drifting snow problem that had been observed for median barrier applications. During the 2-year evaluation, 12 incidents occurred and were analyzed. It was noted that damage to vehicles was found to be relatively minor and, in most cases, the vehicles were driven away after the impact. The barrier also restrained a large truck. The author concluded that the experience of the trial suggests that the fears of injury to low sports cars and overriding by heavy vehicles are unfounded.

The design of a TL4 cable median barrier for the Deerfoot Trail in Calgary was described in a 2007 paper [32]. This paper describes the preliminary engineering and design of an NCHRP Report 350 Test Level 4 high-tension cable barrier installed in the depressed median of an 11 km (6.8 mi) stretch of highway that had median side slopes of 6H:1V or flatter. At the time, three manufacturers met the NCHRP Report 350 requirements for four prestretched, post-tensioned cable barriers—namely, Brifen Canada, Gibraltar, and Trinity Highway Safety Products.

The major design issues that were dealt with during the design and associated guidelines included

- Lateral placement of median cable barrier
  - TL4 barriers can be installed in medians that have side slopes of 6H:1V or flatter.
  - On 6H:1V sloped medians, a cable barrier should be placed within 0.3 m (1 ft) of the ditch bottom or beyond 2.4 m (8 ft).
  - The ground under the barrier must be stable and free from obstructions or depressions.
- Placement of the barrier
  - On a horizontal curve, the barriers were installed on the near side of the roadway, which is on the concave side of the barrier.
- Connection to or separation from the existing barriers
  - At locations where existing barriers were in place, the median cable barrier was installed between the barrier and the travel lanes.
- Existing hazards
- Emergency crossovers
  - Crossovers were removed and the side slopes of the median graded to allow for continuous installation of the median cable barrier.
- End treatments/terminals
- Potential for vehicles to be trapped between barrier systems

There was limited guidance for some of the design issues.

Evaluation

Various summaries of safety measures generated in the 1990s noted that wire rope systems had been promoted among the options for addressing safety problems. There were some small-scale evaluations of safety performance discovered, but nothing of a large scale. For example, Marsh and Pilgrim analyzed the performance of wire rope for the Centennial Highway in New Zealand [33]. A significant drop in the societal costs of crashes was noted for the 2+1 type application. The authors identified challenges for future installations of cable barriers in narrow medians. Levett, Job, and Tang compared the relative effectiveness of wide painted centerlines and wire rope systems on crossover occurrences and severity as part of a safe systems approach [34].

Candappa, D'Elia, and Newstead undertook a before and after study of flexible barriers along Victorian highways [35]. The study noted effectiveness of such barriers, particularly for reducing loss of control crashes. A 2004 study by McTiernan, Thoresen, and McDonald analyzed crash results and maintenance costs and found positive benefit-cost ratios when the Pacific Coast Highway installation was compared to other similar highways [36]. They recommended further application of modern wire rope barrier.

Manuals and Guidance

A document on cable barrier maintenance was generated in Western Australia. It identified conditions that need inspection during cable barrier system maintenance [37]. These included

- Stretching of the rope
- Movement of the anchors
- Failure of the fittings
- Release of the ropes from the anchors
- Damaged posts or broken fixings
- Lack of rope tension

Wire rope and attachments are inspected for broken wire, reduction of wire diameter by abrasion, crushing or flattening of rope, kinking or notching, weakening by corrosion, damage to galvanizing, and any damage to the attachments and fittings. Actions to be taken when a defect is found included

- Lubricate or replace a screw thread that is rusty or tight and
- A competent person to decide whether to discard, or if possible, repair a damaged screw thread, distorted body, distorted fittings, nicks, gouges, cracks, or corrosion on any component

Brifen Europe produced "Guidelines for the Installation, Inspection, Maintenance, and Repair of New and In-Service EN1317 Brifen Wire Rope Vehicle Restraint Systems (Europe)" [38]. This document sets out procedures for the installation and inspection of new and in-service Brifen wire rope safety fence systems. It presents various design requirements such as setback at verge, setback at central reserve, working width, number of ropes and tension factors for different containment levels, ground profile, height and length of fence, requirements on post foundation and anchors, and maximum length of ropes. It also lists various limitations on the use of wire rope fence. The document gives the guidelines for installing a Brifen wire rope fence including post selection, concrete foundations, filter drain foundations, anchors (end and intermediate), assembly, tensioning, and measuring tension in ropes. The document also explains the inspection program and the procedure for adding existing Brifen wire rope system to it. Various steps involved in maintenance of a Brifen wire rope system are explained in brief. These include mounting height, setback, working width, rope tension after impacts, component replacement, and various repairs after an impact.

Woof noted in 2006 that although new barriers, like wire rope systems, were being developed, there are inadequacies in the testing requirements [39]. Nilsson and Prior described the decision process used by New South Wales to implement wire rope barriers in 2004 [40]. Roper et al.

Table 2.13. Japan's various configurations of cable barriers.

Type	Section	Road Class	Post Diameter	Cable Diameter (# of Cables)	Tension per Cable
C	Roadside	Local road	114.3 mm	18 mm (3)	9.8 kN
B	Roadside	Highway	114.3 mm	18 mm (4)	9.8 kN
A	Roadside	Freeway	139.8 mm	18 mm (5)	20 kN
B_m	Median	Highway	114.3 mm	18 mm (3)	9.8 kN

noted that there were changes made in the 1987 AustRoads "Safety Barriers" guide that include flexible systems incorporating wire ropes [41].

Cable barriers in Japan are mainly used in snowy locations and scenic locations [42]. The main reasons for using cable barriers include easiness to remove snow from the roads and highways, unrestricted visibility, and that it is more economical when compared to other types of guardrails. Because of usual limited space for cable deflection, strong type posts are used to reduce barrier deflection. The number of cables and tension per cable varies depending on where the system is installed: roadside or median, highway, freeway, or local road. Cable size is common and is 18 mm (0.71 in.) in diameter. Tension per cable is 20 kN (4.3 kips) if installed on roadside in a freeway, otherwise it is 9.8 kN (2.1 kips). The number of cables varies from three to five depending on the location of installation. Table 2.13 shows the various configurations of cable barriers.

Applications

In Sweden, the use of cable barriers for 2+1 applications on two-lane roads is reported as a means to improve safety. Carlsson and Larsson in 2003 ("Sweden Vision Zero Experience") reported on the early experience of this application. Data from test sections showed that in eight incidents there were no fatalities and only six severe injuries [43]. This represented a 60 percent decrease in severe injuries compared to similar roads without the 2+1 design. They also noted that cable median barriers, although frequently hit, were normally occurring without personal injuries.

A Swedish National Road Administration (SNRA) report indicated that the 2+1 roads were a "success story" [44]. In the 1990s almost 100 people were killed and more than 400 were severely injured on 13 m (43 ft) wide two-lane roads in Sweden. Seventy percent of these fatalities were due to vehicle run-offs and head-on accidents. SNRA started to explore cost-effective measures to improve traffic safety. The main alternative was the 2+1 concept, i.e., with central overtaking lane changing permitted every 1.25 km (0.78 mi) with a separating cable barrier preferably within the existing width of 13 m (43 ft). The results from this alternative design were compared with two other designs: 2+2 concept (i.e., to widen existing 13 m [43 ft] roads to two lanes in each direction separated with a cable barrier with a paved width of 16 m [52 ft]) and four-lane concept (i.e., with full access control and 18 m [59 ft] crown width including a 2.5 m [8.2 ft] median). The main results and findings until mid 2004 are as follows:

- Safety effects for 2+1 concept are better than expected. Fatality rate reduced to 0.0017 (fatalities per million axle pair km), an 80 percent reduction. Reduction in severe injuries was about 55 percent. The 2+2 and 4-lane concepts provided not much better results than 2+1 concept.
- Median cable crashes were, as expected, very frequent but normally without severe consequences. This rate is 0.51 crashes per million axle pair km.
- Maintenance costs have increased by 70 percent, 65 percent of this being for barrier repairs.
- Two fatalities and seven severe injuries have been reported involving motorcycles and cable barriers. No indication that the barrier created the accident or worsened the consequence.
- Drivers and public opinion are very positive.

Other Concerns

Schermans and Van der Hoek indicated that the 2+1 concept was being considered for the Netherlands. They noted that there are more motorcyclists in the Netherlands than in Sweden, which may cause a problem [45]. The opposition was already labeling cable barrier systems as “egg cutters.” Concerns raised by motorcyclists over the use of wire rope safety barriers (WRSB) included their potential to act as a “cheese cutter” in the event of a collision by a motorcyclist.

Transit New Zealand generated a report to provide general guidance on the use of WRSBs with respect to the needs of motorcyclists [46]. The State Highway Geometric Design Manual, which is based on NCHRP Report 350 and *AS/NZS 3845:1999 Road Safety Barrier Systems*, provides guidance on the placement and layout of road safety barriers for both roadside and median barrier systems. The guide specifically states that unprotected road users, which includes motorcyclists, pedal cyclists, and pedestrians, should be taken into consideration. Crash data involving motorcyclists in New Zealand between 2001 and 2005 shows that only a third of all motorcycle crashes occurred on the state highway network, whereas 70 percent of the fatal crashes that occurred were on these roads. Of the total 3,762 injury crashes involving motorcycles, 54 (1.4 percent) involved collision with a road safety barrier and 2 involved WRSB, but none of the motorcycle fatalities involved WRSB. The two crashes with WRSB resulted in the police reporting one serious injury and one minor injury.

Several tests have been carried out on various types of barriers to assess the severity of injuries to the motorcyclists. Regardless of the various tests carried out, as noted in the 2006 ACEM Guidelines for PTW (Powered Two Wheelers)—Safer Road Design in Europe, “limited research done so far does not warrant the conclusion that cable barriers are more hazardous than other types of barrier” [47].

The report concludes that there is no reliable evidence to indicate that the wire rope barriers present greater or lesser risk than other barrier types, or indeed, no barrier at all [46]. The lack of evidence is due to the limited amount of accurate real world or microsimulation testing, along with the limited number of reported crashes involving motorcyclists and WRSBs. It also concludes that, depending on the use and positioning of WRSBs, they may result in a worse crash than if they had otherwise not been provided. Hence, care is required when specifying the need for road safety barriers, as well as when determining the type and location of such measures.

A coroner’s report of an investigation of motorcycle death in Australia after crashing the motorcycle into high-tension cable barrier highlights concerns [48]. The cable barrier system was from Brifen and was installed in accordance with Australian Standards AS/NZS 3845:1999 Road Safety Barrier Systems. The location of the fence was site specific, meaning that it could not be positioned in any other location due to the steep drop on the other side. If the fence had been positioned part way down the embankment, an out-of-control vehicle would more likely travel over the fence. The only way to change the position of the fence would be if major road work was undertaken to change the configuration of the central median strip. From the investigation, it was concluded that the reasons for the death were that the person riding the motorcycle had a blood alcohol level more than three times the legal limit and was going at or about double the 110 km/h (62 mph) posted speed limit. Investigators did not believe that the cable barrier fence was to blame for the motorcycle rider’s death.

Szwed presented a summary of the experience with wire rope barriers in Victoria [49]. He concluded based upon 10 years of deployment, a literature review, and a before and after crash analysis, that wire rope barriers are generally the safest type of barriers, and they are very cost-effective.

2.11 Summary

The literature review covered a broad spectrum of information sources and provided a viable snapshot of the current state of the practice. From the literature review, it is possible to conclude the following:

- Cable barriers have a long history of use on highways. Improved designs for cable barrier systems have emerged over the past 10 years.
- There is increasing use of cable median barriers across the country.
- There is a general consensus that cable barrier systems have a high degree of effectiveness and lower crash severity when hit.
- Although the generic low-tension systems are still an option for some, there seems to be a greater interest in high-tension cable systems.
- Five companies are marketing proprietary cable barrier systems. The new cable barrier systems they are marketing vary considerably in their design features.
- The new generation of cable barrier systems has been crash-tested to ascertain that they meet the requirements of NCHRP Report 350 or MASH. In assessing the performance of these barrier tests, it is important to note which criteria were used, because there is a difference in testing requirements between NCHRP Report 350 and MASH.
- Efforts to evaluate the safety performance of cable barrier systems have not been uniform. The data, until recently, were not detailed enough to ascertain whether cross-median events actually resulted in crashes.
- Differences in the data from the states, abilities to effectively isolate cross-median crashes, and limited data about site features resulted in a range of effectiveness estimates.
- There only has been limited effort to analytically or physically evaluate the effectiveness of cable barrier systems to reflect the manner in which they are being used.
- Placement of cable barriers has generally followed the accepted guidance for other barriers. There have been more tendencies to deploy cable barrier on sloped medians, but without analyses or test results to confirm effectiveness. The influences of median configuration, width, and slopes began under some research of the FHWA.
- The heights, number, and arrangement of cables for any barrier system design vary. There is limited data to understand the influences of these cable factors on effectiveness.
- The use of vehicle dynamics analysis (VDA) to assess vehicle-to-barrier interface has been shown to explain the occurrence of override and underride events. VDA tools provide a convenient means to consider the potential for bi-directional impacts of the barrier.
- Issues with cable barrier anchorage failures have led to requirements for site-specific design anchorages. There has been some analysis of the effects of varying lengths of cable barriers. There are practices for setting the tension levels in cable barrier systems.
- The relatively limited experience with cable barrier system deployments and maintenance over time implies that there is little data on initial and maintenance costs to provide clear guidance for selecting systems and ancillary features (e.g., mow strips, socketed posts).
- Guidance is needed for determining where cable median barriers should be deployed, which systems should be selected, the needed design features, and their ultimate maintenance. The literature noted that there is only limited guidance of this nature and even where there is some guidance, like the Roadside Design Guide, it is dated, limited, and not specifically derived to reflect the features and functionality of cable barrier systems.
- Most of the reported efforts are related to median applications, but these results are transferable to roadside applications.
- The international literature noted uses of cable barriers or wire rope safety fences has occurred across the world. In some cases, the use of modern cable barrier technologies predates its use in the United States by more than 10 years.

- The few evaluations of systems deployed in other parts of the world generally have concluded that wire rope systems have been effective in reducing the number and severity of crossover crashes. They have been judged to be "cost effective."
- The success with median applications has inspired the use of cable barriers in other applications. Most notably, in Sweden, Australia, and New Zealand, applications on 2+1 roads with narrow medians have been reported with good results.
- There seems to be limited formal guidance or guidelines developed in other countries, and differences in basic road design practices render these guidelines of limited value to U.S. needs.

CHAPTER 3

Cable Barrier Current Practices

In order to establish an up-to-date picture of current agency efforts to utilize the emerging cable barrier technology, a survey was conducted at the outset of the project. To maximize the potential to capture information, the survey was similar to the one used in an earlier study. In 2007, the Texas Transportation Institute (TTI) completed work on NCHRP Project 20-7(210), "Guidelines for the Selection of Cable Barrier Systems (Generic Design vs. High-Tension Design)," which included a comprehensive survey of all state agencies to gather detailed information on the selection and use of cable barrier systems and on the effectiveness of these barriers in the field [1]. Responses were received from 29 states. This survey provided a snapshot of the extent of cable barrier usage and of the state of the practice relative to the design, selection, installation, and maintenance through 2005. This approach allowed updating the information from the earlier survey, and it offered states that did not respond to the TTI survey an opportunity to provide input on their experiences with cable barrier systems.

The questionnaire was designed to acquire information about the use of cable barriers in the states and the guidelines, if any, that were used in the design and construction process. A copy of the survey questionnaire is included in Appendix A of the contractors' final report. Initially the survey was sent to the states in November 2008, and 16 responses were received. In August 2010, the survey was re-sent to states that had not responded to the initial request, and 24 additional responses were received. The survey of the states was supplemented with requests to high-tension cable barrier manufacturers to get their estimates of barrier-miles installed. The summary of the survey results is presented in the following sections.

3.1 Extent of Cable Barrier System Use

The first question on the survey asked the states to indicate approximately how many miles of cable barrier had been put in place or were currently being installed in their state. Based on the responses from 40 states, 3 states did not have any installed cable barriers, 7 states had less than 10 mi (16 km) of installations, 15 had less than 100 mi (160 km) of cable barriers, and 15 states had several hundreds of miles of cable barriers. Figure 3.1 shows the extent of cable barrier usage by state. The majority of cable barriers, 58 percent, were high-tension systems, and 35 percent were generic low-tension systems. The remaining 7 percent were reported as other systems by the states (this included cases where a decision to install cable barrier has been made but the choice of system has not been finalized). Figure 3.2 shows the percentage of different high-tension, low-tension, and other systems. Figure 3.3 shows the total miles of cable barrier obtained by summing reported numbers from the 37 states using cable barriers.

Figure 3.4 shows the total installed miles of high-tension barriers reported by two of the manufacturers. The mileage reported by the states was less than that reported by the manufacturers.

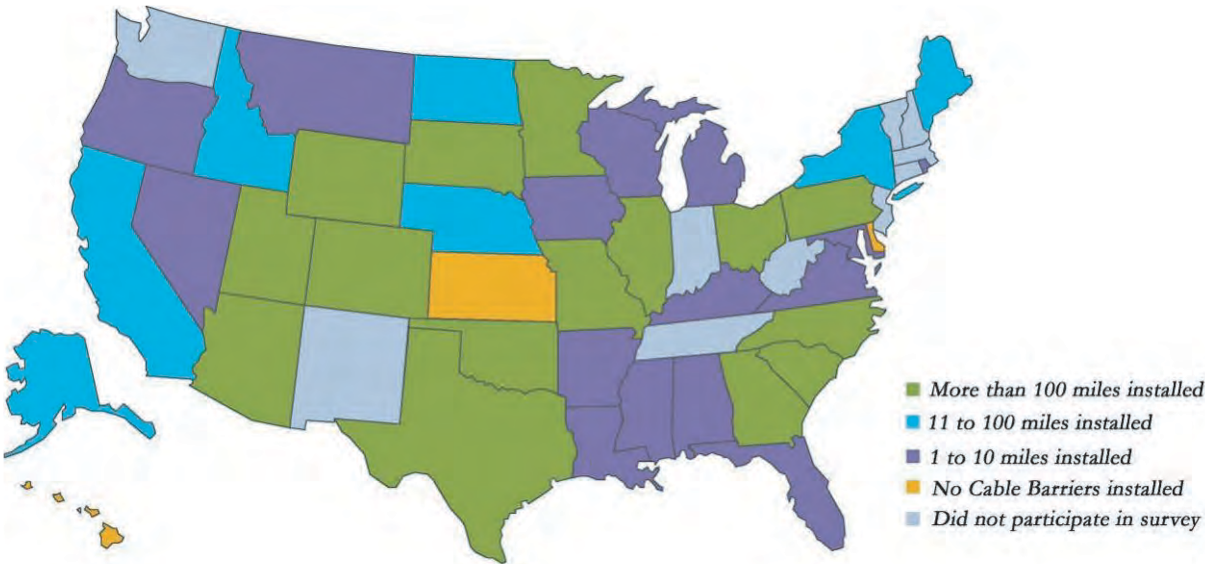


Figure 3.1. Map of cable barrier usage by state (as of November 2010).

The difference could be a result of errors in the approximations made by some states and/or the lack of data from 10 states that did not respond to the survey.

Ninety-seven percent of cable barrier systems were placed in the median while only 3 percent were used on the side of the road. Most of the barriers, 70 percent, were TL3 systems while the remaining 30 percent were TL4 systems. Overall, 79 percent of installed barriers had three cables and the remaining 21 percent had four cables.

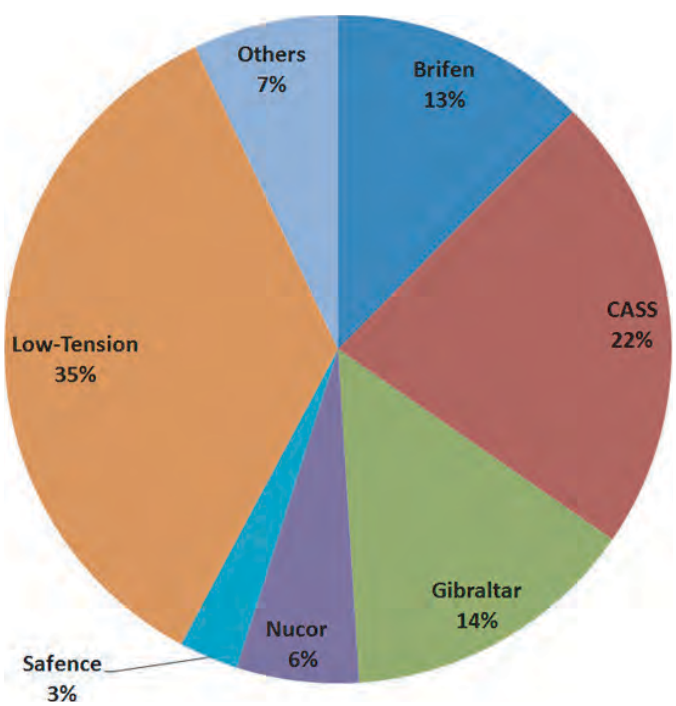


Figure 3.2. Percentage of states using different types of cable barriers.

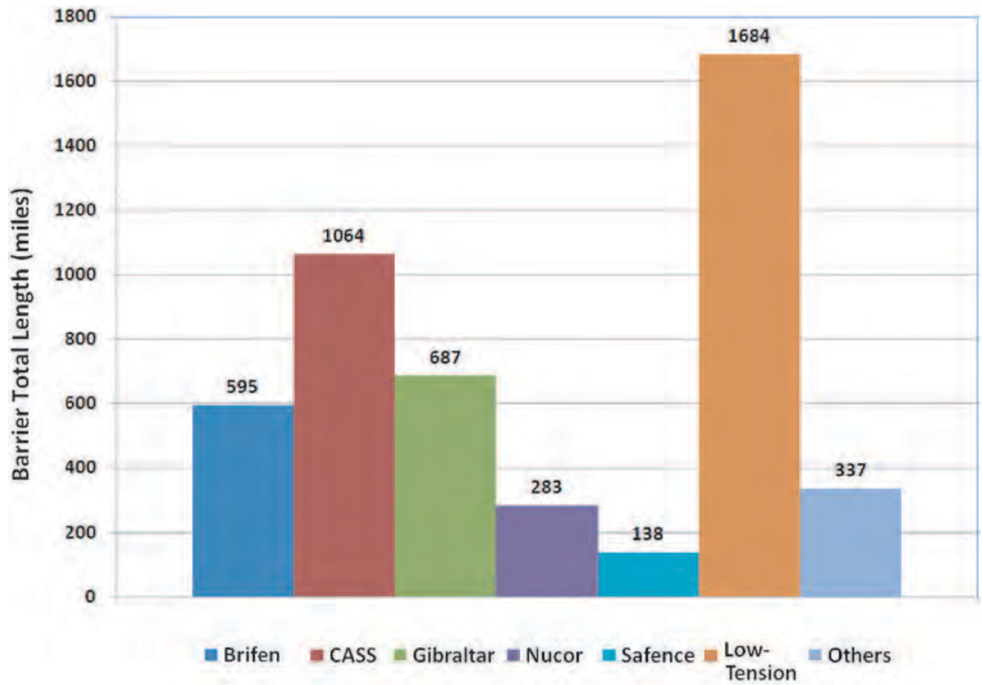


Figure 3.3. Total miles of cable barrier by manufacturer as reported by 37 states.

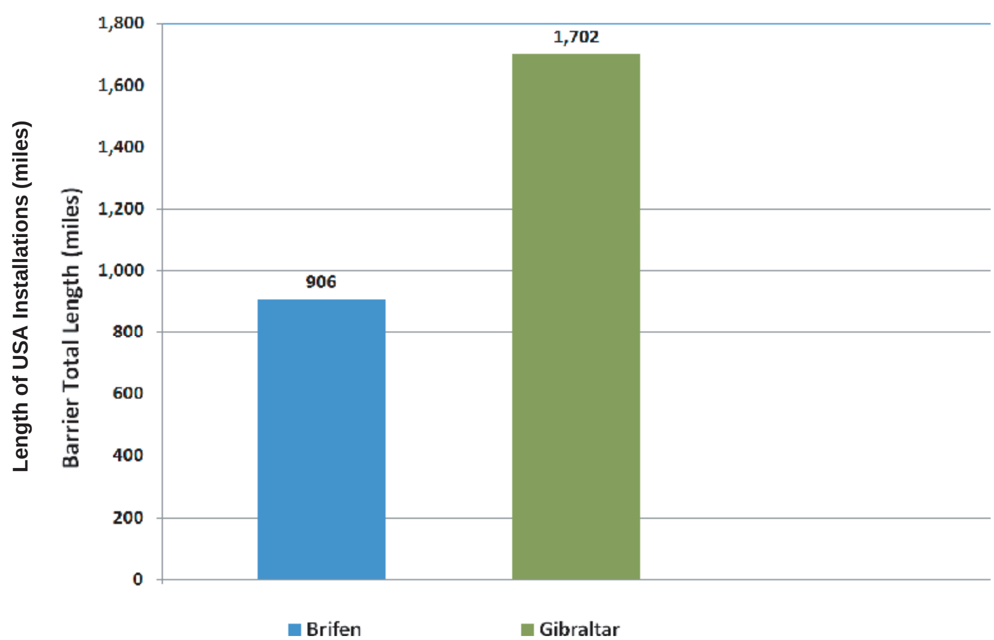


Figure 3.4. Total miles of cable barrier installation reported by manufacturers.

3.2 Median Conditions for Cable Barrier Installation

The survey next posed four questions about the conditions or configurations of the medians where cable barrier systems were installed. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 2: Please estimate the median slopes that exist in your state for which cable median barriers have been, or are planned to be, installed to reduce cross-median crashes.
- Question 3: Please indicate the typical median geometry used in conjunction with the different cross slopes used in your state. If available, cite the number of miles for each case.
- Question 4: Please estimate the median widths (from one break or hinge point to the other) associated with the different cross slopes used in your state.
- Question 5: For the flat-bottom and rounded-bottom median configurations (if used), please specify the typical width of the flat/rounded section.

The survey responses were based on the total mileage reported by the states. The majority of barriers, 55 percent, installed in the median had 6H:1V side slopes and 15 percent had 8H:1V slopes. Steep sloped medians of 4H:1V or 5H:1V represented 20 percent of the medians and 8 percent had flat, 10H:1V slopes. Figure 3.5, based on reported mileage where cable barriers have been installed, shows the distribution of median side slopes.

The different median shapes queried in the survey included the V-shape, flat-bottom, rounded-bottom, non-symmetric, and other. Figure 3.6 shows usage by state for various combinations of median shape and slope for medians where cable barriers are installed. The V-shaped median with a 6H:1V slope is used by 21 states, while the second most common configuration, the flat-bottom-shaped median with a 6H:1V slope is used by 14 states. The V-shaped median with a 4H:1V slope is used by 11 states. Overall V-shape is the most common median shape followed by flat-bottom.

Survey responses showed a wide range of median widths existed among the states. Three states, two of which used cable barriers, reported a minimum median width that is less than 3 m (10 ft), which was significantly lower than the other 23 states that answered Question 4. To avoid unduly distorting the data, these states were excluded from the analysis. The minimum, maximum,

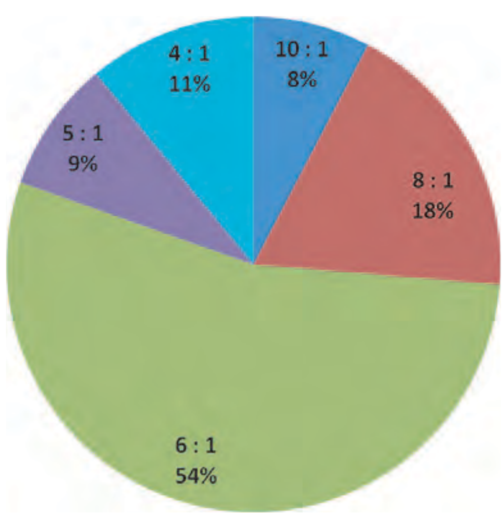


Figure 3.5. Distribution of median side slopes based on total miles reported.

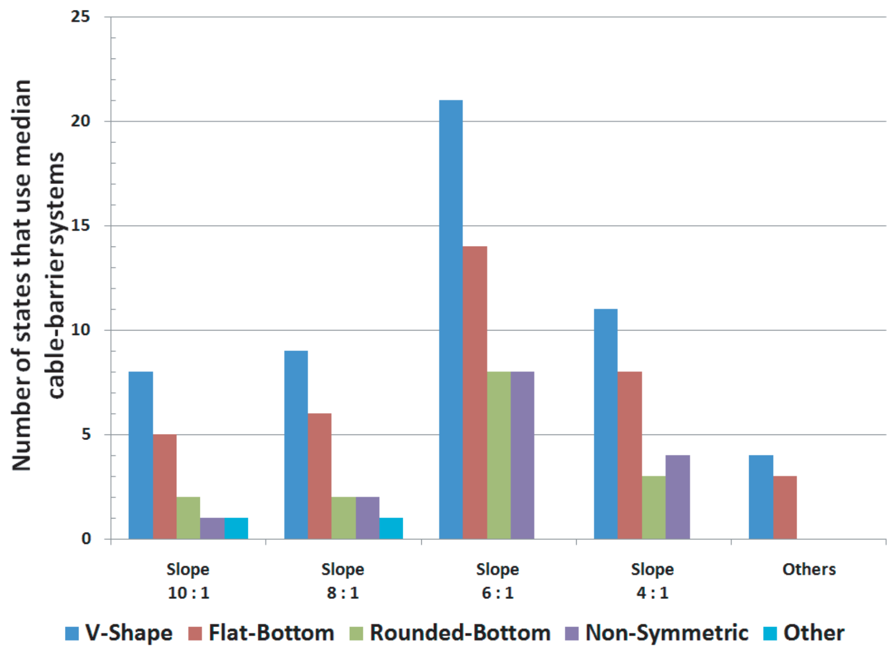


Figure 3.6. Median shape and slope combinations used by states.

and average median widths reported from the 23 states by side slope are shown in Table 3.1. The minimum median widths ranged from 3.5 to 8.5 m (12 to 28 ft), the maximum median widths ranged from 24 to 32 m (80 to 104 ft), and the average ranged from 11.2 to 14 m (37 to 46 ft).

Table 3.2 shows the minimum, average, and maximum width of the flat/round section of flat-bottom and rounded-bottom medians for the 14 states that responded to Question 5.

Table 3.1. Median width with respect to slope grade.

Slope	10H:1V	8H:1V	6H:1V	4H:1V	Other
[1]Minimum Median Width in m (ft)	4.6 (15)	7.3 (24)	6.1 (20)	3.7 (12)	8.5 (28)
[2]Maximum Median Width in m (ft)	30.5 (100)	24.4 (80)	31.2 (104)	24.4 (80)	21.3 (70)
[3]Average Median Width in m (ft)	14.0 (46)	11.2 (37)	14.0 (46)	11.2 (37)	12.8 (42)

[1]Minimum of all minimum widths reported
[2]Maximum of all maximum widths reported
[3]Average of all average widths reported

Table 3.2. Round/Flat median section width with respect to slope grade.

	Slope	[1]Minimum Width Reported in m (ft)	[2]Average Width Reported in m (ft)	[3]Maximum Width Reported in m (ft)
Flat/Round Bottom Width	10:1	1.8 (6)	3.4 (11)	4.6 (15)
	8:1	0.9 (3)	2.1 (7)	3.0 (10)
	6:1	0.6 (2)	6.1 (20)	21.3 (70)
	4:1	0.6 (2)	3.7 (12)	3.0 (10)
	Others	1.2 (4)	9.8 (32)	18.3 (60)

[1]Minimum of all minimum flat/rounded section widths reported
[2]Average of all average flat/rounded section widths reported
[3]Maximum of all maximum flat/rounded section widths reported

3.3 Factors Considered in Selecting Cable Barriers

The survey posed four questions about the factors or criteria considered in determining that cable barriers would address the safety needs for a given situation. The intent was to determine if warrants, state experience with cable barriers, and/or existing standards provided an impetus or direction for specific decisions. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 6: What criteria are used to decide if a barrier is warranted: For median application? For roadside application?
- Question 7: What criteria are generally used to select a cable barrier system over a rigid or semi-flexible system in locations and conditions where any system can be used: For median application? For roadside application?
- Question 8: What criteria, if any, are generally used to select a specific cable barrier system, i.e., Brifen, CASS, Gibraltar, Nucor, Safence, or generic low-tension?
- Question 9: Does your state have specific standards/guidelines for the system design, alignment, construction, and/or maintenance of cable barriers?

For median applications, the states reported the following warranting factors, although not all cited a specific warrant:

- Median width (19 states)
- Crash history data and analysis (19 states)
- Vehicles crossover frequency (11 states)
- Traffic volume (8 states)
- Roadway geometry (slopes and vertical alignment) (6 states)
- AASHTO Roadside Design Guide & Highway Design Manual (5 states)
- Speed (3 states)
- Benefit/cost ratio and analysis (2 states)
- Other (clear zone, maintenance, trucks percentage, etc.)

For the roadside application, 13 states indicated that they do not use cable barriers in this type of installation while 22 noted the following considerations:

- AASHTO Roadside Design Guide (7 states)
- Clear zone and distance to hazard (7 states)
- Crash history data (7 states)
- Fixed objects (5 states)
- Roadway geometry and alignments (3 states)
- Other (speed, traffic volume, maintenance, snow drifting, etc.)

For median applications, the top two selection criteria for cable barriers over other types of longitudinal systems (rigid and semi-rigid) were median width and cost. These and the other criteria mentioned are summarized as follows with the number of responses indicated:

- Median width (23 states)
- Cost (21 states)
- Allowable deflection (8 states)
- Slopes (8 states)
- Roadside features, terrain (7 states)
- Accident crash data (5 states)
- Ease of installation and maintenance (5 states)
- Crossover accidents (4 states)
- High traffic volume (3 states)
- Other (snow drifting, drainage, FHWA, and speed)

Selection criteria for cable barriers over other longitudinal barriers in roadside applications were provided by 33 states as follows:

- Allowable deflection (10 states)
- Distance to hazard (8 states)
- Cost (5 states)
- Slope (5 states)
- Snow drifting (5 states)
- Ease of installation and maintenance (4 states)
- Accident crash data (3 states)
- Other (high traffic volume, roadside features, crossover)

The criteria used to select a specific cable barrier system (i.e., Brifen, CASS, Gibraltar, Nucor, Safence, or the generic low-tension) are shown in Figure 3.7. Fifteen states indicated that the bid is restricted to low-bid that is open to all NCHRP Report 350-approved systems. Ten states used previously specified vendors, while five states used system-specific bid documents. Additionally, 12 states reported other criteria, and these are grouped in four categories that follow:

- Use a low bid for at least 2 approved systems (4 states)
- Use a low bid for a preapproved system (3 states)
- Use experimental or proprietary systems (3 states)
- Use a bid document for a system with specified features (e.g., post spacing, type of post installation, type of anchors, etc.) (3 states)

Based upon the premise that cable barriers would be more often considered as a safety option, the survey attempted to determine how many states already had design and construction standards. There were 21 states that reported having cable barrier design standards and 15 states that did not. These standards typically include soil testing and properties, end-terminal requirements, etc. Twenty-eight states have alignment guidelines that cover lateral placement and adjustment at drainage structures. Thirty states have construction guidelines for post and anchor foundations, tolerances, and other requirements. Only 18 states reported having maintenance guidelines

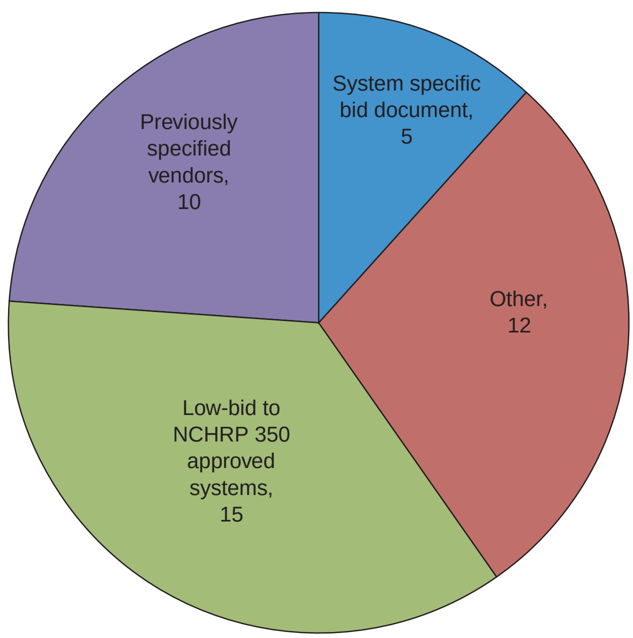


Figure 3.7. Criteria used to select a specific cable barrier system.

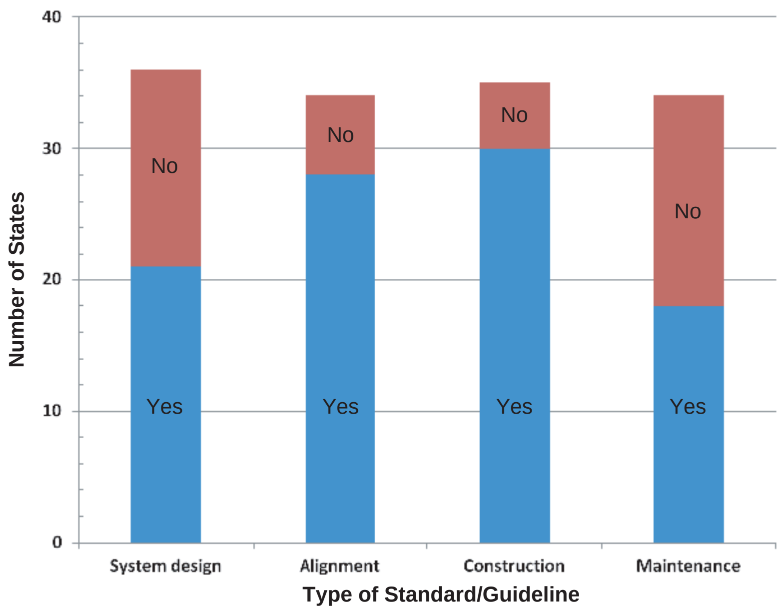


Figure 3.8. Number of states having cable barrier standards.

for tasks such as retensioning, anchor monitoring, and reinstallation and for keeping the cable barrier system in operating condition.

Figure 3.8 shows the number of states having cable barrier standards for system design, alignment, construction, and maintenance.

3.4 Cable Barrier Impacts, Penetrations, and Crashes

The survey posed questions about barrier impacts, penetrations, and crossover crashes for medians where cable barrier systems were installed. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 10: Approximately, every year, how many reported impacts (i.e., crashes) into cable barriers occur on average in your state?
- Question 11: Approximately how many of these reported cable barrier impacts resulted in vehicular penetration? (Penetration is defined as an impact where the vehicle completely passed through the system.)
- Question 12: How many cable barrier penetrations have resulted in crashes into opposite-direction traffic?
- Question 13: Based on the penetrations you experienced, is there a factor or factors that most likely contributed to the penetrations (e.g., barrier type, median feature, impact condition, barrier placement, etc.)?
- Question 14: Are you aware of any crashes into cable barriers by motorcyclists? If so, please summarize the number, circumstances, and severity of such crashes.
- Question 19: Please indicate (yes/no) if the cable barrier failure modes below occurred in your state.

Participants were asked a number of questions about their experiences with cable barrier crashes. Twenty-three states provided information on their yearly average number of reported crashes into cable barriers. Three states did not have any recorded accidents while five states had less than one crash per mile per year. Thirteen states had average accidents between one and six crashes

Table 3.3. Opposite-traffic crashes per year from cable barrier penetrations in 7 states.

Vehicle Penetrations Resulting in Opposite-Direction Crashes							
Year	2003	2004	2005	2006	2007	2008	2009
Number of Crashes	38	31	38	21	35	26	20

per mile per year. Additionally, two states, which have a total cable barrier length of less than 15 miles, reported a higher rate of about 25 crashes per mile per year.

Vehicle penetrations, defined as an impact where the vehicle completely passed through the cable barrier system, were reported by 17 states to have occurred in a combined total of 178 crashes. All but one of the penetrations occurred in the median. There were 25 crashes that involved overrides, 28 crashes were underrides, and the remaining 124 crashes were reported as "other" or unknown. The number of "unknown" crashes is high because some states do not have in-depth details about each accident.

For the 17 states reporting cable barrier penetrations, 10 states had no opposite-direction crashes. The other 7 states reported, on average, a combined total of 30 opposite-direction traffic crashes per year. The combined length of the cable barrier systems reported by these 7 states is 1,434 miles. Table 3.3 shows the combined yearly number of opposite-direction crashes occurring in these 7 states for the period from 2003 to 2009. The number of crashes for 2008 and 2009 years might be lower because of data unavailability for recent years.

It is important to note that the fatalities reported by North Carolina for the years from 2003 to 2005 represent the majority of the fatalities listed in Table 3.3. This is attributed to the fact that North Carolina had data from a comprehensive study conducted on 255 miles of cable barrier systems from January 1, 2003 through December 31, 2005. Of the 2,635 total crashes 96 (3.6 percent) involved penetrations of the median barrier in which the vehicle actually reached the opposite-direction travel lanes. Of these 96 crashes, 38 occurred in 2003, 31 in 2004, and 27 in 2005.

Twenty-two states provided information on possible factors that contributed to median cable barrier penetrations as follows:

- Unstable impact conditions before hitting the barrier caused by, but not limited to, wet conditions, travelling over irregular terrain in the median, or interacting with other vehicles (6 states)
- Severe impact angle and speed (5 states)
- Vehicle's shape and its interaction with different cable heights (5 states)
- Lateral barrier location within the median (3 states)
- Median slope (2 states)
- Others (commercial vehicles and trucks, braking applied at impact point, snow, quality of construction, etc.)

Only 7 states provided information on motorcyclist crashes into a cable barrier. Their responses are as follows:

- One state had one crash where the motorcycle slid under the cables with a low injury severity.
- One state reported two crashes. The first was at a high speed on a curve and the motorcyclist was killed. The other crash involved a motorcyclist who ran off the roadway, laid the bike down, and skidded between posts. The motorcyclist had serious injuries.
- One state reported three fatal crashes where speed was the major contributing factor.

- One state had one crash where the motorcyclist came upon stopped traffic and decided to go into the median rather than hit the rear of a stopped vehicle. The driver was thrown off the motorcycle and took out two of the support posts. The driver appeared okay to the reporting officer, but was taken to the hospital and died three days later.
- One state reported approximately 100 crashes. Two of these crashes were fatal, the first involved speed, and the other one involved alcohol. These two fatalities occurred in locations where the cable barrier was placed near the inside shoulder.
- One state reported a total of 24 cable median barrier hits by motorcyclists over an 8-year period. Of these 24 crashes, 6 were fatal, 5 had A-Injuries, 8 had B-Injuries, 4 had C-Injuries, and 1 was a property-damage-only crash.
- One state reported one injury crash where the motorcyclist was forced off the road into the median cable barrier by a pickup truck that changed lanes and did not see the motorcyclist.

In an effort to understand the possible causes of cable barrier penetrations and crashes, a question on failure mode was posed. The responding states indicated the following:

- Cable failure during impact (6 states yes, 22 states no)
- Failure at end of cable connections (cable extension) (7 states yes, 24 states no)
- Failure at connection between cables and end anchors (8 states yes, 22 states no)
- Excess barrier deflection during impact due to horizontal curvature (9 states yes, 21 states no)
- Excess barrier deflection due to long anchor-to-anchor segments (4 states yes, 25 states no)
- Penetrations/excess deflection due to long post spacing (6 states yes, 24 states no)
- Penetration/excess deflection due to cable spacing or number cables (7 states yes, 22 states no)
- End-anchor pull-out due to soil condition (14 states yes, 16 states no)
- Post foundation pull-out due to soil condition (12 states yes, 18 states no)

3.5 Repair or Maintenance Concerns

The survey next posed two questions about repair and maintenance concerns and practices related to cable barrier systems. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 15: Have you experienced any significant or recurring repair or maintenance concerns? If so, please elaborate by cable barrier type as appropriate.
- Question 18: Please describe your maintenance practices.

Thirty-three states responded to this, seven of which did not have any major repair or maintenance concerns. Below are the reported repair and maintenance concerns.

- Weak soil, motion of post foundation especially after spring thaws, crack in foundation (5 states)
- Foundations break upon impacts even when concrete strength tested exceeds manufacturing specifications (4 states)
- Wet or icy median conditions delay repairs since it is hard to get maintenance vehicles to the cable barrier, and posts get frozen into the sockets in winter (4 states)
- Anchors creep, progressive movement of cable end-anchor blocks (3 states)
- Posts gradually lean over as a result of repeated snowplow shoving, spacer blocks collapse on snow loads (2 states)
- Unreported crashes and nuisance hits create repair expenses without the ability to file claims against insurance companies (2 states)
- For curvature hits, cables end up near travel lanes (2 states)
- Maintenance costs, especially when median is narrow, because it gets hit more frequently (2 states)
- Posts twist with cable tensioning (1 state)

- Posts shearing off instead of bending during crashes cause some difficulty in removing the remaining post from the socket (1 state)
- Frequent hits make it difficult to keep up with repairs by contractors (1 state)
- Repair more than a mile stretch of cable (1 state)
- Repair costs are higher with short post spacing (1 state)
- Safety concerns and maintenance difficulties when cable barriers are installed without use of a "mow strip" (1 state)
- Lack of maintenance guidelines for different systems (especially, low tension) (1 state)
- Others (rusting or oxidation of components that are galvanized due to cutting or punching, sockets have been pulled out by severe accidents, end-terminal of a cable barrier system is not crashworthy).

The request for information on maintenance practices yielded the following responses:

Typically, how often do you inspect cable barrier systems?

- Once a year (10 states)
- Twice a year (8 states)
- Once a month (2 states)
- Once every two weeks (1 state)
- Once a week (2 states)
- No inspections (3 states)

Typically, how long after impact is the barrier repaired?

- Less than 2 days (4 states)
- Within 3 or 4 days (4 states)
- Within 5 to 7 days (5 states)
- Within 8 to 14 days (6 states)
- Up to a month (3 states)

Typically, how many posts are replaced per impact?

- Fewer than 5 posts (5 states)
- From 6 to 8 posts (11 states)
- From 8 to 12 posts (4 states)
- Twenty posts (1 state)
- Do not know (5 states)

What is a typical cost of repair per impact?

- Less than $500 (5 states)
- Less than $1,000 (12 states)
- From $1,000 to $2,000 (4 states)
- From $2,000 to $3,000 (2 states)
- More than $3,000 (2 states)
- Do not know (4 states)

Do you use mow strips? If yes, what is the additional cost?

- Yes, $6 to $25 per linear foot for asphalt, $12 per linear foot for concrete (15 states)
- No (19 states)

Do you utilize used parts in repairs? If yes, has this caused problems?

- Yes, some problems (8 states)
- Yes, no problems (5 states)
- No (21 states)

3.6 Other Critical Issues

The survey next posed two questions regarding general concerns about the deployment of cable barrier systems. These addressed basic issues as well as concerns related to procurement, design, and addressing regional conditions. As such, they represent topics that new guidelines might try to address. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were as follows:

- Question 16: Please list the most critical issues that you believe need to be addressed in the guidelines for design, selection, installation, and maintenance of cable barriers. List the most critical first.
- Question 17: Please answer the following design/construction-related cable barrier questions.

Thirty-three states indicated the following critical issues for the design, selection, installation, and maintenance of cable barriers:

- Placement guidelines including median configuration, placement location, cable barrier offset from the roadway, minimum and maximum median width (21 states)
- Different slopes and their impact on barrier effectiveness for 4H:1V and 6H:1V slopes (15 states)
- System performance differences between field data and NCHRP Report 350 tests; a comparison between systems tested under MASH and NCHRP Report 350; standardize test requirements (9 states)
- Cable heights and cable spacing to accommodate small and large vehicles (8 states)
- Geotechnical properties (soil conditions) and creep (8 states)
- Minimum post spacing, recommend post spacing, and a chart for deflection vs. post spacing (7 states)
- Costs and benefits (6 states)
- Recommendation between three vs. four and TL3 vs. TL4 cable barrier systems (6 states)
- Foundation design for terminals, concrete collars, and end terminals (6 states)
- Maintenance guidelines that contain easy repair procedures, especially during winter, as well as budget guidance (6 states)
- Transition to other barrier systems and crashworthiness (5 states)
- Recommended frequency of retensioning for high-tension barriers and force level to prestretched cables (4 states)
- Warrants for a new system (3 states)
- Effect of sharp angle and high-speed impacts on deflection, as well as vehicle dynamics (3 states)
- Spacing between anchors and its effects on cable performance (how far apart can the anchors be spaced before the cable performance goes down?); address the effects on deflection of anchor-to-anchor barrier length differences between field applications and crash test installations (2 states)
- Barrier performance on curved alignments (2 states)
- Ways to eliminate penetration, and if a single run is to be installed, which side of roadway is ideal? (2 states)
- Weaved vs. parallel cable barrier systems (2 states)
- Cable systems that do not allow cables to separate and act individually or in subgroup(s) can result in underride or override (1 state)
- Barrier's ability to work after being struck (1 state)
- Deflection degradation over time without pretensioning (1 state)
- Other (crash history, crash risk, motorcycle safety, design criteria and tolerances, trucks, non-proprietary designs, drainage)

One state recommended not installing breakaway signs and luminary support of any kind within the zone of deflection of a cable barrier system. Also, if cable barrier is used in shoulder applications, reduce post spacing to 4 ft and provide 4 ft behind barrier before the slope break point for steep slopes (such as 2H:1V). Another state suggests that AASHTO Roadside Design Guide Figure 6:18 does not apply to flexible cable barrier systems.

The general design, procurement, and deployment concerns questions revealed the following:

Do you have typical guidelines for cable barrier placement?

- Have placement guidelines (26 states)
- Have placement guidelines in draft form (4 states)

Is barrier performance better when placed near the shoulder instead of in the median area?

- Unknown (11 states)
- Yes, better near shoulder (9 states)
- No consensus (4 states)
- Equally effective in either location (2 states)

Do you have requirements for placement near median ditches, drainage inlets, and dikes?

- Yes (23 states)
- No (9 states)
- Use FHWA recommendations (3 states)
- Use AASHTO recommendations (2 states)

Do you provide soil data during request for procurement?

- Have soil data requirements (19 states)
- Do not have soil data requirements (12 states) [many rely on the contractor or manufacturer to do its own testing]

Do you require contractor to repair/replace anchors when excess movement of anchor occurs?

- Yes (25 states)
- No (5 states)
- Do not have this problem (3 states)

Do you have requirements on the type of ends used on the cables?

- Yes (19 states)
- No (9 states)
- Require end terminal to be NCHRP Report 350 accepted (6 states)
- Follow manufacturer's recommendation (6 states)

Do you require pull testing of fully fitted splices to determine breaking strength?

- Yes (10 states)
- No (22 states)

Do you require expected deflection values when anchor-to-anchor length is greater than the crash-tested length?

- Yes (12 states)
- No (19 states)
- Do not install systems longer than what was tested (6 states)
- Other states add a factor of safety, or define maximum deflection values, or do not allow a cable length of more than 2,000 ft.

Do you have inspection requirements?

- Yes (22 states)
- No (7 states)

- Use construction requirements included in the contract specifications and state's standards (5 states)
- Use only the manufacturer's recommendations (3 states)

Do you have construction tolerance limits?

- Yes (24 states)
- No (5 states)
- Use the manufacturer's recommendations (6 states)

What design and placement considerations are complementary with effective maintenance?

- Mowing strips (5 states)
- Keep the barrier at least 10 ft away from roadway (7 states)
- Place the cable barrier as far as possible from the roadway but not in the ditch (4 states)
- Place the cable barrier at the edge of the paved roadway since it eliminates the possibility of erosion and slope problems in front of the cable rail (3 states)
- Require cable barriers to have cast-in-place foundations with embedded sleeves for the posts (4 states)

What practices have you found to make maintaining the roadside around where cable barriers are installed easier?

- Use mowing strips (8 states)
- Use herbicides around posts (4 states)
- Widening the pavement shoulder to cover under the cables (3 states)
- Use vegetation control mats (2 states)
- Use rock liner (1 state)
- Keep the barrier out of the ditch bottom (1 state)

3.7 Summary

Based upon the agency survey the following can be concluded:

- Cable barrier systems are being used by many states, and the extent of use seems to be expanding.
- Low-tension systems were reported for 35 percent of the applications, but at least 58 percent of the applications select high-tension systems from one of the various vendors. Agencies select both three- and four-cable systems and many opt for TL4 systems.
- There is considerable variation in the approaches used to determine if cable barriers should be used. The responses indicated that 54 percent place cable barriers on 6H:1V or flatter slope medians. Placement on 4H:1V sloped medians was reported by 11 percent of the respondents.
- The current practices of states vary relative to the width of median and the slopes that are considered appropriate for the placement of cable barriers. The basic median configurations (i.e., cross-sections) also vary. The requirements for barrier placement in any median configuration also vary.
- Only about a quarter of the states have formal standards for cable barrier design, alignment, construction, and/or maintenance.
- There are varying factors that serve as the basis for the selection across the agencies. These include median configuration, deflections, costs, crash data, traffic levels, ease of maintenance, and potentials for snow accumulation. The number and relative importance of these factors in the selection process is not the same among agencies.
- Impacts, penetrations, and crossover crashes are occurring, but the rate and causes (i.e., failure modes) have not been fully established.

- Less than half the states provided information about the possible factors attributed to barrier penetration. The factors cited included wet conditions, vehicle type and shape, severe angle and speed, lateral position of the barrier, the slope conditions, soil conditions, and commercial vehicles.
- There was limited information available on the contribution of failures of the cable barriers when penetrations occurred.
- Maintenance concerns for cable barriers included weak soil, foundation breaks, repair delays caused by wet or icy medians, anchor creep, post lean, unreported nuisance hits, and costs.
- The agency practices for inspection and routine maintenance vary considerably.

CHAPTER 4

Descriptions of Available Cable Barriers

Six types of NCHRP Report 350-accepted cable barrier systems are currently available for use on U.S. highways, as follows:

- Weak-Steel Post Cable (3-Strand) Guardrail (low-tension)
- Brifen Wire Rope Safety Fence (high-tension)
- Gibraltar Cable Barrier System (high-tension)
- Nucor Steel Marion Cable Barrier System (high-tension)
- Safence Cable Barrier System by Gregory Industries Inc. (high-tension)
- Trinity CASS Cable Barrier System (high-tension)

Several full-scale crash tests have been conducted to evaluate these systems and, based on these tests, Acceptance Letters have been issued by FHWA. Table 4.1 lists the different systems and the corresponding FHWA Acceptance Letters. A more detailed list of these systems is presented in Appendix B of the contractors' final report. Each of these systems is available in a variety of configurations with variations in the number of cables, cable heights, post spacings, post sizes, post embedments, test levels, etc. The following sections give a general description of the different available systems.

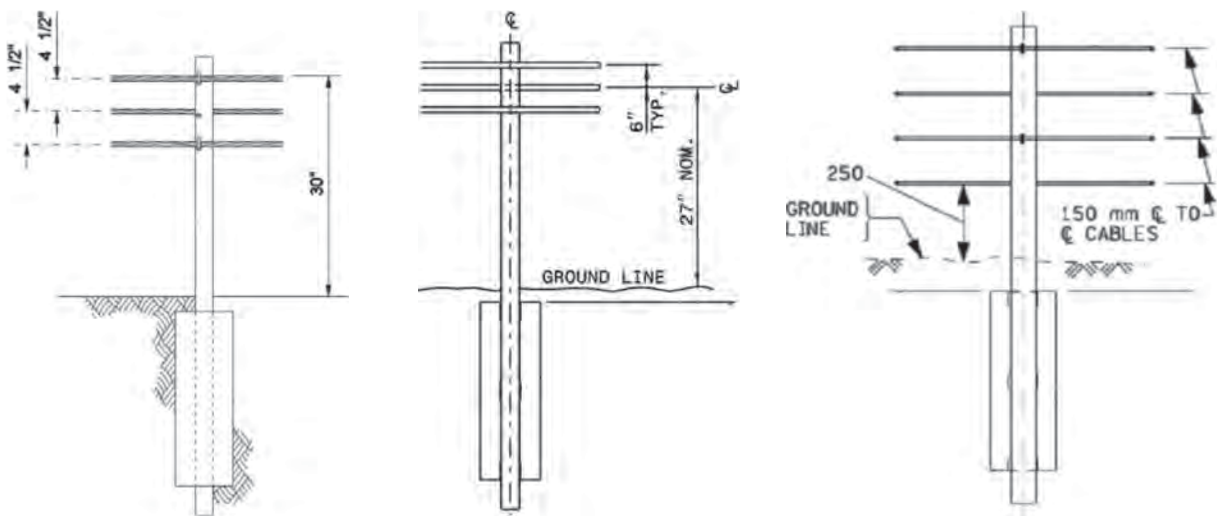
4.1 Weak-Steel Post Cable (Three-Strand) Guardrail

Prior to the recent advances in cable barrier technology, the most common design was the generic cable guardrail, also known as a low-tension system. A low-tension cable system, based on the Washington State design, has been tested in accordance with the NCHRP Report 350 TL3 recommendation at the Texas Transportation Institute [50]. The tested system consisted of three 19 mm (0.75 in) 3 × 7-steel-strand galvanized wire rope cables having a minimum tensile strength of 110 kN (25 kips). The cables were supported at the appropriate heights above ground by S75 × 8 rolled steel posts, 1,778 mm (70 in.) in length, using hook bolts. The hook bolts open up to permit the cable to release from the post when a force ranging from 2,240 N (500 lb) to 4,450 N (1,000 lb) is applied normal to the longitudinal axis of the post. The posts were spaced 4.9 m (16.0 ft) apart.

Steel soil plates, 203 mm × 610 mm × 6 mm (8 in. × 24 in. × ¼ in.) in size, were connected (welded) to the posts at a height of 100 mm (4 in.) from the lower end. The posts, with the welded soil plates, were embedded 851 mm (33.5 in.) in soil. The cable ends were connected to the ground by cable anchors attached to large concrete blocks. The concrete blocks were about 1450 mm × 1150 mm × 990 mm (57 in. × 45 in. × 39 in.) in size. The cables were pretensioned using turn-buckles attached to spring compensator end-assemblies. The spring compensators had a spring rate of 2,000 ± 222 N/mm (450 ± 4.5 lb/in.). The tension in the cables is set based on the atmospheric temperature (about 4,450 N [1,000 lb] at 18°C [65°F]).

Table 4.1. Currently available cable barrier systems.

Manufacturer/Product Name	Acceptance Letter No.	NCHRP 350 Test Level
Generic Weak-Post Cable Guardrail	B-64, B-64 Sup, B-161	TL3
Brifen Wire Rope Safety Fence	B 82 B82 A, B, B1, C, C1,D	TL3, TL4
Gibraltar Cable Barrier System	B-137 B137 A, A1, B, C	TL3, TL4
Nucor Steel Marion Cable Barrier System	B-96, B96A, B167	TL3, TL4
Safence Cable Barrier System by Gregory Industries Inc.	B-88, B-88A-E	TL3, TL4
Trinity CASS Cable Barrier System	B-119,A,B B-141,A,B,C,D,E,F B-157	TL3, TL4



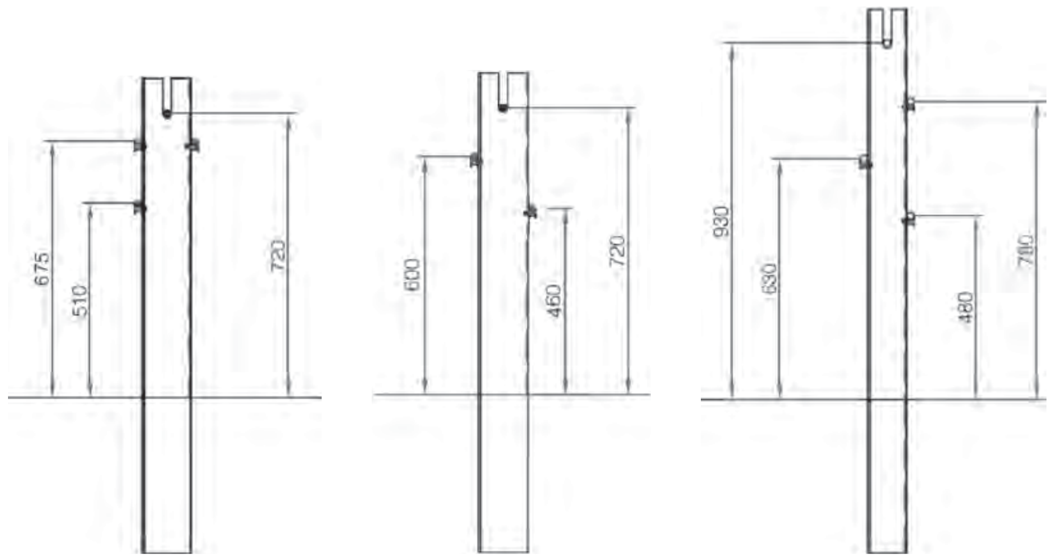
(a) three cables, 4.5" spacing (b) three cables, 6" spacing (c) four cables, 6" spacing

Figure 4.1. Sample cable heights for generic cable barriers.

Generic cable barrier systems are available in different configurations. Three different posts are used with these systems: S75 × 8 steel I-beam (Acceptance Letter B64—SGRO1-a), flanged steel U-channel (Acceptance Letter B64—SGRO1-b), and weakened rounded timber post (Acceptance Letter B64 sup–SGRO1-c). Additionally, different cable setups are used. For roadside applications, all cables are placed on the same side of the post, the side closer to the road. When the barrier is placed in the median, two cables are placed on one side of the post and the other cable is placed on the opposite side. The heights of the cables relative to ground level also varied for different generic cable barrier installations. The most common cable heights are similar to the tested configuration. The lowest cable in this design is set at 533 mm (21 in.) from the ground with the other two consecutive spaces at 114 mm (4.5 in.) above (see Figure 4.1a). In other cable barrier designs, the heights for the three cables are set at 533 mm (21 in.), 686 mm (27 in.), and 838 (33 in.) from ground level (see Figure 4.1b). New York State recently introduced a four-cable barrier design (Acceptance Letter B-161). The heights of the four cables in this design are set at 254 mm (10 in.), 406 mm (16 in.), 559 (22 in.), and 712 mm (28 in.), as shown in Figure 4.1c.

4.2 Brifen Wire Rope Safety Fence

The Brifen Wire Rope Safety Fence (WRSF) system is available in different configurations. The distinctive characteristics of the system are the Z-shaped post and the interweaving of the cables between adjacent posts. Three- and four-cable configurations are available. For



(a) TL3 – four cable (b) TL3 – three cable (c) TL4 – four cable

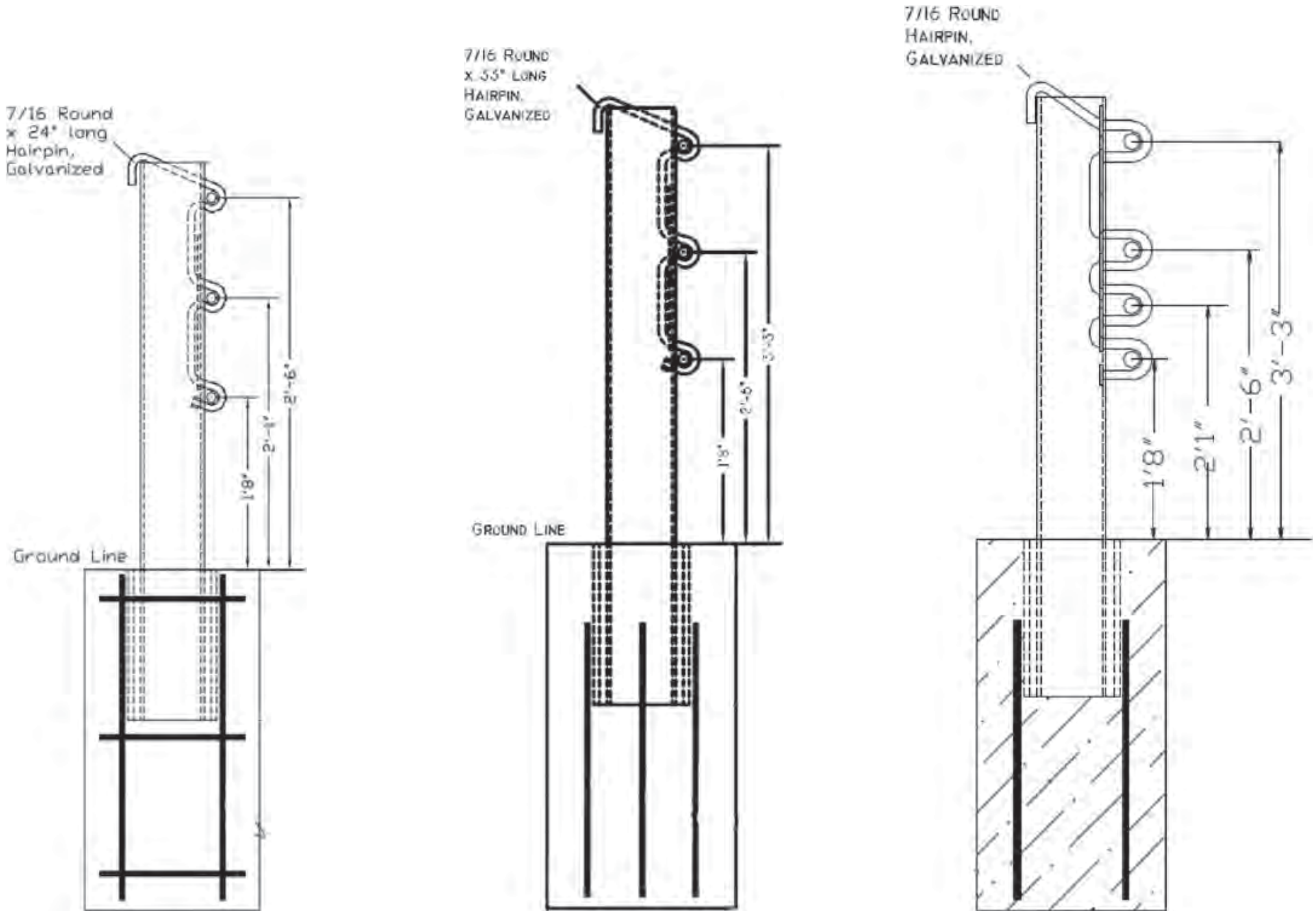
Figure 4.2. Cable height configurations for Brifen WRSF systems.

both configurations, the top cable is placed in a slot at the center of the post. The other two or three cables are woven around the posts. Different cable height configurations have been tested and accepted as TL3 and TL4 roadside barriers. The first system tested was a TL3 four-cable design as shown in Figure 4.2a (Acceptance Letter B-82). In this design, the top cable is placed at a height of 720 mm (28.4 in.) from ground level. The bottom cable is placed at a height of 510 mm (20 in.). The middle two cables are placed at a height of 675 mm (26.57 in.). A three-cable design is also available and has been tested for TL3 condition, as shown in Figure 4.2b (Acceptance Letter B-82C). The heights of the three cables for this system are 460 mm (18 in.), 600 mm (23.5 in.), and 720 mm (28.4 in.). A third design, a TL4 system with four cables, has also been tested and accepted by FHWA (Acceptance Letter B-82B). The heights of the cables for this design, as shown in Figure 4.2c, are at 480 mm (18.9 in.), 630 mm (24.8 in.), 780 mm (30.7 in.), and 930 mm (36.6 in.).

The Brifen WRSF designs are high-tension systems. The cables are tensioned based on the ambient temperature. This tension varies from 14.0 kN (3.1 kips) at 30°C (86°F) to 36.0 kN (8.1 kips) at 10°C (50°F). The posts are typically placed inside a tubular steel socket embedded in a 305 mm (12 in.) diameter × 760 mm (30 in.) deep concrete footings. Driven posts or posts set in driven steel sleeves are also acceptable with the Brifen systems. Typical post spacing of the Brifen system is 3.2 m (10.5 ft). Post spacing of 2.4 m (7.87 ft) and 6.4 m (21 ft) were also tested in accordance with NCHRP Report 350.

4.3 Gibraltar Cable Barrier System

The Gibraltar high-tension cable barrier system is available in different configurations. The distinctive characteristic of the system is that the cables are attached to the post using a single 30 mm (7⁄16 in.) diameter steel hair pin. The system consists of three or four 19 mm (0.75 in.) 3 × 7-steel-strand galvanized wire rope cables. Prestretched and non-prestretched cables can be used with the system. The cables are connected to C-channel posts that are 83 × 63.5 × 3.8 mm (3.25 × 2.5 × 0.15 in.) in cross section. The posts are placed such that adjacent posts are on opposite sides of the cables. The posts are typically connected to the ground through steel sockets that are embedded in reinforced concrete cylinders. Other connections, such as driven posts, have been accepted by FHWA. Varied post spacing can be



(a) TL3 – three cable (b) TL4 – three cable (c) TL4 – four cable

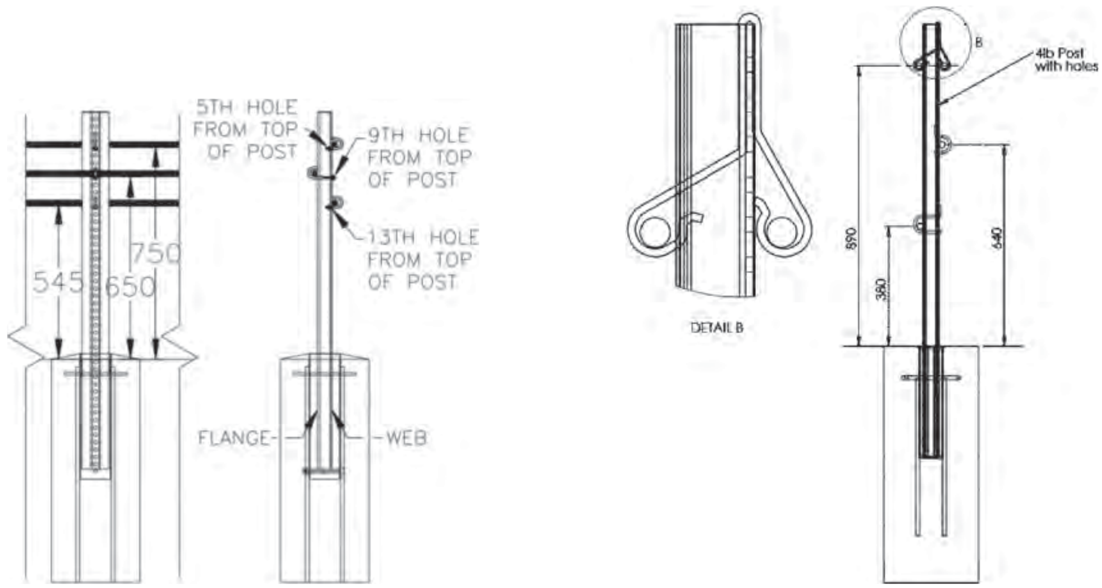
Figure 4.3. Cable height configurations for Gibraltar cable barrier systems.

used with the Gibraltar cable barrier system. Spacing from 3 m (10 ft) to 9 m (30 ft) can be used with the system.

The Gibraltar cable barrier system has been tested in accordance with NCHRP Report 350 and is accepted for TL3 and TL4 conditions. The main difference between the TL3 and TL4 systems is cable spacing and length of the posts. For the TL3 three-cable system, the cable heights are set at 508 mm (20 in.), 635 mm (25 in.), and 762 mm (30 in.) from ground level, as shown in Figure 4.3a (Acceptance Letter B137). For the TL4 three-cable system, the heights are 508 mm (20 in.), 762 mm (30 in.), and 990 mm (39 in.), respectively, as shown in Figure 4.3b (Acceptance Letter B137a). A third system with four cables has also been accepted at TL4 condition (Acceptance Letter B137b). The heights of the cables from ground level are 508 mm (20 in.), 635 mm (25 in.), 762 mm (30 in.), and 990 mm (39 in.), as shown in Figure 4.3c.

4.4 Nucor Steel Marion Cable Barrier System

Two Nucor high-tension cable barrier systems are accepted for use on the National Highway System: a three-cable TL3 system (Figure 4.4a—Acceptance Letters B96 and B96A) and a four-cable TL4 system (Figure 4.4.4b—Acceptance Letter B167). Both systems use 19 mm (0.75 in.) 3 × 7-steel-strand wire rope cables. Prestretched as well as non-prestretched cables can be used



(a) TL3 – three cable (b) TL4 – four cable

Figure 4.4. Cable height configurations for Nucor cable barrier systems.

with these systems. The cables in both systems are attached to 6 kg/m (4 lb/ft) U-channel steel posts. Locking hook bolts, 6.4 mm (.25 in.) in diameter, are used to connect the cables to the posts.

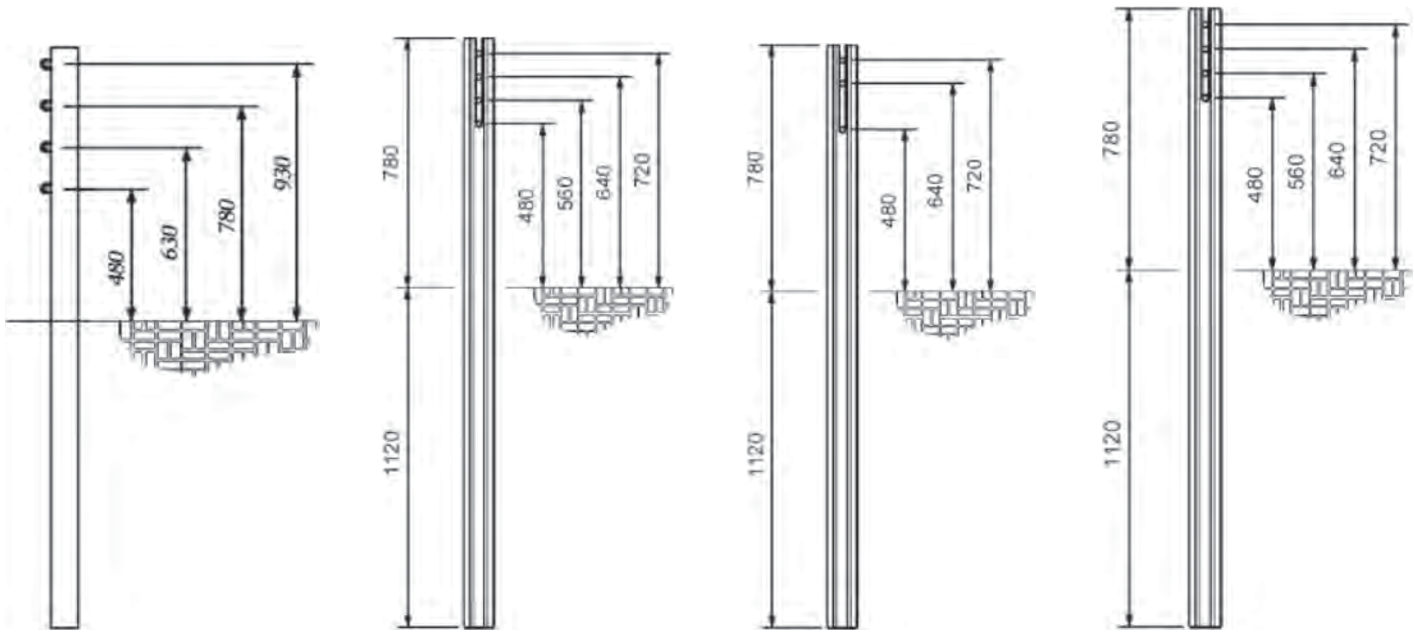
For the TL3 design, the three cables are placed at heights of 545 mm (21.5 in.), 650 mm (25.6 in.), and 750 mm (29.5 in.), as shown in Figure 4.4a. The top and bottom cables in this design are placed on one side of the post while the middle cable is placed on the opposite side. The TL3 design was tested with three different post spacings: 2 m (6.5 ft), 3.8 m (12.5 ft), and 5.1 m (16.7 ft). All tests met the NCHRP Report 350 criteria with variation in barrier deflections. Two different post embedment types were used in the TL3 tests: Direct driven posts with a trapezoidal soil plate, and a socket steel sleeve set in a 300 mm (12 in.) diameter concrete cylinder are available.

For the TL4 design, the bottom cable is placed at 380 mm (15 in.), the top two cables are placed at 890 mm (35 in.), and the remaining cable is placed at 640 mm (25.2 in.) from ground level as shown in Figure 4.4b. Two of the four cables are placed on one side of the post and the other two are placed on the opposite side. Each post is fixed to the ground by means of a plastic socket that is embedded in a 300 mm (12 in.) diameter concrete foundation. The spacing between the posts is 6.1 m (20 ft).

4.5 Safence Cable Barrier System

Safence high-tension cable barrier systems have been tested under TL3 and TL4 conditions. The cables in these systems consist of 19 mm (0.75 in.) 3 × 7-steel-strand prestretched wire rope cables. Systems with three different types of line post have been tested. These post types include an elliptically shaped steel post, an I-shaped post (41 mm flange width and 80 mm web width), and a C-shaped post (95 mm × 30 mm). All three posts have a thickness of 4 mm.

The elliptical posts were used in the original TL3 Safence design (Acceptance Letter B88). This system had four cables that are placed at heights of 480 mm (18.9 in.), 630 mm (24.8 in.), 780 mm (30.7 in.), and 930 mm (36.6 in.) from ground level, as shown in Figure 4.5a. All four cables in this system are placed on the same side of the post and attached using twisted hooks.



(a) 1st TL3 design four cables

(b) 2nd TL3 design four cables

(c) 1st TL4 design three cables

(d) 2nd TL4 design four cables

Figure 4.5. Cable height configurations for Safence cable barrier systems.

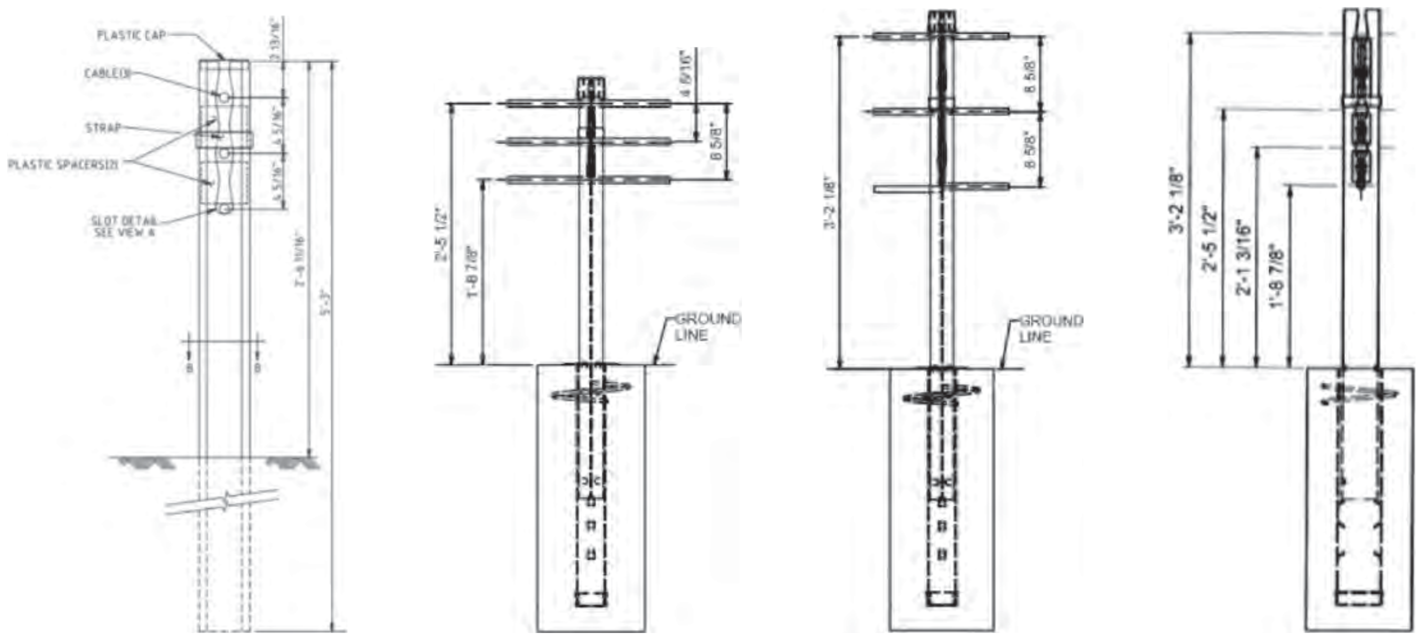
This system is intended for non-median applications (roadside application only). The posts in this design are spaced at 2.5 m (8.2 ft) and embedded 1.11 m (3.6 ft) in soil.

The I-shaped post was used in the second TL3 Safence cable barrier design (Acceptance Letter B88-a). In this design, the four cables are placed at heights of 480 mm (18.9 in.), 560 mm (22 in.), 640 mm (25.2 in.), and 720 mm (28.3 in.) from ground level, as shown in Figure 4.5b. All four cables are inserted in a slot at the center of the post and separated by plastic spacers. This design can be used for both median and roadside applications. A similar design, using C-shaped posts instead of the I-shaped post, has been accepted by FHWA (Acceptance Letter B88c). The posts, in both designs, can be driven directly into the ground or embedded in 200 mm (8 in.) diameter by 600 mm (24 in.) deep concrete footings. Additionally, post spacings of 2 m (6.5 ft) or 3 m (9.8 ft) can be used with this TL3 design.

Two Safence designs have been accepted by FHWA at the TL4 level (Acceptance Letter B88d and B88e). Both designs are similar except for the number of cables. The first design uses three cables placed at heights of 480 mm (18.9 in.), 640 mm (25.2 in.), and 720 mm (28.3 in.) from ground level, as shown in Figure 4.5c. The second design has an additional cable at 560 mm (22 in.) height, as shown in Figure 4.5d. The TL4 designs are similar to the second TL3 design. The posts, however are made stronger, ATSM A50 steel is used instead of the A36 steel used in TL3 designs. Each post was also stiffened at the ground line by adding a steel plate inside the C-post. Additionally, a steel hook was added to the top of each post to delay the release of the cables from the posts during the impact.

4.6 Trinity CASS Cable Barrier System

The Trinity CASS high-tension cable barrier systems have been tested under TL3 and TL4 conditions and are available in different configurations. The cables in these systems consist of 19 mm (0.75 in.) 3 × 7-steel-strand prestretched or non-prestretched steel wire ropes. Three and four cable systems are available. The cables are placed in a slot at the center of the post and



(a) 1st TL3 design
C-Post - three cables

(b) 2nd TL3 design
I-Post - three cables

(c) 1st TL4 design
I-Post - three cables

(d) 2nd TL4 design
I-Post - four cables

Figure 4.6. Cable height configurations for Trinity CASS cable barrier systems.

separated by plastic spacers. The posts can be anchored to the ground using steel sockets that are cast into concrete cylinders, steel tubes driven in soil, or posts directly driven in the soil. Different post spacings, ranging from 2 m (6.5 ft) to 10 m (32.5 ft), can be used with the CASS systems.

The original CASS design uses cold-formed C-shaped posts and has been accepted at TL3 condition (Acceptance Letter B-119). The cable heights relative to ground level in this design are 530 mm (21 in.), 640 mm (25.2 in.), and 750 mm (29.5 in.), as shown in Figure 4.6a. The second CASS TL3 design uses hot rolled posts (Acceptance Letter B-141). The posts in this design are weakened by drilling two 17.5 mm (11⁄16 in.) diameter holes through each flange at ground level. The cables were kept at the same heights as the original design, as shown in Figure 4.6b. A TL4 design, using the same weakened S4 × 7.7 posts, has been tested and accepted by FHWA (Acceptance Letter B-141). This design uses three cables placed at heights of 530 mm (21 in.), 750 mm (29.5 in.), and 968 mm (38 in.) from ground, as shown in Figure 4.6c. A second CASS TL4 design that uses four cables instead of three, has been accepted by FHWA (Acceptance Letter B-157). The cables, in this design are set at heights of 530 mm (21 in.), 750 mm (29.5 in.), 640 mm (25.2 in.), and 968 mm (38 in.).

4.7 Other Designs

A new generic high-tension cable barrier system is in development at the MwRSF and is currently being tested in accordance with MASH. The tests are selected such that the system would be placed anywhere along the lateral direction of 4H:1V or shallower sloped medians.

The system uses four 19 mm (0.75 in.) steel wire ropes (Figure 4.7). The cable heights are at 343, 610, 876, and 1,143 mm (13.5, 24, 34.5, and 45 in.). The four cables are attached to S3 × 5.7 steel posts via specially designed keyway brackets. The brackets are designed to fracture at a certain load level and allow the cables to separate from the posts. The brackets are connected to the posts using 8 mm (5⁄16 in.) diameter bolts, washers, and nuts (two per cable). The posts,

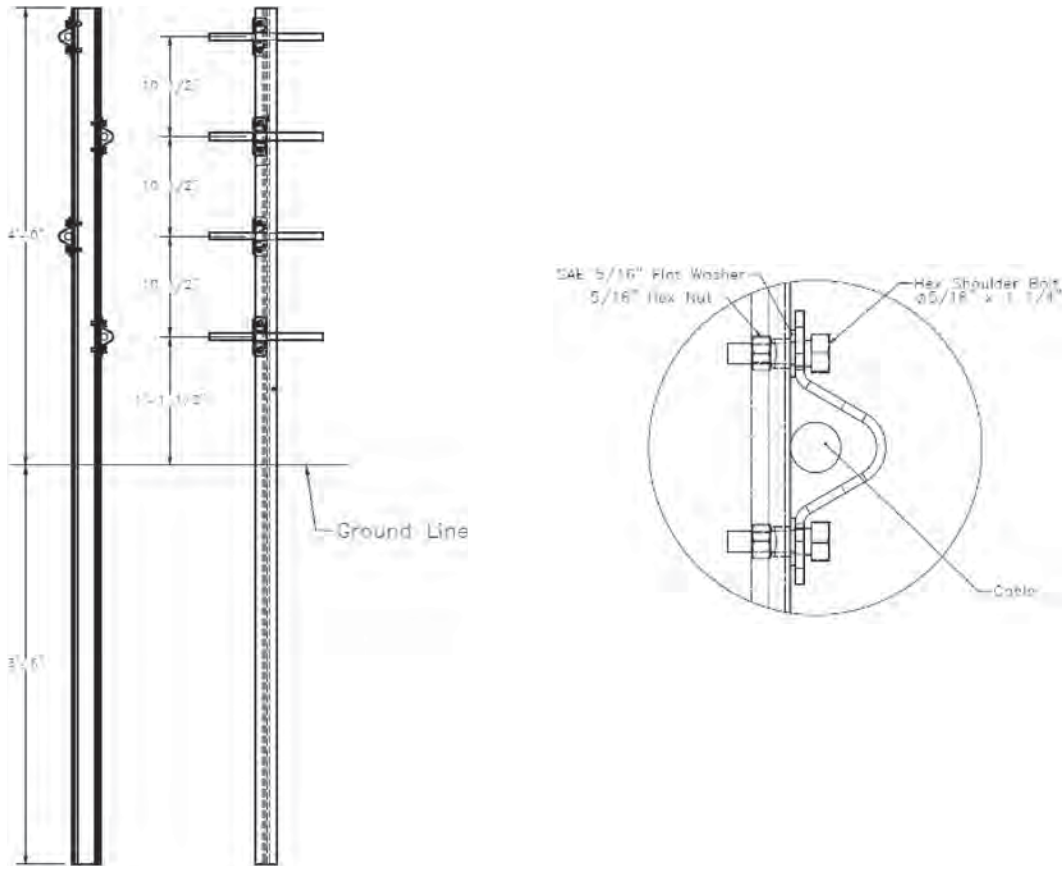


Figure 4.7. MwRSF generic high-tension cable barrier system.

in the tests, are imbedded 1.0 m (3.3 ft) in the ground. The installation length in the tests was 183 m (600 ft), which is the minimum length required under MASH. Even using this length, load cells placed at the end anchors showed a 136 kN (30 kips) increase in cable tension force due to an impact with the 2270 P vehicle. This leads to the conclusion that higher deflection would be observed for longer installations.

Four full-scale crash tests have been conducted on this system, and three additional tests are planned in the near future. The tests vary in vehicle type (1100C, 1500A, and 2270P), barrier location (near side, far side, placement relative to the median), and soil strength (weak and strong soil). A matrix of tests for barrier systems that would be placed anywhere in 4H:1V sloped median will be finalized based on observations from the tests conducted on this system.

CHAPTER 5

Analyses and Results

As noted in Chapter 1, the panel directed the contractor to pursue analyses in the seven areas outlined in Table 1.1. This chapter will provide the details about the approaches used, the factors considered, and the results obtained for the following seven areas:

- Cable barrier placement
- Cable barrier deflection
- End-anchoring and post-anchoring systems
- Interconnection with other systems
- Horizontal curvatures
- Construction and maintenance tolerances
- Installation and maintenance costs

The intent of conducting the analyses in these areas was to derive science- and data-based insights on the influence of various factors with the subsequent translation of these findings into guidelines that would facilitate the deployment of effective cable barrier systems for median and roadside applications.

As one ventures into these analyses, it is necessary to be cognizant of the many factors associated with cable barriers that may need to be considered.

There are many variations in cable barrier system designs, placement, and maintenance. These variations include the following:

- Cable barrier system design
  - Number of cables
  - Cable positions (i.e., heights)
  - Cable placement on posts
  - Cable connectors
  - Post design
  - Post spacing
  - Post embedment including driven vs. placement in foundations
  - Anchorage features
  - Anchor spacing
  - Tensioning elements
  - Cable type
  - Tension levels
  - Transition options
- Placement considerations
  - Median cross-section
  - Changes in median cross-section

  - Tangent and curved roadway sections
  - Obstacles in the median or roadside
  - Shoulder/slope design
  - Drainage requirements
  - Soil conditions
  - Seasonal effects
  - Transitions to other barriers
  - Installation operations
- Maintenance considerations
  - Probability of nuisance hits
  - Anchor movement
  - Post foundation failures
  - Retensioning
  - Maintenance cycles
  - Ease of repair
  - Requirements for lane closure

These factors can have different types and degrees of effects on cable barrier performance. The need exists to assess the implications of the factors to identify the critical ones and translate them into generic guidance. The following sections describe the analyses performed under this study to investigate the effects of some these factors and address the identified cable barrier issues. The results of these analyses were used to develop guidelines for the selection, use, and maintenance of cable barriers.

5.1 Cable Barrier Lateral Placement

One of the most critical factors that affects the performance of cable barriers is the lateral placement relative to configuration (i.e., width, slope, shape) of the roadside or median. On flat terrain, almost all currently available/accepted cable barrier systems will perform adequately and can safely redirect most errant vehicles departing the roadway under nominal conditions. However, this is usually not the case when the cable barrier is placed on a sloped median/roadside. The sloped terrain affects the relative height at which the vehicle impacts the cable barrier, i.e., the vehicle could impact the barrier at a higher or lower vertical position compared to that on flat terrain. This phenomenon could lead to a vehicle not fully engaging the cables and consequently underriding or overriding the barrier. It is, therefore, critical to ensure that the barrier is placed at a location where it can capture and/or redirect the majority of vehicles successfully.

To investigate the full effects of terrain profiles on cable barrier performance and to develop guidelines for a barrier's optimum placement, a comprehensive analysis was performed. Vehicle dynamics simulations were conducted to compute the trajectories of vehicles as they traverse a median on a diagonal path. Two commercially available vehicle dynamics programs were used to conduct the simulations and generate data and animations reflecting the trajectories. For each vehicle type considered in these analyses, two points were defined to represent the primary interface (engagement) region on the front of the vehicle. These points are labeled 1 and 2 in Figure 5.1. A trace of these two points viewed from a position standing in the center of the median downstream from the point a vehicle leaves the roadway is shown as the dark lines in Figure 5.2.

These same data points can be plotted on a diagram of the median cross-section (as shown in the lower part of Figure 5.2). It can be noted that in moving from left to right, after passing the breakpoint between the shoulder and the median onto a sloped surface, the vehicle will be airborne or at least have a low compression load on its suspension system. At some point the

Figure 5.1. Critical interface points.

vehicle will land (or return to a distribution of weight on all wheels), and the suspension will compress to absorb the dynamic load. As the vehicle continues its movement across the median there will be a rebound of the suspension as it dissipates energy. Thus, as the vehicle traverses the median, the height of its interface area will vary depending on the state of the vehicle's suspension system and the slopes of the median. Effective lateral placement of the barrier involves finding the locations where the vehicle's interface area matches the barrier's cable heights. For median applications, finding these locations is complicated by the need to have an effective interface for impacts from either direction.

The vehicle dynamics programs that were used in this study included HVE (Human Vehicle Environment, by the Engineering Dynamics Corporation) [51] and CarSim (by Mechanical Simulation Corporation) [52]. The programs were developed for use by engineers and safety researchers to study interactions among humans, vehicles, and their environment. They are high-level simulation tools aimed at creating three-dimensional models of vehicles and environments and allow the study of their dynamic interaction under selected conditions. Physical and

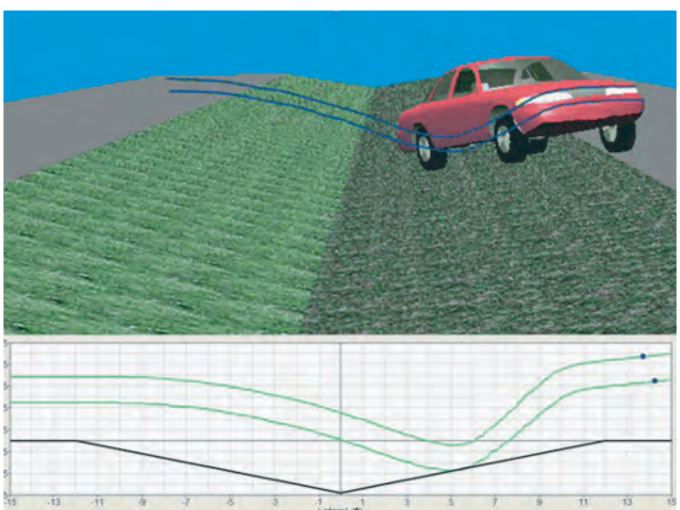


Figure 5.2. Trajectory of interface points as the vehicle crosses the median.

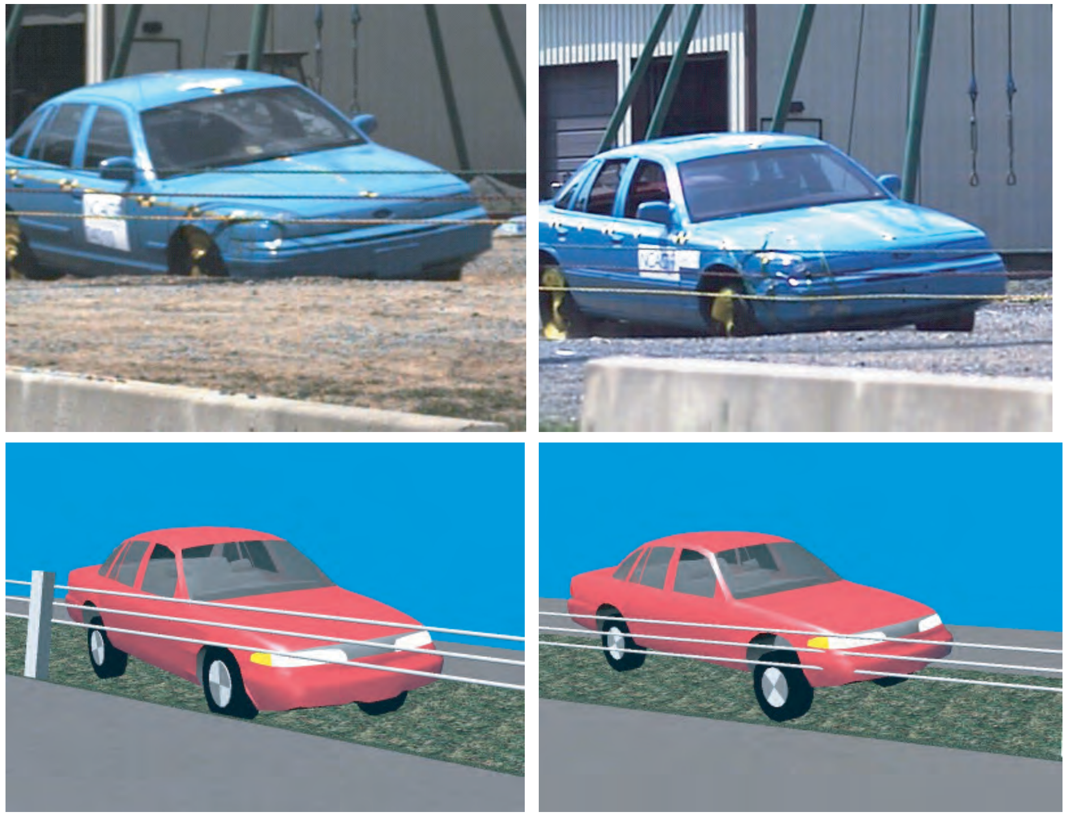


Figure 5.3. Comparisons of HVE predictions and full-scale crash test results.

mathematical models provide a detailed description of a motor vehicle that considers the influence of weight, suspension system, and other vehicle factors. Available databases include a wide range of high-fidelity vehicle models that can be used in dynamic reconstructions and simulations. HVE and CarSim provide physical and visual environment models to simulate selected conditions. Weather attributes, road geometry, and pavement friction properties can be computed and their effects on vehicle dynamics analyzed. Driver's action (e.g., throttle, brakes, steering, and gear selection) can also be simulated. The models have been thoroughly validated and are capable of predicting accurately a vehicle's trajectory for different terrain profiles. NCAC used these programs in several cable barrier research studies, and the results were compared to full-scale crash tests. The predictions were a close match to the full-scale crash tests. Figure 5.3 shows predictions from HVE at the start of impact compared to two full-scale crash tests.

The research considered a broad set of influencing factors as shown in Figure 5.4. This figure shows a typical divided highway where the median is the green area between the shoulders. The median can be of different widths and cross-sections. The cable median barrier is placed somewhere in the median and can be hit from either side. For the situation shown in Figure 5.4, a vehicle leaving the bottom roadway would have a "nearside" hit on the barrier. From the upper roadway, the vehicle would have a "farside" hit. A cable median barrier has to be located such that it functions effectively for both nearside and farside hits.

Today's vehicle fleet is a heterogeneous mix of vehicles with varying shapes and sizes. Figure 5.5 shows a sample assortment of vehicles from the fleet and the variations in the heights of their bumpers and primary structures. To address the effect of vehicle type on barrier performance, several vehicle models were used in the analyses to create an envelope of vehicle trajectories.

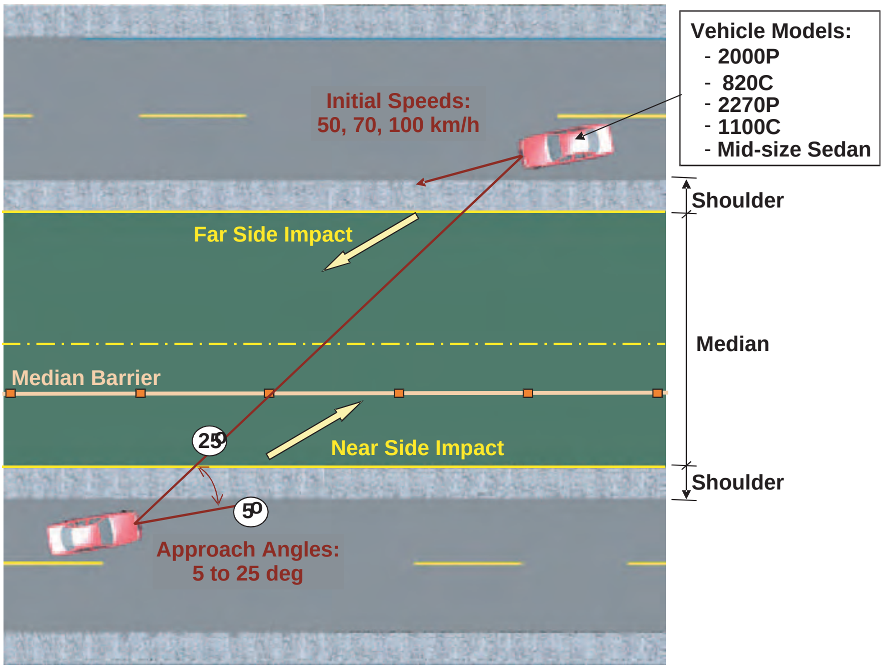


Figure 5.4. Factors considered in cross-median events.

These vehicle models included a pickup truck (Chevrolet C2500) and a small car (Honda Civic) to represent the two NCHRP Report 350 required test vehicles. A large sedan (Crown Victoria) was also included in the analysis. This vehicle type has been found in previous studies to be critical for cable barrier performance due to its front profile (similar to a small car) and its mass (similar to a pickup truck). Additionally, a larger pickup truck and a sedan representing the new MASH 2270P and 1100C vehicles, respectively, were included in the vehicle dynamics analyses.

Defining "effective interface conditions" for any cable barrier design and any median configuration can be accomplished in various ways. For this analysis, effective interface conditions were determined by the following:

- Assessing relative positions of the vehicle to the barrier such that
  - To minimize the potential for override, the top cable should contact the vehicle above Point 1 (lower critical point in Figure 5.1).
  - To minimize the potential for avoid underride, lower cable should contact the vehicle below Point 2 (upper critical point in Figure 5.1).

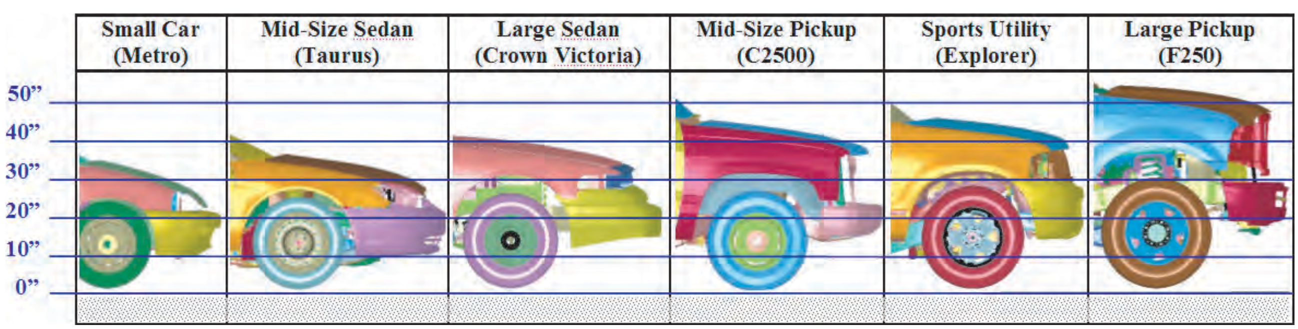


Figure 5.5. Variation in vehicle front profile.

- Defining the impact conditions to be considered. One approach would be to follow NCHRP Report 350 or MASH requirements. In this analysis, a broader view was taken requiring that the conditions should reflect a broader range of approach angles, speeds, and vehicle types.
- Associating interfaces with specific median configurations (i.e., width, shape, side slopes, and depth).

Two critical points (Points 1 and 2) were used for each vehicle to assess its interface with the barrier when placed at different locations along the lateral direction of the median. These critical points were selected based on the geometry of the front structure of the vehicles and by examining full-scale crash tests of these vehicles impacting different cable barrier systems. (Please note that references to colors in the following text will be clear in the color figures which are available in the online version of the report which can be found by searching the TRB website for *NCHRP Report 711.*) Using the results of vehicle dynamics simulations, trace paths of Point 1 for vehicles crossing a median from both directions were plotted in Figure 5.6 with each individual trace representing a specific vehicle, speed, impact angle, and crossing direction. These curves are "normalized" to relate the relative heights of individual cables in the barrier, or the height of the effective interface area on the front of a vehicle to a horizontal plane. For any position across the median, the vertical height of the normalized plot to actual sloped surface is equivalent. Normalization is useful for comparing various types and features of medians and cable barriers. The array of lines represents the broader set of impact cases for the specified parameters. The heavy blue line represents the overall maximum heights for Point 1 for the set of impact cases associated with this particular median configuration. Similarly, plotting all cases for Point 2 yielded the array of lines in Figure 5.7 for the set of impact cases for a given median configuration. The heavy green line represents the overall minimum heights for Point 2. These plots were generated for different median profiles and can be used to define vehicle-to-cable-barrier engagement based on cable barrier lateral position and its cable heights.

Comparing the resulting blue (minimum) override limit and green (maximum) underride limit lines for a given median provides a means of determining the interface effectiveness across all lateral positions for any given barrier design. The three yellow lines in Figure 5.8 represent the coverage of a particular barrier design (in this case a generic three-cable barrier). Where the blue

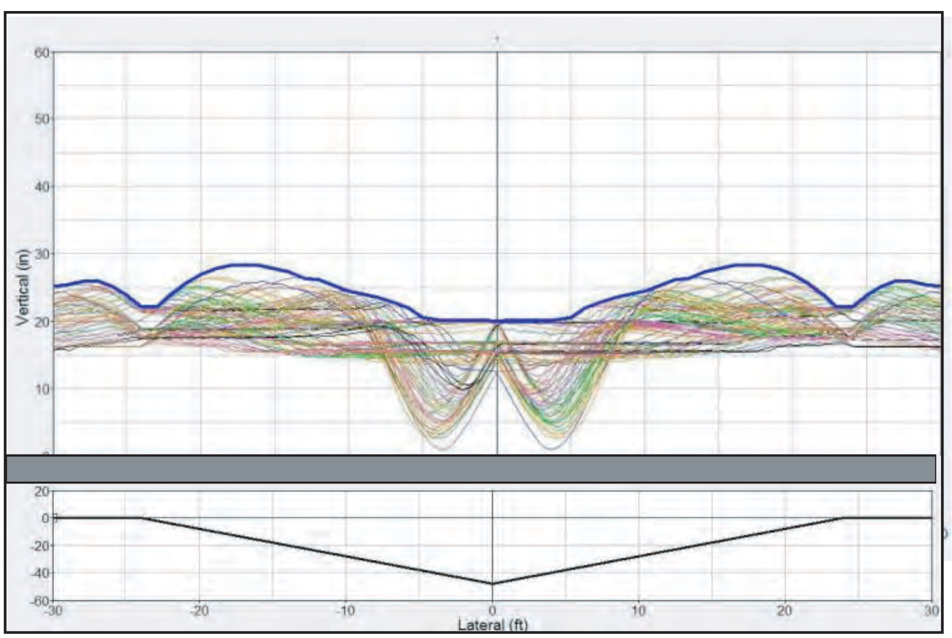


Figure 5.6. Sample override limit curve.

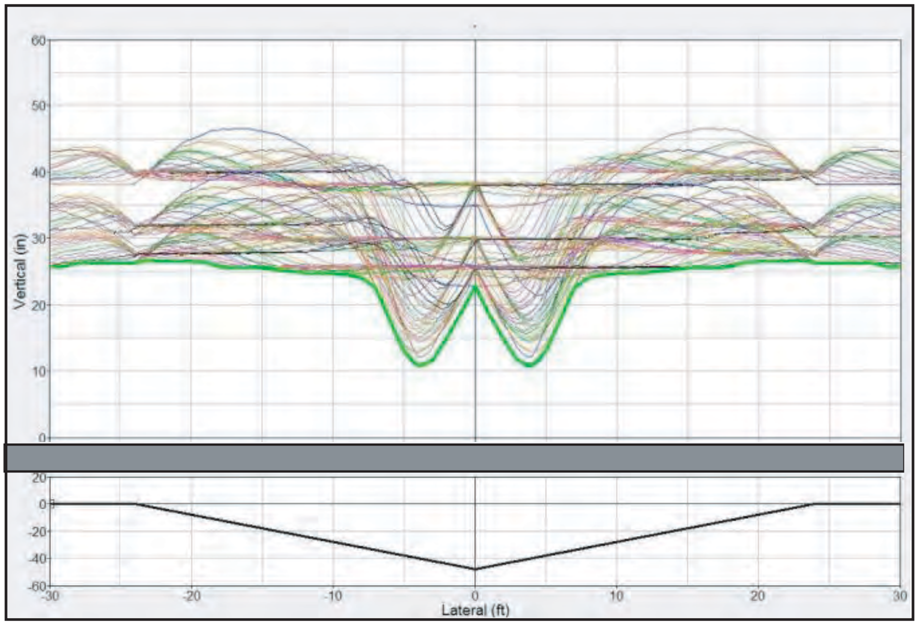


Figure 5.7. Sample underride limit curve.

line goes above the highest yellow line there is an opportunity for an override to occur. Where the green line falls below the lowest yellow line, the possibility of an underride exists.

This approach is used to determine the potential effectiveness for varying cable barrier systems (e.g., number of cables, relative heights) across all possible lateral positions for a given median configuration. The following figures show more specific examples of how this metric can be applied.

Figure 5.9 shows an example of the results for a specific median. The upper portion shows the normalized representation of the interface envelope, the minimum upper cable height curve, the maximum lower cable height curve, and the relative position isobars for a specific type of cable barrier (i.e., generic, low-tension, 3-cable system). The Barrier Interface Envelope is the gray shaded area that surrounds all of the trace bars for different vehicles traversing the median at varying angles and speeds from both directions.

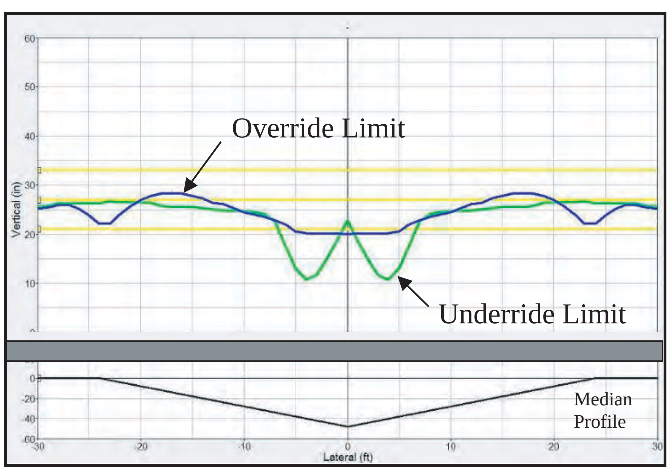


Figure 5.8. Sample override and underride limits plot.

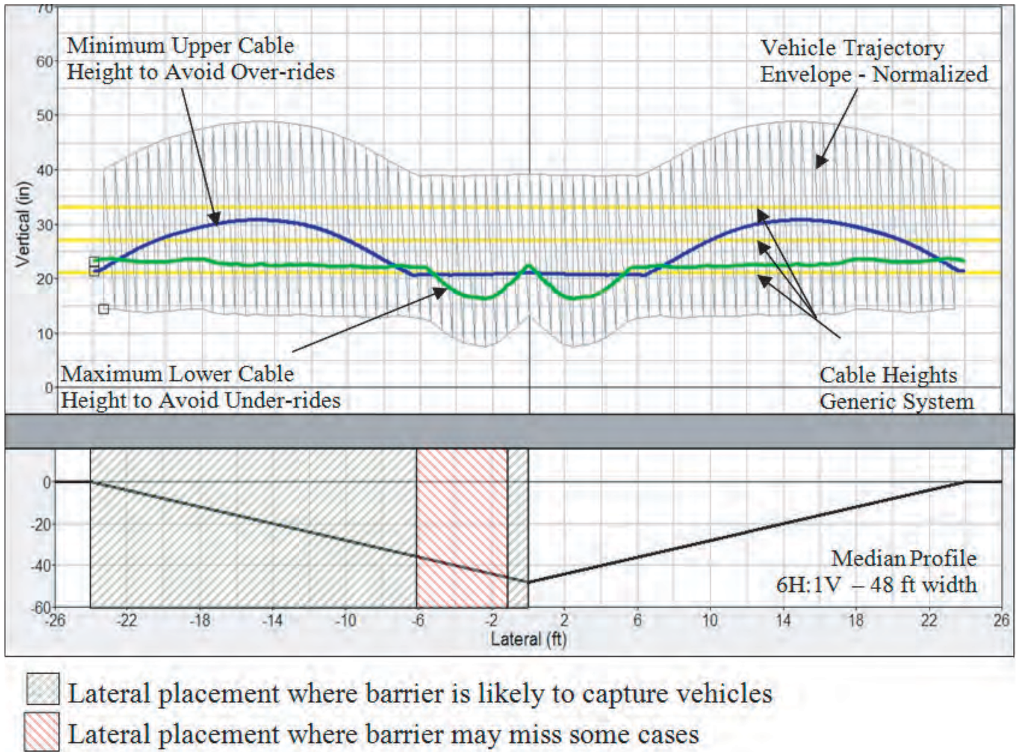


Figure 5.9. Sample plot generated using the results of vehicle dynamics analysis.

The lower portion of Figure 5.9 shows the profile or cross-section of the median related to the upper graph. The green hatched portions indicate the lateral positions where this specific barrier will be effective. Since the median in this case is symmetric, the effectiveness regions are a mirror image on the opposite side. The red hatched area defines the lateral positions where the specific barrier has a cable arrangement that has a lower cable above the maximum lower cable height curve (green) and/or an upper cable below the minimum upper cable height curve (blue). Effective lateral placement occurs where both criteria are met. It can be noted that for this specific barrier system, the red region corresponds to the lateral placement range where the maximum lower cable curve height falls below the lowest cable in the system. This plot would indicate that for this 14.6 m (48 ft) wide median (measured from hinge point to hinge point of median) with 6H:1V side slopes, there is an area from about 0.3 to 1.8 m (1 ft to 6 ft) from the center of the median where placement of this generic cable barrier system is not recommended because of the risk of underriding. Numerous plots of this type for different median profiles were generated and were used in developing the guidelines. Some of these plots are included in Appendix C of the contractors' final report.

In this research, a number of different possible conditions for a median crossing were considered. The following conditions were assumed in the analyses:

- Median has firm surface. Ploughing (or furrowing) into the surface by tires is negligible. Modeling the ploughing condition is beyond the capability of current computer simulation software. This condition has not been incorporated in all previous related research studies (using full-scale tests or computer simulations) and is considered beyond the scope of this project.
- Vehicles are "tracking" as they enter the median (i.e., vehicle's initial speed vector is in the same direction at its longitudinal axis). Even though it is possible to investigate non-tracking conditions using the vehicle dynamics programs, incorporating all non-tracking scenarios would render the number of simulations impractical. Different vehicle types, impact angles, and initial speeds are considered in this study, which should account for most vehicle/barrier interface situations.

- Initial velocity occurs when the vehicle leaves the shoulder. Some deceleration is expected to occur (3–5 mph was noted in the research) for vehicles as they cross the median.
- There are no driver inputs (e.g., steering, braking) that affect the vehicle trajectory.
- No edge rounding was considered in this study. Based on previous investigations, edge rounding reduces the potential of overrides with no significant effect on the underrides.
- A vehicle must have effective engagement with a minimum of one cable to be captured by the barrier.

It is important to note that review of full-scale crash testing has indicated that for low-tension systems an engagement with one cable is sufficient to capture the small car but may not be sufficient to redirect mid-size and larger vehicles. Engagement with one cable was shown to be sufficient for the small vehicle and pickup truck for high-tension systems. This difference could be attributed to the fact that the connection between the cables and posts is stronger in high-tension systems than in low-tension systems. Additionally, the green hatched regions in the generated plots indicate barrier lateral placement where a minimum of one cable would engage the vehicle. This is a minimum condition that has to be satisfied but does not ensure a successful redirection or controlled stopping of the vehicle. In addition to this engagement condition, the barrier needs to have adequate strength to withstand the vehicle impact forces. This can be achieved through full-scale crash testing. At the time that this report was written, a matrix of full-scale crash tests that evaluate cable barrier systems when placed on sloped medians was being developed. These tests will ensure that the cable barrier design (e.g., the strength of connection between cables and posts, the post spacings, the cable vertical spacings, etc.) is adequate to capture and redirect the vehicle without leading to rollover, override, underride, or penetration in between the cables.

The approach described in the previous sections allows for identifying optimum placement of cable barriers for specific median configurations. To develop generalized guidelines that can be used for a wider range of median geometries, the analysis was taken a step further. This was achieved by superimposing (i.e., overlaying) results from median profiles with varied widths. As an example, to evaluate the overall cable barrier performance on 4H:1V slope V-shaped medians, the results from all simulations from this type of median with varied widths are combined.

Figure 5.10 shows the lower cable maximum limits from 4H:1V slope V-shaped medians with varied median widths (5 to 17 m, 16 ft to 56 ft). The minimum of all curves is computed (shown in thick green line in the figure). Similarly, Figure 5.11, shows the upper cable minimum limit

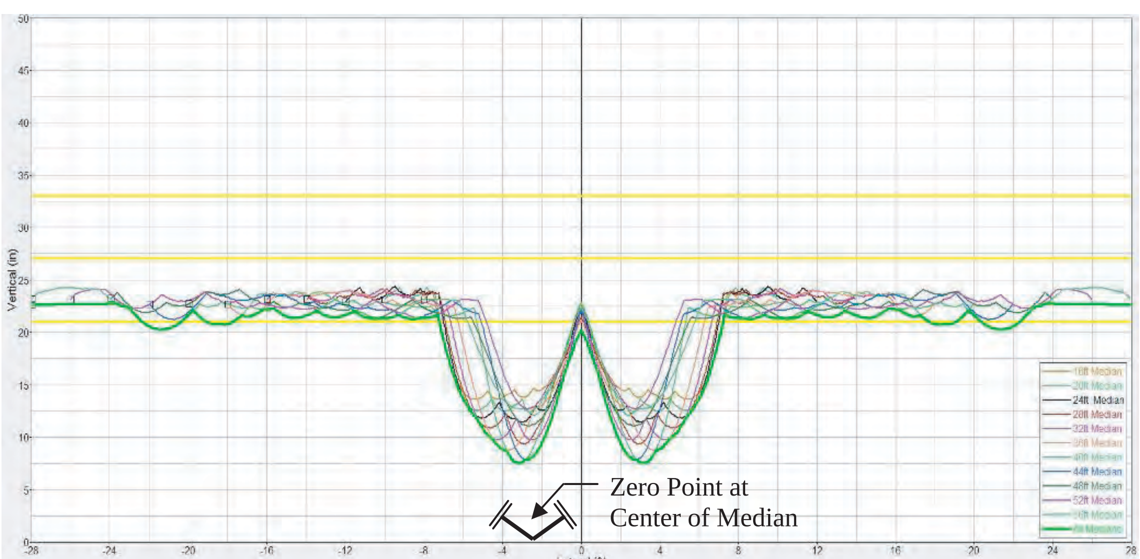


Figure 5.10. Normalized underride limit plot for 4H:1V V-shaped medians, varied widths.

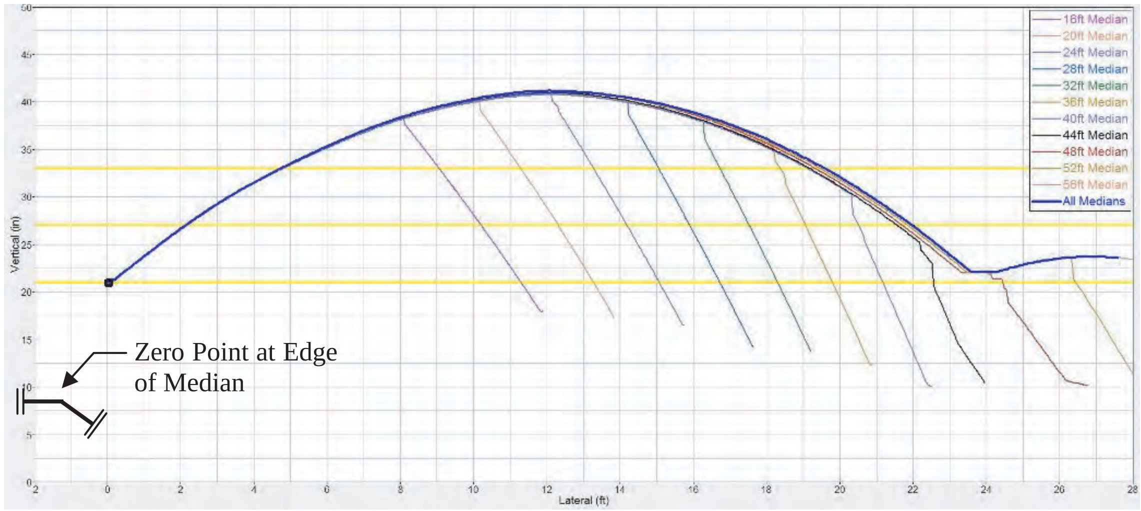


Figure 5.11. Normalized override limit plot for 4H:1V V-shaped medians, varied widths.

for the same medians with varied median widths (5 to 17 m, 16 ft to 56 ft) and the combined maximum curve (thick blue curve). Together, the minimum and maximum curves can be used to assess barrier performance on any 4:1 V-shaped median.

The research considered a wide range of median profiles. The medians varied in shape, slope, and width. For each median profile, simulations with different vehicle types traversing the median at different speeds (from 50 to 100 km/h, 31 to 62 mph) and angles (from 5° to 25°) were performed, and the vehicle trajectory was determined. These trajectories were used to assess vehicle-to-barrier interface when the barrier is placed at different locations across the median. Figures 5.12 and 5.13 present summaries of the results for symmetric V-shaped medians. Figure 5.12 shows the underride limit plots for medians with slopes of 4H:1V, 6H:1V, 8H:1V, 10H:1V, and 12V:1H (with median widths from 5 to 17 m, 16 to 56 ft—not including shoulders). Cable heights of 533, 686, and 838 mm (21, 27, and 33 in.) are included in the plot to assess vehicle engagement

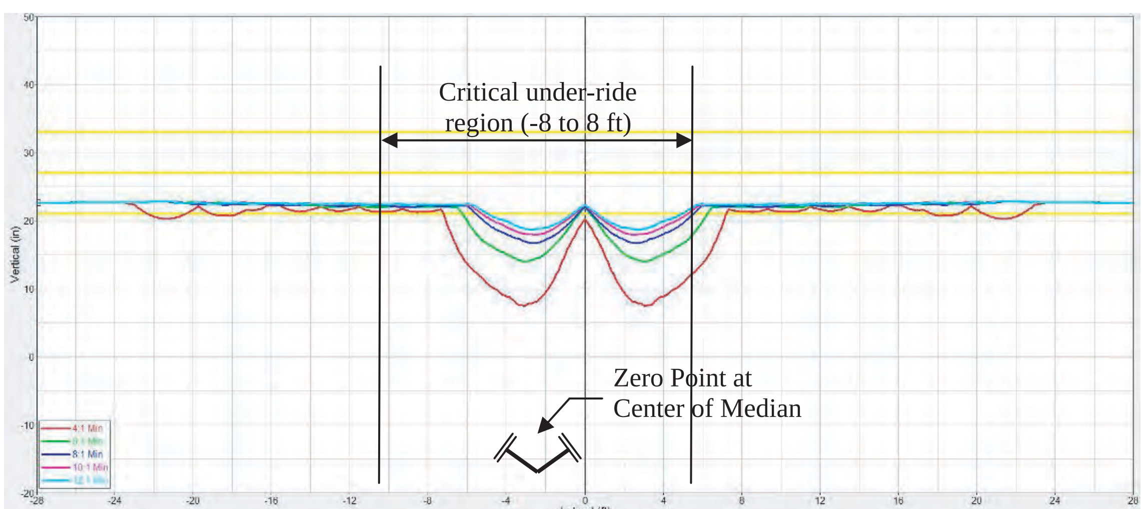


Figure 5.12. Normalized underride limit plot for V-shaped medians 4H:1V to 12H:1V slope, varied width.

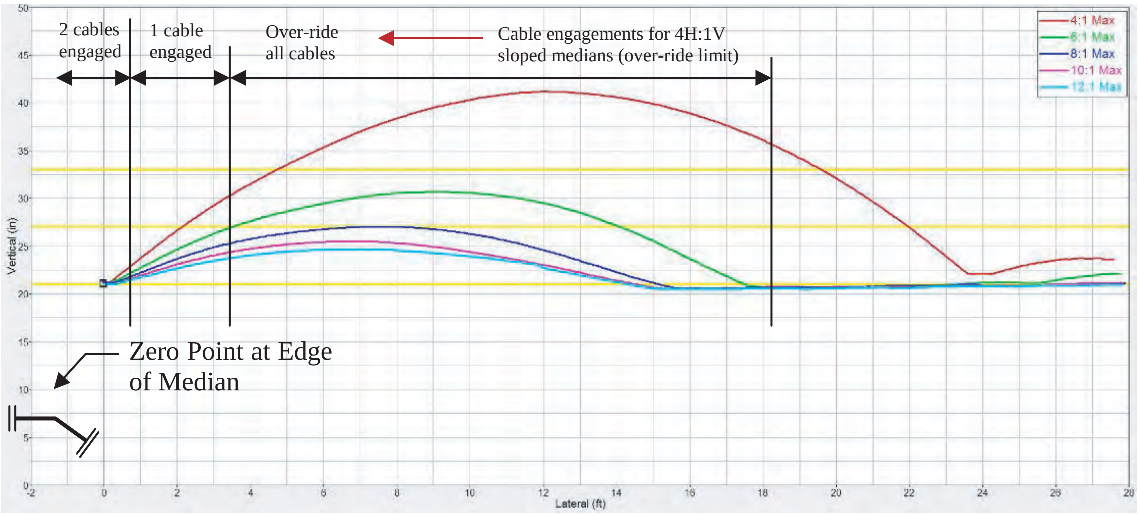


Figure 5.13. Normalized override limit plot for V-shaped medians 4H:1V to 12H:1V slope, varied width.

for systems where the top cable is at least 838 mm (33 in.) and the bottom cable is no higher than 533m (21 in.), which covers the majority of available and installed cable barriers. It can be noticed from the plots that there is potential for underride in the region between 0.3 and 2.4 m (1 ft and 8 ft) from the median center. The plot shows that even for shallow (12H:1V slope) medians there is potential for underride near the bottom of V-shaped medians. In the outer region, farther than 2.4 m (8 ft) from the median center, the results indicate that the vehicle is likely to engage at least one cable if the cable height is at 533 mm (21 in.) or lower. For the center region, between –0.3 and 0.3 m (–1 ft and 1 ft) from the center of the median, the plot shows that the barrier would engage one cable for 6H:1V and shallower slopes, while there is a potential for underride with the 4H:1V slope.

Figure 5.13 shows the override limit plots for symmetric V-shaped medians with slopes of 4H:1V, 6H:1V, 8H:1V, 10H:1V, and 12H:1V. For 4H:1V sloped medians, the results indicate that there is potential for override in the region between 1.2 and 6.0 m (4 ft and 20 ft) from the edge of the median. In the region between 0.6 and 1.2 m (2 ft and 4 ft) and between 6.0 and 6.7 (20 ft and 22 ft) from the edge of the median, the vehicle would likely engage only the top cable. In the region between 0 and .6 m (0 and 2 ft), the vehicle would engage two cables. Similarly, in the region farther than 6.7 m (22 ft) from edge of the median, two cables would be engaged. For medians with slopes flatter than 6H:1V, the plot shows that there is no potential for override, i.e., the vehicle would engage a minimum of one cable if placed anywhere in the median.

Similar plots were generated for flat-bottom medians. The plots; shown in Figures 5.14 through 5.16, include flat-bottom medians with slopes of 4H:1V, 6H:1V, and 8H:1V. For each slope, three depths, 0.6, 1.2, and 1.8 m (2 ft, 4 ft, and 6 ft), were analyzed. A third parameter that was varied is the width of the flat-bottom section, which was varied from 1.2 to 12.2 m (4 ft to 40 ft). The trajectories from all cases (i.e., different flat-bottom median profiles, vehicle type, speed, and angle) were included when generating the underride and override limits. Figure 5.14 shows the underride limit for the three slopes analyzed. The plot shows that for the 4H:1V slope profiles, there is potential for underride in the region between –1.8 and 3 m (–6 ft and 10 ft) from the flat-bottom breakpoint. In the outer region, farther than –1.8 m (–6 ft) in the up-sloped region and farther than 3 m (10 ft) in the flat region, the results indicate that the vehicle is likely to engage at least one cable if the bottom cable height is at 533 mm (21 in.) or lower. For 6H:1V

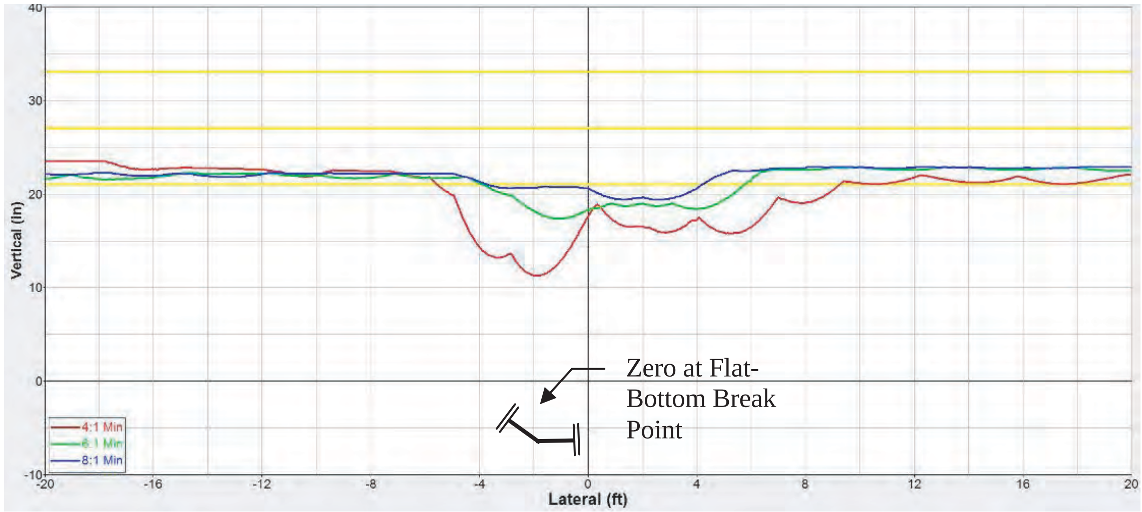


Figure 5.14. Underride limit plot for flat-bottom shaped medians 1.2 to 12.2 m (4 ft to 40 ft) flat-bottom width.

sloped profiles, the underride region is smaller (−1.2 m to 1.5 m [−4 ft to 5 ft] for 6H:1V and −1.2 m to 1.2 m [−4 ft to +4 ft] for 8H:1V).

Figure 5.15 shows a plot similar to Figure 5.14 except that only medians with the flat-bottom section wider than 2.4 m (8 ft) are included. If the flat-bottom section is wider than 2.4 m (8 ft), the plot shows that the barrier will engage the vehicle if it is placed at the flat bottom breakpoint for medians with 6H:1V slopes and shallower.

Figure 5.16 shows the override limit plots for symmetric flat-bottom medians with slopes of 4H:1V, 6H:1V, 8H:1V. The results are very similar to the V-shape profiles. For 4H:1V sloped medians, the region between 1.2 to 6.0 m (4 ft and 20 ft) from the edge of the median shows potential for override. In the regions 0.6 to 1.2 m (2 ft to 4 ft) and 6.0 to 6.7 m (20 ft to 22 ft) from the edge of the median, the vehicle would likely engage the top cable only. In the region between 0 to 0.6 m (0 to 2 ft), the vehicle would engage two cables. Similarly, in the region farther than

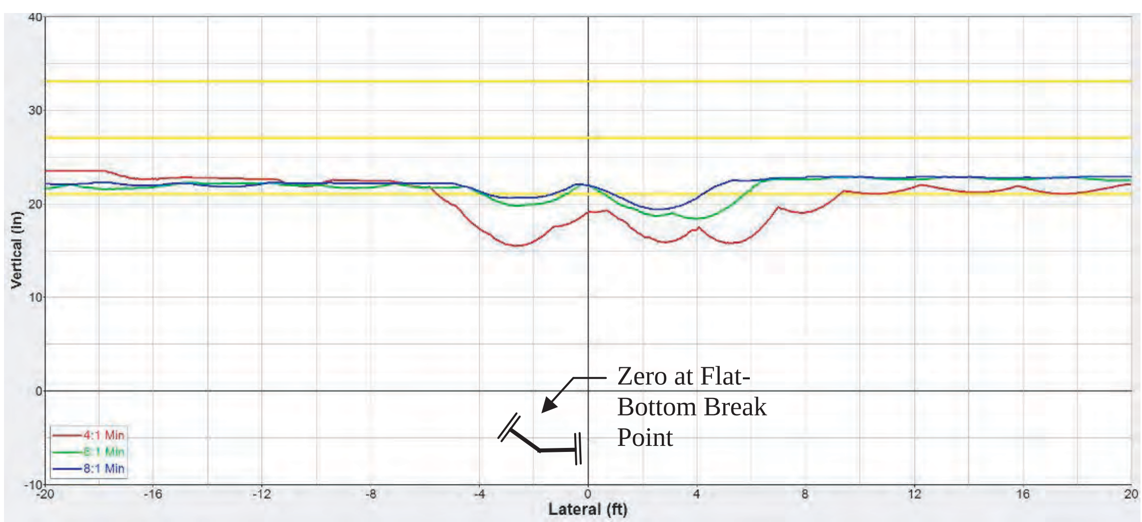


Figure 5.15. Underride limit plot for flat-bottom shaped medians 2.4 to 12.2 m (4 ft to 40 ft) flat-bottom width.

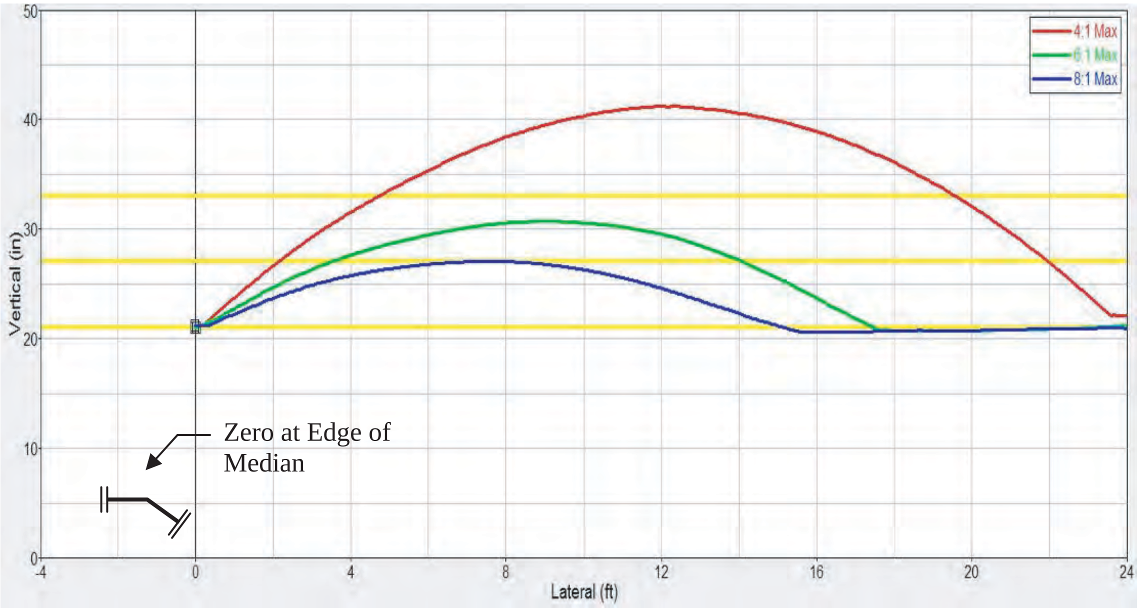


Figure 5.16. Override limit plot for flat-bottom shaped medians.

6.7 (22 ft) from the edge of the median, two cables would be engaged. For medians with slopes flatter than 6H:1V, the plot shows that there is no potential for override, i.e., the vehicle would engage a minimum of one cable if placed anywhere in the median.

Vehicle dynamics analyses were conducted to investigate vehicle-to-barrier interactions on non-symmetric medians. Figure 5.17 depicts a typical override and underride plot from these analyses. The plot shows that the side with the shallower slope is less susceptible to overrides. The underride region is similar on both sides of the median. Comparing this plot to symmetric medians, similar observations can be made for the critical override and underride regions.

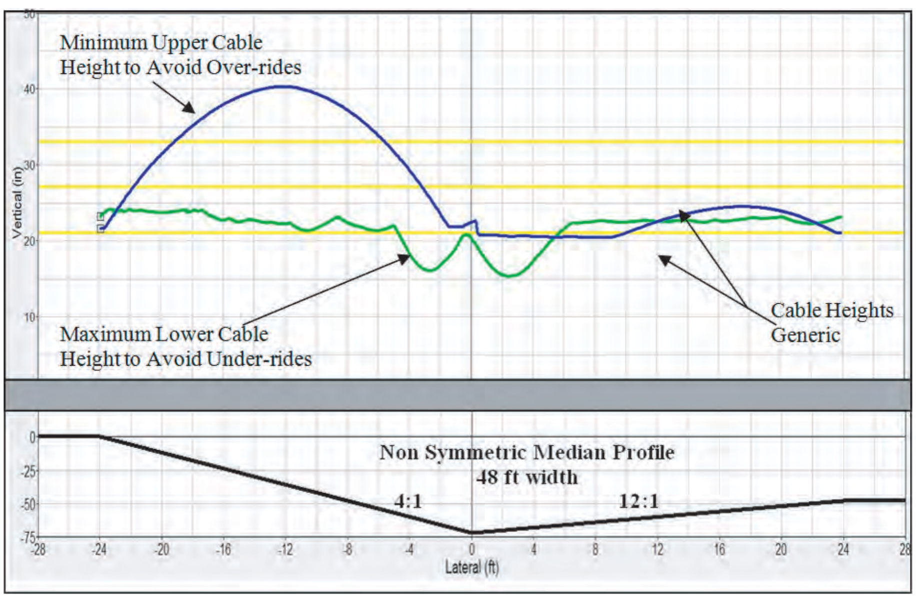


Figure 5.17. Sample underride and override limit plot for non-symmetric medians 4H:1V and 12H:1V slope—14.6 m (48 ft) median width.

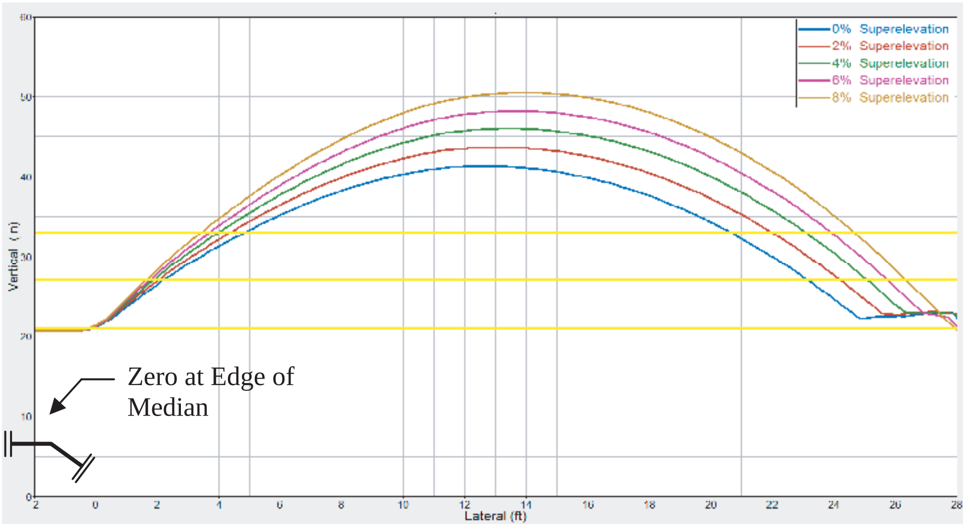


Figure 5.18. Override limit plots for 4H:1V slope medians at varied superelevations.

To investigate the effects of superelevation on vehicle to barrier interface, vehicle dynamics simulations with varied superelevations (0 percent, 2 percent, 4 percent, 6 percent, and 8 percent) were conducted. Two symmetric V-shaped medians, with 4H:1V and 6H:1V side slopes, were used in the analysis. The width of both medians was 17 m (56 ft), from break point to break point (similar results are expected for other median types and widths).

Simulations with varied vehicle types, initial speeds, and approach angles were performed to investigate the superelevation effects on the vehicle trajectories. The simulation results showed that higher superelevation increases the chance of overrides. This is especially critical for medians with steep side slopes (steeper than 6H:1V). Figures 5.18 and 5.19 show the normalized override limit plots for the 4H:1V and 6H:1V sloped medians, respectively. It can be noticed from the figures that the vehicle height relative to ground level increased with increased superelevation. The simulation results showed that the superelevation had negligible effects on the underride limit plots.

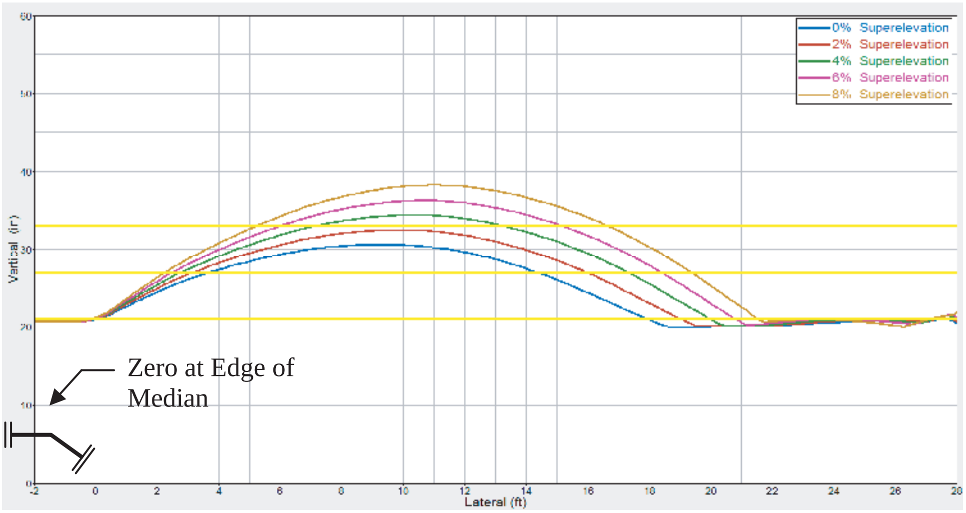


Figure 5.19. Override limit plots for 6H:1V slope medians at varied superelevations.

5.2 Cable Barrier Deflection

The dynamic deflection of a cable barrier during impact is an important characteristic for many reasons. Compared to semi-rigid W-beam barriers and rigid concrete barriers, cable barriers have greater deflections, which is the reason that cable barriers typically are more forgiving to the impacting vehicle's occupants. For the barrier to be safe, adequate space behind the barrier that is clear of hazards must be provided to accommodate the expected deflections. If deflections exceed the space provided, the errant vehicle could impact rigid objects behind the barrier, or worse yet, in median applications on divided highways, cross into opposing traffic.

Various cable barrier systems have been crash-tested successfully and accepted for use on U.S. highways. High-tension cable systems, when compared to low-tension systems, have lower deflection during impacts and reduced maintenance costs. NCHRP Report 350 and MASH require that dynamic deflections observed in the crash tests be reported. These requirements do not standardize all of the test installation features for cable barrier systems. For example, cable barriers are typically tested at 90 to 180 m (300 to 600 ft) installation lengths with the cables anchored at both ends. However, field installations on U.S. highways are typically much longer with anchor-to-anchor distances more than 10 times longer than the ones used in crash tests. With longer anchor-to-anchor spacing, the deflection of the barrier could be significantly higher and could lead to higher likelihoods of barrier penetration. Barrier deflection is also affected by the spacing between the posts, the strength of the posts, the connection between the cable and posts, and the amount of tension in the cable. Understanding the influence of these features on deflection during impact is critical to making effective design decisions about the features of cable barrier systems.

To evaluate the influence of critical installation parameters, such as end-anchor spacing, cable tension, post spacing, etc., on cable barrier deflection, crash scenarios with varied configurations have to be analyzed. To conduct such analyses using only full-scale crash tests would be very costly. Additionally, conducting full-scale crash tests with very long cable barrier installations (300 m [980 ft] and longer) is often not practical and beyond the capabilities of most test facilities. The approach used in this study is based on the coupling of full-scale crash testing with computer simulations using the LS-DYNA finite element program [53]. First, the cable barrier modeling approach was validated using previously conducted full-scale crash tests. Several full-scale crash tests with varied barrier design, barrier length, and post spacing were used in the validation process. Upon completing the validation of the modeling approach, a matrix of simulations with varied design parameters and installation configurations was run to investigate the effects on cable barrier deflection. The installation configuration variations included the following:

- End-anchor spacings—Anchor spacings of 100 m (328 ft) (typical spacing used for NCHRP 350 crash tests), 200 m (656 ft), 300 m (984 ft), 500 m (1,640 ft), and 1,000 m (3,280 ft).
- Initial cable tensions in the system before impact—Cable tensions, 15 kN (3.4 kips) and 24 kN (5.4 kips). These tensions approximately represent typical hot weather (38°C, 100°F) and average weather (10°C, 50°F) conditions, respectively, for high-tension cable barriers.
- Post spacings—Post spacings of 1.6 m (5 ft), 3.2 m (10 ft), 4.8 m (15 ft) and 6.4 m (20 ft).

Five systems were selected for the analyses: Brifen Wire Rope Safety Fence, Gibraltar Cable Barrier System, Nucor Steel Marion Cable Barrier System, Safence Cable Barrier System, and Trinity CASS Cable Barrier System. Information was collected for these five systems, including design drawings, crash test reports, crash test video clips, test data, and acceptance letters. The information for these five proprietary systems was obtained from the manufacturers. These systems are available in different configurations. One system from each cable barrier manufacturer was selected. To assist in the selection, the team contacted the manufacturers to get their feedback on which system should be selected. When selecting the systems, emphasis was placed on choosing systems that are most commonly installed and have multiple full-scale crash test data available. This process ensured that the computer models could be validated fully with crash test data and that the analyzed systems would represent the majority of installed systems.

NCAC models for standard NCHRP Report 350 test vehicles were used in the simulations. These included the Chevrolet C2500 pickup truck (2000P) model and the Geo Metro (820C) vehicle models. These vehicle models were originally validated and subsequently updated over years of application in many crash simulation efforts [54, 55, 56]. These models conformed to the test vehicles reflected in the available crash test data. Since maximum dynamic deflections were the metric of interest, impacts with the 2000P vehicle at 100 km/h (62 mph) and 25° impact angle were the focus. Similar impact location along the barrier was used for all simulations. The impact location was selected such that the maximum deflection would occur at the center of the barrier installation. Simulations with all of the above-stated installation variations were carried out, and the results are presented to show the effects on deflection of end-anchor spacings, post spacings, and initial cable tensions.

Model Development and Validations

Highly detailed computer models of cable barrier systems were created and used in this study. A sophisticated modeling approach was used in creating these models to ensure that they would accurately capture the barrier response during simulation of the crash. The approach used in modeling the different cable barrier systems is described in the following sections.

To create the finite element models of the cable barrier systems, several key features were examined carefully, and appropriate modeling techniques were used to ensure that the models were accurate representations of the actual systems. First, explicit geometry of all components of the system was incorporated in the model including, for example, the cables, the posts, the sleeves, etc. This step was important to ensure that the correct mass, inertia, and stiffness of the different parts are reflected in the model. The soil and concrete were also modeled explicitly using solid elements. The shape of the post/sleeve was incorporated in the soil or concrete mesh to simulate the post/soil interactions. The cables for the models were created using beam elements with the cross-sectional and material properties of the specified cable. To replicate the cable-to-vehicle and cable-to-post interactions accurately, each beam was surrounded by shell elements with null material properties. The beams were connected to the null shell elements using nodal rigid body connections. The necessary initial stress was applied to the beam elements in the initialization phase of the simulation to simulate the pre-crash tension in the cables. For all systems, the connection between the cables and end anchor was considered rigid.

To validate the modeling approach, computer simulations, setup in a similar configuration to the full-scale crash tests, were conducted and the results were compared to the tests. Full-scale crash tests, with varied barrier design, end-anchor spacing, and post spacing were used in the validations. Some of these validations are described in the following sections.

Gibraltar Cable Barrier System

The three-cable, high-tension median cable barrier from Gibraltar Cable Barrier Systems was accepted by the FHWA for use on U.S. highways [57, 58]. This cable barrier system consists of three 19 mm (¾ in.) diameter steel cables supported by steel 83 × 63.4 × 3.8 mm thick (3.25 × 2.5 × 0.15 in. thick) and 1,500 mm (4.9 ft) long C-posts. The bottom, middle, and top cable heights are set at 508 mm (20 in.), 762 mm (30 in.), and 990 mm (39 in.), respectively. The three cables are locked in place using an 11 mm (7⁄16 in.) diameter galvanized steel hairpin and lock plate that fits inside each post. The finite element model of the Gibraltar cable barrier system was created and validated with two full-scale crash tests. The full-scale crash tests were conducted by Karco Engineering, LLC (Test Report No. TR-P26021-01-B and TR-P26028-01-B). Figure 5.20

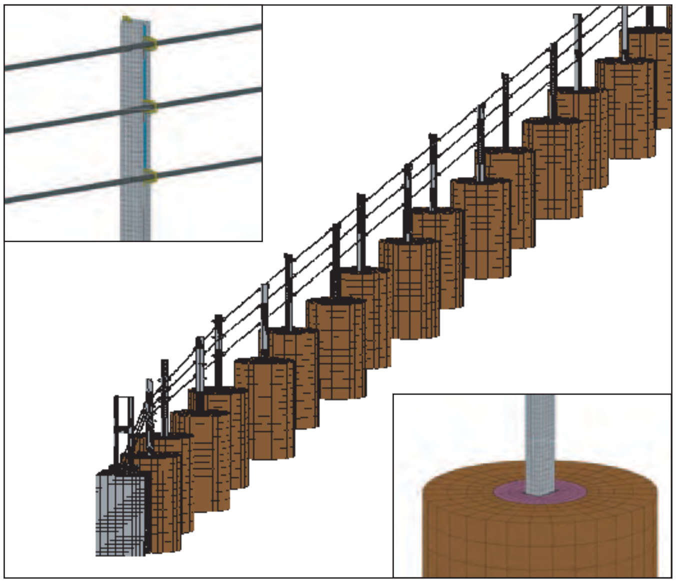


Figure 5.20. Finite element model of the Gibraltar cable barrier system.

shows the details in the finite element model of the Gibraltar cable barrier system. The geometry and design details of all components were obtained from FHWA acceptance letters. The total installation length for both tests was 93 m (305 ft), and the cables were tensioned to 25 kN (5.7 kips). For the first test, the line posts were set on 3 m (10 ft) centers and for the second test, 9.1 m (30 ft) centers. For both tests, a 2000P C2500 vehicle was used, the impact angle was 25°, and impact speed was 100 km/h (62 mph).

Figure 5.21 shows side-by-side comparisons of sequential images from the first crash test and its simulation. In the simulation, the two top cables engaged and redirected the vehicle with a maximum dynamic deflection of 1.9 m (6.4 ft), and the maximum dynamic deflection for the crash test was 2.0 m (6.8 ft). Figure 5.22 shows side-by-side comparisons of sequential images from Crash Test 2 and its simulation. In the simulation, the two top cables engaged and redirected the vehicle with a maximum dynamic deflection of 2.9 m (9.5 ft), and the maximum dynamic deflection for the crash test was 2.8 m (9.3 ft).

Safence Cable Barrier System

The Safence Wire Rope Barrier produced by Blue Systems was accepted as an NCHRP Report 350 TL3 traffic barrier in 2001 [59]. The original design consisted of four 19 mm (¾ in) diameter steel cables supported on 2.1 m (83 in) long elliptically shaped posts spaced on 2.5 m (8.2 ft) centers. In its current design [60], the cables are supported using Safence C-shaped posts embedded in concrete footings. Each post was stiffened at the ground line by adding a steel plate inside the C-post to increase its resistance to bending, and a steel hook was added to the top of each post to retain the cables within the post center slot for a longer time upon barrier impact.

The finite element model of the Safence system was developed and validated using a VTI crash test (Test Report No. 56649). The design drawings and details were obtained from the FHWA acceptance letter [61] and manufacturer's drawings. Figure 5.23 shows details of the finite element model of the Safence cable barrier system.

The overall dynamics of the vehicle in the finite element simulation were similar to those reported in the crash test. The maximum dynamic deflection for the simulation was 3.6 m

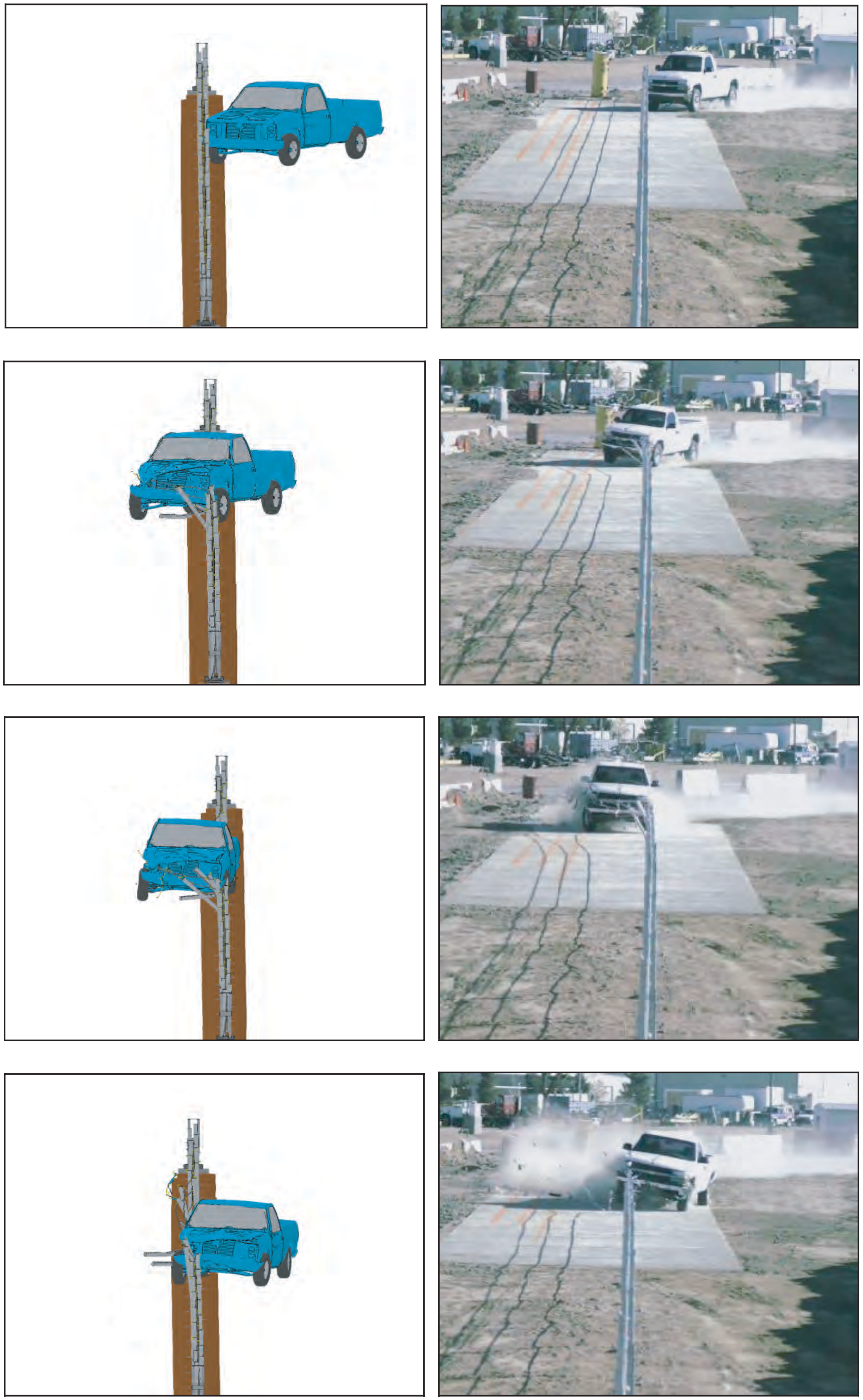


Figure 5.21. Comparison of sequential plots; Gibraltar Test 1.

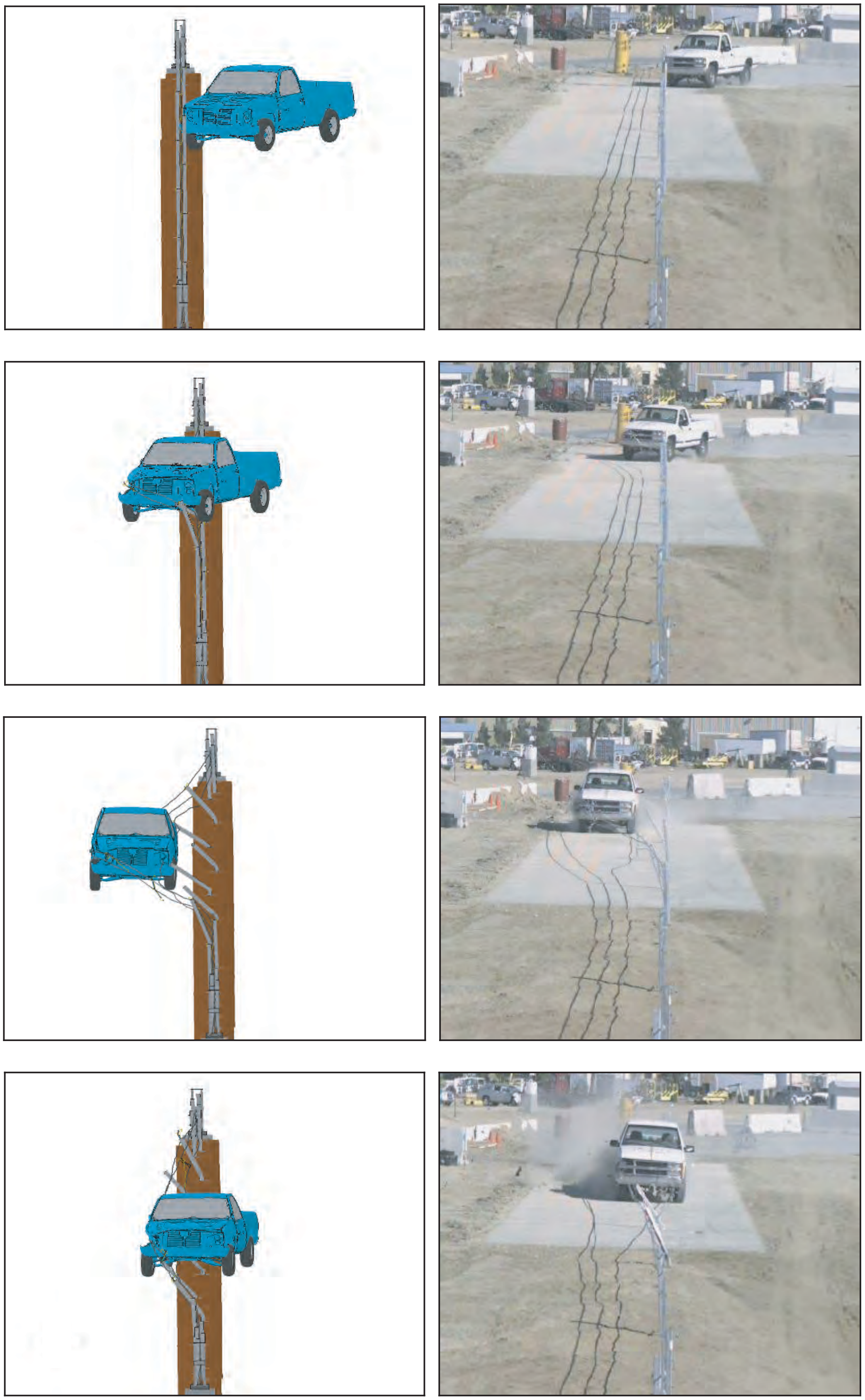


Figure 5.22. Comparison of sequential plots; Gibraltar Test 2.

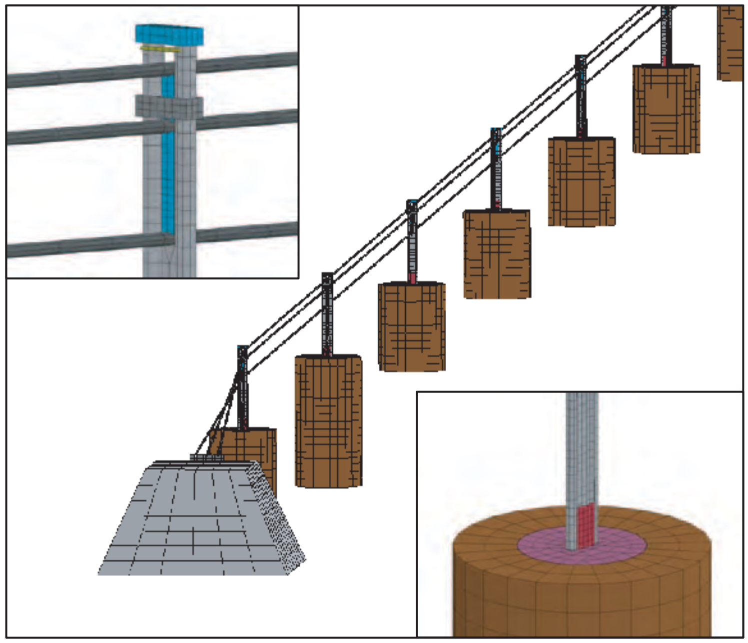


Figure 5.23. Finite element model of the Safence cable barrier system.

(11.7 ft) and for the crash test, 3.7 m (12.1 ft). Side-by-side comparisons of sequential images of the test and simulation are shown in Figure 5.24.

Brifen Cable Barrier System

Brifen Cable Barrier Systems incorporate a proprietary interweaving concept. The systems have 19 mm (¾ in) cables supported by S-shaped posts that are 100 mm × 55 mm × 4.55 mm thick (4 in. × 2 in. × 0.18 in.) and manufactured from ASTM A-36 steel. The top cable is set in a 101 mm deep × 22 mm (4 in. × 1 in.) wide slot cut into the top of each post and bottom cables (two in case of a 3-cable system and three in case of a 4-cable system) are interwoven between the posts.

Figure 5.25 shows the details of the finite element (FE) model of the Brifen wire rope system. The FE model was validated using two full-scale crash tests (Test B-USA-C-2 and Test BCR-1).

In the first test, the test vehicle was a 2000P C2500 pickup truck impacting a 3-cable system at a 25° angle and 100 km/h (62.1 mph). The test article, installed on flat terrain, had a total length of 278 m (912 ft) and post spacings of 3.2 m (10.5 ft). Figure 5.26 shows side-by-side comparisons of sequential images from the test and simulation. In both cases, the top two cables engaged and redirected the vehicle. Maximum dynamic deflection observed in the test was 2.6 m (8.6 ft) and, in the simulation, 2.7 m (8.9 ft). The overall dynamics of the vehicle showed a good correlation with the test. Figure 5.27 shows the comparison of vehicle CG yaw between the test and simulation.

In the second test, the vehicle was a 2000P C2500 pickup truck impacting a 3-cable system at a 25° angle at 100 km/h (62 mph). The test article, installed on flat terrain, had a total length of 111 m (365 ft) and post spacings of 3.2 m (10.5 ft). Figure 5.28 shows side-by-side comparisons of sequential images from the test and simulation. Vehicle behavior in the simulation showed

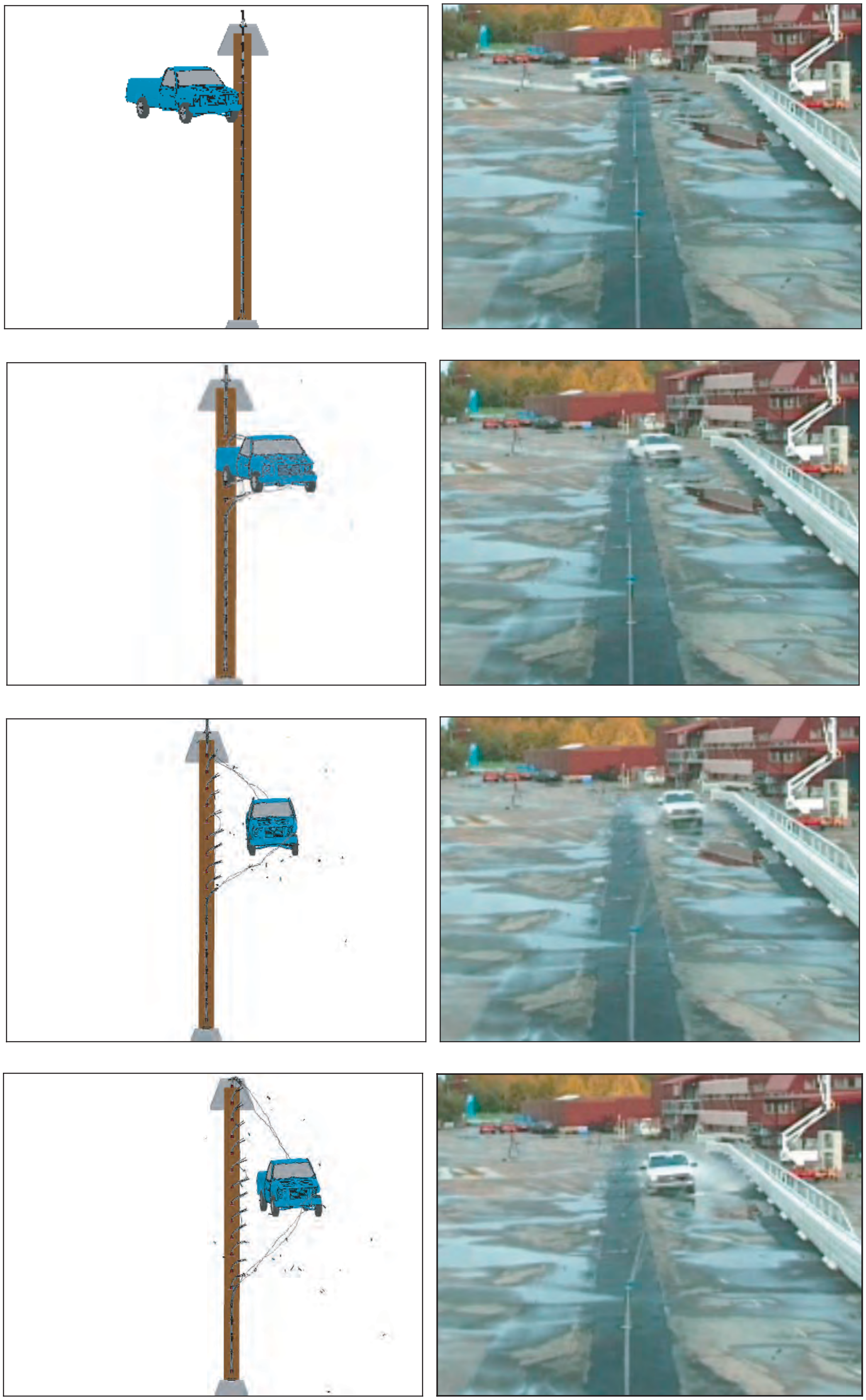


Figure 5.24. Comparison of sequential plots; Safence cable barrier system.

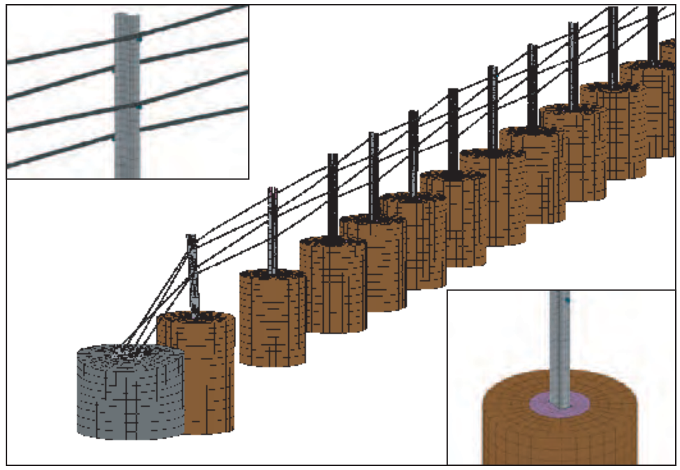


Figure 5.25. Finite element model of the Brifen wire rope system.

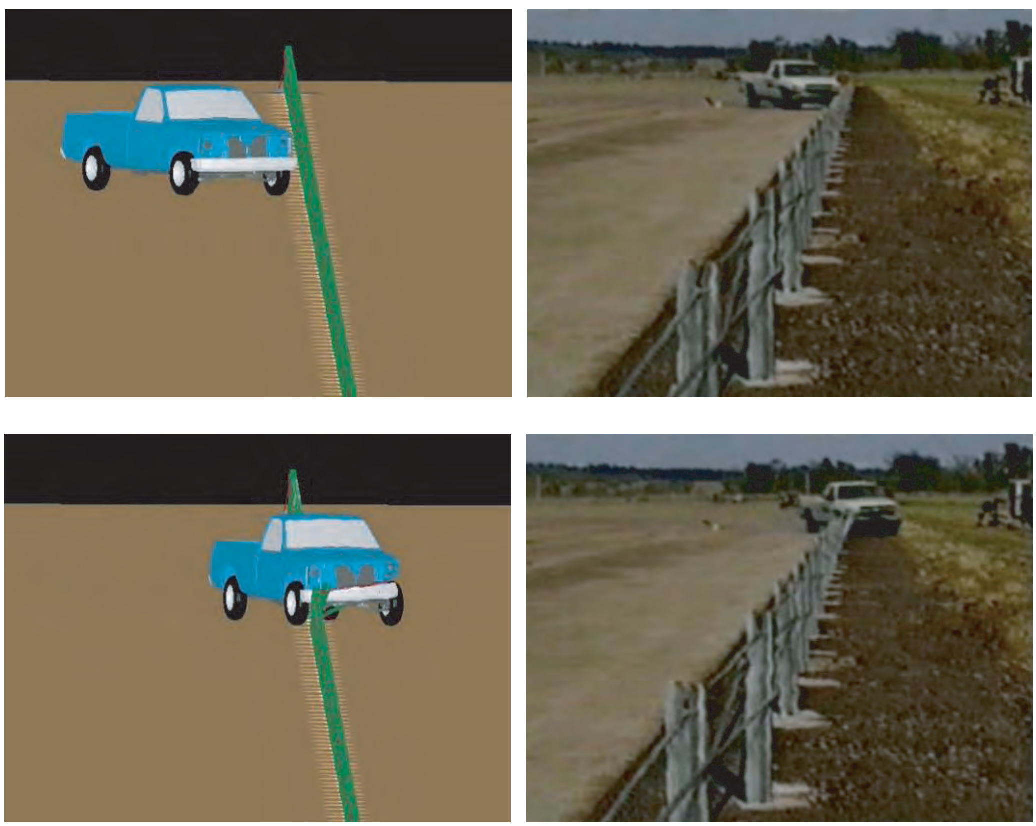


Figure 5.26. Comparison of sequential plots; Brifen Test 1.

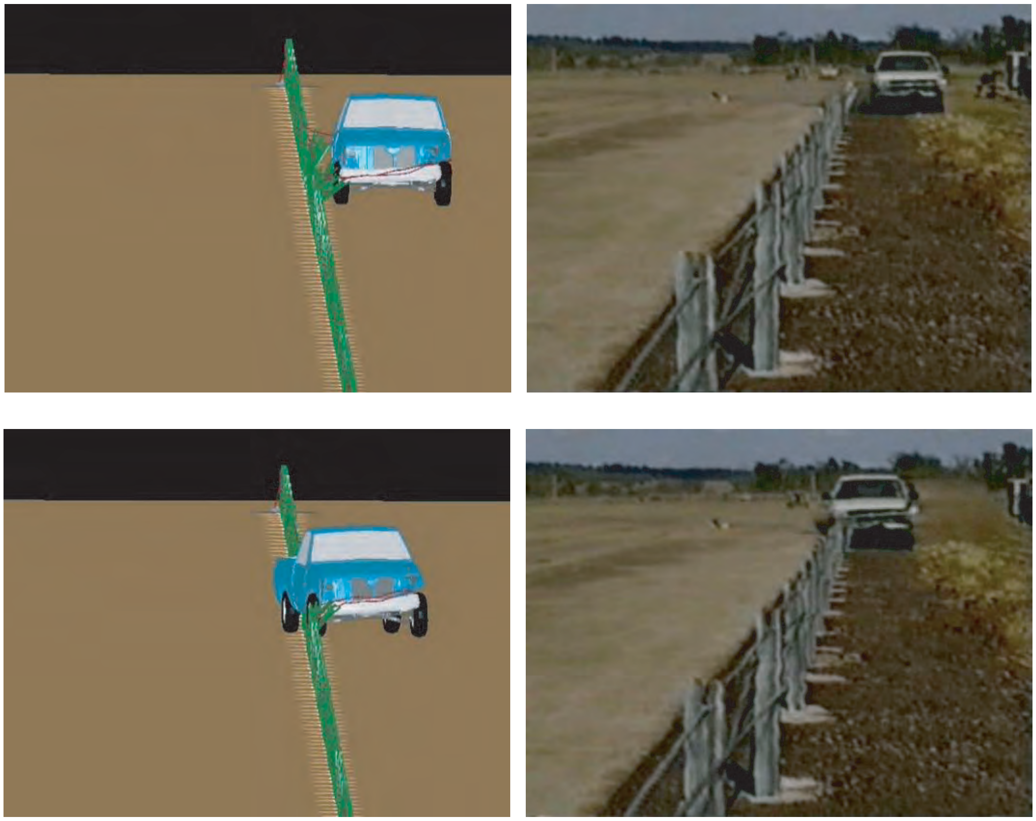


Figure 5.26. **(Continued).**

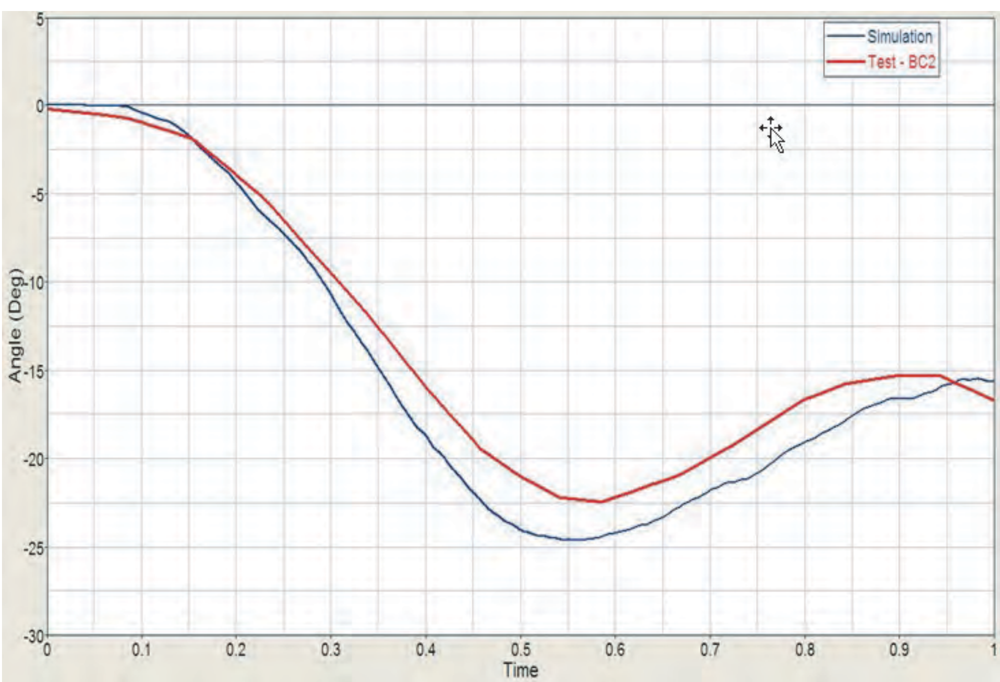


Figure 5.27. Vehicle yaw comparison; Brifen Test 1.

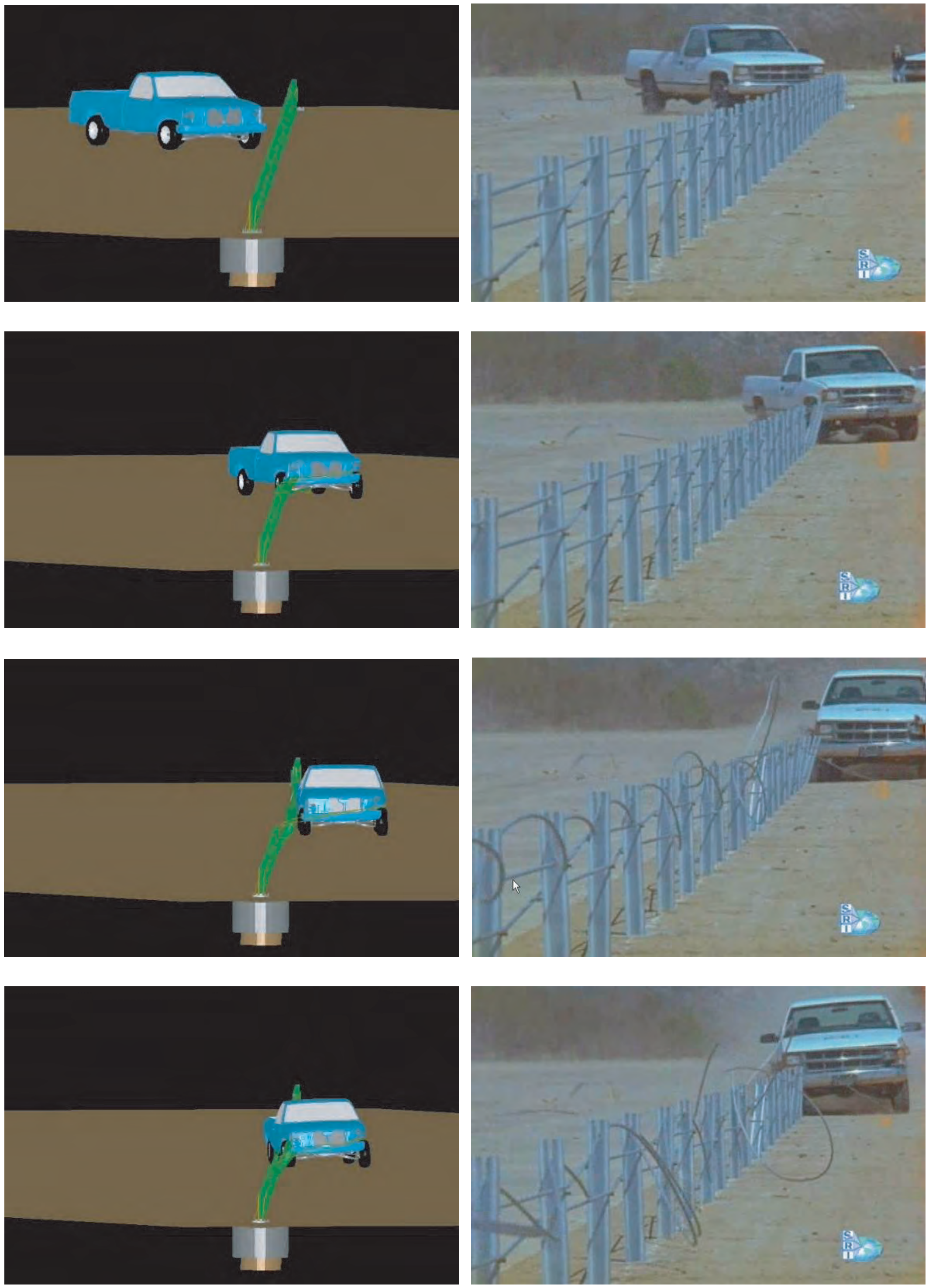


Figure 5.28. Comparison of sequential plots; Brifen Test 2.

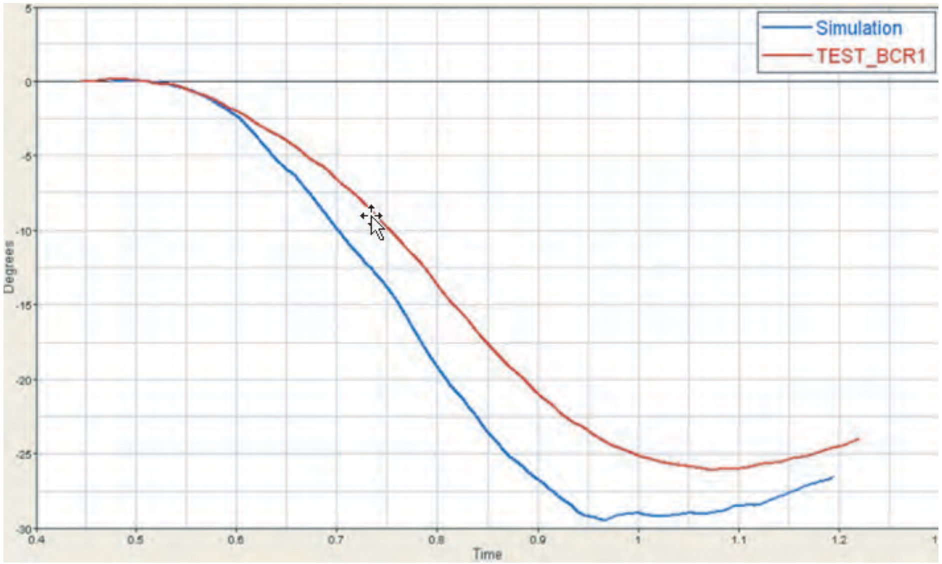


Figure 5.29. Vehicle yaw comparison; Brifen Test 2.

a good correlation with the test. Maximum dynamic deflection observed in the test was 2.1 m (6.9 ft) and, in the simulation, 2.2 m (7.3 ft). Figure 5.29 shows the vehicle yaw comparison between the test and simulation.

Trinity CASS Cable Barrier System

The details of the finite element model of the Trinity CASS Cable Barrier System are shown in Figure 5.30. The system consisted of three 19 mm (3/4 in) steel cables supported on posts that were spaced 3 m (10 ft) apart. The posts were installed in concrete foundations that were 300 mm (1 ft) in diameter and 760 mm (2.5 ft) deep. The test vehicle was a 2000P C2500 pickup. The impact speed was 100 km/h (62 mph), and the impact angle was 24.2°. The total installation length was 102 m (335 ft).

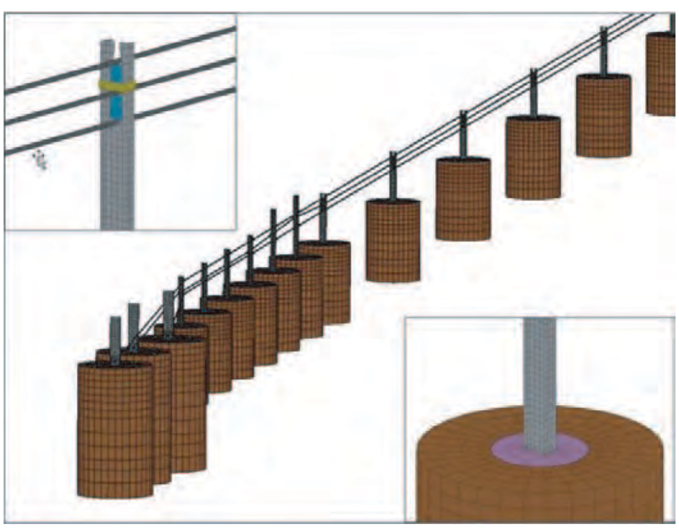


Figure 5.30. Finite element model of the CASS cable barrier system.

In both the test and simulation, the top two cables engaged the vehicle and redirected it. The maximum dynamic deflection for the simulation was 2.5 m (8.1 ft) and, for the crash test, 2.4 m (7.9 ft). Comparisons of the limited sequential plots are shown in Figure 5.31. The vehicle trajectories in the crash test and simulation show good comparison.

Nucor Cable Barrier System

The details of the finite element model of the Nucor cable barrier system was created and used for validation (Figure 5.32). This system uses three 19 mm (0.75 in.) steel 3 × 7 cables. The cables are attached to 6 kg/m (4 lb/ft) U-channel steel posts using locking hook bolts, 6.4 mm (0.25 in.) in diameter. The three cables are placed at heights of 545 mm (21.5 in.), 650 mm (25.6 in.), and 750 mm (29.5 in.). Two of the cables (top and bottom) are placed on one side of the posts while the other cable (middle) is placed on the opposite side. The posts are spaced at 3.8 m (12.5 ft) and anchored using 100 mm (4 in.) diameter 12-gauge steel pipe sockets embedded in a 300 mm (12 in.) diameter by 760 mm deep reinforced concrete footing and embedded in soil with a trapezoidal soil plate. The barrier length was 101.4 m (333 ft).

In both the test and simulation, the top two cables engaged the vehicle and redirected it. The maximum dynamic deflection for the simulation was 1.9 m (6.2 ft) and, for the crash test, was 1.8 m (5.9 ft). Comparisons of sequential plots from the simulation and test are shown in Figure 5.33.

Simulation Results

After completing the development of finite element models of the available cable barrier systems and validating them by comparison to previously conducted full-scale tests, computer models reflecting various post spacings, end-anchor spacings, and cable initial tensions were created. In all cases, the barrier was set up on flat, level terrain and impacted with the 2000P (Chevrolet C2500) pickup truck at 100 km/h (62 mph) initial speed and 25° impact angle. The posts in all systems were placed in sockets embedded in concrete foundations. The systems used in these simulations do not have the exact design as the ones used for the validations. The designs were chosen based on consultations with the cable barrier manufacturers to select the systems that are most commonly installed and most crash-tested. It is important to note that not all systems selected for the analysis use the same number of cables.

Cable Initial Tension Effects

Figure 5.34 shows barrier deflections for two different systems at two initial tension levels (15kN and 24 kN, 3.4 and 5.4 kips) and varied barrier lengths (100 to 1,000 m, 328 to 3,280 ft). The simulations showed that lower initial tension leads to increased barrier deflection. However, the magnitude of the increase in deflection is small compared to the actual deflection. The simulations showed that the maximum tension reached in the cables at the end anchors to be four to five times higher than the initial tension. A reduction in initial tension from 24 kN to 15 kN (5.4 to 3.4 kips), 38 percent, would therefore have less of an effect on the significantly higher maximum tension and, consequently, small effects on barrier deflection.

Full-scale crash tests showed that barrier deflections from generic low-tension cable barrier systems are significantly higher (almost twice) than those observed in the high-tension systems. The reason for this difference in deflection between low-tension and high-tension systems seen in the crash tests is attributed more to the cable/post connections than the initial tension. Most high-tension systems have a significantly stronger cable-to-post connection (by weaving the cables, using a splice at the center of the post, etc.) than the low-tension systems (which typically use open

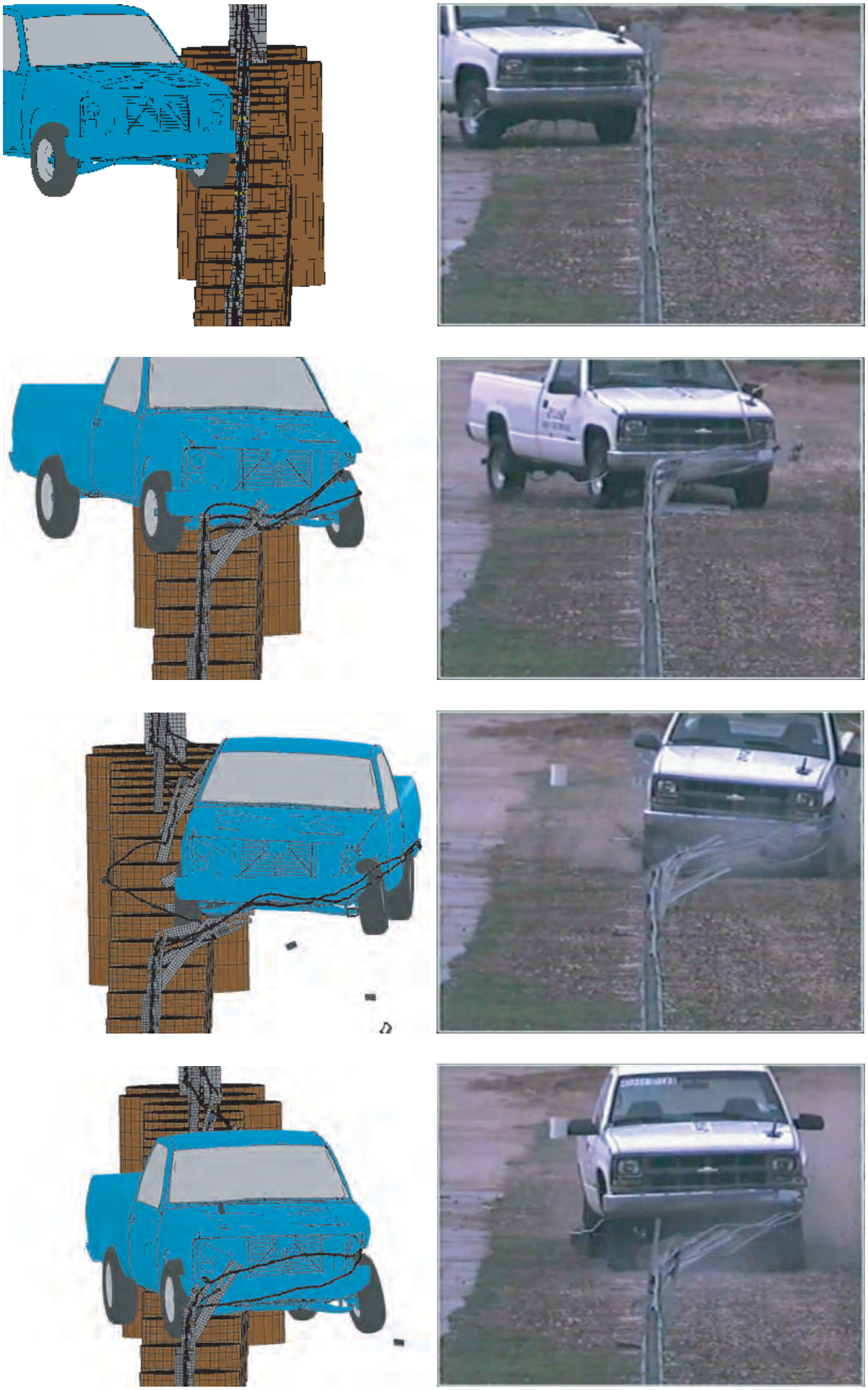


Figure 5.31. Comparison of sequential plots from CASS simulation.

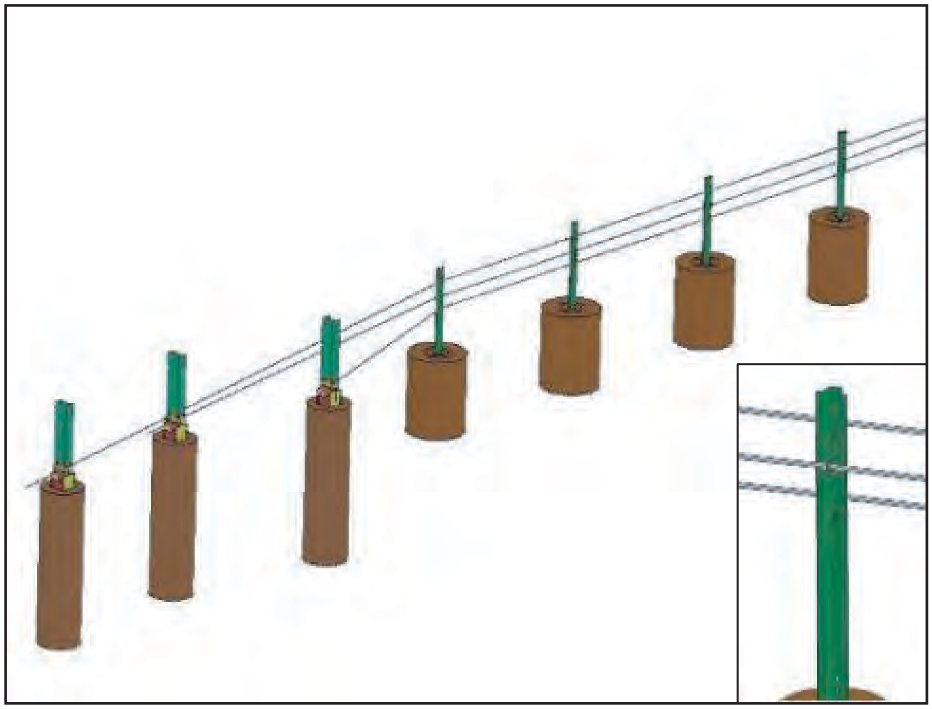


Figure 5.32. Finite element model of the Nucor cable barrier system.

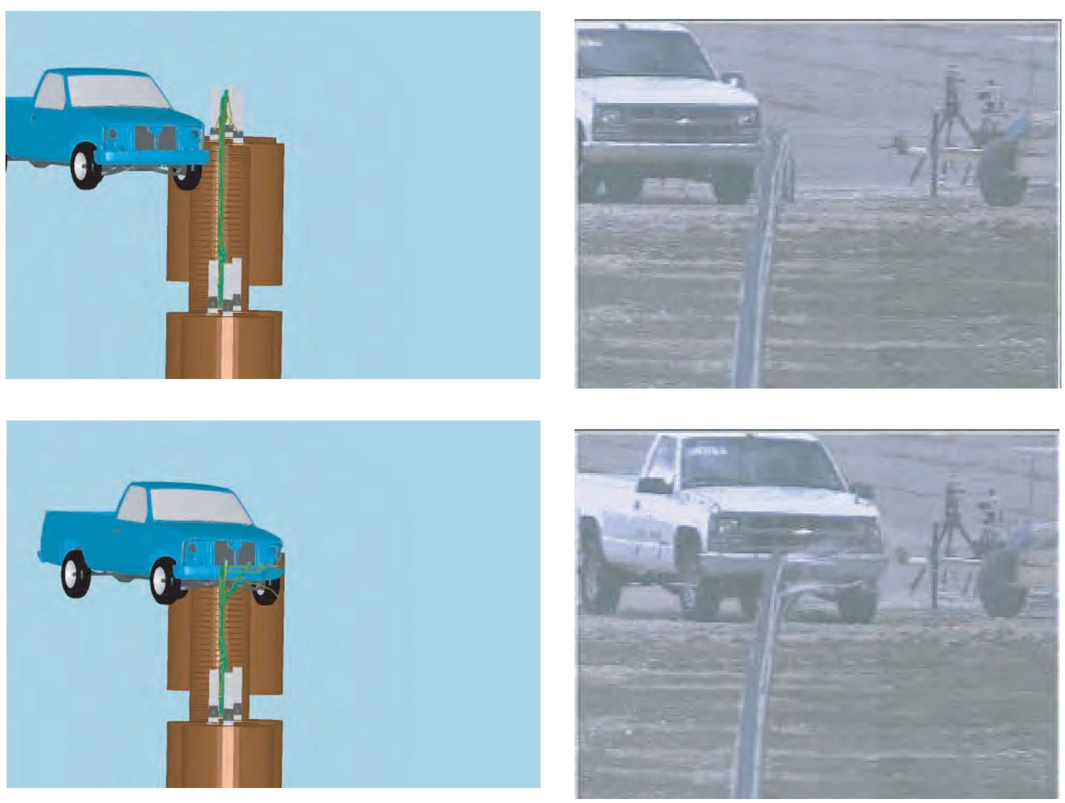


Figure 5.33. Comparison of sequential plots from Nucor simulation.

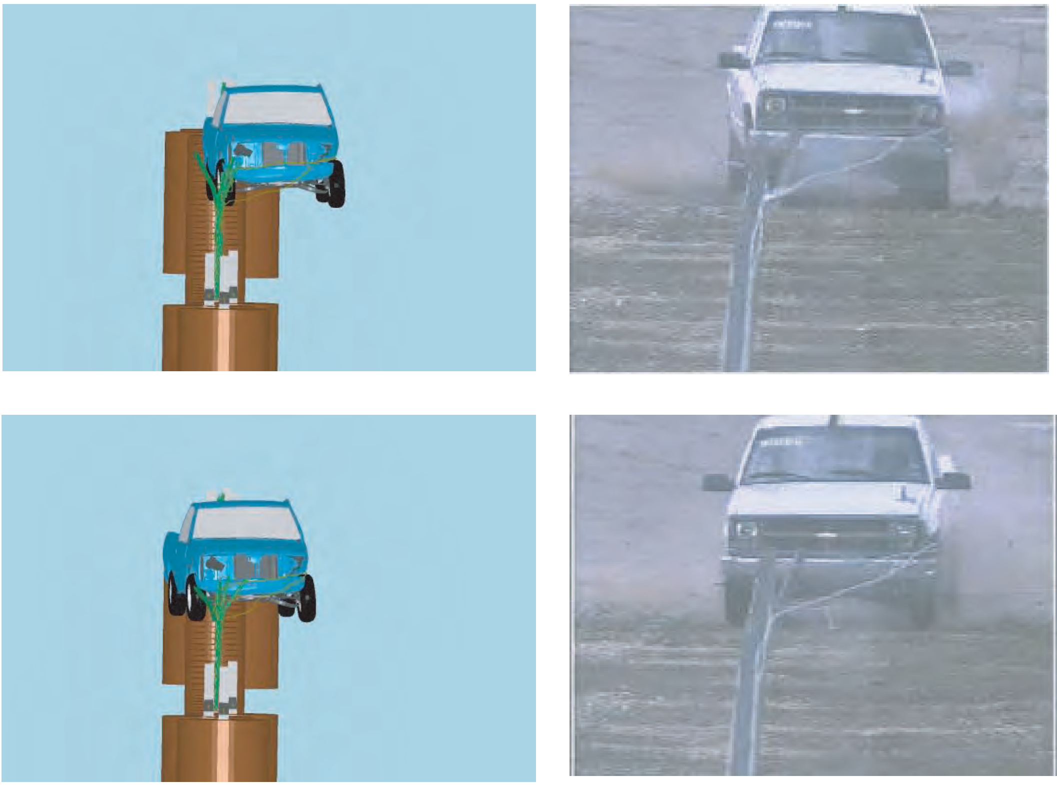


Figure 5.33. **(Continued).**

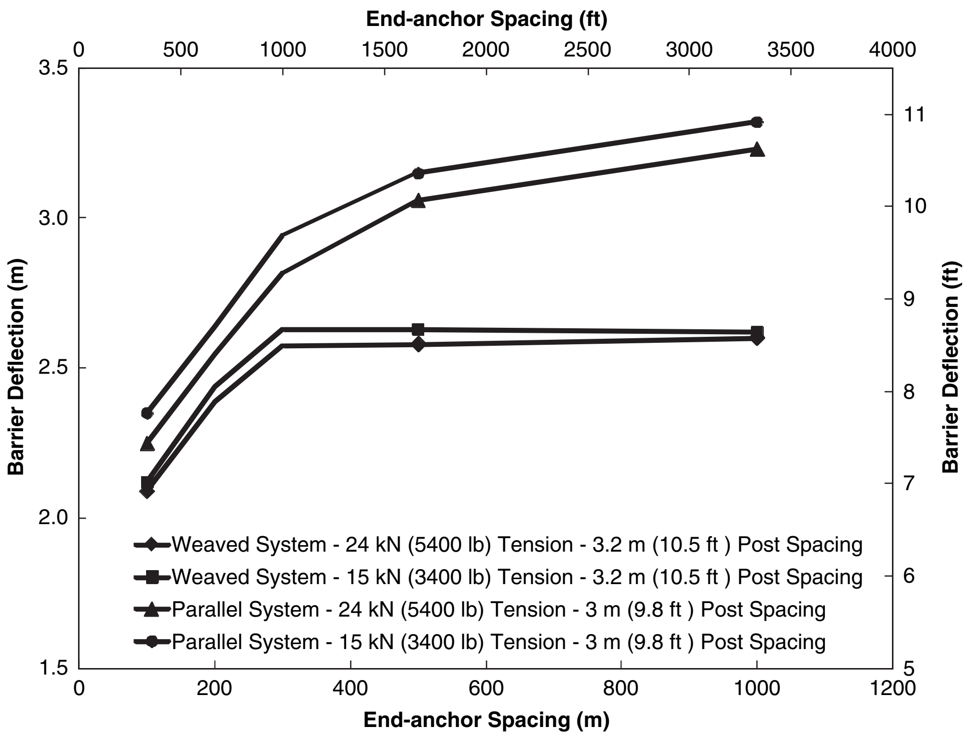


Figure 5.34. Effect of initial cable tension on barrier deflection.

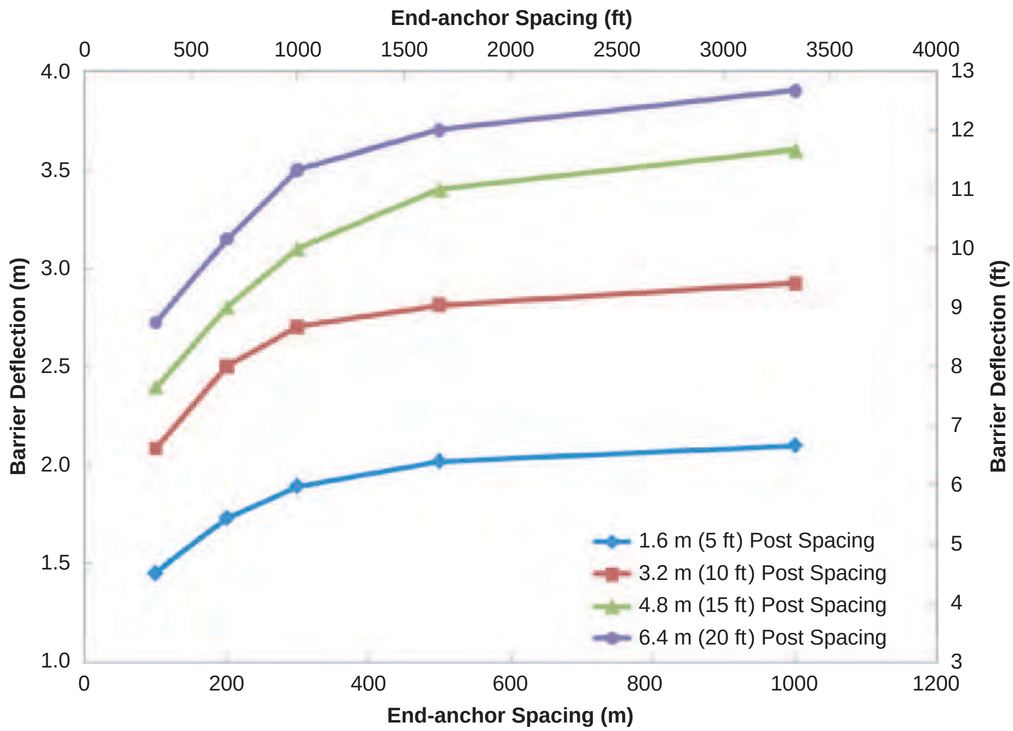


Figure 5.35. Deflection plots for Gibraltar cable barrier system.

hooks to hold the cables to the posts). These stronger cable/post connections delay the release of the cable and lead to reduction in barrier deflection.

End-Anchor Spacing and Post Spacing Effects

To investigate the effects of end-anchor spacing and post spacing on barrier deflection, the simulations with different cable barrier lengths and post spacings were compared. Figures 5.35 through 5.38 show computer-predicted deflections of five cable barrier systems. The figures show the deflections at different end-anchor spacings (100 m to 1,000 m, 328 to 3,280 ft) and post spacings (1.6 to 6.4 m, 5 to 20 ft).

The simulation results show that for all systems the deflection increases as the spacing between the end anchors is increased. The results also show that the effect of end-anchor spacing is different for different cable barrier systems. The difference is mainly attributed to the effect of the cable/post interaction. Systems that restrict the longitudinal sliding of the cables relative to the posts (by engaging the posts or other means) lead to a smaller deflection increase when the end-anchor spacing is increased. The simulations show that the ratio between the increase in barrier deflection and the increase in anchor spacing was less between the 300 m (980 ft) and 500 m (1,640 ft) anchor spacings and even less between the 500 m (1,640 ft) and 1,000 m (3,280 ft) anchor spacings.

For all systems, the simulations show that barrier deflection increases as the post spacing increases. The rate of increase in deflection decreases as the post spacing increases. There was about 30 to 50 percent increase in deflection from 1.6 m (5 ft) post spacing to 3.2 m (10 ft) post spacing, about 10 to 28 percent increase in deflection from 3.2 m (10 ft) post spacing to 4.8 m (15 ft) post spacing, and about 6 to 14 percent increase in deflection from 4.8 m (15 ft) post spacing to 6.4 m (20 ft) post spacing.

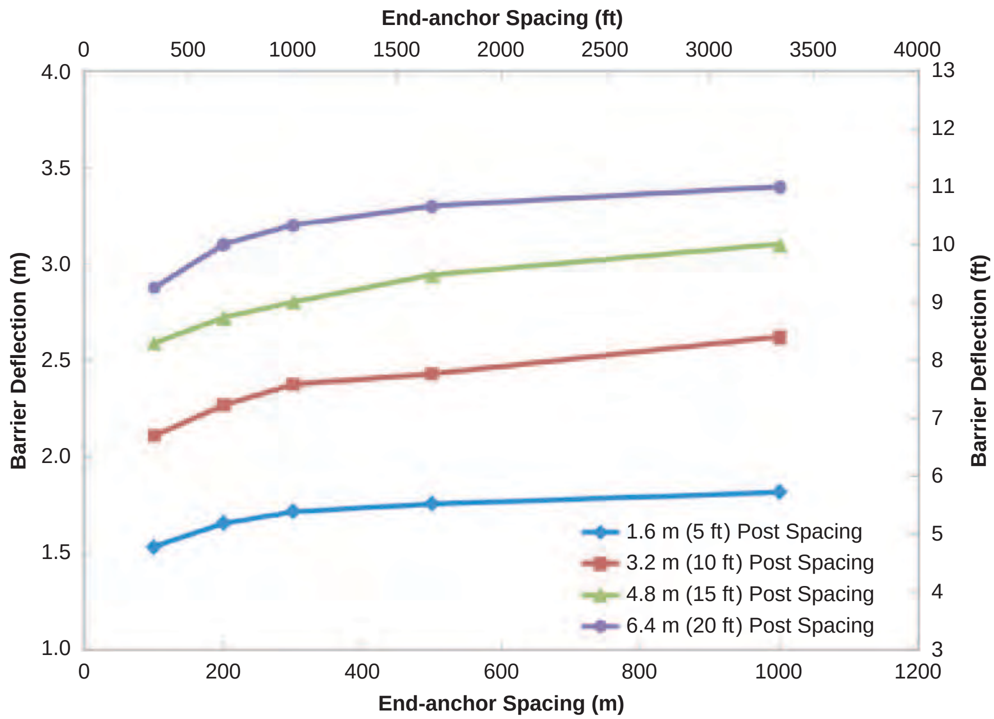


Figure 5.36. Deflection plots for Safence cable barrier system.

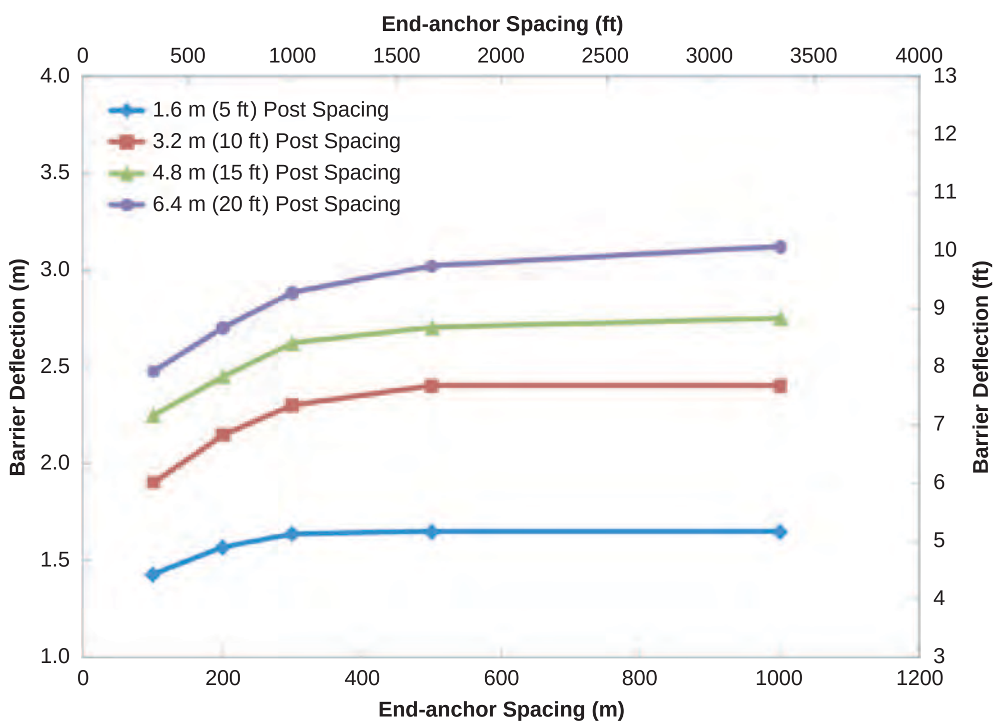


Figure 5.37. Deflection plots for Brifen cable barrier system.

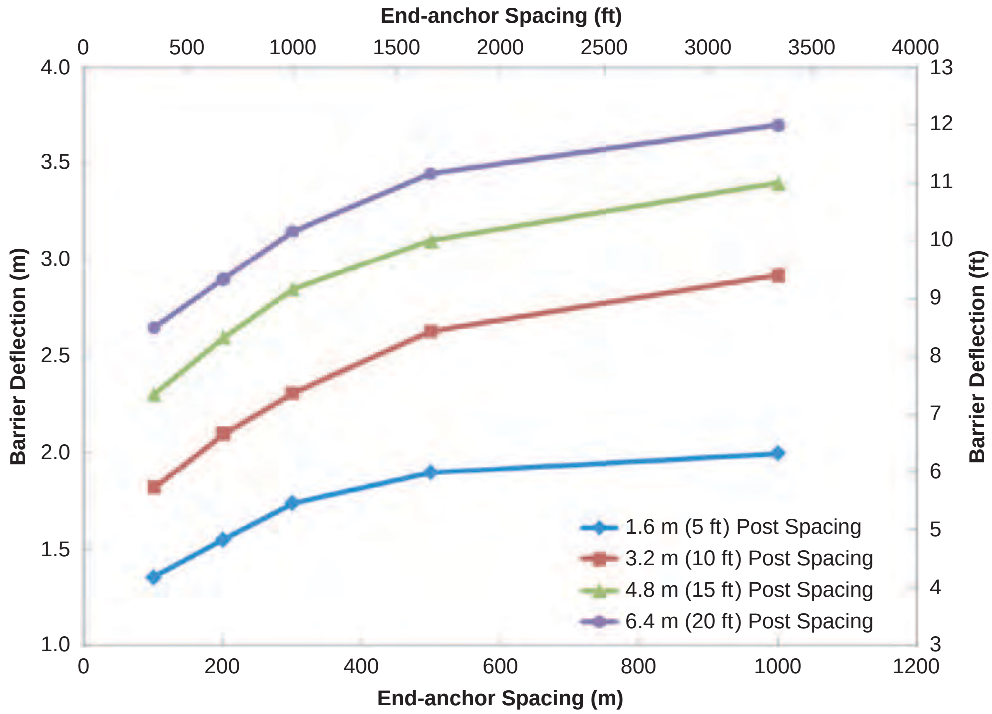


Figure 5.38. Deflection plots for CASS cable barrier system.

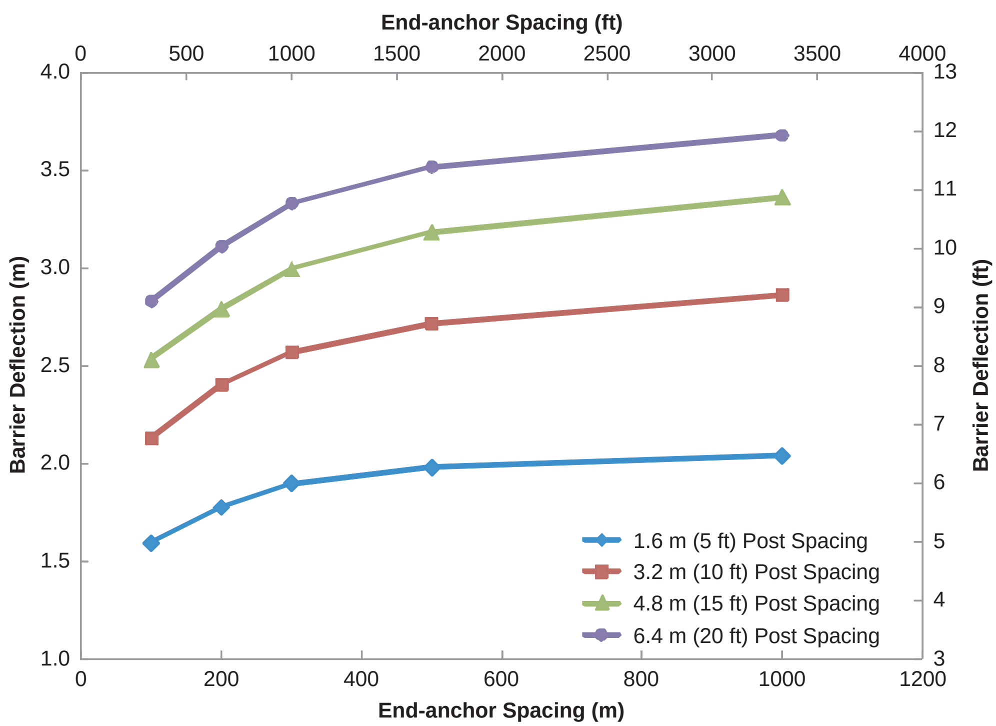


Figure 5.39. Deflection plots for Nucor cable barrier system.

Figure 5.40. End-anchor pull-outs.

5.3 End-Anchoring and Post-Anchoring Systems

Adequate anchoring of the cables is critical to ensure satisfactory barrier performance during impact. Anchor movements lead to lower tension in the cables, which results in larger deflection of the system. The movement could also lead to sagging of the cables, which affects cable heights and consequently affects the barrier's ability to engage the vehicle. Anchor movements are often attributed to weak soil conditions and the substandard-sized anchors. Weather conditions in certain regions of the country can also lead to anchor movement. Temperature decreases lead to higher cable tensions, which, in turn, apply higher forces on the anchors. Anchor pull-outs have been observed in several states, and many state DOTs consider this one of the most critical cable barrier issues. Figure 5.40 shows cases where the anchor has pulled out of the ground.

A recent study conducted at the MwRSF investigated end-anchor movement due to dynamic impact and temperature variation loads [62]. The maximum dynamic impact load used in the analyses was obtained from a MASH Test 3-11 full-scale crash test where load cells were attached to the cables at the end-terminals. The maximum dynamic impact load was found to be 137 kN (31 kips). The maximum thermal load was calculated based on a temperature change of 130°F (from 110 to −20°F). The maximum load due to this change in temperature was computed to be 125 kN (28 kips).

To develop recommendations for end-anchor sizes, the MwRSF researchers used the LPILE software with various sizes and soil strengths [63]. A load of 177 kN (40 kips) was used in the analysis. Figure 5.41 shows the predicted end-anchor movements for different anchor depths,

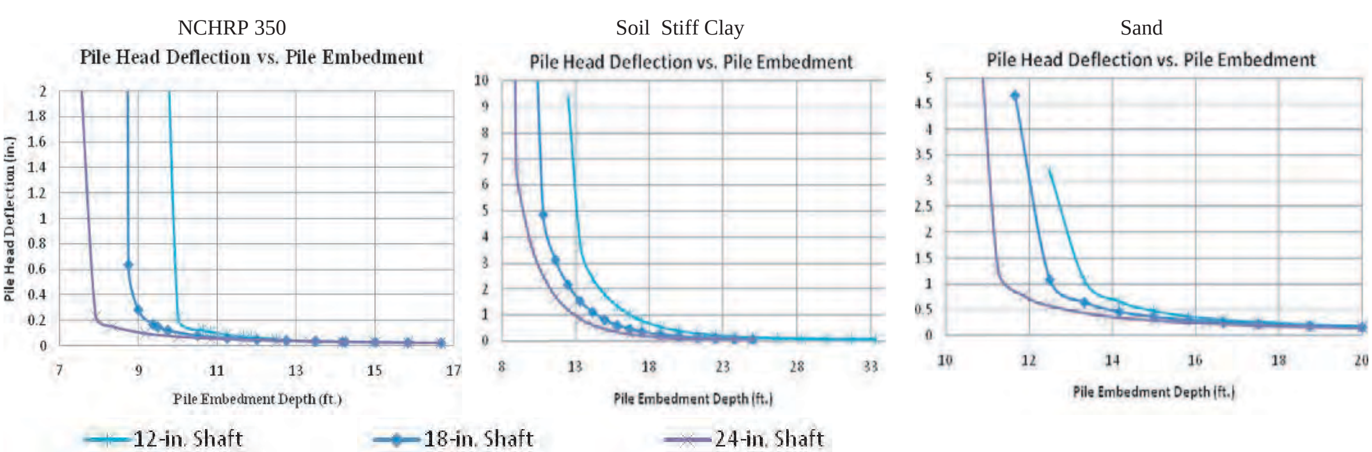


Figure 5.41. Pile deflection for different soil types and end-anchor sizes.

Table 5.1. Recommended end-anchor sizes from MwRSF study [62].

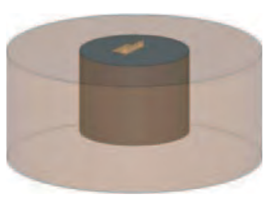
	12-in. Diameter Shaft	18-in. Diameter Shaft	24-in. Diameter Shaft
	Minimum Embedment Depth (ft)	Minimum Embedment Depth (ft)	Minimum Embedment Depth (ft)
350 Soil	10	9	8
Stiff Clay	13	11	9
Sand	13.5	12.5	11.5

anchor diameters, and soil strengths. Based on the assumption that a 50 mm (2 in.) end-anchor movement would lead to complete tension loss in the cables, a recommendation for anchor sizes was developed. Table 5.1 lists the recommended anchor sizes for the different soil conditions. The research indicated these recommendations are very conservative and should not be utilized to indicate the inadequacy of existing foundation designs.

A similar analysis was conducted under this study using the LS-DYNA finite element program. Computer models of cable barrier end anchors with different sizes and geometry were created and subjected to a dynamic load of 140 kN (the 140 kN magnitude was extracted from the simulations performed under Task 5.2 of this study and previously described in Section 5.2). The finite element model setup is shown in Figure 5.42. The soil used in the analysis was based on NCHRP Report 350 strong soil. The soil model was calibrated based on pendulum tests and was used in previous studies and found to give good predictions of the NCHRP Report 350 soil response. Efforts were made under this study to investigate soils with different strengths but, due to lack of test data to calibrate these soil models, the analysis could not be performed. Consequently, the results from this study should be considered as less conservative than the MwRSF results and should be regarded as the minimum size for adequate cable barrier anchoring.

The results from the analysis are shown in Table 5.2. (Readers are reminded that color versions of figures and tables are available in the online version of the report which can be found by searching the TRB website for *NCHRP Report 711*.) End-anchor movement of more than 50 mm (2 in.), shaded in red in the table, are considered inadequate. Movements of 25 to 50 mm (1 to 2 in.), shaded in orange, are considered marginal. Movement less than 25 mm (1 in.), shaded in green, are considered acceptable. It is important to emphasize here that these results are for strong soil and the results do not account for weaker and saturated soils.

Since soil types and conditions vary significantly for different site locations, end-anchor size should be determined on a case-by-case basis. Soil analysis, using similar approaches to the two methods presented above, should be conducted based on the soil data and climate information. Likewise, many designs use posts set in concrete foundations to facilitate removal and replacement of damaged posts. These foundations too must be sized properly based on existing soil and climate conditions so they are not damaged or pulled out of the ground in a crash.



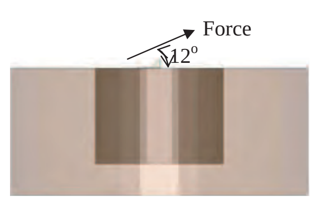


Figure 5.42. End-anchor computer model setup.

Table 5.2. End-anchor movement for different foundation sizes.

Anchor Movement In mm (in.)		Anchor Diameter in m (ft)			
		0.3 (1)	0.6 (2)	0.9 (3)	1.2 (4)
Anchor Depth in m (ft)	0.6 (2)	>55 (2)	>55 (2)	>55 (2)	>55 (2)
	0.9 (3)	>55 (2)	49 (1.93)	20 (0.79)	14 (0.55)
	1.2 (4)	29 (1.14)	24 (0.94)	11 (0.43)	9 (0.31)
	1.5 (5)	19 (0.75)	12 (0.47)	7 (0.28)	6 (0.24)
	1.8 (6)	16 (0.63)	7 (0.28)	5 (0.20)	5 (0.20)
	2.1 (7)	13 (0.51)	6 (0.24)	5 (0.20)	4 (0.16)
	2.4 (8)	11 (0.47)	5 (0.20)	4 (0.16)	4 (0.16)

5.4 Interconnection with Other Systems

There have been accepted systems for the interconnection of cable barriers with strong post guardrail systems. These designs are reflected in FHWA acceptance letters B-147 and B-147A. The letters list several cable-to-W-beam transition designs as meeting NCHRP Report 350 test conditions at Test Level 3. The designs are accepted based on one full-scale crash test. The test was conducted using a South Dakota design wherein a U.S. generic 3-cable barrier was carried over and under a W-beam guardrail and anchored independently behind the metal beam rail. Subsequent to this testing, several of the manufacturers of proprietary cable systems proposed similar transitions, with the basic difference being the cables were attached directly to the W-beam rail element, thus eliminating the need for a separate anchor for the cables. Because the low-tension design performed adequately, there was no reason to suspect that the high-tension proprietary designs would not function as well (or better). Thus, these designs were accepted without full-scale testing. Figure 5.43 depicts a few of these cable barrier to W-beam guardrail transition designs.

In the cable barrier to W-beam transition test, the end terminal of the W-beam guardrail was flared 1.22 m (4 ft) behind the cables. Figure 5.44 shows the vehicle behavior during the impact. As seen in the figure, the vehicle exhibited significant roll due to the impact with the end terminal. The vehicle did not roll over in the test and the transition met the NCHRP Report 350 requirements. Based on the results from this test, 1.22 m (4 ft) should be considered as the minimum flare of the end of the guardrail behind the barrier to avoid vehicle rollover.

Another critical issue with cable barrier transitions is the force between the cable barrier and the system it is connected to (often a W-beam guardrail). It is important to ensure that the cable barrier static tension forces (due to temperature variations) and the impact forces do not lead to pull-out the W-beam barrier from its anchors or failure of the connections between the cables and the W-beam rail. This is especially critical for high-tension cable systems. The W-beam barrier must be long enough and adequately anchored at its downstream end to resist the tension in the cables.

Under this study, simulations were conducted to identify the minimum length needed for strong post W-beam systems when connected to cable barriers. Sections of a G41S W-beam guardrail system were subjected to a longitudinal load of 140 kN (31 kips). This loading was obtained from the simulations performed under Task 5.2 of this study and previously described in Section 5.2. The section length was varied until a movement of the end-post (last post) of the W-beam barrier was less than 25 mm (1 in.). The simulation setup is shown in Figure 5.45. The end-post movement at different G41S section lengths is listed in Table 5.3. The minimum section length was found to be 22.9 m (75 ft).

(a) Generic (b) Brifen

(c) CASS (d) Gibraltar

Figure 5.43. Sample cable to W-beam barrier transitions [64].

Figure 5.44. Sequential images from cable barrier to W-beam transition.

Figure 5.45. Simulation setup for G41S section subjected to a longitudinal load.

Similarly, the connection between each cable and W-beam rail should be designed such that it can withstand 90 kN (20 kips), the maximum load on the cables observed in the simulations under Section 5.2 of this study.

In some installations, the transition was accomplished by placing the cable barrier behind the W-beam guardrail. Figure 5.46 shows a post-crash picture of one of these installations. The picture depicts a case where the vehicle hit the cable system and went between the two barriers. After rebounding from the cable barrier, the vehicle hit the back of the W-beam guardrail. It is therefore recommended that this type of transition should not be used until further analyses and/or testing is conducted to ensure adequate performance is achieved [64].

5.5 Horizontal Curvature

Limited research has been conducted on the performance of cable barrier systems on horizontal curves. Impacts on the convex side of a curved cable barrier will result in larger deflections due to the slackening of the cables that occurs when posts are removed and the cables follow the alignment of a chord rather than the arc. To investigate this effect for high-tension cable barrier systems, finite element simulations were performed.

The models in this study were based on the high-tension, 4-cable CASS system used in the analysis described in Section 5.2. Computer models with varied curve radius and the post spacing were used in the analysis. Curve radii of 150 m (500 ft) (12° curvature), 300 m (1,000 ft) (6° curvature), 450 m (1,500 ft) (4° curvature), and straight alignment were incorporated in the models. For each curve radius, barriers with post spacings of 1.6 m (5 ft), 3.2 m (10 ft), and 6.4 m (20 ft) were created. A total of 12 simulations were performed for the four different horizontal curvatures and three different post spacings. A barrier length of 200 m (650 ft) was used, which provides sufficient length for the barrier to redirect the vehicle. The cable heights were set at 530 mm (21 in.), 640 mm (25.2 in.), 750 mm (29.5 in.) and 968 mm (38 in.). In all simulations, a 2000P Chevrolet C2500 pickup truck impacted the barrier at 100 km/h and 25° angle to the tangent of the curve. In all cases, the barrier was set up on flat, level terrain. Figure 5.47 shows the plan views for the three curves with one of the post spacings, 6.4 m (20 ft).

The maximum deflections of the barrier in the simulations were determined by measuring the distance from the impact side of the vehicle to the original alignment of the barrier. Figure 5.49 shows the location of the initial impact and the deflections for the 150 m (500 ft) (12° curvature), 300 m (1,000 ft) (6° curvature), 450 m (1,500 ft) (4° curvature) simulations for 0.4, 0.6, and 0.8 second time intervals. The deflection results are shown in Figure 5.48.

Table 5.3. W-beam movement for different section lengths.

Section length in m (ft)	17.4 (57)	19.2 (63)	21.0 (69)	22.9 (75)	24.7 (81)
End-post movement in mm (in.)	30 (1.2)	27 (1.06)	26 (1.02)	24 (0.94)	22 (0.87)

Figure 5.46. Post-crash picture of overlapping cable barrier to W-beam guardrail transition.

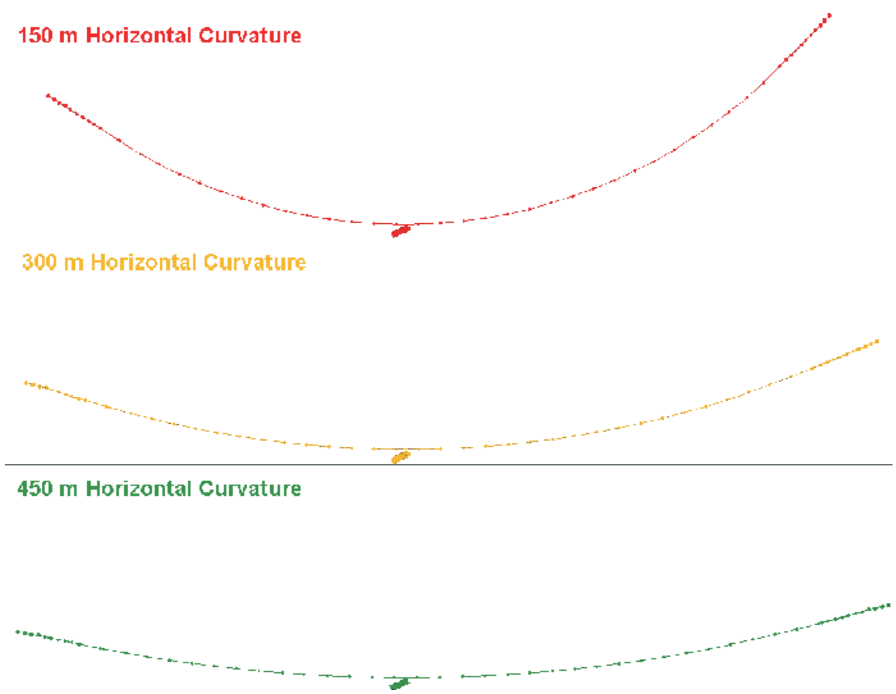


Figure 5.47. Plan views for the three convex curve simulations, 4-cable CASS system.

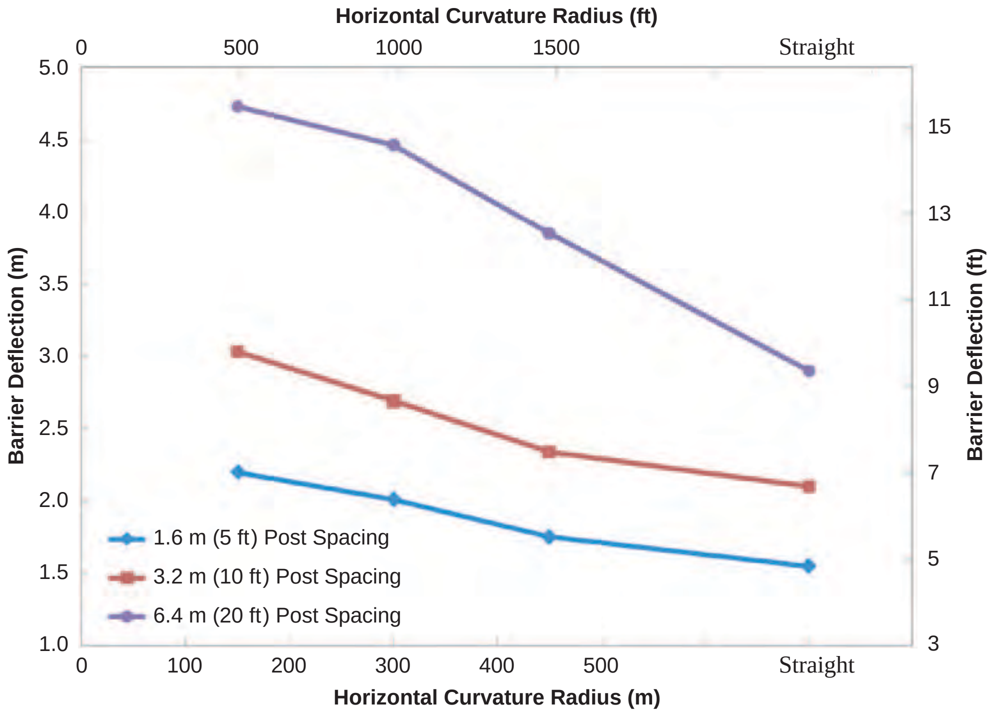


Figure 5.48. Deflection plots for different horizontal curvatures for convex-side impacts.

Figure 5.50 shows the percentage increase in deflection due to horizontal curvature for the three different post spacings. The base deflection is from the simulations using a straight alignment, i.e., zero degree curvature. The results were nearly identical for post spacings of 1.6 m (5 ft) and 3.2 m (10 ft), but going to a wider post spacing of 6.4 m (20 ft) shows a significant increase in deflection. For a curve with a 450 m radius (1,500 ft) (4° curvature), the increase in deflection is only about 10 percent for close post spacings but is 33 percent greater for post spacings of 6.4 m (20 ft). For this level of curvature, the maximum design speed is approximately 100 km/h (62 mph). For the sharpest curve simulated, 150 m radius (500 ft) (12° curvature), the deflection is 63 percent higher for a wide post spacing of 6.4 m (20 ft) and about 43 percent greater for the close post spacings. This level of curvature is associated with a maximum design speed of approximately 70 km/h (43 mph).

These findings suggest that wide post spacings for cable barriers should not be used on horizontal curves where convex hits are possible and the curve radius is less than 400 m (1,300 ft) (degree of curvature greater than 4°). Even if adequate clear area is available, the greater deflection could adversely affect the barrier's ability to capture and redirect impacting vehicles. Also, in median applications on sharp curves, placing barriers on each side of the median should be considered to reduce the likelihood of vehicles impacting the convex side of the barrier and intruding into on-coming traffic.

5.6 Installation Costs

The selection of any roadway element should be made considering the associated life-cycle costs. Life-cycle costs include the costs of installation and costs associated with both routine periodic maintenance and occasional repair costs. The following sections describe the process and available data for life-cycle cost analyses for cable barrier deployments.

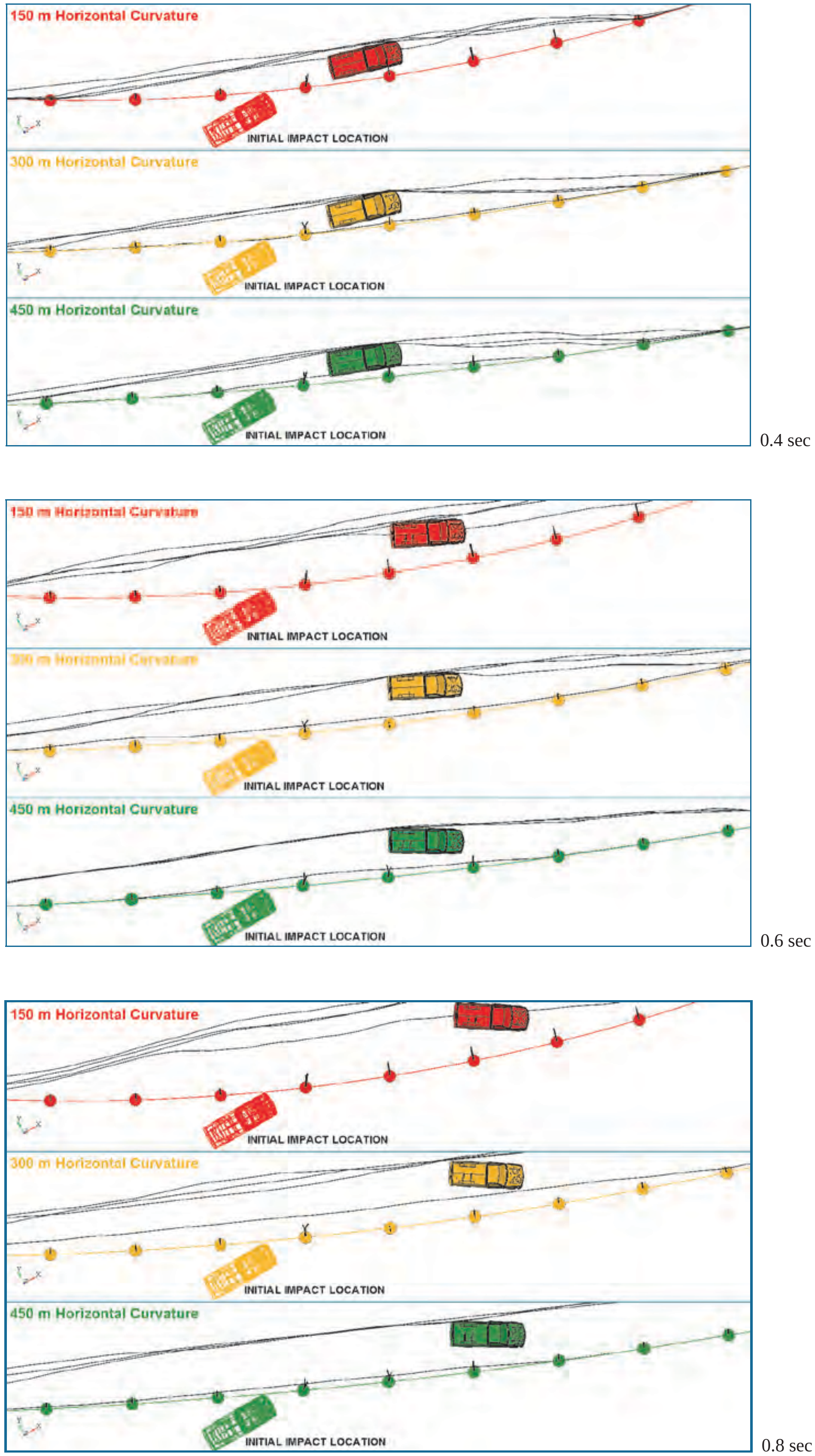


Figure 5.49. Sequential plots from convex-side impacts for different horizontal curvatures.

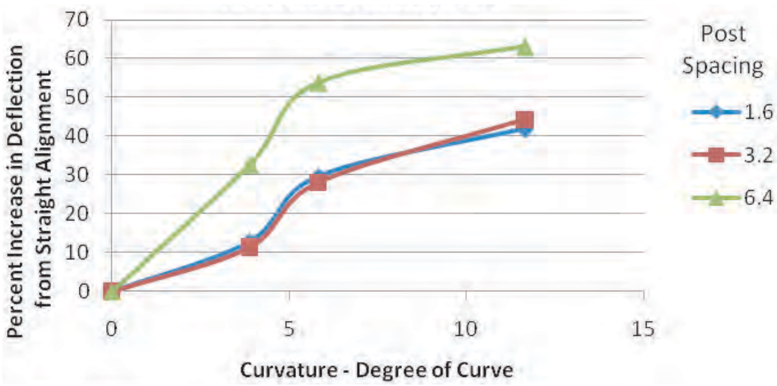


Figure 5.50. Influences of horizontal curvature and post spacing on deflection in convex-side impacts.

Installation Costs

Installation costs for cable barriers include the cost of the barrier and its end anchors as well as costs for modifications to the median or shoulder area. In some cases, the preparatory costs can exceed the cost of the barrier, particularly when major grading work is done and mow strips are constructed. This section of the report addresses costs for only the barrier and its end anchors.

Installation costs for high-tension cable barriers vary widely from state to state. Some factors contributing to these variations could be associated with the length of the installation, cable barrier type, soil condition, and weather environment. Recent (2010) costs for TL3 systems in Texas average less than $5 per linear foot (LF, 0.3 m) but average costs in South Dakota in 2009 were over $15 per LF. An analysis of bid tabulations from Colorado for 2009 through 2011 showed that for 11 projects totaling 151,388 LF (29 mi, 46 km), the average and median winning bid for high-tension cable barriers was $11.69 per LF and $11.10 per LF, respectively. Among the 57 bids for these 11 projects, the unit bid price ranged from $6.10 to $27.00.

Ignoring competitive factors, installation costs for high-tension barriers should depend on post spacing, anchor spacing, number of cables, soil conditions, and type of post foundation. The least expensive system would be a 3-cable system with driven posts, wide post spacing, and wide anchor spacing located in an area with very good soil conditions. The most expensive system would be a 4-cable system with posts in concrete foundations with short anchor spacing located in poor soil conditions.

In general, lowering installation costs by increasing post and anchor spacing will be offset by decreased barrier performance. Barrier deflection during impact would likely be higher and the potential for barrier penetrations would possibly increase. Similarly, installation cost savings achieved by using driven posts instead of concrete foundations with inserts will be offset by increased impact repair costs.

Life-cycle cost analysis provides a way to combine the effects of the tradeoffs mentioned above. For cable barrier systems, life-cycle costs include installation costs, maintenance costs, repair costs, and disposal costs at the end of the system's useful life. The time value of money (i.e., discount rate) needs to be included in the analysis for it to be valid. Performance reductions and barrier failures also need to be included in the analysis.

Data are not available to allow complete life-cycle analyses for the various cable barrier systems. Detailed cost and in-service performance data are needed to perform these analyses, and many state DOTs have not collected this information or accumulated enough data to have meaningful averages. However, it is possible to provide information on some aspects of cable barrier costs that can be used to estimate life-cycle costs.

Effects of Service Life and Discount Rate

Service life of cable barriers is long, which reduces the impact of installation costs on total life-cycle costs. The longer a barrier is in use, the lower the average annual cost of installation will be since these costs are spread over more years. The discount rate determines how future costs are "discounted" so that the average annual costs reflect the time value of money and the opportunity costs associated with the initial investment. Higher discount rates increase the annual cost of installation costs.

Service life for cable barriers can be very long if the roadway where they are installed is not modified in a way that requires the barrier to be moved or removed. For example, cable barriers in medians may have to be removed if the highway is widened by taking land from the median. The width of the modified median may be too narrow to accommodate cable barriers because of the relatively large dynamic deflections associated with flexible cable barriers. Shoulder improvements, pavement overlays, and alignment adjustments are other highway modifications that could shorten the service life of a cable barrier installation. Service lives of 5 to 50 years are used in the analysis to cover the expected range for cable barriers.

The discount rate is primarily affected by interest rates, now and in the future. Interest rates in 2010 are at historic low levels because of the current economic situation. Since interest rates are effectively zero today, the only way they can move is up. During times of high inflation, such as the early 1980s, interest rates were in the high teens. Forecasting future interest rates is difficult, so analyses have been done on a wide range of interest rates from 0 to 14 percent, which should cover the likely range of future rates.

As mentioned above, installation costs for cable barriers vary widely. To allow for the wide variation in costs, calculations have been done for a $1 unit installation cost per linear foot of barrier. Thus, to determine the equivalent average annual cost for an installation costing $10 per linear foot, the numbers in the Table 5.4 need to be multiplied by 10.

Table 5.4 shows how significant the effect of service life and discount rate can be on the contribution of installation costs to total life-cycle costs. For a barrier that costs $1 per linear foot to install, the average annual cost for 1 mile of barrier can range from $106 for a service life of 50 years and a 0 percent discount rate to $1,538 for a 5-year service life and a discount rate of 14 percent.

Table 5.4. Effect of service life and discount rate on life-cycle costs—installation costs.

	Annual cost ($ per mile) per $1.00 of installation cost per linear foot									
Discount	**Service Life of Cable Barrier (years)**									
Rate	5	10	15	20	25	30	35	40	45	50
14%	1,538	1,012	860	797	768	754	747	743	741	740
12%	1,465	934	775	707	673	655	646	640	637	636
10%	1,393	859	694	620	582	560	547	540	535	533
8%	1,322	787	617	538	495	469	453	443	436	432
6%	1,253	717	544	460	413	384	364	351	342	335
4%	1,186	651	475	389	338	305	283	267	255	246
2%	1,120	588	411	323	270	236	211	193	179	168
0%	1,056	528	352	264	211	176	151	132	117	106

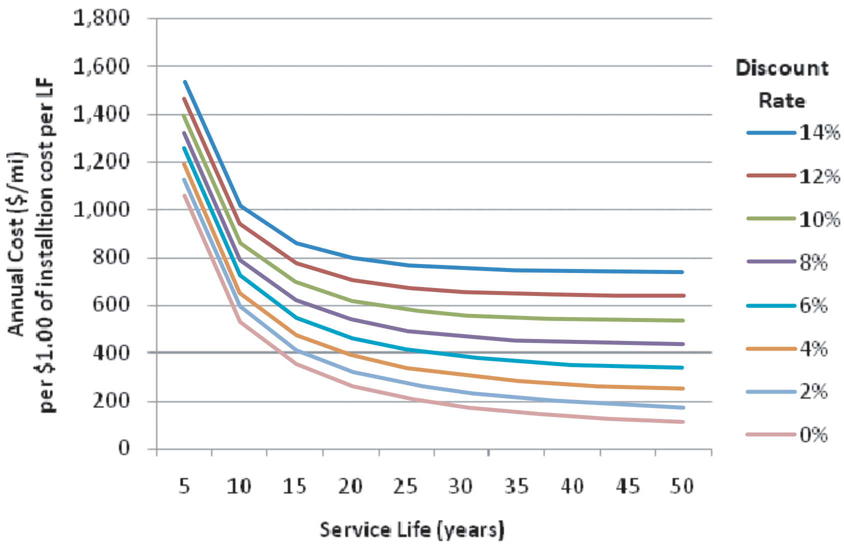


Figure 5.51. Effect of service life and discount rate on life-cycle costs—installation costs.

The data in Table 5.4 is shown graphically in Figure 5.51. This figure shows that for higher discount rates the average annual cost is insensitive to changes in service life beyond 20 years. For discount rates in the "normal" range of 6 to 10 percent, insensitivity to service life occurs around 25 to 30 years. This analysis suggests that using a service life of 25 years for cable barrier projects is appropriate unless it is known that the service life of the system will be shorter because of planned or expected roadway modifications.

Effects of Anchor Spacing on Installation Costs

The spacing of anchors for high-tension cable systems varies widely from project to project. The impact of anchor spacing on barrier performance is discussed elsewhere in the report. Wider spacing of anchors reduces the cost of the system since fewer anchors are needed. If an anchor is destroyed in an impact, the longer the anchor spacing, the greater the length of barrier that is out of service until the anchor is replaced and the system is retensioned.

Anchor cost varies widely because of different designs used by the manufacturers and because of soil condition variations. Undersized anchors have been a significant problem, particularly for states that have not required soil-specific designs. Several anchors have pulled out of the ground during periods of cold weather. Recent average TL3 anchor costs in Texas were $1,512 from December 2009 to February 2010 and $2,300 from October 2009 to December 2009. In 2009, TL3 anchors in South Dakota cost an average of $3,881. Part of the difference in costs between Texas and South Dakota can be attributed to the larger anchors required in northern climates. Stricter specifications in South Dakota may also be responsible for part of the higher costs.

For the previously mentioned 11 recent projects in Colorado, the average and median winning bid for the 127 anchors in these projects was $2,718 and $2,500, respectively. In only 4 of the 11 projects was the unit price of the low bid (contract winner) the lowest price for the anchors. The overall average for the 57 anchor bids was $2,388 and individual bids ranged from $1,500 to $6,000.

For the Colorado projects, the average spacing between anchors ranged from 74 m (241 ft) to 507 m (1,663 ft) with a median of 160 m (525 ft). One long 2010 project in Kentucky totaling 26.6 km (16.5 mi) of high-tension cable barrier used only 24 anchors, giving an average anchor spacing of 2,213 m (7,260 ft). The bid prices (9 contractors) averaged $2,621 per anchor and

Table 5.5. Effect of anchor spacing on installation cost.

Anchor Spacing (ft)	Extra Cost ($) per linear foot due to end anchors — Cost per end anchor ($)						
	1,000	1,500	2,000	2,500	3,000	3,500	4,000
200	10.00	15.00	20.00	25.00	30.00	35.00	40.00
500	4.00	6.00	8.00	10.00	12.00	14.00	16.00
1,000	2.00	3.00	4.00	5.00	6.00	7.00	8.00
2,500	0.80	1.20	1.60	2.00	2.40	2.80	3.20
5,000	0.40	0.60	0.80	1.00	1.20	1.40	1.60
7,500	0.27	0.40	0.53	0.67	0.80	0.93	1.07
10,000	0.20	0.30	0.40	0.50	0.60	0.70	0.80
15,000	0.13	0.20	0.27	0.33	0.40	0.47	0.53
20,000	0.10	0.15	0.20	0.25	0.30	0.35	0.40

ranged from $2,000 (winning bidder) to $3,200. Two recent projects in Oklahoma had average anchor spacings of 2,500 m (8,200 ft) and 2,256 m (7,400 ft). Anchor costs were $3,900 for the first project and $2,000 for the other.

To allow for the wide variation in anchor costs, a range of costs from $1,000 to $4,000 has been used in the anchor analysis. Using these anchor costs, the extra cost that the anchors add per linear foot of barrier is shown in Table 5.5 for anchor spacings of 61 to 6,100 m (200 to 20,000 ft).

End-anchors can add a lot to the cost of a cable barrier system; but without adequate anchors, high-tension cable barrier systems are ineffective. The dynamic deflection from an impact increases with increased anchor spacing, and the increase in deflection varies for different cable barrier systems. Also, anchors that are undersized cost less, but can lead to failures of the system and costly repairs. Effective end anchors must be designed for site-specific soil and climate conditions. The values highlighted in the table represent typical values for many states and systems: anchor spacings from 300 to 1,500 m (1,000 to 5,000 ft) with anchor costs of $1,500 to $3,000. The impact on barrier installation cost ranges from minor for low-cost anchors separated by 1,500 m (5,000 ft) to major for higher-cost anchors separated by only 300 m (1,000 ft). There is a 10-fold difference in unit cost between these two conditions.

Effects of Post Spacing on Installation Costs

For most installations of high-tension cable barriers, post spacings vary between 10 and 20 ft. Post spacing narrower than 10 ft is used where deflections need to be low to avoid obstructions close behind the barrier. Post spacings greater than 20 ft have been used, but concerns about the increased risk of penetrations at wide post spacings have discouraged states from using very wide post spacings.

Post costs depend on the cost of steel, the amount of steel in the post, the accessories (lock plates, hair pins, spacers, stiffeners, caps, etc.) required by the particular design, and the installation method (concrete foundation, steel sleeves, or driven). Most often these costs are included in the unit bid price for the barrier so that actual post costs are difficult to identify.

Table 5.6 shows the impact of post spacing and post cost on cable barrier installation costs. The table covers a wide range of post costs from $20 to $90. These costs include the material costs for the post and foundation as well as the installation costs. Driven steel posts are the least expensive, and steel posts in concrete foundations designed for poor soil conditions in cold climates are the most expensive. Material costs for posts also vary among the manufacturers due to post size and design.

The post spacings in Table 5.6 range from 1.2 m (4 ft), which is used only in special, low-deflection cases, to 6.4 m (20 ft) which is the upper limit of post spacings for most new installations. Common post spacings are 3.0 m (10 ft) and 4.9 m (16 ft).

Table 5.6. Impact of post spacing and post cost on cable barrier installation costs.

	Cost ($) per linear foot due to posts and foundations							
Post Spacing (ft)	Cost ($) per installed post and foundation							
	20	30	40	50	60	70	80	90
4	5.00	7.50	10.00	12.50	15.00	17.50	20.00	22.50
6	3.33	5.00	6.67	8.33	10.00	11.67	13.33	15.00
8	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25
10	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
12	1.67	2.50	3.33	4.17	5.00	5.83	6.67	7.50
14	1.43	2.14	2.86	3.57	4.29	5.00	5.71	6.43
16	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63
18	1.11	1.67	2.22	2.78	3.33	3.89	4.44	5.00
20	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50

Posts are a major component of overall barrier installation costs, but they are less variable than anchor costs. For the highlighted values in Table 5.6, which represent typical values, the highest value is 2.4 times the lowest value. However, in the case of typical anchor costs as shown in Table 5.5, the highest value is 10 times the lowest value. Coincidentally, the highest typical unit value for post costs is exactly the same as the highest typical cost for anchor costs indicating an equal contribution of post and anchor costs to installation cost. However, the lowest typical post cost is more than 4 times as high as the lowest typical anchor cost.

Effects of Cable Costs on Installation Costs

Cable cost is the most predictable of all of the cable barrier components. Galvanized wire rope used for the cables is a standard commodity; the price varies mostly with the cost of steel. Now that so much prestretched wire rope is being used for highway barriers, there is no significant difference in cost between prestretched and regular wire rope.

Installed cost for cable is approximately $1.00 per linear foot per cable, plus or minus 20 percent. All high-tension cable barriers have either three cables or four cables. The 4-cable systems provide coverage for a wider range of vehicles for a small incremental increase in cost over 3-cable systems.

For barriers with 4.9 m (16 ft) post spacing, the cable costs and post costs are approximately the same. For barriers with closer post spacings, the cable costs are less than the post costs. End anchor costs are usually less than the cable costs except when anchor spacing is less than 610 m (2,000 ft).

Increasing anchor spacing is a way to reduce cable barrier installation cost, but it does have a significant effect on barrier performance. Cable barriers have typically been crash-tested at anchor spacings of approximately 100 m (328 ft) under NCHRP Report 350 guidelines and at 183 m (600 ft) under MASH guidelines. Research discussed in Section 5.2 indicates that an anchor spacing of 305 m (1,000 ft) will result in increases in deflection of approximately 25 percent from crash-test-reported values. Going to an anchor spacing of 1,524 m (5,000 ft) will result in increases in deflection of up to 50 percent from crash-test-reported values, depending on the cable barrier system.

Increasing post spacing is another way to reduce installation costs, but deflection is increased, which affects barrier performance. Increases in deflection resulting from increases in post spacing appear to be independent of anchor spacing. Increasing the post spacing from 3.2 m (10 ft) to 4.8 m (15 ft) can lead to an increase in deflection of approximately 20 percent. An increase of post spacing from 3.2 m (10 ft) to 6.4 m (20 ft) can result in an increase in deflection of approximately 30 percent.

Many states have opted for 3-cable systems instead of 4-cable systems for cost reasons. Also, it may not be clear to these states that 4-cable systems provide greater safety than 3-cable systems for very little extra cost. Penetrations of barriers are caused when vehicles go under, through, or over cable barriers. By adding a fourth cable, a wider range of heights can be achieved, as well as a closer vertical spacing of cables to reduce the likelihood of penetrations.

The inflation-adjusted 2010 societal cost of a highway fatality is estimated to be approximately $3.575 million by FHWA. The average annual cost of adding a fourth cable to a 3-cable barrier is $413 per (1.6 km) mile for a barrier with a 25-year service life and a 6 percent discount rate (see Table 5.4). Adding the fourth cable to 1,600 km (1,000 miles) of barrier has an average annual cost of $413,000. Thus, if the added cable would reduce the number of fatalities by 1 over this 1,600 km (1,000 mi) of highway over an 8-year period, it would offset the cost of the extra cable.

The small incremental cost of adding a cable opens the possibility of designing barriers with more than four cables particularly when used on steep slopes within medians. As mentioned earlier in the report, the wide range of trajectories of vehicles on steep median slopes makes it difficult for a conventional 3-cable or 4-cable barrier to capture all vehicles. Adding one or two cables increases the range over which the barrier can capture vehicles, allowing the barrier to be located in more areas of the median and reducing the probability of penetrations.

5.7 Cable Barrier Maintenance: Tolerances, Repairs, and Systemwide Maintenance

Tolerances: Construction and Maintenance

Variations in cable barrier dimensions, especially cable heights, could affect the ability of the barrier to perform adequately. Additionally, variations in the terrain shape and slope could also affect barrier performance. The vehicle dynamics and finite element simulations performed under this study, as well as findings from the literature, were used to develop suggested tolerances for cable barrier installations. Table 5.7 lists these tolerances. The tolerances were established such that the variations within the suggested limits should not have significant effects on cable barrier performance.

Based on vehicle dynamics analyses, increasing the height of the lowest cable or decreasing the height of the highest cable could adversely affect the barrier's ability to engage a vehicle and lead to underrides or overrides. Thus, a zero tolerance is suggested for the lowest and highest cables for the critical side (upper for lowest cable and lower for highest cable). Cable heights affect a barrier's ability to engage and capture an impacting vehicle so tolerances must be tight to insure that the barrier will perform as designed. For the middle cables and non-critical side of the top and bottom cables, a tolerance of 25 mm (1 in.) is suggested. This tolerance may be difficult to achieve on vertical curves without having post connections that resist vertical movements of the cables. In particular, extra care is needed around drainage inlets to insure that the cables have the correct heights to reduce the probability of underrides.

Table 5.7. Suggested cable barrier tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in)
Bottom Cable Height	-25,+0 mm (-1, +0 in)
Middle Cable(s)	±25 mm (±1 in)
Barrier Lateral Position	±150 mm (±6 in)
Average Post Spacing	±150 mm (±6 in)
Consecutive Post Spacing	±600 mm (±2 ft)
Cable Tension	±2 kN (±0.45 kips)

The lateral position of the barrier relative to the roadway or median centerline is important for several reasons. These reasons were explained in detail in Section 5.1. Small deviations from the design alignment may be needed to accommodate issues in the field such as imbedded rocks, drainage facilities, and other construction constraints. The suggested tolerance for lateral position is 150 mm (6 in.), which should never be exceeded if the barrier is being placed near the centerline of the median because of the sensitivity of barrier performance to location as discussed in Section 5.1.

Post spacing is less critical since it primarily affects the magnitude of deflection and not the ability to engage a vehicle unless the post spacing is very wide (wider than the maximum spacing used for the crash tests). Most cable barriers have been crash-tested and accepted for more than one post spacing, confirming that barriers can perform adequately at varied post spacings. The suggested tolerance for consecutive post spacings is 600 mm (2 ft). This tolerance should provide enough flexibility to account for field obstacles that prevent a post from being installed in the exact location specified on the plans. The suggested tolerance on average post spacing, in the region free of obstacles, is 150 mm (6 in.).

Cable tension makes cable barriers work, particularly for high-tension systems. However, cable tension changes with temperature, increasing in cold weather and decreasing in warm weather due to thermal contraction/expansion. Simulations of cable barriers at different tensions were discussed in Section 5.2. Minor changes in tension do not have significant effects on deflection. Lower tensions allow some increase in deflection, but higher tensions exert higher static loads on anchors, particularly during cold weather. Because of the day-to-day variations in tension due to climatic changes, specifying a tight tolerance on tension would increase the need for barrier maintenance without a commensurate increase in safety. Therefore, the suggested tolerance for cable barrier tension (as measured against the design tension for the given cable temperature) is 2 kN (450 lb).

Cable Barrier Repairs

Most maintenance costs associated with cable barriers result from crash damage. Since cable barriers are often placed where they can be hit frequently, these costs can be significant. In police-reported crashes, it is usually possible to get the offending driver's insurance company to reimburse the highway agency for these costs. But, because cable barriers are so "forgiving," drivers often are able to drive away after a crash, which makes it difficult to collect from an insurance company. Data from a few states indicates that police reports are usually available for slightly more than half of the crashes. However, non-reported crashes are less severe, which means their repair costs will be lower. Kentucky found that non-reported crashes had approximately half as many damaged posts as the more severe crashes where a police report was filed.

Frequent inspections are needed to identify crash damage, but these inspections can be accomplished by highway agency and police personnel reporting damage they observe as they drive by the barriers during their normal work activities. In addition, periodic inspections should be conducted to identify unreported damage. In the state survey conducted for this study, the frequency of inspections ranged from daily to annually. Previous crash history can be used to determine how frequently inspections should be conducted for each highway. Crash frequency depends on the average daily traffic (ADT), speed limit, location of the barrier relative to the edge of pavement, and weather conditions.

In most crashes, only the posts are damaged. It is rare for the cable to be damaged unless a vehicle gets tangled in the cables or the cables are cut by emergency response personnel. In the majority of crashes, the cables can be reinstalled on the replacement posts without the need to retension. If enough posts have been destroyed to cause the cables to be on the ground, then the tension in the repaired system should be checked. If any of the individual cable wires has been broken or if significant kinks in the cable are visible, the cable should be evaluated to determine if it needs to be replaced. In the rare case of an extremely large deflection caused by a heavy vehicle impact, the cable should be examined to make sure that plastic deformation of the cable has not occurred.

The number of posts damaged in a crash depends on a number of factors including the velocity and mass of the impacting vehicle, impact angle, post spacing, cable tension, barrier type, and vehicle-barrier interactions. Most states have found that the average number of posts damaged in a crash is between four and eight. A few crashes with tractor trailers have resulted in more than 50 posts being damaged.

The cost to repair posts depends on a number of factors. Driven posts are more expensive to replace than posts in socketed concrete foundations. Post repairs in winter can be more expensive if the posts are frozen in the sockets. Little data is available on the difference in cost of using driven posts rather than socketed posts. Many states now use socketed posts routinely because of the ease of post replacement after crashes. Ohio, one of the first states to install high-tension cable barriers, purposely installed some of each kind of post to be able to observe the differences. Shortly into the program they began to replace all damaged driven posts with socketed posts because of the difficulty associated with repairing driven posts. Data from Oklahoma shows an installation cost savings of approximately $3 per LF for driven posts. For a 25-year service life and a 6 percent discount factor this savings is about $1,240 per 1.6 km (1.0 mi) per year. Texas data shows an average of about 6 crashes per 1.6 km (1 mile) per year on their highways with cable barriers while 2007 data from Oklahoma shows an average of about 14 crashes per 1.6 km (1.0 mi). Using the more conservative Texas crash rate, the savings in cost for driven posts is approximately $200 per crash. In Oklahoma, the savings is only $90 per crash. Repairs for driven posts require post-driving equipment, which often requires a lane closure. The extra cost for driven-post repairs will easily exceed the $200 saving per crash. Thus, the added cost of including posts with socketed concrete foundations may be justified except possibly for very lightly traveled roads where the expected crash rates are low.

Repair costs, on a per-post basis, are useful for forecasting future repair costs. Some states have collected good information on repair costs for cable barriers at least for the first couple of years of service.

In the state survey, responders were asked to give the average number of posts damaged per impact and the average cost per impact. The 18 responses for cost per impact fell into two groups of nine, the first being rather precise numbers ranging from $240 to $870 and the other having what appeared to be estimates with all numbers rounded to the closest $100 and most rounded to the closest $1,000. These values ranged from $1,000 to $10,000. It appears that the numbers in the first group, which averaged $520 per crash, were probably based on studies while the numbers in the second group, which averaged $2,320 per crash, were rough estimates. Almost all the state in-service performance studies, primarily on the Brifen system, provided results similar to the first group. For example, Oklahoma DOT kept track of the cost of each of the crashes on the Lake Hefner Parkway during its first year the cable barriers were in service, the first high-tension cable barrier installation in the United States. This 4-cable system experienced 126 crashes which, on average, cost $284 (2002 dollars) to repair an average of 4.7 posts per impact. For this system, the average repair cost per post, including traffic control and all other repair costs, was $60.

Repair costs depend partly on how long it takes a repair vehicle to get to the scene. The Lake Hefner Parkway represents a “best case” situation since it is only 11 km (7 mi) long and is located in Oklahoma City close to response units. In rural areas, crash locations may be more than an hour’s driving distance from the nearest response unit, which will make repairs more expensive.

The lower repair costs appear to be mostly associated with repairs done by highway agency crews rather than by private contractors. It is possible that some of the states reporting costs included only materials costs and not labor costs. Minnesota reported a total repair cost of $58,500 for 45 crashes and gave a breakdown of the cost for labor, material, and equipment. The average $1,300 cost per crash included $631 for materials, $478 for labor, and $191 for equipment.

A major factor in cable repair costs is the price the highway agency pays for replacement posts. Since the high-tension cable barrier systems are proprietary, once the system is installed the manufacturers have control over the price of replacement posts unless the highway agency has included replacement posts in the initial (or follow-up) contract. Since it is known that a significant number of posts will be damaged in impacts, agencies should consider including a sufficient number of replacement posts in the original construction contract.

Typically six posts are damaged in an average impact into a high-tension cable barrier. If posts are socketed in concrete foundations, their repair is usually quick and relatively inexpensive. Often, the repairs can be done in less than an hour without traffic control. Repair costs depend on the extent of the damage, the remoteness of the crash location, and whether highway agency crews or a contractor does the repairs.

Systemwide Maintenance

On-going, maintenance issues for cable barriers are discussed separately from crash-related repairs since they are systemwide issues rather than site-specific crash-related needs. On-going issues include inspecting and maintaining specified cable heights and correct cable tension, as well as ensuring proper functioning of cable connectors and end anchors. Line posts and their foundations may occasionally need maintenance.

Determining if maintenance is needed requires that the cable barriers be inspected. Modern high-tension cable barriers require little on-going maintenance if they have been designed and installed correctly. Problems can occur when end anchors and post foundations have not been designed for in situ soil and local climate conditions. Under-designed anchors and foundations often rotate out of the ground or move enough to cause reductions in cable tension. Inspections are needed to identify these problems as well as to locate damage to the barrier caused by non-reported crashes.

Annual inspections to identify non-crash-related issues should be sufficient unless design flaws in anchors and post foundations are known to exist or if extreme weather events have occurred. Flooding can cause erosion, which will affect the heights of the cables, and very cold weather will exert heavy static loads on the anchors, which could cause anchor movement. If non-prestretched cables were used when the barrier was installed, cable tensions should be checked and adjusted every 6 months for the first several years. Once the wires in the cables have seated themselves, semi-annual retensioning should not be needed.

Cable heights should be checked at the bottom and top of vertical curves to make sure the cables have not moved up or down from their specified heights. On sharp horizontal curves, cable heights can be affected by leaning line posts. Cable heights are also affected by discontinuities in the ground under the cables. Erosion, winter maintenance, crashes, and other activities around the cable barriers can cause ruts or mounds that will affect the effective height of the cables. These discontinuities should be removed if they cause the cable heights to be out of tolerance. Mow strips, as described below, can be effective in minimizing these problems.

Maintaining adequate tension in cable barriers is important particularly for high-tension systems. Cable tension is affected by temperature changes. When the temperature drops, the cable contracts, which increases its tension. Increases in temperature cause the cable to expand,

Table 5.8. Hours of labor savings/mile/year required to justify mow strip.

25-Year Service Life and 6 percent Discount Rate					
Labor & Equip Cost per Hour	Cost of Mow Strip per Linear Foot ($)				
	5	10	15	20	25
$20	103	207	310	413	516
$30	69	138	207	275	344
$40	52	103	155	207	258
$50	41	83	124	165	207
$60	34	69	103	138	172

which lowers its tension. Each cable barrier manufacturer has a temperature-tension table that gives the required tension as a function of cable (not air) temperature. Most manufacturers also sell tension meters to measure cable tension. Friction between the cables and posts, particularly for interwoven systems, can delay the migration of tension changes along the barrier. After retensioning, the cable tension should be checked at several different locations along the barrier to make sure the tension has equalized and that the system has the correct tension. As discussed above, a suggested tolerance for tension is ±2 kN (±0.45 kips) from the specified tension given in the manufacturer's table.

High tensions resulting from cold weather could cause improperly manufactured/installed cable connections to fail. Strength specifications and testing requirements for turn buckles, swaged-on fittings, and other cable connectors should be included in contract documents. For example, Kansas requires a minimum tensile strength of 164 kN (36.8 kips). The strength of the connection should be at least as strong as the breaking strength of the cable.

Mow strips are used by some states to reduce the cost of mowing grass around the cable barriers and to strengthen the post and anchor foundations. Mow strips are expensive and can cost as much or more than the cable barrier itself. In the survey of states, 15 indicated that they use mow strips and 19 indicated they did not. Costs ranged from $6 to $25 per LF (0.3 m). Mow strips can also strengthen the embedment of line post foundations and end anchors, which lessens the chance for anchor/foundation failure. Mow strips also reduce the discontinuities in the natural ground, which should help to maintain proper cable heights. It is difficult to estimate the monetary value of the strengthening of the posts and foundations and reducing ground discontinuities, but they are significant.

Table 5.8 shows how many hours of labor need to be saved each year for 1 mile of highway to justify the addition of a mow strip solely on grass cutting benefits. This table is based on a 25-year life for the mow strip and a discount rate of 6 percent. For example, if a mow strip costs $15 per LF and labor and equipment costs for grass mowing is $40 per hour, to justify a mow strip, a total of 155 hours of labor would have to be saved each year for each mile of highway where the mow strip is installed. These hours should be reduced by anticipated benefits from the strengthening of the posts and anchors and reducing ground discontinuities.

CHAPTER 6

Guidelines for Cable Barriers

Although strong-post cable barriers were in use in some states as early as the 1950s, New York pioneered the development and testing of the weak-post design in the 1960s. This design, included in the 1977 AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers* as the G1 Cable Guardrail, may have been the first design guidance for a cable barrier system. This system was originally used primarily as a roadside barrier in a few states that were concerned with snow collecting in front of more solid barrier systems such as the W-beam guardrail. In the 1990s, several states became aware of an increase in cross-median head-on crashes along sections of freeways and began to install cable barriers to minimize the likelihood of these severe crashes. Today, there are several thousand miles of cable median barriers in the United States – both the initial low-tension generic designs and the more recent proprietary high-tension designs. The following sections summarize the principal findings of this research effort and translate them into guidelines that can be used by highway agencies to design cable barrier projects or formalize their own policies and procedures.

6.1 Warrants

Barrier warrants address the need for, and cost-effectiveness of, any type of traffic barrier system for specific highway situations. This study made no attempt to assess, develop, or revise any existing warrants for either median barriers or roadside barriers. Current warrants, either as recommended in the AASHTO *Roadside Design Guide* or individual state guidelines, were considered appropriate and adequate for determining if a barrier is needed. Once the decision to install a barrier has been made, the next step is to select the most appropriate barrier type to use. In this regard, cable barrier is often a cost-effective choice for installation in wider medians because it is relatively lower in cost than other designs, can be installed on non-level terrain (within limitations), and can often be maintained relatively easily.

6.2 Structural Details and Crash Performance Characteristics

Over the years, various cable barrier designs have been developed for use in medians and on roadsides. Early designs, known as generic, low-tension cable barriers, were adopted by state DOTs such as New York, Washington, North Carolina, Missouri, and others. These designs were found to be an effective means of preventing most median crossover events where deployed. The designs had limitations that prompted efforts to develop the several proprietary designs that emerged in the early 2000s. These new designs, known as high-tension systems, have higher cable tension, stronger cable-to-post connections, and, consequently, lower barrier deflection than generic systems. These new designs were also found to be a cost-effective means for reducing run-off-the-road fatalities and severe injuries. High-tension cable barrier systems are available from five manufacturers: Brifen, Gibraltar, Nucor Steel Marion, Gregory Industries (Safence systems), and Trinity (CASS systems).

The available cable barrier systems vary in number of cables, cable heights, post size and geometry, cable-to-post connections, post spacing, and end-anchoring systems. Descriptions of these systems are presented in Chapter 4 and Appendix B of the contractors' final report. A summary of the full-scale crash tests conducted on cable barrier systems is presented in Appendix D of the contractors' final report.

6.3 Cable Barrier Guidelines

The cable guardrail guidelines developed under this project addressed seven areas of concern: barrier lateral placement on sloped surfaces, influences of post spacing and end-anchor spacings on barrier deflection, post and terminal anchoring, interconnection with other barrier systems, construction and maintenance tolerances, placement along horizontal curves, and installation and maintenance costs. The principal recommendations or guidance that evolved for each of these areas are discussed below. A summary of the developed guidelines as well as others from the literature are listed in Appendix E of the contractors' final report, which is published herein.

Lateral Barrier Placement

Vehicle dynamics analyses were performed to develop guidelines for effective cable barrier placement on sloped medians. These guidelines were developed for systems where the top cable is at 838 mm (33 in.) or higher and the bottom cable is at 533 mm (21 in.) or lower. This covers most currently available cable barrier systems. For systems that do not meet these requirements, vehicle dynamics analysis for the specific median profiles and specific barrier systems, following a similar approach to the one described in Section 5.1, can be used to find the effective placement locations. Nomographs for many basic median configurations and barrier designs are provided in Appendix C of the contractors' final report and can be used to determine effective locations where there are consistent conditions. Additionally, similar analysis can be performed to determine effective cable barrier placement if this cannot be achieved based on the following guidelines.

The analysis showed that changes in slopes are the main factors contributing to median barrier penetrations and vehicle intrusion into opposing traffic lanes. A negative change in slope (down slope), typically located at the edge of the median or roadside, can lead to vehicle overrides for high-speed and high-angle impacts. A positive change in slope (upward slope) typically located near or at the center of the median, can lead to vehicle underrides. The greater the change of slope, the more critical effect it has on barrier performance. The guidelines listed below provide recommendations for reducing vehicle underrides and overrides. Because these guidelines were based on a relatively limited number of vehicle types, impact speeds, and impact angles, and do not factor driver inputs such as braking and steering, it is important to note that adherence to these guidelines will not prevent all penetrations of the barrier.

General Placement Guidelines

- Cable barrier systems should not be placed on slopes steeper than 4H:1V (unless the system has been designed for and successfully crash-tested under these conditions).
- Cable barrier systems can be used on 4H:1V or shallower sloped medians or roadsides (6H:1V or shallower sloped medians or roadsides are preferable), provided the placement guidelines listed below are followed.

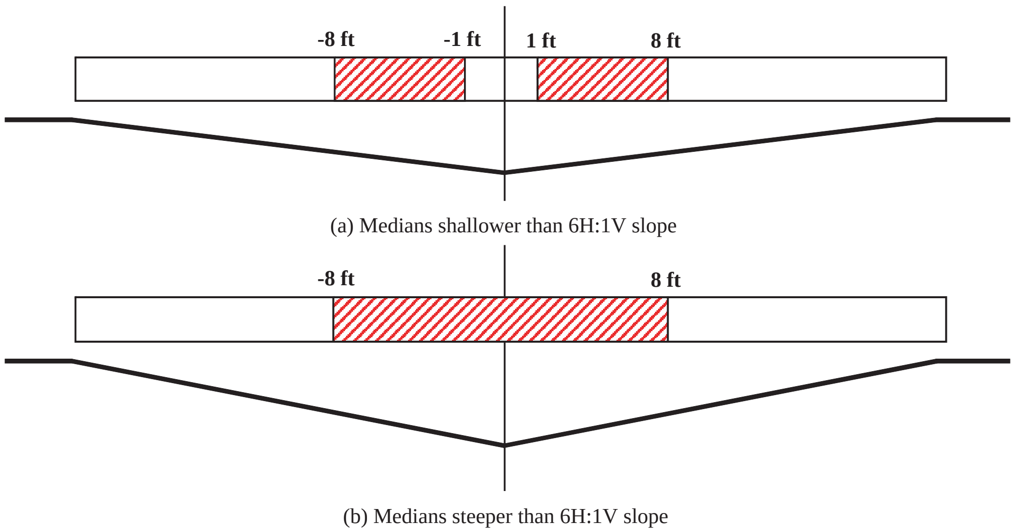


Figure 6.1. Underride criteria for V-shaped medians.

- The gentler the slope, the lower the effects on the trace of the vehicle interface area and the greater the potential for an effective vehicle-to-barrier interface.
- Wider medians offer more effective lateral placement options.
- Median cross-section shape influences the effective lateral placement areas.

Symmetric V-Shaped and Rounded-Bottom Medians

- To avoid underrides of small and mid-size vehicles, the barrier should not be placed in the region between 0.3 m (1 ft) and 2.4 m (8 ft) from either side of the center of the V-shaped section (Figure 6.1a). For medians with slopes steeper than 6H:1V, the region between –0.3 m (–1 ft) and 0.3 m (1 ft) from the center of the median should also be avoided (Figure 6.1b). The cross-hatched areas in the figures indicate the lateral positions where the cable barrier may not be effective.
- To avoid override of larger vehicles (SUVs and pickup trucks), the barrier should not be placed in a region between 1.2 m (4 ft) and 6.0 m (20 ft) from the edge of the median (breakpoint) when the median slope is steeper than 6H:1V (Figure 6.2).

Symmetric Flat-Bottom Medians

- To avoid underrides of small and mid-size vehicles, the barrier should not be placed in the region between 0.3 m (1 ft) and 2.4 m (8 ft) from either side of the flat-bottom breakpoints (Figure 6.3a). If the median slope is steeper than 6H:1V or if its flat-bottom section is less than 2.4 m (8 ft) in width, the region between –0.3 m (–1 ft) and 0.3 m (1 ft) from the flat-bottom breakpoint should also be avoided (Figure 6.3b).

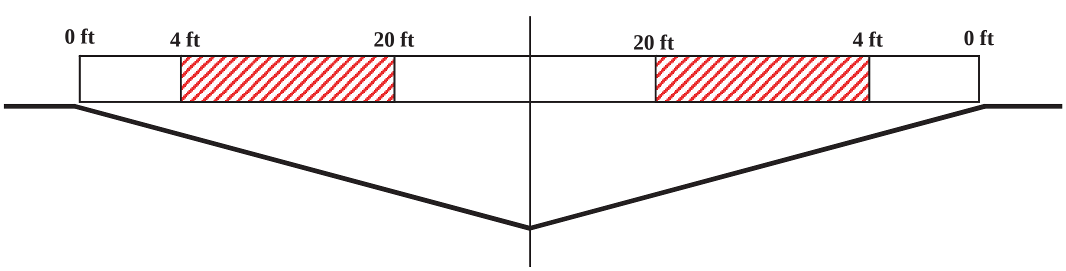
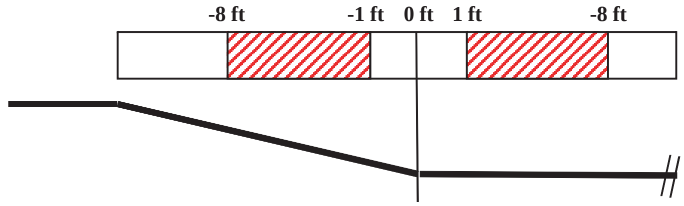
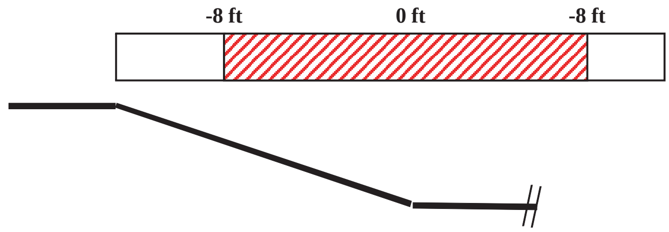


Figure 6.2. Override criteria for V-shaped medians steeper than 6H:1V slope.



(a) Medians shallower than 6H:1V slope and flat bottom wider than 2.4 m (8 ft)



(b) Medians steeper than 6H:1V slope or flat bottom width less than 2.4 m (8 ft)

Figure 6.3. Underride criteria for flat-bottom medians.

- To avoid override of larger vehicles (SUVs and pickup trucks), the barrier should not be placed in a region between 1.2 m (4 ft) and 6.0 m (20 ft) from the edge of the median (breakpoint) when the median slope is steeper that 6H:1V (Figure 6.4).

Non-Symmetrical Medians

- It is preferable to place the cable barrier on the side of the median with the shallower slope.
- The guidelines for V-shaped and flat-bottom medians should be followed to avoid vehicle underrides or overrides.

Shoulders and Superelevations

- Shoulders with slopes of 6 percent or flatter do not lead to any negative effects on vehicle-to-barrier engagement and consequently do not affect barrier performance.
- For roads with superelevation steeper than 3 percent, the barrier should be placed not farther than 0.6 m (2 ft) from the edge of the median for medians steeper than 6H:1V slope and not farther than 1.5 m (5 ft) for medians shallower than 6H:1V. The barrier could be placed on the opposite side of the median (away from the superelevation).

Cable Barrier Deflection

Computer simulations using validated cable barrier models were conducted to study the effects of end-anchor spacing and post spacing on the dynamic deflection. The simulation

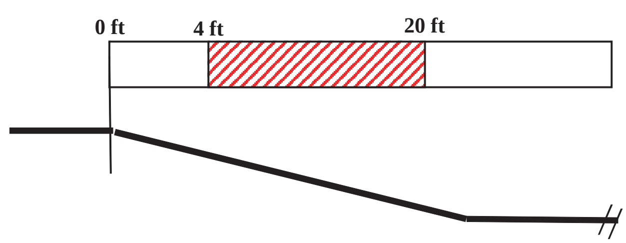


Figure 6.4. Override criteria for flat-bottom medians steeper than 6H:1V slope.

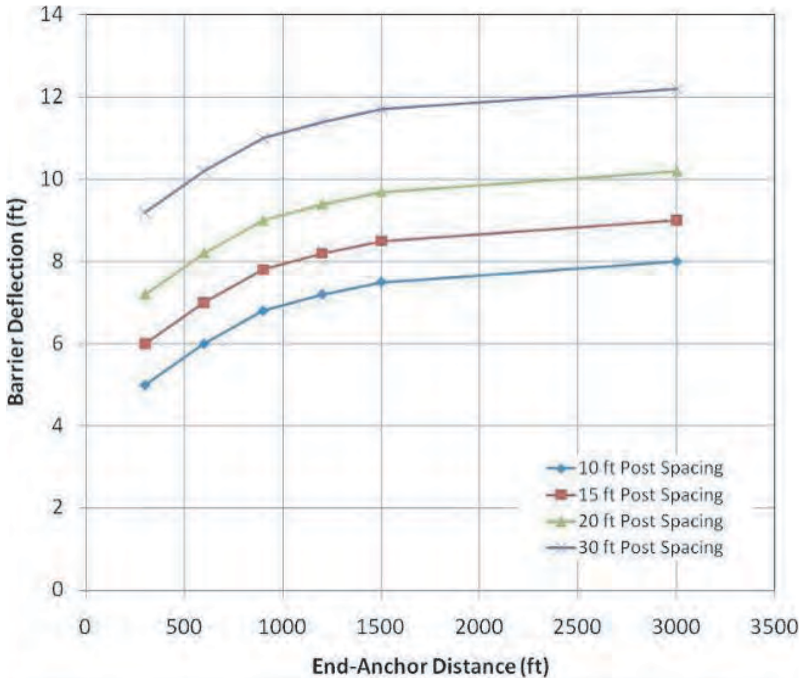


Figure 6.5. Hypothetical plot of barrier deflection vs. end-anchor and post spacings.

results, as expected, indicated that in impacts with cable barriers, the maximum dynamic deflection is affected significantly by the end-anchor spacing and post spacing. Greater end-anchor spacing leads to increased barrier deflections. The rate of increase in deflection is greater for end-anchor spacing of less than 500 m (1,640 ft). Similarly, the results showed that post spacing affects the barrier deflection with longer post spacing leading to increased deflection. The results indicate that these effects vary for different types of cable barrier systems. Based on these findings the following guidelines are recommended.

- Design deflection should not be based solely on deflection data from full-scale crash tests.
- Highway designers should investigate the differences in deflections associated with a specific design (e.g., end-anchor spacing, post spacing, post type, cable-to-post connection) of a cable barrier system.

It is important to know that the "design deflection" distances noted by each manufacturer are based on the deflection that resulted from a 100 km/h (62 mph), 25° test with a pickup truck impacting a cable barrier with specific post and end-anchor spacings. In the field, deflections can be greater depending on the specific impact conditions that occur and the installation setup.

A hypothetical plot, showing the effect of end-anchor and post spacings on barrier deflection, is shown in Figure 6.5. Similar plots should be generated for the different cable barrier systems. It should be the individual manufacturer's responsibility to ensure that such plots are available for each of its systems.

End Anchors and Post Embedment

End anchors perform a critical function for cable barriers by keeping the cables in tension to minimize deflection upon impact by a vehicle. Some problems have been noted in the field when these anchors have moved in the soil, either because of initial cable tension, increased cable tension caused by lower temperatures, or as a result of crashes into the barrier. Movement of the anchor in the soil decreases the tension in the cables which, when extreme, may result in unsatisfactory barrier performance. Therefore, anchors should be designed based upon an analysis of the soil where the cable barrier will be placed. Based on the soil data and climate information, static and dynamic geotechnical analyses or testing should be performed to determine the appropriate size for the end anchor. Likewise, many designs use posts set in concrete foundations to facilitate removal and replacement of damaged posts. These foundations also must be sized properly, based on existing soil and climate conditions, so they are not damaged or pulled out of the ground in a crash. Below are guidelines to ensure adequate size for the end-anchor and post footings.

- Soil analysis must be performed to determine the appropriate size for the end-anchor and post footings.
- The anchors should withstand a dynamic and static load (due to temperature variation) of 140 kN (31 kips) if all cables are connected to a single anchor or 90 kN (20 kips) if the cables are individually anchored. The anchor should not be damaged, and anchor movement should be less than 50 mm (2 in), preferably less than 25 mm (1 in.) under this load.
- Fitting hardware used to connect the cable ends to the end terminal and/or end anchors should be properly installed to avoid cable pull-out from the connector during impact.
- When a concrete footing is used for the posts, the footing should be designed to withstand a load higher than the plastic capacity of the post (i.e., the post would bend before the post footing breaks or moves significantly).

Interconnection with Other Systems

Because of the deflection distances inherent in a cable barrier, there will often be locations where cable cannot be used to shield a fixed object hazard effectively, such as where bridge piers are set in a narrow median. In such cases, a median cable barrier must be terminated and a semi-rigid barrier introduced.

FHWA has issued acceptance letters for several cable-to-W-beam transition designs as meeting NCHRP Report 350 test conditions at Test Level 3. The designs were accepted based on full-scale crash testing conducted under NCHRP Report 350 with a South Dakota design in which a generic 3-cable barrier was carried over and under a W-beam guardrail (which was anchored separately) and anchored independently behind the metal beam rail. Subsequent to this testing, several of the manufacturers of proprietary cable systems proposed similar transitions, with the basic difference being the cables were attached directly to the W-beam rail element, thus eliminating the need for a separate anchor for the cables.

At this time, only transitions where the cable barrier system is in line with the other system have acceptance letters and all accepted transitions connect to semi-rigid (strong-post W-beam) barriers. Also, all transition acceptance letters are based on one full-scale crash test (South Dakota design). The new transitions have been accepted without additional full-scale crash testing. Based on the findings described in Section 5.4, the following guidelines are recommended:

- Cable barrier should not be transitioned into rigid (concrete) or flexible (weak-post W-beam) barriers unless further analyses and/or testing are conducted and adequate performance is achieved.
- Transitions achieved by overlapping a section of the cable barrier in front or behind semi-rigid systems should not be used until further analyses and/or testing are conducted to ensure adequate performance is achieved.
- The semi-rigid barrier to which the cables are connected must be long enough and adequately anchored at its downstream end to resist the tension in the cables. The semi-rigid barrier should withstand a 140 kN (31 kips) load with less than 25 mm (1 in.) movement of its end

post or end anchor. Under this study, simulations were conducted to identify the minimum length needed for strong-post W-beam systems, and it was found to be 23 m (75 ft).

- The connection between each cable and the rail of the semi-rigid barrier should be designed such that it can withstand 90 kN (20 kips).
- The semi-rigid barrier should be appropriately flared back with adequate offset between it and the cable barrier. A minimum of 1.2 m (4 ft) flare is recommended.
- The heights of the cable barrier system should be compatible with the semi-rigid barrier over the length of the transition.
- The cable barrier needs to be transitioned from its lateral position to that of the semi-rigid system.

Cable Barrier Tolerances

The tolerances listed in Table 6.1 are recommended to minimize the effects of installation variations on cable barrier performance (see Section 5.6).

Placement along Horizontal Curves

There are two concerns that must be considered when cable barrier is located along a curved section of roadway. The first is that the high-tensioned cables can exert significant lateral pressure on the support posts and may cause them to bend over time, regardless of whether the barrier is on the inside of a highway curve to the left (convex) or on the outside (concave). The second concern is crash performance. When a convex installation is impacted, the tension in the barrier immediately decreases as the cables are separated from the posts and become slack, resulting in deflections in excess of the barrier's design deflection.

Limited research has been conducted to study the effects of horizontal curvature on the performance of cable barrier systems. To investigate this effect, finite elements simulations were performed. Barrier models with varied curvature radii, 150, 300, and 400 m (492, 984, and 1,312 ft), and varied post spacing, 1.6, 3.2, and 6.4 m (5, 10, and 20 ft), were created. The models are based on one of the high-tension systems used in analysis described in Section 5.2 (a 4-cable CASS system). It is expected that similar results with other high-tension systems would be observed.

The simulations were conducted for impacts with a 2000P vehicle traveling at 100 km/h (62 mph) and 25° angle. The barrier length used for all simulations was 200 m (656 ft). The deflections of the barrier from these simulations were extracted, and the results are plotted in Figure 5.48. The simulations clearly indicate that convex curvature leads to increased deflection. The increase in deflection was as high as 70 percent. Thus, it is important to consider this effect when selecting barrier location.

The simulation results suggest the following guidelines:

- Shorter post spacings should be used to account for the increase in deflection when cable barriers are placed on horizontal curves with a radius less than 400 m (1,300 ft).

Table 6.1. Suggested cable barrier tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in.)
Bottom Cable Height	-25,+0 mm (-1, +0 in.)
Middle Cable(s)	±25 mm (±1 in.)
Barrier Lateral Position	±150 mm (±6 in.)
Average Post Spacing	±150 mm (±6 in.)
Consecutive Post Spacing	±600 mm (±2 ft)
Cable Tension	±2 kN (±0.45 kips)

- Shorter post spacings should also be used to reduce the bending of the posts over time due to lateral forces applied by the cables on the posts.
- The lateral placement guidelines developed under Section 5.1 should be followed to ensure adequate vehicle-to-barrier interface.
- The barrier should be placed as close as possible to the convex side to allow more space behind the barrier for the added deflection. This will also reduce the number of cable barrier hits since it is placed farther away from the more frequent impacts with vehicles coming from the concave side [1].
- For narrower medians, the use of two cable barriers (one on each side of the median) or a more rigid barrier should be considered to reduce the likelihood of vehicles impacting the convex side and intruding into on-coming traffic.

Placement on Vertical Curves

Placing cable barriers on vertical curves also creates potential concerns for barrier performance. In such installations, the tensioned cables exert upward vertical forces on the posts, which are significantly lower in elevation than the end anchors, particularly at the bottom of the vertical curve. Depending on the specific design details of the barrier, i.e., post embedment and cable-to-post connections, these upward forces could pull the posts out of the ground, pull the posts out of the sockets, or pull the cables off the posts, resulting in less cable tension and cables at the incorrect height in relation to the ground. Designers should be aware of this possibility.

Placing the end anchors as close as possible to the minimum and maximum points of the vertical curvature reduces the upward vertical forces. Similarly, placing the end anchors at locations where there is a sudden change in the vertical slope would reduce the vertical variation effects. Another possible solution is to use closer post spacing through sharp vertical curves to reduce the vertical component of force on individual posts. Suggested guidelines for cable barrier when placed on vertical curves are listed below.

- End anchors of the cable barrier should be placed as close as possible to the bottom and top points of the vertical curvature.
- End anchors should be placed at points where there is a sudden change in vertical slope.
- Post spacings should be reduced in sharp vertical curves.
- Regrading short sections of the median that have sharp vertical curvatures should be considered.
- Regular checks should be performed at the bottom and top of vertical curves to ensure that the cables have not moved up or down from their specified heights.

Installation and Maintenance Costs

An analysis of installation and maintenance costs for cable barriers was conducted to ensure effective use of limited safety resources (Section 5.7). Based on these findings, the following guidelines have been developed:

- Life-cycle cost analyses should be used to evaluate cable barrier systems rather than selecting systems on the basis of lowest bid for installation. All FHWA-accepted systems do not perform the same.
- End-anchor and post foundation specifications should require designs based on in situ soil conditions and expected climate conditions that are reflected in the costs.
- If a maximum design deflection has been set for a project, then the combined effects of post spacing and anchor-to-anchor spacing for each specific type of high-tension cable barrier should be considered to ensure that the required maximum deflection will not be exceeded.

- Because of the small marginal cost of adding an extra cable and the likelihood of improved safety performance of the barrier with an extra cable, benefit/cost analyses should be used to determine when a fourth or fifth cable is justified.
- Periodic inspection schedules based on expected frequency of impacts should be established for each cable barrier installation.
- Maximum response times for repairing damaged barriers should be established based on the class of highway and the extent of damage.
- Cable heights on barriers at the bottom and top of vertical curves should be checked periodically to make sure they remain at design heights.
- Post spacings should be reduced for horizontal curves with a radius 400 m (1,300 ft) or less.
- A benefit/cost analysis should be conducted to determine when a mow strip is justified.
- Cable barriers should be inspected after severe weather events, including flooding and extremely cold temperatures, to check for erosion, end anchor movement, and cable heights on vertical and sharp horizontal curves.
- Driven posts should not be used except when the expected rate of impacts is too low to justify socketed posts.
- Manufacturers should provide training on barrier installation, maintenance, and repairs for highway agencies and emergency response crews.

CHAPTER 7

Summary and Conclusions

Following the tasks prescribed under this project, a comprehensive effort to identify and develop guidelines for the use, selection, and maintenance of cable barriers was undertaken. The focus of the effort was to undertake analyses that would provide a sound basis for the guidelines. The efforts included the following:

- A comprehensive literature review of U.S. and international cable barrier studies was undertaken. The focus was to capture all ideas relevant to the design, performance, evaluation, and maintenance of cable barrier systems. Chapter 2 of this report documents the findings of this effort and includes a summary of the conclusions drawn.
- It is noteworthy that there are various “modern” cable barrier systems that are being deployed in a majority of the states. These deployments are proceeding with the best available insights, but the approaches, selection criteria, and design practices vary considerably. Information was gathered related to state guidelines, in-service evaluations (both formal and ad hoc), as well as manufacturer’s design, installation, and maintenance documentation for all cable barrier systems. The features of the various systems and their testing outcomes were gathered. This effort involved direct contacts with the states to gather pertinent information. The findings are documented in Chapter 3.
- An interim report that summarized the findings of the background studies was generated to provide a basis for the specific analyses to be undertaken. The interim report proposed 12 candidate work plans for Phase II of the project. Each work plan described the issue to be addressed, provided a detailed outline of the planned approach, and outlined the expected guidelines to be developed. After deliberations with the panel the following seven work efforts were selected:
  - Analyses of impact of lateral placement on cable barrier effectiveness
  - Investigation of cable barrier deflection for varying designs
  - Assessment of end-anchoring systems (anchor size and soil condition)
  - Review of requirements for interconnection with other barriers (transitions)
  - Formulation of construction tolerance for cable barrier systems
  - Evaluation of the influences of roadway horizontal curvature
  - Identification of installation and maintenance costs
- The panel approved these work plans and authorized the contractor to proceed.
- The research efforts were executed in accordance with the plans. This research will help agencies currently moving forward with cable median barrier systems to have additional knowledge on which to base impending decisions. The results of these research efforts are presented in Chapter 5.
- The research was undertaken with a focus on formulating guidelines for cable barrier systems. These efforts were undertaken considering the variations in cable barrier technology, median configurations, potential impact conditions, highway design, operational issues, and other factors. The resulting guidelines were compared to, and supplemented with, existing guidelines reflected in current practices and those proposed in other research.

- After review of the preliminary guidelines by the panel, presented in this draft report, a workshop was held to solicit feedback on the draft guidelines from state agencies, industry representatives, and other practitioners who would be the primary users of the guidelines. The feedback and comments from the workshop participants serve as the basis for updates to the guidelines.
- A final report documenting the updates was prepared. The final report presents the final recommended guidelines, document limitations of the analysis, cite the sources of the material presented, and suggest needs for future research.

7.1 Research Findings

The research efforts led to the following conclusions:

- There is continued growth in the application of cable barriers and accumulating evidence that they are highly effective. Although the newer technologies for cable barriers date back to the 1990s, many agencies may have been cautious about applying the technology due to the lack of experience and limited guidance in doing it effectively.
- Despite interest in understanding the safety problem and the effectiveness of cable barriers, there is still no definitive data for the identification of problem locations and/or the evaluation of treatment effectiveness. Changes in FARS 2008 to define median crossovers as a specific crash type will help to address the need for better data.
- Vehicle dynamics analysis (VDA) reveals useful insights into influences of terrain on barrier performance. It provides the basis for "interface analyses," which should be considered the first issue to be addressed for barriers on slopes.
- There are many factors that influence vehicle dynamic response when traversing sloped terrain. Primary factors include vehicle mass, speed, angle of departure, and slope. Secondary factors include the distribution of vehicle load, condition of vehicle subsystems (e.g., suspension), surface conditions, driver control inputs, and surface friction.
- The design of any barrier and its placement influence interface effectiveness for any sloped conditions (i.e., design and placement sensitivity).
- Median or roadside conditions can vary widely, even along a particular highway. Median configuration is a function of width, shape, slope, and depth. Median analysis must include bi-directional crossings.
- This research builds upon efforts that were initiated by FHWA and expanded to cover a wider range of median profiles: V-shaped, flat-bottomed, rounded, and asymmetrical medians from 5 to 30 m (16 to 100 ft) wide.
- The interface analyses were undertaken for a broader set of conditions than is normally used to evaluate roadside hardware. More specifically, the analyses considered the following conditions/factors:
  - Impact speeds of 50 to 100 km/hr (31 to 62 mph)
  - Impact angles of 5 to 25 degrees
  - Vehicle types 820C, 1100C, 2000P, and 2270P
- VDA was used to generate bi-directional trace paths for each vehicle type, speed, angle, and median configuration. Individual trace paths were aggregated to define interface envelopes. The interface envelopes provided the basis for establishing override and underride limits for each median configuration.
- Aggregation of the override and underride limits across varying median configurations provides a basis for establishing functional design requirements.
- Finite element models of the major proprietary cable barrier systems were developed to reflect their design differences. These models were compared to the acceptance crash tests for each system to provide validity for the analysis.

- Crash simulations were conducted to analyze the influences of post spacing on dynamic deflection. There was a uniformity of increase in deflection for all systems with greater post spacing.
- Simulation was used to analyze the effects of distance or lengths between anchorages on cable deflections. It was noted that deflection increases rapidly up to distances of about 300 m (1,000 ft) and then increases continually but more slowly up to the 1,000 m (3,300 ft) modeled.
- The change in cable barrier deflection due to end-anchor spacing variation is different for different barrier systems.
- Anchorage design requirements were noted to be critical to system functionality. The need to design anchorages for local conditions was highlighted.
- Construction tolerances were cited based upon the results of the various analyses.
- Interconnections were noted to be necessary for situations where the cable barrier system cannot adequately protect some obstacles. Examples of common interconnections were provided.
- Interconnections require that there be adequate offset or overlap flaring of the semi-rigid system. These semi-rigid systems should be designed to withstand the tension forces exerted by the cable barrier. It is also necessary to make sure that the heights of the barriers are consistent and that the cable line is transitioned to the semi-rigid barrier line.
- Analysis of cable barrier performance on horizontal curves noted the greater deflection possible on convex curves and the need to consider shorter post spacing.
- Installation costs were based upon available data where compiled as a basis for estimating the potential costs of new systems. The relative influences of the various components, discount rates, service life, and related factors were discussed.
- Maintenance elements including inspection and routine servicing were identified and, to the extent possible, costs of these activities were cited.
- Repair costs were noted to be hard to estimate because the number and severity of crashes are hard to predict.
- Elements of repair costs and the available data on associated costs were presented.

7.2 Development of Guidance, Guidelines, and Procedures

The results from this research consist of guidelines for the selection, use, and maintenance of cable barrier installations. This information will help highway agencies optimize the performance of cable barriers and decrease serious injuries and fatalities, as well as reduce barrier maintenance costs. These guidelines will have an impact only if they are accepted by FHWA and state DOTs.

The process of developing the guidelines for the selection, use, and maintenance of cable barriers followed a hierarchal approach to the various factors listed above considering the tradeoff between factors. The research team formulated the first draft of the guidelines. At this point, the research team arranged a workshop that included the panel and up to 10 other knowledgeable individuals representing DOTs, industry, and other groups to critique, revise, and enhance the guidelines.

7.3 Future Research Needs

Although this research extended the knowledge about the use, design, selection, deployment, and maintenance aspects of cable median barriers, there remain topics that need further study. In-service evaluations and research investigations identified several key topics/issues that need to be addressed. A few of these topics are listed below.

- Collect detailed in-service performance information for the various cable barrier systems.
- Analyze the relationship between inter-cable spacing and the risk of vehicle penetrations between the cables.

- Conduct further investigations for connecting cable barriers to other systems such as concrete and weak post barriers (transitions).
- Develop guidelines for the steepness of fill-embankment slope behind cable barrier in roadside installations.
- Develop a systematic method for determining end-anchor and post footing sizes for different soil and environment conditions.
- Develop criteria for maintenance actions for damaged sections of cable barrier (to possibly be integrated with the results of NCHRP Project 22-27).
- Develop warrants for using TL4 cable barrier systems rather than TL3 systems.
- Investigate the use of intermediate anchors to maintain barrier effectiveness on long runs of cable barriers.
- Develop guidelines and/or technologies for upgrading of existing systems (e.g., low to high tension, adding cables).
- Develop guidelines for using cable barrier on vertical alignment and in the proximity of intersections and interchanges.
- Investigate the influences of post type, connectors, and embedment (e.g., driven vs. sleeve) on barrier performance.
- Study the crashworthiness and effectiveness of interfaces for trucks.
- Develop improved testing protocols and evaluation criteria to provide a more robust crashworthiness evaluation that would allow the potential effectiveness of cable barriers on slopes to be considered in selecting a specific cable barrier design. Also, develop testing criteria specifically for trucks.
- Revisit the benefit/cost relationships for various types of median barriers relative to traffic to derive an updated set of warrants that reflects the favorable economics of cable barriers.
- Use the cable barrier models developed in this study to test new concepts for improving cable barrier designs.

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Glossary

Acceptance Testing—Crash tests reported to FHWA to obtain a letter accepting a roadside hardware item to be considered acceptable for use on the National Highway System.

Anchor—a mass designed to counter the tension forces in a cable barrier system at either end. These are usually large concrete blocks whose size and depth are a function of the soil conditions.

Anchor Spacing—The distance between end anchors for a continuous length of cable barrier.

Anchorage—See Anchor.

Asymmetric Cross-Section—A median cross-section that has unequal side slopes.

Barrier Interface Envelope—A graph or plot that depicts variations in vehicle vertical position as it traverses the median at different speeds and angles. In some cases, more than one vehicle type is incorporated in the envelope.

Barrier Transition—The device or hardware used to link one type of barrier to another in a fashion that will function safely.

Cable Barrier Technology—Various designs for cable barrier systems.

Cable Tension—The amount of tensile force in the cable.

Cable Post—A semi-rigid steel beam of varying shape used to provide support for cables before and during an impact.

Cable Connector—A device (e.g., hook bolt, hair pin, or similar fixture) designed to hold the cable at a specific height.

Cable Splices—Connection between cable sections that are physically joined to provide the needed continuity.

CarSim—Commercially available software for vehicle dynamics analysis distributed by Mechanical Simulation Corporation.

Central Reserve—Common international term for median. See Median.

Crash Simulation—A computer process that predicts the vehicle and/or barrier response of a crash event.

Cross Median Crash—A crash between two or more vehicles that follows a vehicle crossing over the median from the opposite side of the highway.

Cross-Median Event—An event where a vehicle wholly or partially crosses the median. These may or may not result in a crash.

Crossovers—Points along a divided highway where vehicles can transfer to travel in the opposite direction. Usually restricted to emergency or maintenance vehicles.

Deflection—The amount of lateral displacement of a barrier from its original position to that during or after an impact.

Durability—The ability of a material or device to function effectively over time.

Finite Element Models—Representations of objects created by subdividing the entire item into small pieces for which their geometry, material characteristics, contacts, and failure modes are defined. In time-based simulations, each element is subjected to forces that cause movement, deformation, or failures. Systematic updates of the changes to each element allow replication of impacts or other physical changes.

Furrowing—The sinking into the median soil when wet or very dry causing the vehicle's interface area to be lower at point of impact.

Guidelines—A structured set of guidance statements reflecting a consensus.

Guidance—Statements that provide soundly based directives for undertaking an action.

GWU—George Washington University.

High-Tension—A cable barrier system that has higher initial tension and stronger post-to-cable connection than the original generic cable barrier systems. The high-tension systems experience lower deflection during impacts than the original systems but may require larger anchors.

HVE (Human Vehicle Environment)—Software tool for vehicle dynamics analysis distributed by Engineering Dynamics Corporation.

Interface Trace Plot—A diagram showing the relative position of points defining the interface region of the front of a vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Interface Region—The front area of a vehicle that has sufficient structural integrity to interact with a barrier. This varies by vehicle.

Interface Envelope—The area subtended by the points defining the primary structural region on the front of the vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Lower Trace Limit—See Underride Limit.

Low-Tension—A term used to define the original generic cable barrier system in which the tension in the cables is about 4,450 N (1,000 lb) at 18°C (65°F).

LS-DYNA—Finite element simulation software developed by the Livermore Software & Technology Corporation.

Maintenance Cycles—Repetitive actions in time to keep a device functional.

MASH—Manual for Assessment of Safety Hardware. AASHTO hardware crashworthiness testing protocols and standards.

Maximum Lower Cable Height—The highest a bottom cable can be to allow engagement between the vehicle and barrier to avoid underride for the selected vehicle or set of vehicles.

Median—An unpaved area between opposing lanes of traffic and associated shoulders.

Median Configuration—The features of the median cross-section.

Median Cross-Section—The dimensions, slopes, and shape that result from passing a plane perpendicular to the road at any given point.

Median Profiles—The features of the median cross-section.

Median Shape—See median profiles.

Median, Asymmetrical—A cross-section with unequal side slopes that converge to a central point.

Median, Flat Bottom—A cross-section with equal side slopes that extend to a flat-bottomed area of a given depth.

Median, Multi-Slope/Broken Back—A cross-section with two or more side slopes that converge to a central point.

Median, Raised—Medians have up-slopes from the edge of the shoulder.

Median, Rounded Bottom—A cross-section with equal side slopes that converge to a central point that has a rounded transition from one side to the next.

Median, V-Shaped—A cross-section with equal side slopes that converge to a central point.

Minimum Upper Cable Height—The lowest a top cable can be to allow engagement between the vehicle and barrier to avoid override for the selected vehicle or set of vehicles.

Mow Strips—A paved area along the cable line that eliminates the need for grass mowing around the posts.

MwRSF—Midwest Roadside Safety Facility at University of Nebraska-Lincoln.

NCAC—National Crash Analysis Center at George Washington University.

NCHRP Report 350—Report 350 was adopted as the national standard for roadside hardware crashworthiness testing.

Normalized Trace Plot—A trace plot or interface trace plot in which the vertical height of the reference points above the ground line (or surface) is plotted on a horizontal axis.

Nuisance Hit—A random impact of a cable barrier that results in minor damage but often goes unreported because the vehicle recovers and is able to continue. May also occur from impacts associated with maintenance operations.

Off-Tracking—The path of a vehicle that involves some degree of lateral sliding.

Override—An event where all or part of a vehicle gets over the top of a barrier.

Override Limit—A line (curve) defining the minimum height of the top cable that allows engagement between the vehicle and barrier to avoid overrides. The line defines the minimum height at different lateral placements of the barrier.

Ploughing—See Furrowing.

Prestretched Cable—Cable that is statically loaded after manufacture to reduce the slack in individual strands of the cable before installation.

Primary Structural Region—See Interface region.

Position Isobars—A continuous line that indicates the relative position of the cables for any lateral position across the median.

Post Embedment—The method used to place a post to support the cables including direct driven, placed in a socket, or installation in a drilled footing with compacted material or concrete.

Retensioning—The mechanical process of increasing the tension in existing cables.

Retrofit—Changing the configuration of the cable barrier design after initial deployment.

Roadside—The area beyond the shoulder adjacent to the highway.

RDG—AASHTO Roadside Design Guide.

Sleeve—A type of footing that allows a post to be readily inserted or removed after installation.

Slope Rounding—The process of regarding sloped medians such that the edges at the breakpoint are curved with a certain radius.

Socket—A concrete foundation for posts that allows them to slide in or out. Sockets greatly facilitate rapid repair of damaged cable barrier posts after an impact.

Socketed Posts—See Socket.

Spring Response—The incremental dampening of forces by a spring directed toward restoring equilibrium.

Strand—A single wire in the bunch of twisted wires that constitutes the cable or wire rope component. Sometimes used to refer to the bunch of cables (e.g., three-strand, low-tension system).

Safety Fence—Common international term for guardrail or cable barrier system.

Trace Plot—The diagram showing the relative position of a point on a vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Tracking—See Off-Tracking.

Tension Compensators—A device that incorporates springs to regulate the tension in the cables. These devices are used in generic, low-tension cable barriers.

Tolerances—The permissible range of variation in construction and installation of cable barriers (these could be dimensions, mechanical properties, measurements, etc.).

Transitions—See Interconnections.

TTI—Texas Transportation Institute at Texas A&M University.

Underride—An event where all or part of a vehicle goes under the lowest longitudinal element of a barrier.

Underride Limit—A line (curve) defining the maximum height of the bottom cable that allows engagement between the vehicle and barrier and avoids underrides. The line defines the maximum height at different lateral placements of the barrier.

Upper Trace Limit—see Override Limit.

Validation—The process of determining how well a model represents the real situation.

Vaulting—See Override.

Vehicle Dynamics—The physics of the forces acting on a vehicle as it moves across a surface considering the features of the vehicle.

Vehicle Dynamics Analysis (VDA)—The analysis of the physics of a moving vehicle with specific design characteristics (e.g., mass, suspension features, length) that is influenced by the loaded mass, speed, and direction of the vehicle and surface conditions (e.g., slope, surface firmness, friction) of the vehicle's path.

Vehicle Trajectory—the path a vehicle takes as it traverses across roadway and roadside features.

Verge—International term for shoulder or gore area at on- or off-ramps of highways.

Wire Rope Safety Fence—International term for cable barrier. See Cable Barrier.

APPENDIXES

Appendixes A through D of the contractors' final report are not published herein but are available on the TRB website by searching for *NCHRP Report 711*. Appendix E is published herein and follows.

APPENDIX E

Summary of Recommended Guidelines

In NCHRP Project 22-25, Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems, a comprehensive review of the state of the art relative to cable barrier systems was undertaken. These efforts included a review of the literature, a survey of highway agencies, and discussions with knowledgeable professionals from government, industry, and academia. These efforts identified current practices and the rationale behind them, as well as issues that needed attention. In research efforts that followed, various analyses were undertaken in an attempt to address the issues and provide a sound basis for additional guidance. For example, thousands of vehicle dynamics simulations were run to understand the trajectories for various vehicles traversing different median configurations to establish criteria for lateral placement that would maximize the effectiveness of the vehicle-to-barrier interface. The following sections provide a summary of the guidance derived from all of these efforts. The guidance was vetted in a 2-day meeting that involved the project panel and invited professionals from government, industry, and academia. The consensus guidance is outlined below. It is believed to provide a solid basis for agencies that have been using cable barriers to update their practices to enhance safety performance or cost effectiveness as well as to aid agencies interested in considering the use of cable barriers for the first time.

1. Planning and Feasibility (Use)

The process of deploying a cable barrier system begins with planning and feasibility studies for a given highway corridor to determine whether a barrier is needed and whether a cable barrier system is an appropriate type of barrier. The safety history of the corridor is often the primary consideration followed by considerations of the highway features, traffic conditions, system considerations, available products, and environmental factors. Guidance on the things that need to be considered at the planning and feasibility stage are cited below. These were derived from information documented in the research report.

1.1. Safety Needs

1.1.1. Numerous studies have shown that cable barriers are one of the most effective means of reducing median crossover fatalities and serious injuries.

1.1.2. An analysis of cross-median crash history should be conducted to determine those sections with the greatest need. State crash records and/or FARS data provide a basis for analyzing cross-median crashes. The 2008 improvements to FARS provide a specific data item of cross-median crashes to facilitate the capture of these types of crashes.

1.1.3. Crashes should be characterized by environmental, traffic, road features, contributing causes, and other factors to determine candidate countermeasures.

1.1.4. Crash rates should be compared to appropriate (e.g., national or state) benchmarks to prioritize sites.

1.2. Facility Features

1.2.1. Median configurations should be inventoried because placement is influenced by changes in width, variations in alignment, cross section, and other features.
1.2.2. Obstacles in the median that require special barrier treatment should be identified (e.g., bridge piers, lighting structures, drainage elements).
1.2.3. Aerial images, video logs, or other digital data sources to capture relevant median configuration and obstacles information should be used.
1.2.4. Requirements for median crossover points should be determined considering emergency management, operations, and maintenance.
1.2.5. Soil conditions and implications for cable barrier end-anchors and post embedment should be considered.

1.3. Traffic Considerations

1.3.1. Posted and actual speeds for the highway should be considered as they will have implications for barrier effectiveness.
1.3.2. Roadway facilities with higher truck percentages should receive greater consideration for the use of TL4 cable barriers systems. (See criteria in *NCHRP Report 638*.)
1.3.3. The level and nature of traffic to prioritize candidate projects should be determined on the basis of exposure. Assess the implications of directional flows.
1.3.4. Projected future traffic levels should be considered in the context of the expected project life.
1.3.5. Possible changes in the types of median encroachments that may occur along a highway corridor (e.g., lane change actions near interchanges) should be considered.

1.4. General System Considerations

1.4.1. Barriers should be used where the need exists and a cost-effectiveness traffic barrier system can be deployed.
1.4.2. The AASHTO Roadside Design Guide or applicable state guidelines for deployment considerations should be followed.
1.4.3. Cable barrier is often the cost-effective choice for installation in wider medians because of its lower cost, adaptability to non-level terrain (within limitations), and relative ease of maintenance.
1.4.4. Proper placement, installation, and maintenance is necessary to assure full effectiveness of cable median barriers after deployment.

1.5. Barrier Systems

1.5.1. Only cable barrier designs that have been accepted for use on the National Highway System should be used. Any limitations cited within the acceptance should be considered when selecting the barrier.
1.5.2. Compatibility of the design with other systems in use by the agency should also be considered. This has implications for the number of items in the parts inventory, interconnection options, and staff training.
1.5.3. Consideration should be given to the harmonization of procurement and addressing bid processes as well as related issues.

1.6. Environmental Factors

1.6.1. The prospect for problems with snow accumulation for various types of barriers on their winter performance should be considered.

1.6.2. Drainage needs and the median/roadside soil conditions relative to post and anchorage requirements should be taken into consideration.
1.6.3. Frequency of wet soil conditions should be considered for barrier installation and maintenance.

2. Cable Barrier System Design

There are generic and proprietary cable barrier systems available with varying features. Effective use of cable barrier systems necessitates an understanding of these features and how they influence the performance of the system in a given application as well as how they influence cost, installation, and maintenance requirements over time. Guidelines related to features such as number of cables, post design and spacing, cable-to-post connections, and cable tension and anchorages are listed below. The available options in each case have cost and performance implications. There are a variety of approaches to transition cable barriers into other barrier systems and ancillary features, such as mow strips, that facilitate maintenance. A fundamental requirement for deployment of these systems is that they pass the established crashworthiness requirements to be considered acceptable for use on the nation's highways.

2.1. Number of Cables

2.1.1. Research has shown that the interface area provided by the barrier is increased with additional cables.
2.1.2. There are greater placement options for the increased number of cable options.
2.1.3. Due to the potential for slight variations in lateral placement that may be needed to accommodate changes in the median configuration and/or obstacles, the cable design that offers a greater amount of effective placement area (e.g., with increased number of cables) should be selected.

2.2. Posts and Spacings

2.2.1. Soil conditions need to be assessed to assure that the posts will be able to adequately support the system and provide the necessary resistance when impacted.
2.2.2. Moisture in the soil will influence the functionality of cable barrier posts. Wetter soil conditions may increase the potential deflection.
2.2.3. Placing cable barrier posts in sockets reduces repair time and costs relative to posts driven in soil.
2.2.4. Cable barrier deflection is a function of post spacing. Generally the greater the post spacing, the higher the potential deflection.
2.2.5. MASH requires that cable barriers be evaluated for a minimum 200 meter installation. Longer installations may result in greater deflection.
2.2.6. Soil conditions will influence long-term post maintenance costs; therefore, an appropriate design should be selected.
2.2.7. Post spacing can be reduced where lower deflection is needed or horizontal/vertical curvature may affect cable integrity.

2.3. Cable Tension and Anchorages

2.3.1. Pre-stretched cables reduce the number of times the system needs to be retensioned, which may be an advantage over non pre-stretched cable.
2.3.2. Cable tension needs to be maintained over the length of the barrier run.

2.3.3. An anchorage designed for the local soil conditions is needed for each run of cable barrier. Since anchorages can be expensive, a minimum run of 1,000 feet may be considered. There is no physical maximum length of run, but practical considerations may apply (e.g., need for openings, other features).

2.4. Acceptance Testing

2.4.1. Determine whether the barrier was tested to NCHRP Report 350 or MASH criteria. Systems tested under MASH are subjected to higher impact severity conditions (heavier test vehicle, longer installation, sloped medians, etc.). Also, MASH requires a longer test article length, so cable barrier deflections will be different. Hence the use of MASH tested systems has advantages over Report 350 tested systems.

2.4.2. Assess the variations in side slope conditions, if any, from the test conditions relative to the anticipated slope placement.

2.4.3. Determine whether the testing was for TL 3 or TL 4 and associated slope conditions.

2.4.4. The "working width" established in testing of the system provides a useful rule of thumb for estimating cable barrier deflection.

3. Deployment

The deployment process involves taking a preferred cable barrier system and fitting it into the specific environment of a highway corridor. Many applications of cable barriers are retrofit efforts to address crash problems or the potential for crashes. Often, the existing highway environment was designed for lower traffic volumes and design standards that have been revised to reflect acquired knowledge about highway operations, safety, drainage, and maintenance. The environment may not provide desired widths, side slopes and median configurations may vary, and a variety of other objects may exist in the median or on the roadside. This section provides guidance for deployment related to road alignment, cross sectional features, and other aspects.

3.1. Lateral Placement

3.1.1. General: The potential effectiveness of cable barriers is a function of lateral position in a given median configuration (i.e., width, side slopes, shape, and depth). Basic lateral placement guidelines below are developed for a single run of systems where the top cable is at 33" or higher, and the bottom cable is at 21" or lower. This range covers most currently available cable barrier systems. The guidelines are applicable to all median widths. For systems that do not meet these criteria, or if lateral placement cannot be achieved based on the below guidelines, optimal placement needs to be determined by the use of lateral placement charts or specific vehicle dynamics analyses.

The guidelines are based upon analyses which considered vehicles ranging from 820 kg to 2270 kg, departing the roadway at angles from 5 to 30 degrees, at speeds ranging from 30 to 62 mph. This implies that the guidelines cover a greater range of possible impact scenarios than traditional crashworthiness criteria.

<u>Basic Cable Barrier Placement Guidelines:</u>

- Cable barrier systems should not be placed on slopes steeper than 4H:1V (unless the system has been designed for and successfully crash tested under these conditions).
- Cable barrier systems can be used on 4H:1V, or shallower sloped medians, or roadsides (6H:1V, or shallower sloped medians, or roadsides are preferable), provided the placement guidelines listed below are followed.

- Parallel runs of cable barrier may be appropriate for situations such as differential profile grades, narrow medians, or when objects such as high-mast light poles are located in the middle of the roadway median.
- A minimum clear distance equivalent to the likely deflection of cable barrier should be maintained between the cable barrier system and any obstruction. This should be adjusted for horizontal curve situations.
- A cable barrier system should be placed as far away from the travel lane as practical while maintaining proper orientation and performance of the systems to reduce nuisance hits.
- If the cable barrier switches from one median side to the other and terminals are not protected, overlapping runs of cable barrier are recommended to reduce the risk of crossovers.

<u>Symmetric V-Shaped and Rounded-Bottom Medians:</u>

- To avoid underrides, the barrier should not be placed in the region between –8 ft and 8 ft from the center of the median.
- For medians with slopes 6H:1V or shallower, the barrier may be placed in the region between –1 ft and 1 ft from the center of the median (special treatment, such as a mow strip, may be needed to compensate for poor soil condition in this region).
- To avoid overrides of larger vehicles (SUVs and pickup trucks), the barrier should not be placed farther than 4 ft from the edge (break point) of the median when the median side slope is steeper than 6H:1V.

<u>Symmetric Flat-Bottom Medians:</u>

- To avoid underrides, the barrier should not be placed in the region between –8 ft and 8 ft from the flat-bottom break points.
- For medians with slopes 6H:1V or shallower, the barrier may be placed in the region between –1 ft and 1 ft from the flat-bottom break points (special treatment, such as a mow strip, may be needed to compensate for poor soil condition in this region).
- To avoid overrides of larger vehicles (SUVs and pick-up trucks), the barrier should not be placed farther than 4 ft from the edge (break point) of the median when the median side slope is steeper than 6H:1V.

<u>Nonsymmetrical Medians:</u>

- It is preferable to place the cable barrier on the side of the median with the shallower slope.
- The guidelines for the v-shaped and flat-bottom medians listed above should be followed to minimize the risk of vehicle underrides or overrides.

<u>Shoulders and Superelevations:</u>

- Shoulders with down slopes of 6% or flatter are not detrimental to vehicle-to-barrier engagement and consequently do not affect barrier performance.
- For roads with superelevation steeper than 3%, the barrier should be placed not farther than 2 ft from the edge of (break point) medians when the slope is steeper than 6H:1V, and not farther than 5 ft when the slope is shallower than 6H:1V.

3.2. Deflection

3.2.1. Simulation analysis indicated that in impacts with cable barriers, the maximum dynamic deflection is affected significantly by the end-anchor spacing and post spacing. Greater end-anchor spacing leads to increased barrier deflections. Similarly, wider post spacing leads to higher deflection.

3.2.2. The results indicated that these effects are different for different types of barrier systems.

3.2.3. Cable barrier design deflection should not be based solely on deflection data from full-scale crash tests. Highway designers should investigate the differences in deflections associated with a specific design (e.g., anchor spacing, post spacing, post type, cable-to-post connection) of a cable barrier system.

3.2.4. Deflection plots for different barrier systems were generated under this study and used to investigate barrier deflection based on the barrier system, end-anchor spacing, and post spacing. Similar analyses, or other sources of data, should be used to provide a basis for understanding deflections for cable barrier systems.

3.3. End-anchors and Post Footings

3.3.1. End-anchors perform a critical function for cable barriers by keeping the cables in tension to minimize deflection upon impact by a vehicle. Some problems can occur in the field when these anchors have moved in the soil, either because of initial cable tension, increased cable tension caused by lower temperatures, or as a result of crashes into the barrier. Movement of the anchor in the soil decreases the tension in the cables which may result in unsatisfactory crash performance.

3.3.2. Soil analysis should be performed to determine the appropriate size for the end-anchor and post footings for each installation.

3.3.3. End-anchor and post footings should be designed for site-specific soil conditions.

3.3.4. The anchors should withstand a dynamic and static thermal load of at least 40 kips if all cables are connected to a single anchor, or at least 30 kips if the cables are individually anchored.

3.3.5. Special care and procedures should be used for installation of end cable connectors (terminations) to avoid premature cable pull out during impacts.

3.3.6. Very cold climatic conditions may require higher design loads. Anchors should be designed to limit movement to less than 1 in.

3.3.7. When a concrete footing is used for the posts, the footing should withstand a load higher than the plastic capacity of the post (i.e., the post would bend before the breaking or significant movement of the post footing).

3.3.8. Cable barrier system design should account for the potential of frost heave.

3.3.9. It may be appropriate to design for the durability of post sockets where multiple impacts might be expected. Other elements may be needed to provide adequate movement resistance.

3.4. Horizontal Curve Placement

3.4.1. The use of cable barrier along a curved section of the roadway can exert significant lateral pressure on the support posts and may cause them to bend over time. This occurs for cable barriers on the inside (convex) or outside (concave) of a highway curve.

3.4.2. Decreased post spacing from that on tangent sections may be appropriate for sections of cable barriers on horizontal curves.

3.4.3. Impacts on the convex side of a curved cable barrier will result in larger deflections. This effect was analyzed using simulations and an increase in deflection, even with high-tension systems, was as high as 70%.

3.4.4. With the increased deflection, the chance for loss of engagement is greater when the posts are damaged. Damaged posts should be replaced as soon as practical.

3.4.5. Reduced post spacings should be used to account for the increase in deflection when cable barriers are placed on horizontal curves with a radius less than 1,300 ft. This will also reduce the bending of the posts overtime due to lateral forces applied by the cables on the posts.

3.4.6. The barrier should be placed as close as practical to the convex side to allow more space behind the barrier for the added deflection. This may also reduce the number of cable barrier hits since it is placed further away from the more likely impacts with vehicles on the concave side.

3.4.7. For narrower medians, the use of two cable barriers (one on each side of the median) or a more rigid barrier may be considered appropriate to reduce the likelihood of vehicles impacting the convex side and intruding into oncoming traffic.

3.4.8. Placement of the cable barrier on the convex side (i.e., inside of the curve relative to near traffic) is recommended to allow maximum median space for recovery of vehicles leaving opposing travel lanes.

3.5. Vertical Curve Effects

3.5.1. On vertical curves, an upward force is exerted between the cable and the posts which could pull the posts out of the ground or pull the cables off the posts, resulting in less cable tension and cables at the incorrect height in relation to the ground. These effects adversely affect crash performance.

3.5.2. Manufacturers recommendations for keeping posts on vertical curves properly anchored in the soil should be observed.

3.5.3. End-anchors of the cable barrier should be placed as close as practical to the bottom and top points of the vertical curvature.

3.5.4. End-anchors may be placed at points where there is a sudden change in vertical slope.

3.5.5. Post spacing may be reduced in sharper vertical curves to offset the upward force effects.

3.5.6. Closer end-anchor spacing through extremely sharp vertical curves to reduce the vertical component of force on individual posts should be considered.

3.5.7. Re-grading short sections of the median that have sharp vertical curvatures should be considered.

3.5.8. Placement of cable barrier systems on some sag vertical alignments may be prudent. For example, Texas suggests that they should be avoided where the parabolic factor has a K-value of 11.

3.5.9. Periodic inspections should be performed at the bottom and top of vertical curves to ensure that the cables have not moved up or down from their specified heights.

3.6. Transitions and Interconnections

3.6.1. Cable barrier should not be transitioned into rigid (concrete) or flexible (weak post) barriers until further analyses and/or testing is conducted.

3.6.2. For transitions achieved by overlapping independent systems, the basic principle that each system should protect the hazard should be followed.

3.6.3. For transitions where the cable barrier is directly attached to the adjacent system, the following are recommended:

- The barrier to which the cables are connected should be long enough and adequately anchored at its downstream end to resist the forces from impacts and temperature variations in the cable barrier system. For w-beam strong-post guardrail, a minimum length of 75 ft is recommended. For other systems, the section connected to the cable barrier should be capable of withstanding a minimum of 40 kips of combined force.
- Similarly, the connection between each cable and the barrier should withstand the impact and thermal loads. The connection should be designed so that it can withstand a minimum of 30 kips.

- Adequate offset (flare) should be used between the cable barrier and the other system to prevent vehicle instability during the impact. A minimum of 4 ft offset behind the cable barrier is recommended for w-beam strong-post guardrails.
- The heights of the cable barrier and the other system should be compatible over the length of the transition region.

3.7. Mow Strips

3.7.1. A benefit/cost analysis may be conducted to determine when a mow strip is justified.
3.7.2. A maintenance consideration is the use of mow strips to reduce hand-moving and herbicide operations.
3.7.3. Distance between the edge of the travel lane and the cable barrier should consider mower width, if practical.
3.7.4. Delineation of cable barrier should be at 100 ft spacing, unless otherwise approved by the engineer.
3.7.5. Footing for terminal anchors should be designed to keep static loads well below the ultimate strength.

3.8. Design for Operations

3.8.1. There is a higher probability of high angle traffic conflicts in the vicinity of interchanges and hence the potential for barrier impacts at sharper angles. These concerns might dictate the use of a higher level barrier or reducing post spacing to limit deflection for such impacts.
3.8.2. Cable barrier deployment should consider the needs for turnarounds, crossovers, and access points to accommodate emergencies, enforcement, and maintenance operations.
3.8.3. Crossovers require full end treatments for safety and anchorages since the cable barrier runs are terminated.
3.8.4. Locations should be selected such that the risk of a crossover of an errant vehicle is minimized.
3.8.5. The distance between breaks in the cable barrier system to allow emergency vehicles access should be approximately 2 to 3 miles unless interchanges provide opportunities for emergency vehicles to get to the other side of the median barrier.

4. Costs and Benefits Analyses

Highway agencies seem to always operate with limited resources making costs and benefits critical metrics in justifying cable barrier projects. Cable barrier systems have features that are often thought to make them cost-effective. In this project efforts were devoted to gathering data and outlining a process for analyzing the costs and benefits for a cable barrier project. The guidelines focus on factors that need to be included in the analyses and efforts to compile the time and costs data needed to effectively evaluate periodic maintenance and post-crash repair costs for deployed cable barrier systems.

4.1. Initial Costs

4.1.1. Initial cable barrier system costs will be a function of the median configuration in the corridor, soil conditions, traffic and environmental factors, the barrier type selected, and the options.
4.1.2. Initial costs may vary by the barrier manufacturer, installation contractor, options available, regional cost factors, and other items.

4.1.3. Initial cost estimates should be based upon a clear understanding of the placement of the cable barrier installation, obstacles, environmental factors, associated anchorages, interconnections, and other factors.
4.1.4. End-anchor and post foundations should require designs based on in situ soil conditions and expected climate conditions that are reflected in the costs.
4.1.5. If a maximum design deflection has been set for a project, then the combined effects of post spacing and anchor-to-anchor spacing for each specific type of high-tension cable barrier should be considered to ensure that the required maximum deflection will not be exceeded.

4.2. Repair Costs

4.2.1. Repair costs will be a function of the degree of damage and nature of the elements that need to be replaced.
4.2.2. Some cable barrier options, such as socketed posts, may reduce long-term maintenance costs.
4.2.3. Agencies should maintain databases for cable barrier repair costs to develop improved capabilities to estimate these over time.
4.2.4. Maximum response times for repairing damaged barriers should be established based on the class of highway and the extent of damage.
4.2.5. There is only limited data available for cable barrier repair costs by DOTs at this time.

4.3. Periodic Costs

4.3.1. Periodic inspection schedules based on expected frequency of impacts should be established for each cable barrier installation.
4.3.2. Cable heights on barriers at the bottom and top of vertical curves should be checked periodically to make sure they remain at design heights.
4.3.3. Cable barriers should be inspected after severe weather events including flooding and extremely cold temperatures to check for erosion, end-anchor movement, and cable heights on vertical and sharp horizontal curves.

4.4. Benefits

4.4.1. All accepted systems do not perform the same, which implies that the benefits are not equivalent. Use the best available system-specific performance data in decision making (e.g., severity aspects).
4.4.2. Because of the small marginal cost of adding an extra cable and the likelihood that safety performance of the barrier is improved, the option should be considered.
4.4.3. Manufacturers may provide training on barrier installation, maintenance, and repairs for highway agencies and emergency response crews.

4.5. Trade-off Analyses

4.5.1. Life-cycle cost analyses should be considered to evaluate cable barrier systems, instead of selecting systems on the basis of lowest bid for installation.
4.5.2. Procedures for systematically considering all aspects of the trade-offs for various options should be followed.
4.5.3. The trade-off option of driven posts versus socketed posts requires estimates on expected number of hits and time-to-repair. Agencies should consider capturing such data to enhance the effectiveness of trade-off analyses.
4.5.4. Post spacing options for cable barrier systems can be a trade-off item.
4.5.5. Leaving trade-off items as part of the bid specification may make the selection of a contractor more difficult.

5. Construction

Proper construction of any barrier system is necessary for it to perform properly. This applies to cable barrier systems as well, but given that these systems can be deployed with limited heavy construction some needs may be overlooked. There have been reported problems with the construction of modern cable barrier systems that can be attributed to limited installation experience in many areas. Some guidance generated in this project is summarized below.

5.1. Tolerances

5.1.1. Recommended tolerances for construction are listed in Table E-1:

Table E-1. Cable barrier parameters and tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in)
Bottom Cable Height	-25,+0 mm (-1, +0 in)
Middle Cable(s)	±25 mm (±1 in)
Barrier Lateral Position	±150 mm (±6 in)
Average Post Spacing	±150 mm (±6 in)
Cable Tension	±2 kN (±0.45 kips)

5.2. Median Grading and Slope Rounding

5.2.1. Computer simulations showed that gentler slopes lead to greater potential for effective vehicle-to-barrier interface, increased lateral placement options, and reduced vehicle instability. Hence, designing the median in new construction for a gentler slope (6H:V1 or shallower) is encouraged.

5.2.2. Slope rounding reduces the impulse to the vehicle's suspension and hence the response when negotiating fore and backslopes. Slope rounding occurs to some extent naturally due to erosion over time.

5.2.3. Spot grading may be useful towards enhancement of lateral placement options.

5.3. Field Adjustments

5.3.1. The barrier effectiveness areas for each system and median configuration provide the basis for determining the latitude in making field adjustments.

5.3.2. Cross drainage structures with less than 36 in of cover pose a challenge for placing cable barrier posts. Structures of less than 16 ft can be spanned in order to avoid post placement on the drainage structure.

5.3.3. Field adjustments to anchor locations may necessitate new soil analysis and foundation design.

6. Maintenance and Operations

The responsibility for addressing highway safety needs does not end with the appropriate selection, design, and deployment of a cable barrier in a highway corridor. All barrier systems must be properly maintained to assure that they will effectively perform safety functions over time. That implies the need to inspect, adjust, repair, and/or replace barriers. To some extent, these needs are greater for cable barriers than other types, particularly the more rigid barriers, as one of their features is that they allow deflections that reduce crash severity by sacrificing elements of the system. It is not unusual for vehicles to drive away from impacts with cable barriers after an impact, but it is critical that any damage be repaired before the next impact. There are also design features of cable systems that are susceptible to maintenance needs, such as cable tensioning or post pull out on installations on vertical curves. Guidance for maintenance needs is provided below.

6.1. Periodic Maintenance

6.1.1. When developing plans for implementation of new cable barrier projects, the needs for periodic maintenance should be programmed and coordinated within the budget cycle.

6.1.2. Checks on cable tension on at least an annual basis should be undertaken to ensure effective system performance. The tension checks may be less frequent after the system has been in place for several years.

6.1.3. Coordination with other agency personnel to report damaged sections of cable barriers promptly should be considered.

6.1.4. Periodic inspections of critical cable system components, identified by manufacturer, should be conducted on a regular basis. Special attention is appropriate for cable barriers placed on horizontal and vertical curves due to the potential for greater post problems that can increase the degree of deflection.

6.2. Emergency Response

6.2.1. Emergency responders need to be made aware of and trained for rescue efforts where a vehicle is entwined in a cable barrier.

6.2.2. Cutting of the cables should be avoided due to the adverse implications of restoring the system.

6.2.3. Safe cutting procedures need to be defined when they become necessary.

6.2.4. Emergency response agencies should have educational materials to provide them with clear and concise guidance on when and how to safely disconnect or cut cables when a vehicle is entangled after an impact.

6.3. Post-Crash Repair

6.3.1. Accepted practices for cable splicing should be followed to insure adequate strength and to minimize the potential that they will represent a snag point. Splices should be offset on each of the cables.

6.4. Monitoring Performance

6.4.1. Motorcycle and truck crashes into median barriers should be monitored.

6.4.2. Unusual crashes (e.g., motorcycles and trucks) should be monitored to apply appropriate ancillary treatments.

6.4.3. Before and after crashes should be compared for treated sites to determine effectiveness achieved.

Epilogue

The process of planning, designing, operating, and maintaining highways is a constantly evolving effort. Guidance develops incrementally over time and its value is ascertained by safe and efficient movements of people and goods. These guidelines are believed to provide an incremental step in advancing the process. Not all those involved in reviewing this research and the formulation of guidelines agreed on every aspect. Where there was majority agreement the guidelines were retained, but a number of suggested guidelines were excluded. Certainly experience, changing traffic conditions, advances in technologies, adjustments to cost and benefits measures, and alterations in policies and regulations will lead to new insights and guidance that can be incorporated in future versions under the wisdom of national organizations.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 711

Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems

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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 and Transportation 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 Transportation Research Board of the National Academies 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 the National Research Council is an insurance of objectivity; 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 and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation 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 the responsibilities of the National Research Council and the Transportation 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.

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCHRP REPORT 711

NCHRP PROJECT 22-25 PANEL
Field of Design—Area of Vehicle Barrier Systems

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FOREWORD

By Mark S. Bush
Staff Officer
Transportation Research Board

This report provides guidance for the selection, use, and maintenance of cable barrier systems. While cable barrier systems have been in use for more than 70 years, their use has been on the rise and is expected to continue in the future. The increase in use of cable barrier systems has been attributed to the success rate in keeping vehicles from crossing the median, reducing roadway departures, and decreasing impact severity. Due to advancements in cable barrier system technology, installation and repair costs are lower and cable barrier use has increased in varying roadway environments. Safety studies, although limited, have shown that cable barriers help reduce those median cross-over collisions that lead to some of the most severe head-on type crashes. This document will be of particular interest to design, maintenance, traffic, and safety engineering professionals.

Cable barriers installed in the United States prior to 2000 were primarily low-tension, non-proprietary systems. With the first new generation high-tension cable barrier system installed in 2000 on an experimental basis, the proprietary product performed well, which led DOTs and manufacturers to have an increased interest in high-tension cable barriers. Since 2000, the use of both low- and high-tension cable barriers has expanded. In recent years, the popularity and rate of deployment of cable barrier systems along roadsides and in medians of the nation's roads and highways has significantly increased. As the use of these products has increased, so has knowledge about critical placement issues and the need for guidance relative to the design, selection, and maintenance to achieve the highest level of performance in various environments. Research, testing, and experience with these systems has revealed that the location and placement of the system has a significant influence on system performance.

The available generic and proprietary systems have performance differences and commonalities. Agencies have deployed the available generic and proprietary cable barrier systems based on limited performance information available from crash tests. Although there is general agreement that cable barriers are highly effective in reducing median cross-over accidents, there have not been sufficient analyses to establish reliable crash reduction factors. Cable barriers as a roadside device are most suited in locations with sufficient space to accommodate the lateral deflections that may occur during crashes, but lateral deflection information is not available for all barrier and roadside conditions. Cable barriers have been noted to function for a wide range of vehicle and limited truck types; however, various problems have also been reported. Further, design guidance currently available is dated and does not reflect the capabilities of the current generation of cable barrier systems. These issues prompted research to better understand cable-barrier effectiveness and the influence of factors related to design, median configurations, roadway geometrics, and impact conditions. Given the results of previous research, the variety of cable barrier systems available, and the inadequacy of past deployment practices for new systems, there was a need to establish better guidance for highway engineers.

George Washington University completed this research under NCHRP Project 22-25. The research involved (1) efforts to determine agency experiences with cable barrier systems and their practices for design, selection, and maintenance and (2) the identification of cable barrier system features available. Research focused on issues related to lateral placement, system length, anchorage requirements, transitions, and cost and maintenance. Computer simulation was used extensively to investigate key factors on performance with varied design parameters, installation configurations, road median geometrics, and impact conditions to isolate the effects of these parameters on barrier response. The research results coupled with the findings of previous studies provided the basis for developing the recommended guidelines. This report consists of Chapters 1 through 7, a glossary, and Appendix E (which summarizes the guidance recommended in the report). The entire contractor's report is available on the TRB website and includes several appendices to provide details relative to the cable barrier systems studied, the approaches employed, the detailed results, and related materials. The information included in this report will help highway agencies use better design and appropriate placement of cable barrier systems to reduce serious injuries and fatalities as well as operational costs.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains color versions if supplied.

CHAPTER 1

Introduction

Cable barriers are longitudinal roadside devices used to contain and/or redirect errant vehicles that depart the roadways. These barriers gradually redirect or arrest an impacting vehicle by stretching of the cables, minimizing forces on the vehicle and its occupants. While cable barriers have been used on U.S. highways for more than 60 years, their use has been on the rise and is expected to increase in the future. This increase in use is attributed to cable barriers' success rate in keeping vehicles from crossing the median or leaving the roadway, reduced impact severity, availability of new cable barrier technologies, low initial installation cost, and suitability for various median and roadside environments.

Cable barriers as a roadside device are most suited in locations where there is sufficient space to accommodate the lateral deflections that may occur during crashes. Figure 1.1 shows a generic 3-cable low-tension barrier installed on a divided highway with narrow median and relatively flat side slopes. Such low-tension systems are still in use and continue to be used, but new technologies have led to the development of a host of proprietary cable barrier systems. Figure 1.2 depicts some of these systems. Differences in the number, heights, and arrangement of cables, post types, cable connectors, embedment, and other features are obvious in these pictures. Not so obvious is the difference between the high-tension and low-tension cable systems. Although these systems have been tested to current standards and have been "accepted" for use on U.S. highways, the differences complicate efforts to select a system for a particular application. More specifically, high-tension cable systems, when compared to low-tension systems, have the advantage of lower deflection during impacts and supposedly reduced maintenance costs. These have seen increased usage in many states and hundreds of miles of new installations are added yearly.

Several studies have shown that cable barriers reduce median crossover accidents that could lead to some of the most severe head-on crashes, which are often fatal. Although there is general agreement that cable median barriers are "highly effective" with some reporting success rates higher than 90 percent, there have not been sufficient analyses to establish reliable crash reduction factors. Cable barriers have been noted to function for a wide range of vehicles, including tractor-trailer trucks. There have, however, been problems reported. These have included overrides, underrides, shearing vehicle roof pillars, post fracture, and anchorage failures. The frequency and causes of these occurrences, however, is not fully understood.

The noted occurrence of vehicles underriding the barrier, crossing the median, and penetrating into the opposite traffic lanes has been the impetus for research to identify the cause of the problems and find means to mitigate them. This prompted FHWA to initiate research studies on cable median barriers to identify some of the reasons for median crossovers and to develop design guidelines to optimize the safety performance of cable barriers. In these studies, finite element analyses, vehicle dynamics analyses, and full-scale crash tests were used to assess factors that could influence the effectiveness of cable barriers in redirecting or arresting errant vehicles. These

Figure 1.1. Typical generic, 3-cable, low-tension median cable barrier installation.

Figure 1.2. Typical new proprietary cable barrier systems available.

factors included the terrain geometry and shape, speeds and angles of the vehicles as they leave the road, lateral placement of the barrier, barrier system configuration (heights of cables), vehicle type (front geometry and mass), post spacing, and barrier lengths. These efforts provided an explanation for the occurrence of underrides and revealed a much stronger relationship between barrier placement and median configuration on barrier effectiveness than had been assumed.

The need to better understand the effectiveness of cable barriers and the influence of factors related to the design of cable barrier systems, the configuration of medians, and the nature of impact conditions prompted an interest in further research. The variety of cable barrier systems available, the inadequacy of past deployment practices for new systems, and the need to establish better guidance to highway engineers provided further stimulus for this research.

1.1 Project Objectives and Scope

The objective of this NCHRP project was to develop guidelines for the selection, use, and maintenance of cable barrier systems. The first part of the study involved conducting a comprehensive literature search to collect all studies, state guidelines, in-service evaluations, design drawings, installation manuals, and maintenance documentation related to cable barrier systems. Based on the findings from the literature search, different cable barrier issues were investigated to develop a better understanding of the effects of key factors on the performance of cable barrier systems. The investigation consisted of conducting computer simulations with varied design parameters, installation configurations, and impact conditions to identify the effects of these parameters on the barrier response. These investigation results, coupled with the findings from previous studies, were analyzed and used to develop the guidelines.

The request for proposals for this project outlined eight tasks to achieve these objectives, namely:

- Task 1: Conduct a literature review of recent studies, including international studies, relating to cable barrier systems.
- Task 2: Identify, collect, and review state guidelines and in-service evaluations for cable barrier systems. Additionally, collect and review manufacturers' design, installation, and maintenance documentation for all proprietary cable barrier systems.
- Task 3: Prepare an interim report that summarizes Tasks 1 and 2, identifies additional information needed to develop the guidelines, provides a revised work plan detailing the scope of Phase II, and includes a detailed outline of the proposed guidelines.
- Task 4: Meet with the NCHRP Project Panel to review the Task 3 interim report and submit a revised interim report addressing the panel's review comments.
- Task 5: Execute the approved Phase II work plan using quarterly progress reports to incrementally share research findings.
- Task 6: Prepare draft guidelines detailing the entire range of typical installations for cable barrier systems.
- Task 7: Formulate and execute a plan to solicit feedback on the draft guidelines, incorporating review by state agencies and industry representatives. Synthesize the comments received in the external review and recommend revisions to the guidelines for NCHRP approval.
- Task 8: Submit a final report documenting the entire research effort including the revised guidelines as an appendix. The final report should document limitations on analysis and sources of the material presented and cite needs for future research.

These tasks were embodied in the project research plan that led to this report.

The first interim meeting with the NCHRP Project Panel held in September 2009 further focused the research efforts. Based upon the initial efforts, 13 subtasks were proposed to the panel as possible topics for more detailed study. The findings of the research completed under Tasks 1 and 2 and the recommendations for more detailed research were summarized in the interim report. Based upon the discussions with the panel and the proposed efforts, the panel directed the research team to undertake in Task 5 the seven critical research areas summarized in Table 1.1. Other proposed topics are described in future research needs in Chapter 7.

Table 1.1. Proposed subtasks to be performed under Task 5.

Subtask	Description
5.1	**Title:** Cable Barrier Lateral Placement **Objective:** Assess barrier performance when placed at different positions across the median. **Approach:** Conduct vehicle dynamics simulations to compute vehicle trajectory as it crosses the median and assess vehicle/barrier engagements. **Varied Factors:** • Vehicle type (820C, 1100C, 2000P, 2270P, Crown Victoria, single-unit truck) • Median profiles (v-shaped, flat bottom, rounded bottom, non-symmetric) • Median slopes (10H:1V, 8H:1V, 6H:1V, and 4H:1V) • Median widths (5 to 17 m, 16 to 56 ft) • Approach speed (50 to 100 km/h, 31 to 62 mph) • Approach angle (5 to 25°) (Note: This supplements work already conducted under FHWA projects. The tools used to carry out this task have been previously developed.)
5.2	**Title:** Barrier Deflection **Objective:** Study effect of end-anchor spacing on barrier deflection. **Approach:** Conduct finite element simulations to study the effects of different design parameters on barrier deflection. **Varied Factors:** • Barrier designs (generic, Brifen, Gibraltar, Nucor, Safence, and Trinity) • Installation length (100 to 1,000 m, 330 to 3,300 ft) • Post spacings (1.5 to 6 m, 5 to 20 ft) • Cable tensions (15 to 24 kN, 3.4 to 5.4 kips) • Impact location (at post and in between posts)
5.3	**Title:** Post-Anchoring and End-Anchoring Systems **Objective:** Evaluate post foundation and end-anchor movement, failure, and pull-out. **Approach:** Conduct finite element computer analyses to investigate post and end-anchor movement/pull-out/failure. **Varied Factors:** For line post anchoring systems • Soil strength (weak and strong) • Embedment (post driven in soil, socket driven in soil, socket in concrete) • Footing size For end-anchoring systems • Soil strength (weak and strong) • End-anchor size • Anchoring type (single-cable and multi-cable)
5.4	**Title:** Interconnection with Other Systems **Objective:** Evaluate safety performance of cable barrier transitions and end terminals. **Approach:** Use existing practices for connecting cable barriers to adjacent semi-rigid barriers and finite element computer analyses. **Varied Factors:** • Cable barrier systems (generic, Brifen, Gibraltar, Nucor, Safence, and Trinity) • Connecting barrier (W-beam and Three-beam) • Transition designs (two to three common designs) • Test level (TL3 and TL4)
5.5	**Title:** Construction and Maintenance Tolerances **Objective:** Assess effect of construction tolerance on barrier performance. **Approach:** Use computer simulation, literature findings, and survey results to establish acceptable tolerances on different design and installation parameters. **Varied Factors:** • Tolerance on cable heights (settlement) • Tolerance on changes in median width • Tolerance on median slope • Tolerance on post spacings • Soil tolerances • Effect of other objects in median

Table 1.1. (Continued).

Subtask	Description
5.6	**Title:** Guidance on Placement Relative to Horizontal Curvatures **Objective:** Assess barrier performance when placed on roads with horizontal curvatures. **Approach:** Use finite element and vehicle dynamics computer analyses to study the effects of horizontal curvature on barrier performance (vehicle engagement and barrier deflection). **Factors to Vary:** For vehicle dynamics simulations • Curvature radius (75 to 300 m, 250 to 1,000 ft) • Vehicle types (820C, 1100C, 2000P, 2270P, Crown Victoria) • Speed and angle • Median width For finite element analyses • Curvature radii (75 to 300 m, 250 to 1,000 ft) • Post spacings (1.5 to 6 m, 5 to 20 ft) • Cable barrier length (100 m and 500 m, 330 and 3,300 ft)
5.7	**Title:** Installation and Maintenance Costs **Objective:** Approximate overall cable barrier installation and maintenance costs. **Approach:** Use data from the literature and State DOT survey to estimate overall costs of CMB and benefits/cost tradeoff between different options. **Factors to Consider:** • Installation costs • Maintenance and repair costs • Post embedment (driven/socket/mow strip) • Barrier placement (affect maintenance and number of cable barrier hits) • Environment condition (temperature/soil condition) • Average daily traffic

1.2 Report Organization

This report is organized into seven chapters as follows:

- Chapter 1—Introduction
- Chapter 2—Literature Review
- Chapter 3—Cable Barrier Current Practices
- Chapter 4—Descriptions of Available Cable Barriers
- Chapter 5—Analyses and Results
- Chapter 6—Guidelines for Cable Barriers
- Chapter 7—Summary and Conclusions

The contractors' final report also includes several appendices to provide details relative to the cable median barrier systems studied, approaches employed, detailed results, and similar materials. Appendix E is included in this report. Appendixes A through D *are not* published herein but are available on the TRB website by searching on *NCHRP Report 711*.

CHAPTER 2

Literature Review

At the outset of the project a detailed literature review was performed to gather information related to cable barriers with a focus on the design, performance, evaluation, maintenance, and application of cable barrier systems. Many types of documents were collected, organized, and reviewed including cable barrier research papers and reports, presentations, DOT guidelines, in-service evaluations, international studies, usage and safety performance statistics, and success stories. A synthesis of the collected information is presented in the following sections and the documents are available at http://crash.ncac.gwu.edu/dmarzoug/CableBarrierLiterature/.

2.1 History and Usage

Cable barriers have been used in the United States for more than 60 years. New York DOT played an important role in the development and refinement of the cable barrier. Early use of cable barriers was concentrated in the northern states because of the openness of the barrier, which allows snow to pass through rather than pile up in front of the barrier as is the case with beam and concrete barriers. A 1982 study by Post and Chastain showed that cable guardrails were more cost-effective than (strong-post) W-beam guardrails for certain types of installations [1]. In 1997, it was reported that 18 states had 3-cable low-tension barriers in use; however, only 4 states were still installing cable barriers [2].

Until 2000, all cable barriers in the United States were low-tension, non-proprietary systems. In 2000, the first high-tension proprietary cable barrier system was installed in Oklahoma City, OK. A safety barrier, developed by Brifen in the United Kingdom in the 1980s and used in over 30 countries, was installed first on an experimental basis on a 305 m (1,000 ft) section of the Lake Hefner Parkway in Oklahoma City in August 2000. Shortly thereafter it was installed along 11 km (7 miles) of the parkway. The Brifen system performed well, which led other states and other manufacturers to get interested in high-tension cable barriers.

Since 2000, the use of high-tension cable barriers has expanded rapidly in the United States. Table 2.1 shows cable median barrier usage in the United States for 1997, 2004, and 2006 as reported by Ray in a report for Washington State DOT [3]. This table is based on several surveys of state DOTs, and it is not believed to give a complete picture of usage. For example, Oklahoma, which started the movement toward high-tension cable barriers, is not shown as a user of median barriers in the 2004 surveys even though it had been using cable barriers since 2000. Several states shown to be using cable barriers in 2004 are not included in the 2006 survey. From 2000, when Oklahoma installed its experimental section of Brifen cable median barriers, usage of high-tension cable barriers had spread to at least 30 states by 2006.

Table 2.2 gives Ray's estimate of the number of miles of cable median barrier in use at the end of 2006 by state in the United States.

Table 2.1. States using cable median barriers [3].

Year	No.	States Reporting Cable Median Barrier Use
1997	4	North Carolina, Washington, South Dakota, Missouri
2004	12	Alabama, Arizona, Iowa, Mississippi, Missouri, Nebraska, Nevada, New York, North Carolina, South Carolina, Washington, Wisconsin
2004	14	Alabama, Arizona, Iowa, Minnesota, Mississippi, Missouri, Nebraska, Nevada, New Jersey, New York, North Carolina, South Carolina, Washington, Wisconsin
2006	25	Alabama, Arkansas, Arizona, Colorado, Florida, Georgia, Idaho, Illinois, Indiana, Iowa, Maine, Missouri, Montana, Nevada, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, Wisconsin

Table 2.2. Cable median barrier mileage estimate [3].

State	Miles	Year	State	Miles	Year	State	Miles	Year
Alabama	118	2006	Maine	1.5	2006	Oregon	23	2005
Arizona	89	2006	Minnesota	6.3	2003	Rhode Island	1.4	2005
Colorado	40	2005	Missouri	250	2006	S. Carolina	470	2005
Florida	187	2005	N. Carolina	600	2007	Texas	500	2006
Iowa	64	2007	New York	5	1989	Utah	16.4	2003
Illinois	70	2005	Ohio	27.5	2006	Washington	135	2006
Kentucky	13	2006	Oklahoma	23	2005	Total	2,640	

Table 2.3. Approximate miles of installed high-tension cable barriers [4].

Manufacturer	April 2006	September 2006	January 2008	April 2008
Safence	4	17	110	185
Brifen	287	323	405	440
Gibraltar	195	395	540	685
Nucor Steel Marion	221	340	403	453
Trinity Industries	341	570	825	912
Total Miles Installed	1,048	1,645	2,283	2,675

Table 2.3 gives an estimate of installed miles of cable barrier for four different points in time, April 2006, September 2006, January 2008, and April 2008. These data gathered by the Texas Transportation Institute (TTI) show the rapid rate of installation of high-tension proprietary cable barriers that has occurred since 2006. Between September 2006 and April 2008, over 1,000 miles of cable barrier were installed. The growth in use of high-tension cable barriers from 7 miles in 2001 to almost 2,700 miles in 2008 is remarkable. Also, it should be noted that the TTI numbers do not consider low-tension, non-proprietary cable barriers. The difference between Ray's estimate of 2,600 miles at the end of 2006 and TTI's estimate of 1,645 miles can be explained in large part by TTI's exclusion of low-tension barriers. For example, North Carolina is reported by Ray to have 600 miles of barriers installed, and most of these miles were low-tension barriers.

2.2 Cable Barrier Designs

Cable barriers are categorized as weak-post barriers since their posts are designed to fail in a crash to allow the longitudinal structural element (cable) to absorb energy from the impact through elongation (stretching). The elongation of the cable causes the barrier to deflect laterally in a parabolic form that assists in redirecting the impacting vehicle in a smooth and "forgiving" manner. The elastic nature of the barrier reduces the severity of the impact but causes larger dynamic deflections than would be experienced with a semi-rigid or rigid barrier under similar impact conditions. Thus weak-post barriers can be used safely only when adequate clear area exists behind the barrier to accommodate the dynamic deflection.

The development of weak-post barriers is described in a 1967 publication by Graham et al. [5]. The article describes the theory behind weak-post barriers as well as crash tests conducted on the standard 3-cable barrier, the weak-post W-beam guardrail, and the box-beam median barrier. A summary of available cable barrier systems is presented in Chapter 4 of this report.

2.3 Performance of Cable Barriers

Low-tension cable barrier systems have been in use for at least 60 years, and their performance has been studied extensively. Many of the earliest studies were done in New York because New York DOT was the main developer of the 3-cable low-tension barrier. Gabler et al. describe these early studies and later studies of 3-cable low-tension barrier performance. Findings of these studies are summarized in Table 2.4, and more details on these studies are provided in Gabler's *Evaluation of Cross Median Crashes* [6].

North Carolina has been the leading user of low-tension cable barriers, having 966 km (600 miles) installed as of 2007 [3]. In 1998, North Carolina began a program to prevent and reduce the severity of cross-median crashes. The program is being carried out in the following three phases:

Phase I: Add median protection to freeways with historical crash problems;
Phase II: Systematically protect all freeways with median widths of 21 m (70 ft) or less; and
Phase III: Revise design policy to protect future freeways with median widths of 21 m (70 ft).

Between 2000 and 2006 in North Carolina, approximately 1,600 km (1,000 miles) of freeways were enhanced at a cost of over $120 million. The number of crossover fatal crashes decreased from 33 crashes in 1998 to 4 crashes in 2005 (from 16.7 percent of all fatal crashes to 2.8 percent). Similarly, the number of cross-median fatalities was reduced from 47 fatalities in 1998 to 6 fatalities in 2005 (from 20.5 percent of all fatalities to 3.6 percent). It is estimated that 110 fatal cross-median crashes have been avoided and 177 lives saved from January 1999 to September 2006, resulting in crash cost savings of more than $385 million in fatal crash cost alone (using 2001 dollars). Table 2.5 shows North Carolina's fatal crash data for 1990 to 2006 [7].

A long-term median barrier evaluation in North Carolina investigated 689 km (428 miles) of new median barrier installations (203 miles of low-tension cable barrier, 132 miles of W-beam

Table 2.4. Previous studies of performance of low-tension, 3-cable barriers [6].

State	Researchers	Date	No. of Crashes	Findings
NY	Van Zweden, Bryden	1967-1969	375 RS	20% penetrations, 4 fatalities, 15 injuries, 356 no injuries
NY	Carlson, Allison, Bryden	1977	23 RS (12 LON, 11 term)	33% penetrations, 2 minor injuries, 21 no injuries
IA	Schneider	1979	31 RS	23% penetrations, 1 fatality, 4 injuries
NY	Tyrell, Bryden	1989	99 Median	4% penetrations, 24 injuries, 75 PDO
NY	Hiss, Bryden	1992	427 RS	20% penetrations, 38 major injuries, 178 minor injuries, 211 PDO
NY	Hiss, Bryden	1992	16 Median	6% penetrations, 1 major injury, 10 minor injuries, 5 PDO
NC	Mustafa	1997	125 Median	11 major injuries, 28 minor injuries, 88 PDO
OR	Sposito, Johnson	1999	53 Median	6% penetrations, 5 major injuries
WA	McClanahan, Albin, Milton	2004	59 Median per year	No fatalities, 10 penetrations, 5 heavy vehicle containments

RS – Roadside, PDO – Property Damage Only

Table 2.5. North Carolina fatal crashes from 1990 to 2006 [7].

PHASE I AND PHASE II MEDIAN BARRIER PROJECT LOCATIONS

Year	Fatal Crashes	Across Median Fatal Crashes	Percent of Total	Fatalities	Across Median Fatalities	Percent of Total
1990	145	33	**22.8**	177	47	**26.6**
1991	144	26	18.1	188	44	23.4
1992	128	22	17.2	147	31	21.1
1993	158	20	12.7	196	38	19.4
1994	146	23	15.8	179	36	20.1
1995	150	18	12.0	177	28	15.8
1996	159	26	16.4	189	40	21.2
1997	147	33	22.4	194	47	24.2
1998	198	33	16.7	229	47	20.5
1999	178	24	13.5	207	30	14.5
2000	191	23	12.0	226	36	15.9
2001	160	7	4.4	183	11	6.0
2002	152	13	8.6	173	14	8.1
2003	129	12	9.3	146	13	8.9
2004	146	8	5.5	179	13	7.3
2005	144	4	**2.8**	165	6	**3.6**
2006 (Sept)	100	4	4.0	111	4	3.6

Median Barrier Projects Started Here

guardrail, 43 miles of W-beam/cable mix, 31 miles of weak post W-beam, and 18 miles of W-beam/weak post W-beam mix). An analysis of before and after crash data showed that the added median barriers reduced fatal and severe injury crashes and cross-median crashes. For freeways with cable barriers, fatal and severe injury crashes overall were reduced 13 percent while fatal and severe injury cross-median crashes were reduced 74 percent. The data also showed that the added median barriers increased the number of total crashes, the number of minor injury crashes, and the number of property-damage-only crashes. For freeways with cable barriers, the total number of crashes increased 113 percent from 793 to 1,688. Of the 895 additional crashes, only 568 (63 percent) were crashes involving the median barrier. The other 37 percent of the additional crashes may have been a result of the 34 percent increase in ADT between the before period and the after period. The summary data are presented in Table 2.6 [7].

The other state that has installed a lot of low-tension cable barriers is Missouri. As part of Missouri's Blueprint for Safer Roads Program, approximately 800 km (500 miles) of cable barrier, both low- and high-tension, had been installed as of 2007. These cable barriers have been found to be about 95 percent effective in preventing vehicles from entering opposing lanes. Figure 2.1 shows that statewide cross-median fatalities have dropped from an average of about 50 per year to fewer than 10 per year after installation of the cable median barriers [8].

Figure 2.2 shows the relationship between the installation of cable barriers and the reduction in cross-median fatalities on I-70 in Missouri. In 2003, when Missouri began its major program to install median barriers, I-70 had 23 fatalities from cross-median crashes. In 2007, when Missouri had in place 290 km (180 miles) of median barrier on I-70, fatalities from cross-median crashes had dropped 83 percent to 4 cross-median fatalities [8].

In 2006, Missouri used accident data from 1999 to 2005 to evaluate the performance of its low-tension cable barrier on medians with slopes steeper than 6H:1V. Many of these slopes were 5H:1V, but some were steeper. Of the 1,402 accidents investigated, 67 (5 percent) were marked as a "failure," meaning that a crossover was not prevented [1].

In 2004, Washington DOT studied the in-service performance of its low-tension cable barriers. Before and after accident data showed that the average number of crashes per year increased from

Table 2.6. Median barrier before and after crash data at select locations in North Carolina [7].

	All Barrier Types			Cable			W-Beam			W-Beam / Cable Mix		
	Before	After	Percent Change	Before	After	Percent Change	Before	After	Percent Change	Before	After	Percent Change
Mileage	428			203			132			43		
Average ADT	26,600	34,300	29%	22,000	29,400	34%	28,800	36,700	27%	32,800	42,500	30%
Total Crashes	2,048	3,718	82%	793	1,688	113%	695	1,044	50%	251	507	102%
Severe Injury (K & A) Crashes	120	98	-18%	47	41	-13%	38	28	-25%	15	13	-9%
Moderate / Minor Injury (B & C) Crashes	696	1,103	58%	267	448	68%	242	347	43%	83	154	86%
Property Damage	1,232	2,517	104%	479	1,199	150%	414	668	61%	153	340	122%
Across Median Crashes	152	30	-80%	60	23	-62%	41	3	-94%	18	3	-84%
Fatal Across Median Crashes	13	2	-80%	4	2	-56%	3	1	-82%	2	0	-100%
Severe Injury (K & A) Across Median Crashes	20	3	-87%	7	2	-74%	7	1	-91%	2	0	-100%
Crashes Involving Median Barrier	--	1,218	--	--	568	--	--	309	--	--	165	--
Percent of Crashes Involving Median Barrier	--	33%	--	--	34%	--	--	30%	--	--	33%	--
Breach Rate	--	2.4%	--	--	4.0%	--	--	0.9%	--	--	1.6%	--

* All Crash Numbers are Crashes / Per Year

49 to 100; however, the average annual rate of fatal crashes dropped 89 percent from 3.00 to 0.33. Likewise, the average annual rate of disabling crashes dropped 51 percent from 3.60 to 1.76. Washington DOT estimates that the societal costs due to such crashes were reduced 76 percent from $13.58 million to $3.32 million [1].

Ray has summarized the data from several states on reductions in cross-median crashes [3]. These data (shown in Table 2.7) are for installations of both low- and high-tension cable barrier systems. Some of the data is based on small sample sizes, which implies that some of the results

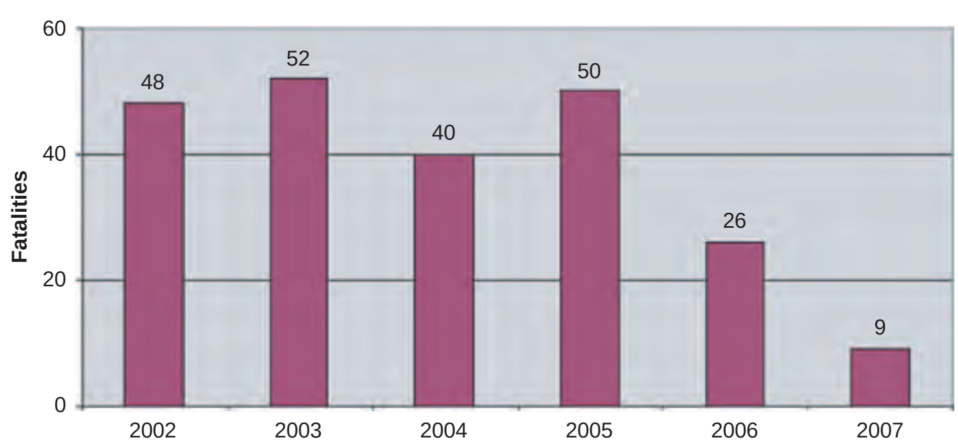


Figure 2.1. Missouri interstate cross-median fatalities [8].

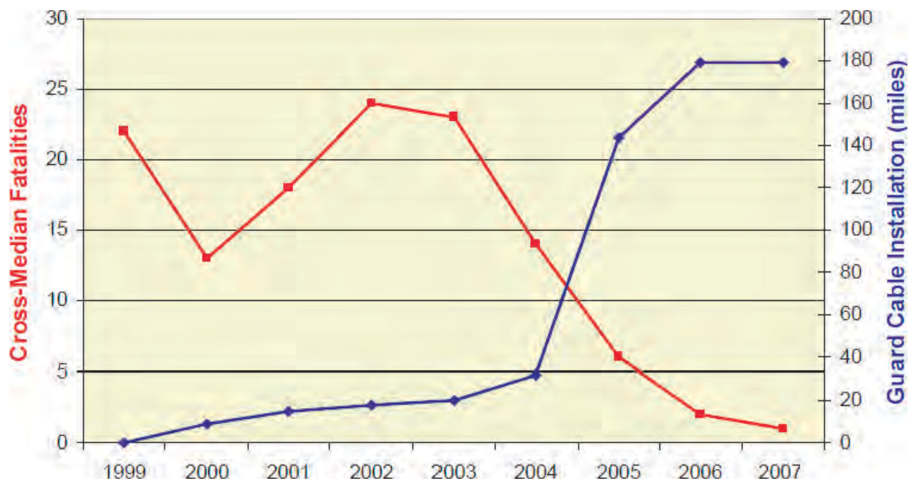


Figure 2.2. Cable installations vs. cross median fatalities—I-70 in Missouri [8].

shown have wide statistical confidence intervals. Table 2.8 shows the effectiveness of cable barriers in preventing cross-median penetrations. All but one state reported 93 percent effectiveness or better. Utah's 88.9 percent effectiveness is based on only 18 crashes. The two states reporting 100 percent effectiveness, Iowa and Rhode Island, also are based on small sample sizes. From these data, the average effectiveness of cable barriers in preventing median barrier penetrations (including or excluding the three states with small sample sizes) is 98.0 percent [3].

A number of states have performed in-service evaluations of high-tension cable barriers since these systems were new to the DOTs. Summaries of these studies are given in Table 2.9. All reports indicate that the high-tension cable barrier systems are effective in reducing cross-median crashes.

Table 2.7. Performance of cable median barriers in various states: reduction in cross-median crashes [3].

State	Annual "Before" (Number)	Annual "After" (Number)	Reduction (percent)
Fatal Cross-Median Crashes			
Alabama	47.5	27	43
Arizona	1.7	0.7	59
Missouri	24	2	92
North Carolina	2.1	0	100
Ohio	40	0	100
Oklahoma	0.5	0	100
Oregon	0.6	0	100
Texas	30	1	97
Utah	15	0	100
Washington	4.4	0.4	91
Cross-Median Crashes			
Florida	---	---	70
North Carolina	25.4	1	96
Ohio	371	27.5	93
Utah	114	55	52
Washington	42.4	11.2	74

Table 2.8. Performance of cable median barriers in various states: effectiveness [3].

State	Collisions (Number)	Penetrations (Number)	Effectiveness (percent)
Arkansas	490	25	94.9
Louisiana	20	0	100
North Carolina	71	5	93.0
New York	99	4	96.0
Ohio	372	4	98.9
Oklahoma	400	1	99.8
Oregon	53	3	94.3
Rhode Island	22	0	100
South Carolina	2,500	10	99.6
Utah	18	2	88.9
Washington	774	41	94.7

Table 2.9. Performance of high-tension cable barriers in various states.

State	System	Miles	Time	Crashes	Fatal	Serious Injury	Minor Injury	Heavy Vehicle	Pene-tration	Ref
AR	Brifen		1 yr	44	0	0	0	1	0	[9]
AZ	Brifen	40	30 mo	104	1[a]	0	4	8	0	[10]
CO	Brifen	2.3	18 mo	9	0	0	0		1[b]	[11]
IN	Brifen	13	1 yr	70	0	0	0	1	4[c]	[12]
IO	Brifen	3.5	21 mo	20	0	1[d]	0	0	0	[13]
OH	Brifen	14.5	3 yr	452	0	0	39		13	[14]
OK	Brifen	7	1 yr	128	0	0	1		0	[15]
RI	CASS	1.4	1 yr	20	0	0	0		0	[3]
TX	Brifen		13 mo	65						
TX	Nucor		6 mo	6						[16]
TX	CASS		13 mo	76						
UT	CASS	8	16 mo	74	0	2			3	[1]
UT	Brifen	2	18 mo	11	0	1			3	

[a] Fatality unrelated to barrier, [b] penetration occurred at a drainage inlet where the cables were higher than specified, [c] no cross-median crashes, [d] injury occurred during impact with tractor-trailer before impact with barrier.

2.4 Placement of Barriers

The TTI report entitled "Guidelines for the Selection of Cable Barrier Systems (Generic Design vs. High Tension)" discusses the tradeoffs involved in the lateral placement of cable barriers. To reduce the number of impacts, the barriers should be placed as far away from the travel lane as possible. To achieve the highest level of performance, the barrier should be placed on near-level terrain, which usually is found close to the travel lanes. Also, adequate clear space behind the barrier must be maintained to allow for dynamic deflection of the barrier during impacts [1].

Cable barriers are typically placed on medians with slopes of 6H:1V or flatter. However, several of the high-tension barrier systems have been crash-tested successfully on 4H:1V median slopes. To reduce the chance of barrier penetration from reverse hits on medians with 6H:1V slopes, barriers should not be placed from 1 ft to 8 ft from the ditch centerline [1, 17]. Barriers placed along the centerline of median ditches have experienced problems from poor and saturated soil conditions and drainage inlets. The poor soil conditions can cause foundation and anchor failures, and the drainage inlets have been found to allow vehicles to penetrate the barrier because of the increased height of the cables at the inlet.

Table 2.10. Cable barrier installation guidelines [3].

State	Installation Guidelines				Max. Slope	Cable Barrier Type	Location
	Median Width Min.	Median Width Max.	Min. Traffic Volume	Crash Rate			
	(ft)	(ft)	(veh/day)		(H:V)		
AZ	30	75	All Urban		6:1	LT33	CM
DE	50	–					
VA	–	40					
OH	–	76	36,000		6:1	HT	GT8BD
NC	36	70			6:1	LT	SDR/SSR/CM
OR	30	–					
MO	36	60	20,000	0.8 cross-median crashes /100MVMT	6:1	LT30 HT	CM/GT14S/ SDR
NY	36	72	20,000		6:1	LT30	CM/SSR/SDR
NY	36	72	20,000		10:1	HT	CM
KY				0.12 fatal crashes/mi/yr			
WA	30	50			6:1	LT30 HT	CM/GT8BD

CM = Center of median
GT8BD = Greater than 8 feet from the bottom of the ditch
HT = High-tension cable median barrier
LT = Low-tension cable median barrier
LT30 = 30-inch low-tension cable barrier
LT33 = 33-inch low-tension cable barrier
SDR = Shoulder double run
SSR = Shoulder single run
GT14S = Greater than 14 feet from the edge of the nearest shoulder

Ray's cable barrier summary [3] contains a table with data from ten states on their guidelines for installing cable median barriers. His table has been reproduced as Table 2.10. The most common recommendations are "center of median" and/or "greater than 8 ft from the bottom of the ditch," which is consistent with the TTI report and the AASHTO *Roadside Design Guide.*

Missouri recommends for medians at least 9 m (30 ft) wide, to place the cable barrier 1.22 m (4 ft) down slope of the edge of median (hinge point). For medians narrower than 9 m (30 ft), the cable barrier should be installed at the vertex of the V or flat-bottomed ditch [18].

FHWA-sponsored research at the National Crash Analysis Center of the George Washington University has investigated the issue of median crossovers by conducting full-scale crash tests of a large sedan impacting a cable barrier placed at a 1.22 m (4 ft) offset from the center of V-shaped 6H:1V sloped median [19]. In addition, vehicle dynamics simulations were used to evaluate and optimize cable barrier performance on sloped medians under different impact conditions.

Vehicle dynamics simulations were conducted to compute vehicle trajectories as they cross or traverse a median on a diagonal path. A commercially available software package was used to undertake the computations and generate an animation showing what happens. In these studies, the vehicle trajectory as it crosses the sloped median was computed and used to determine if the barrier would engage and redirect the vehicle. Simulations with varied vehicle types (small car, large sedan, and pickup truck), impact speeds (50 to 100 km/h, 31 to 62 mph), approach angles (5 to 25 degrees), median profiles (V-shaped and flat bottom), median slope (8H:1V, 6H:1V, and 4H:1V), and median widths (5 to 17 m, 16 to 56 ft), were conducted to assess barrier performance. The vehicle's relative height was compared to vertical locations of the cables to assess vehicle-to-barrier interaction.

The analysis was used to investigate individual cases (i.e., one vehicle, one speed, one angle, and one median profile) as shown in Figure 2.3. The figure shows a trace envelope for the vehicle moving left to right relative to the cross-section of the median and six possible placement locations for this 3-cable barrier design. Interface with all cables is clearly good (Good oval) and missing all cables is bad (Bad oval). Interfacing with only one or two of the cables is considered acceptable.

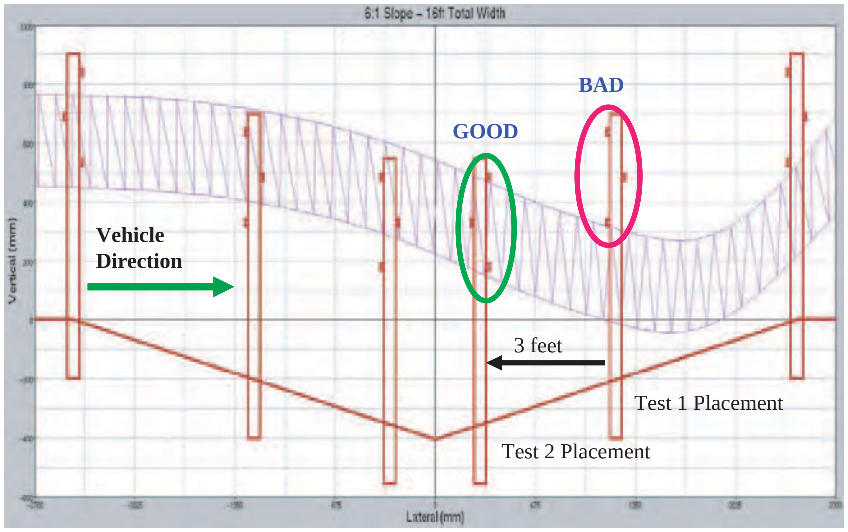


Figure 2.3. Sample trace envelope of vehicle crossing a sloped median.

Additionally, trace envelopes from several cases (varied vehicle types, speeds, and angles) were combined to study optimum placement of cable barriers.

Figure 2.4 shows sample plots highlighting a region in the median between 1 ft and 8 ft where significant variations in vehicle vertical position are observed. Similar variation for this critical region was noticed for different median widths (5 to 15 m, 16 to 48 ft), as indicated by the pattern of "bulges." This plot indicates that barrier placement in this region should be avoided or additional cables are needed [19].

2.5 Cable Heights

Cable heights are important in determining cable barrier effectiveness. Existing cable barriers have either three or four cables (19 mm, ¾ in, 3 × 7 strand galvanized wire ropes). Most high-tension cable barriers use prestretched cables to reduce post-construction tension loss caused by construction stretch (the seating of wire strands during loading). Although cable heights vary among barrier systems, in most systems, the bottom cable is between 432 and 533 mm (17 and 21 in.) high. The top cable height for most systems is between 762 and 1,067 mm (30 and 42 in.). Figure 2.5 shows cable heights for some of the available cable barrier systems. A more complete list of available systems and their cable heights is included in Appendix B of the contractors' final report.

Cable barriers need to accommodate a wide range of vehicle types, from low-profile sports cars to high-center-of-gravity trucks. If the bottom cable is too high, then low-profile vehicles can potentially penetrate under the cables. If the top cable is too low, large vehicles can potentially override the barrier. If the cables are too far apart, vehicles could penetrate between the cables. The 4-cable systems provide for a wider coverage of vehicles (such as TL4 vehicles) than do 3-cable systems, but they are marginally more expensive because of the additional cable. The cable heights for existing barriers work well for impacts on level terrain. However, these heights may not work well when cable barriers are placed on slopes and optimum lateral placement becomes critical to ensure adequate performance.

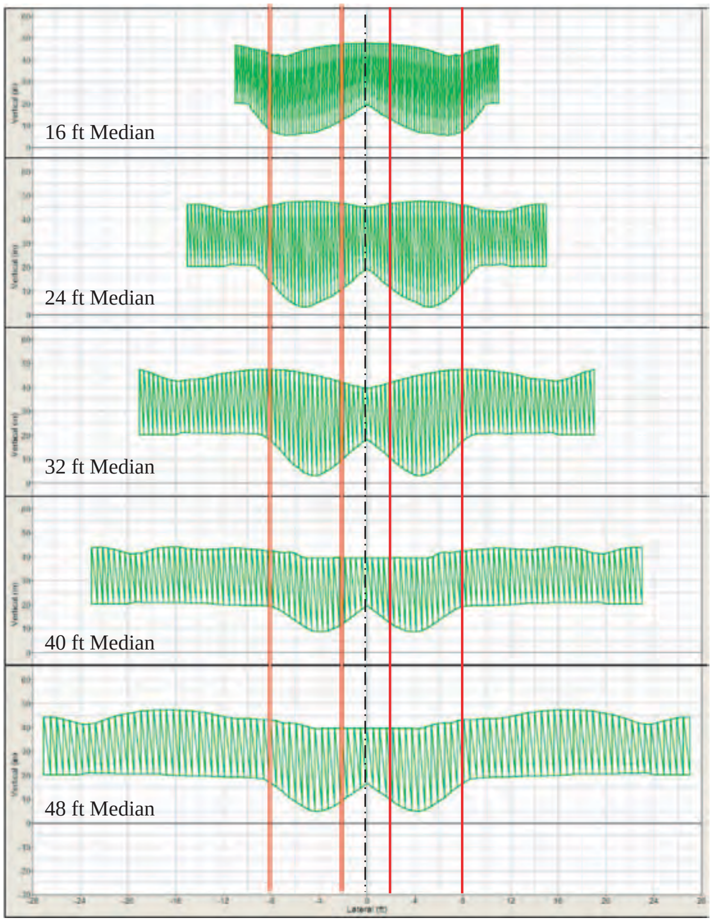


Figure 2.4. Vehicle trajectories from computer simulations of a pickup truck traversing a V-shaped 6:1 sloped median at different impact speeds and angles [19].

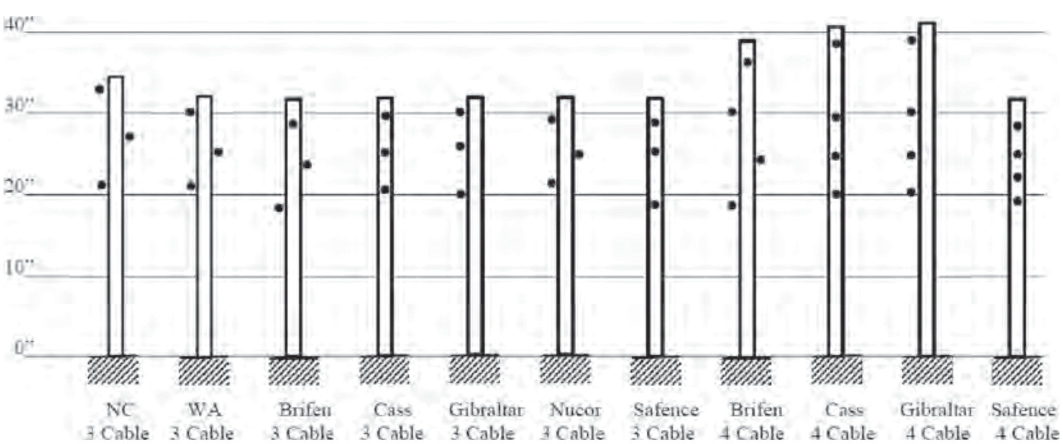


Figure 2.5. Sample cable barrier design variations [19].

2.6 Deflection, Post Spacing, and Anchor Spacing

The dynamic deflection of a cable barrier during impact is an important characteristic for many reasons. Compared to semi-rigid W-beam barriers and rigid concrete barriers, cable barriers have much greater deflections, which is the reason that cable barriers typically are more forgiving to the impacting vehicle's occupants.

However, for the barrier to be safe, adequate space behind the barrier that is clear of hazards must be provided. If deflections are too large, the impacting vehicle could crash into rigid objects behind the barrier or worse yet, collide with a vehicle in the opposing lane of traffic on a divided highway.

The dynamic deflection in a particular crash depends on many factors including impact conditions (vehicle speed, impact angle, and mass), barrier design (post spacing, post cross-section, post foundation/embedment, anchor spacing, cable-post interface/connection, number of cables restraining the vehicle, cable tension, cable modulus of elasticity), and environmental conditions (coefficient of friction of ground, soil strength, terrain slope). Because of these many factors, it is not possible to predict exact deflections that will occur in the field.

Cable barriers were crash-tested according to guidelines contained in *NCHRP Report 350* [20]. Systems developed after 15 October 2009 must be tested according to the procedures described in the *Manual for Assessing Safety Hardware (MASH)* [21]. One of the reported outcomes of crash tests is the maximum dynamic deflection that occurred during the test. Since the NCHRP Report 350 crash tests are conducted under standardized conditions, the reported dynamic deflection may provide a basis for comparing different barrier system designs if similar installation length, post spacing, and initial tension are used. The dynamic deflection, which occurs in the field under conditions that differ from the standard test conditions, will be different from the deflection reported during the crash test.

An FHWA memorandum dated 20 July 2007, and sent to FHWA division administrators, provided detailed information on a number of cable barrier considerations [22], as follows:

- In general, deflection distance is known to increase with longer spacing between posts.
- What is not known, but strongly suspected, is that longer post spacing may also affect the propensity for vehicles to penetrate the cable barrier, i.e., by underride or by traveling between cables.
- The FHWA recommends that the highway agencies specify the post spacing when cable barriers are bid. The conventional range for cable post spacing is 2 to 4.6 m (6.5 to 15 ft).
- Prestretched cables have advantages including reduced dynamic deflection by reducing the "play" between the individual wire strands in the bundle that forms the cable prior to installation.
- The "design deflection" noted in each FHWA acceptance letter is the *minimum* deflection distance that should be provided to fixed object hazards and is based on NCHRP Report 350 Test 3-11 using the 2000P (2,000 kg, 4,400 lb) pickup truck.
- The deflection distance recorded in FHWA letters is also related to the length of the test installation. For example, if a 91 m (300 ft) long barrier is tested and the "design deflection" recorded, the actual deflection under similar conditions will be greater if the barrier length between tie-downs exceeds 91 m (300 ft). Future crash test criteria will specify a minimum installation length for test sections on the order of 183 m (600 ft) to better determine the deflection that can normally be expected.

The National Crash Analysis Center (NCAC) at George Washington University performed a number of simulations on two different types of cable barrier systems for two different initial cable tensions and for three different anchor spacings [23]. Finite element models of an interwoven (weaved) 4-cable barrier and a non-woven (parallel) 4-cable barrier were developed and validated. Post spacings were 3.2 m (10.5 ft) for the weaved system and 3.0 m (10 ft) for the parallel system. Two cable tensions, 15 kN (3.2 kips) and 24 kN (5.2 kips), were used for the initial tension in the system before impact. These tensions approximately represent typical "hot weather" (100°F) and "average weather" (50°F) conditions respectively for high-tension cable barriers. Anchor spacings of 100 m to 1,000 m (3,300 ft) were used in the simulations. The 100 m (330 ft) length is the typical spacing used for NCHRP Report 350 crash tests. The results of the simulations are shown in Figure 2.6.

As expected, the deflections increase for lower cable tensions. The very small change (<5 percent) in deflection for the 38 percent decrease in cable tension is explained by the very large change in cable tension that occurs during an impact. Increases in cable tensions at the anchors during impact are 4 to 5 times as large as the before-impact tension. This finding indicates that for high-tension cable barriers, dynamic deflections from crashes occurring during hot weather when cable tensions are lower should not be much greater than what would occur during average weather.

Anchor spacing was found to have a significant impact on deflection. For both systems, parallel and weaved, the increase in deflection resulting from an increase in anchor spacing from 100 m (330 ft) to 300 m (990 ft) was about 25 percent. However, for anchor spacings greater than 300 m (990 ft), the two systems behave differently. The simulations indicate that the weaved system reaches a maximum deflection at an anchor spacing of approximately 300 m (990 ft), and for anchor spacings greater than 300 m (990 ft) the deflection remains constant. This phenomenon is explained by the very high frictional force exerted on the posts by the interwoven cables, which causes each post to act somewhat like a mini-anchor. With non-woven parallel cable systems, the frictional force exerted on the posts is low, and deflection continues to increase with larger anchor

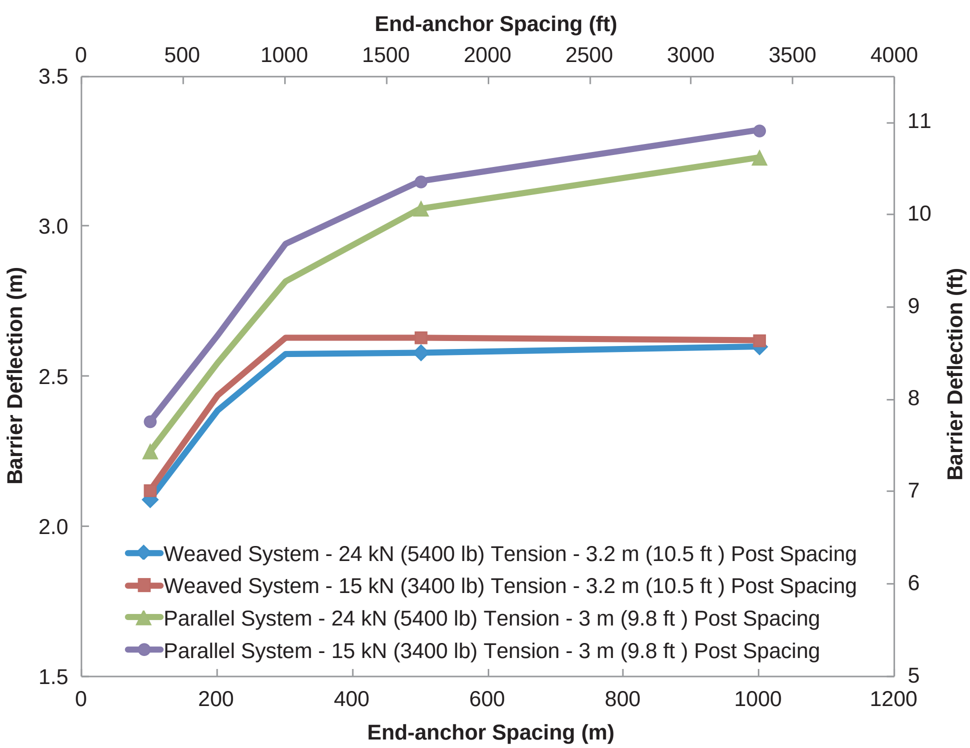


Figure 2.6. Effects of pre-impact cable tension and anchor spacing on deflection [23].

spacings. Simulations were not conducted on anchor spacings longer than 1,000 m (3,300 ft) because of the very long computation time required. Also, simulations were not conducted on other post spacings to determine the impact of post spacing on deflection. These findings are very important, since some highway agencies expect that the deflections reported with crash tests will be what will occur in the field.

2.7 Horizontal Curves

Horizontal curves affect cable barrier performance and must be considered when deciding where to place the cable barriers. Tension in the cables is what allows cable barriers to redirect vehicles. Impacts on the concave side of a curved cable barrier are not a problem; however, impacts on the convex side of a curved cable barrier will result in significantly higher deflections because of the slackening of the cables that occurs. The increase in deflection is a function of the sharpness of the curve and the anchor separation.

Alberson et al. determined deflection magnification factors by using Barrier7 software to conduct a parametric analysis of concave impacts [1, page 46]. This study examined low-tension cable barriers with a 5 m (16 ft) post spacing using as the base a 90 m (295 ft) anchor spacing and a straight section. The analysis gives magnification factors of 1.39 for a 4° curve with 90 m (295 ft) anchor spacing, 1.19 for a 0° curve (straight section) with 450 m (1,500 ft) anchor spacing, and 2.54 for a 4° curve with 450 m (1,500 ft) anchor spacing. These values are not applicable to high-tension cable barriers.

Since roadside encroachments are more common on the outside of a curve, TTI recommends that median cable barriers on horizontal curves be placed on the far side of the centerline ditch away from the outside of the highway curve. Placing the barrier farther away from the more likely encroachment provides more space for the driver to avoid the barrier, and any errant vehicles that hit the barrier will hit it on the concave side. However, this positioning puts the barrier closer to the opposing lanes where an encroaching vehicle will hit the barrier on the more vulnerable convex side [1].

2.8 Maintenance Issues

Cable barrier maintenance can be divided into two areas: repairs after crashes and on-going maintenance. Since cable barriers are used primarily in medians of heavily traveled highways, they tend to get hit quite often. For example, the first high-tension cable barrier installed in the United States on the Lake Hefner Parkway in Oklahoma has been hit over 500 times in 7 years of operation, which is an average of approximately 10 hits per mile per year over the 7-mile-long installation [24]. Therefore, cost of repair can be a major component of the life-cycle cost of cable barriers.

Repairs after Crashes

All current cable barriers have "weak" posts that are sacrificed in a crash and must subsequently be replaced. These posts are typically driven in soil, placed in sockets embedded in concrete foundations, or placed in driven sockets. Damaged driven posts may require special equipment for replacement. Socketed posts, on the other hand, can usually be replaced without specialized equipment, which reduces the repair cost. Post extraction problems can occur during subfreezing weather because the posts are often frozen in their sockets. Extraction problems also can occur when posts are sheared off at ground level rather than being bent over.

Figure 2.7. Cable barrier systems after crash [25].

Low-tension cable barrier systems lose their effectiveness after a crash because of the lack of tension in the cables, which causes the cables to droop, or even lie, on the ground. On the other hand, high-tension systems maintain their effectiveness after crashes as long as the anchors remain in place and a limited number of posts is destroyed. Figure 2.7a shows a low-tension 3-cable barrier after five posts were destroyed in a crash. Figure 2.7b shows a high-tension 3-cable barrier after four posts were destroyed in a crash.

The number of posts damaged in a crash varies depending on the crash conditions. For high-tension systems most states report an average around seven posts that have to be replaced after a crash. Table 2.11 presents data on post replacements from seven states.

Highway agencies report that repair times for high-tension systems typically range from 30 minutes to 2 hours except for crashes involving long sections of barrier. Arkansas recorded the repair time and cost for each crash that occurred during its first year of operation of the Brifen high-tension system. An average crash involved the replacement of 7.6 posts in 73 minutes at a cost of $302 [26]. Texas reported an average crash involved the replacement of 7.8 posts in 75 minutes [16]. Costs of repair reported by other states vary widely, partly depending on who does the repairs: DOT personnel or private contractors.

Table 2.11. Average number of posts destroyed per crash—high-tension barriers.

State	No. of Crashes	Ave No. Posts Damaged	Ref
Arkansas	44	7.6	[26]
Arizona	104	8	[10]
Colorado	19	4	[11]
Indiana		6	[12]
Iowa		4.2	[13]
Oklahoma – Hefner PW	508	6.6	[27]
Oklahoma – I-35	244	6.2	
Texas – Brifen	65	6.6	[16]
Texas – Trinity CASS	76	8.6	
Texas – Nucor	6	9.5	

On-Going Maintenance

Most of the reported non-crash-related maintenance issues have involved soil conditions, post foundations, and/or anchors. Some barriers located along the median centerline have experienced problems with weak, saturated soils. The problems include anchor movement and post foundation failures. However, these same problems have been reported in higher areas where soils are not saturated. In many of these cases, the problem was due to an undersized anchor that was not able to resist the ambient tension in the cables. Figure 2.8 shows examples of anchor failures in Ohio and Texas. Figure 2.9 shows what happens when an anchor is destroyed in a crash. Anchors are critical to the performance of high-tension cable barriers, thus extra care needs to be taken to ensure that they are designed properly and located in areas least likely to be hit. Because of the large number of anchor failures, states are beginning to require greater monitoring of soil conditions and more detailed designs of anchors.

Failure of concrete post foundations also has been a problem as shown in Figure 2.10. Lack of proper reinforcing steel and undersized designs for prevailing soil conditions appear to be the main causes for these failures. Frost heaving also could be associated with concrete footing failure in the northern states.

All of the problems experienced with anchors and post foundations can be fixed by better engineering design, more carefully written specifications, and better oversight of construction.

Another issue that was observed in the field is failure of connectors used at the barrier end-anchoring points. A study conducted by TTI investigated the strength of different types of connectors (termination fittings) used in cable barrier systems [65]. The objective of the study was to develop a more reliable connection that would reduce the likelihood of cable release during impacts. Different connector types were tested under static and dynamic loading conditions. The connectors included Filed Swage, Epoxy Socket, Precision Sure Lock (prototype 2), and Nucor Steel Marion terminations. In all tests, the cable did not pull out from the connector but rather ruptured. The maximum load varied from 140.0 to 177.8 kN (31.5 to 40.0 kips) under static loading and varied from 149.3 to 208.0 kN (33.6 to 46.8 kips) for the dynamic cases. The

Figure 2.8. Examples of anchor failures in Ohio [28] and Texas [16].

Figure 2.9. High-tension cable barrier after its anchor failure due to crash [28].

Figure 2.10. Examples of post foundation failures in Ohio [28].

researchers recommended the use of Field Swage as a retrofit for low-tension systems because it is easier to install than the Epoxy Socket and has higher maximum strength than the other terminations. The importance of proper installation was also emphasized in the study to ensure that full strength is reached and premature cable pull-out is avoided. In addition to static and dynamic testing, full-scale crash tests were conducted using the Epoxy Socket and Field Swage terminations. The tests showed that both terminations meet the NCHRP Report 350 TL3 recommendation with the pickup truck test vehicle. It was noted, however, that due to its larger size in comparison to the Field Swage, the Epoxy Socket may affect the barrier performance when impacted with the small car test vehicle, therefore additional testing with this vehicle was recommended.

2.9 Review of Existing State DOT Guidelines

As part of this project, information from highway agencies having their own cable barrier guidelines was solicited. Eight state DOTs responded (Arizona, Florida, Georgia, Kentucky, Louisiana, Minnesota, Mississippi, and Oklahoma). The majority of these states developed Special Provisions for use on individual projects using cable barriers, but Florida and Minnesota developed guidelines apparently intended to be incorporated as Standard Specifications. The following paragraphs summarize the content common to most of the existing guidelines and highlight the unique aspects contained in some of them.

Although most of these states mandated the use of a 4-cable design tested and accepted as NCHRP Report 350 or MASH Test Level 4 (TL4) barriers, some accepted a 3-cable design at either TL3 or TL4. All states required that the line posts be set in sockets in concrete footings for ease of repair. Most specified a maximum allowed post spacing that ranged from 3 m (10 ft) to 5 m (16 ft). Again, most states specified post delineation (retro-reflective sheeting), ranging from 6 m (20 ft) along curves to 30 m (100 ft). An interval of about 15 m (50 ft) was most often specified.

A site-specific soil analysis was required in the majority of states to ensure adequate end anchorage and post foundation designs. Florida DOT in particular included very detailed requirements in its Standard Specification for Tension Cable Barrier System. Minnesota's Interim Design Guidelines for Tension Cable Guardrails was the only document received that included specific cable barrier design and layout information.

Virtually all the state guidelines required that the cable barrier installers be trained or certified for this type of barrier and most required that training be given to state DOT personnel, particularly to maintenance forces charged with repairing or replacing crash-damaged hardware.

A study undertaken by TTI attempted to formulate a comprehensive set of guidelines for the Texas DOT to provide for sound decision making for cable median barrier projects [29]. The recommendations are summarized in Table 2.12. They are categorized as guidelines for selection, design, placement, and general considerations. Commentary in the report provides the sources and the rationale for these guidelines. Much of the guidance is derived from current practices for other barriers, but the results of some of the analytic studies were incorporated.

A study for the Kansas DOT by the Midwest Roadside Safety Facility (MwRSF) entitled "Cable Median Barrier Guidelines," analyzed crash data to provide guidance for the determination of where cable median barriers would be warranted [30]. This effort considered crash histories and the associated influencing factors, such as weather, terrain, and traffic, in the formulation of guidance. The benefit-cost ratios were computed for typical situations where cable barriers were considered an option. Due to local conditions, it was noted that the warranting conditions for Kansas (as other Midwest states) were different from those in the Roadside Design Guide.

Table 2.12. Guidelines for the selection, design, placement, and use of cable median barriers recommended for Texas [29].

Area	#	Guidelines
Selection	**1**	Utilize the recommended guidelines for installing median barriers on high-speed roadways in Texas.
	2	Cable barrier is for use only in roadway medians in Texas.
	3	Cable barrier is for use only on medians greater than 25 feet in Texas. Median widths of 25 feet or less require the use of a more rigid barrier, such as a concrete median barrier.
	4	A 6:1 approach slope to the cable barrier system from both approach directions is required.
	5	Roadway facilities with truck percentages of 10% or more should receive greater consideration for the use of TL4 cable barrier systems instead of TL3.
	6	Cable barrier systems offer significant cost savings over other median barrier systems such as concrete, which allows for installation of a greater number of miles for the same funding level.
Design	**7**	Four-cable systems should use an end-anchor terminal that provides for a separate anchor connection for cable or that has been crash-tested at the trailing end.
	8	Post spacing for cable barrier systems should be specified when they are put out for bid.
	9	A minimum clear distance of 12 feet should be maintained from the edge of the cable barrier system.
	10	The posts for all cable barrier systems should be placed in concrete drill shafts with sockets.
	11	Use only prestretched cable.
	12	Cable barrier runs should be a minimum of 1,000 feet and a maximum of 10,000 feet in length.
	13	Parallel runs of cable barrier may be appropriate for situations such as differential profile grades, narrow medians, or when objects such as high-mast light poles are located in the middle of the roadway median.
	14	A minimum clear distance of 12 feet should be maintained between the cable barrier systems, and any obstruction should be maintained.
	15	Cable barrier systems should be placed such that there is a minimum of 2.5 feet (6 feet preferred) from the back of the metal beam guard fence posts to the barrier.
	16	Cable barrier systems should be a minimum of 6 feet behind guardrail extruder terminals to allow for extrusion and gating of the end treatment.
	17	Continue to monitor overall cable barrier performance statewide, and evaluate impacts from motorcycles and vehicles exceeding design loads.
Placement	**18**	As a general rule, a cable barrier system should be placed as far away from the travel lane as possible while maintaining proper orientations and performance of the systems.
	19	Cable barrier systems should be placed on relatively flat, unobstructed terrain if possible (10:1 or flatter) and may be placed on 6:1 maximum slopes if necessary.
	20	The preferred placement of the cable barrier within a v-ditch should not be in the area of 1 to 8 feet from the bottom of the ditch.
	21	The acceptable placement of cable barrier allows a maximum 4:1 slope if the cable barrier is placed on the 6:1 slope at a distance of 8 to 1 feet from the ditch bottom.
	22	Closer post spacing through horizontal curves is recommended based upon the radius of curvature.
	23	Placement of the cable barrier on the convex side (i.e., inside of the curve relative to near traffic) is recommended to allow maximum median space for vehicle recovery for leaving opposing travel lanes.
	24	Care should be exercised when placing cable barriers in superelevated sections.
	25	Placement of cable barrier systems on sag vertical alignments with a radius of less than a K-value of 11 should be avoided.
	26	Cross drainage structures with less than 36 inches of cover pose a challenge for placing cable barrier posts. Structures of less than 16 feet can be spanned in order to avoid post placement into the drainage structure.
	27	Designer should follow the Plans, Specifications and Estimates (PS&E) Preparation Manual guidance on identifying utilities with the project and the quality level of utility locates required.
General system considerations	**28**	Emergency response agencies should have educational materials to provide them with clear and concise guidance on when and how to safely cut cable when a vehicle is entangled after an impact.
	29	If the cable barrier is switched from one median side to the other and terminals are not protected, overlapping runs of cable barrier are recommended to provide adequate protection from possible crossovers.
	30	Footings for terminal anchors should be designed to keep static loads well below the ultimate strength.
	31	For future maintenance considerations, the use of mow strips is encouraged to reduce future hand mowing and herbicide operations.
	32	Distance between the edge of the travel lane and the cable barrier should consider mower widths.
	33	Anchor foundations and sockets should be designed for prevailing soil conditions at installation locations.
	34	Cable barrier system design should account for the potential of frost heave.
	35	Delineation of cable barrier should be at 100 foot spacing unless otherwise approved by the engineer.
	36	The maximum distance between breaks in the cable barrier system that allow emergency vehicle access should be 3 miles.

2.10 International Practices

The literature review included an attempt to determine the evolution of the technology and application of cable barriers in other parts of the world. These are summarized relative to use, evaluations, maintenance, and other concerns in the paragraphs below.

Usage

References were found to the use of safety fences, wire rope fences, and flexible barriers in Europe, Canada, Japan, Israel, Australia, and New Zealand. The use of modern cable barrier technology in some cases predates its use in the United States. A 1974 report entitled "Tensioned Cable Safety Barrier, M62," by F. R. Oliver examined a trial installation of tension cable in the "central reserve" or median on the M62 motorway in England [31]. It was noted that the cable barriers' smaller profiles nicely addressed the drifting snow problem that had been observed for median barrier applications. During the 2-year evaluation, 12 incidents occurred and were analyzed. It was noted that damage to vehicles was found to be relatively minor and, in most cases, the vehicles were driven away after the impact. The barrier also restrained a large truck. The author concluded that the experience of the trial suggests that the fears of injury to low sports cars and overriding by heavy vehicles are unfounded.

The design of a TL4 cable median barrier for the Deerfoot Trail in Calgary was described in a 2007 paper [32]. This paper describes the preliminary engineering and design of an NCHRP Report 350 Test Level 4 high-tension cable barrier installed in the depressed median of an 11 km (6.8 mi) stretch of highway that had median side slopes of 6H:1V or flatter. At the time, three manufacturers met the NCHRP Report 350 requirements for four prestretched, post-tensioned cable barriers—namely, Brifen Canada, Gibraltar, and Trinity Highway Safety Products.

The major design issues that were dealt with during the design and associated guidelines included

- Lateral placement of median cable barrier
  - TL4 barriers can be installed in medians that have side slopes of 6H:1V or flatter.
  - On 6H:1V sloped medians, a cable barrier should be placed within 0.3 m (1 ft) of the ditch bottom or beyond 2.4 m (8 ft).
  - The ground under the barrier must be stable and free from obstructions or depressions.
- Placement of the barrier
  - On a horizontal curve, the barriers were installed on the near side of the roadway, which is on the concave side of the barrier.
- Connection to or separation from the existing barriers
  - At locations where existing barriers were in place, the median cable barrier was installed between the barrier and the travel lanes.
- Existing hazards
- Emergency crossovers
  - Crossovers were removed and the side slopes of the median graded to allow for continuous installation of the median cable barrier.
- End treatments/terminals
- Potential for vehicles to be trapped between barrier systems

There was limited guidance for some of the design issues.

Evaluation

Various summaries of safety measures generated in the 1990s noted that wire rope systems had been promoted among the options for addressing safety problems. There were some small-scale evaluations of safety performance discovered, but nothing of a large scale. For example, Marsh and Pilgrim analyzed the performance of wire rope for the Centennial Highway in New Zealand [33]. A significant drop in the societal costs of crashes was noted for the 2+1 type application. The authors identified challenges for future installations of cable barriers in narrow medians. Levett, Job, and Tang compared the relative effectiveness of wide painted centerlines and wire rope systems on crossover occurrences and severity as part of a safe systems approach [34].

Candappa, D'Elia, and Newstead undertook a before and after study of flexible barriers along Victorian highways [35]. The study noted effectiveness of such barriers, particularly for reducing loss of control crashes. A 2004 study by McTiernan, Thoresen, and McDonald analyzed crash results and maintenance costs and found positive benefit-cost ratios when the Pacific Coast Highway installation was compared to other similar highways [36]. They recommended further application of modern wire rope barrier.

Manuals and Guidance

A document on cable barrier maintenance was generated in Western Australia. It identified conditions that need inspection during cable barrier system maintenance [37]. These included

- Stretching of the rope
- Movement of the anchors
- Failure of the fittings
- Release of the ropes from the anchors
- Damaged posts or broken fixings
- Lack of rope tension

Wire rope and attachments are inspected for broken wire, reduction of wire diameter by abrasion, crushing or flattening of rope, kinking or notching, weakening by corrosion, damage to galvanizing, and any damage to the attachments and fittings. Actions to be taken when a defect is found included

- Lubricate or replace a screw thread that is rusty or tight and
- A competent person to decide whether to discard, or if possible, repair a damaged screw thread, distorted body, distorted fittings, nicks, gouges, cracks, or corrosion on any component

Brifen Europe produced "Guidelines for the Installation, Inspection, Maintenance, and Repair of New and In-Service EN1317 Brifen Wire Rope Vehicle Restraint Systems (Europe)" [38]. This document sets out procedures for the installation and inspection of new and in-service Brifen wire rope safety fence systems. It presents various design requirements such as setback at verge, setback at central reserve, working width, number of ropes and tension factors for different containment levels, ground profile, height and length of fence, requirements on post foundation and anchors, and maximum length of ropes. It also lists various limitations on the use of wire rope fence. The document gives the guidelines for installing a Brifen wire rope fence including post selection, concrete foundations, filter drain foundations, anchors (end and intermediate), assembly, tensioning, and measuring tension in ropes. The document also explains the inspection program and the procedure for adding existing Brifen wire rope system to it. Various steps involved in maintenance of a Brifen wire rope system are explained in brief. These include mounting height, setback, working width, rope tension after impacts, component replacement, and various repairs after an impact.

Woof noted in 2006 that although new barriers, like wire rope systems, were being developed, there are inadequacies in the testing requirements [39]. Nilsson and Prior described the decision process used by New South Wales to implement wire rope barriers in 2004 [40]. Roper et al.

Table 2.13. Japan's various configurations of cable barriers.

Type	Section	Road Class	Post Diameter	Cable Diameter (# of Cables)	Tension per Cable
C	Roadside	Local road	114.3 mm	18 mm (3)	9.8 kN
B	Roadside	Highway	114.3 mm	18 mm (4)	9.8 kN
A	Roadside	Freeway	139.8 mm	18 mm (5)	20 kN
B_m	Median	Highway	114.3 mm	18 mm (3)	9.8 kN

noted that there were changes made in the 1987 AustRoads "Safety Barriers" guide that include flexible systems incorporating wire ropes [41].

Cable barriers in Japan are mainly used in snowy locations and scenic locations [42]. The main reasons for using cable barriers include easiness to remove snow from the roads and highways, unrestricted visibility, and that it is more economical when compared to other types of guardrails. Because of usual limited space for cable deflection, strong type posts are used to reduce barrier deflection. The number of cables and tension per cable varies depending on where the system is installed: roadside or median, highway, freeway, or local road. Cable size is common and is 18 mm (0.71 in.) in diameter. Tension per cable is 20 kN (4.3 kips) if installed on roadside in a freeway, otherwise it is 9.8 kN (2.1 kips). The number of cables varies from three to five depending on the location of installation. Table 2.13 shows the various configurations of cable barriers.

Applications

In Sweden, the use of cable barriers for 2+1 applications on two-lane roads is reported as a means to improve safety. Carlsson and Larsson in 2003 ("Sweden Vision Zero Experience") reported on the early experience of this application. Data from test sections showed that in eight incidents there were no fatalities and only six severe injuries [43]. This represented a 60 percent decrease in severe injuries compared to similar roads without the 2+1 design. They also noted that cable median barriers, although frequently hit, were normally occurring without personal injuries.

A Swedish National Road Administration (SNRA) report indicated that the 2+1 roads were a "success story" [44]. In the 1990s almost 100 people were killed and more than 400 were severely injured on 13 m (43 ft) wide two-lane roads in Sweden. Seventy percent of these fatalities were due to vehicle run-offs and head-on accidents. SNRA started to explore cost-effective measures to improve traffic safety. The main alternative was the 2+1 concept, i.e., with central overtaking lane changing permitted every 1.25 km (0.78 mi) with a separating cable barrier preferably within the existing width of 13 m (43 ft). The results from this alternative design were compared with two other designs: 2+2 concept (i.e., to widen existing 13 m [43 ft] roads to two lanes in each direction separated with a cable barrier with a paved width of 16 m [52 ft]) and four-lane concept (i.e., with full access control and 18 m [59 ft] crown width including a 2.5 m [8.2 ft] median). The main results and findings until mid 2004 are as follows:

- Safety effects for 2+1 concept are better than expected. Fatality rate reduced to 0.0017 (fatalities per million axle pair km), an 80 percent reduction. Reduction in severe injuries was about 55 percent. The 2+2 and 4-lane concepts provided not much better results than 2+1 concept.
- Median cable crashes were, as expected, very frequent but normally without severe consequences. This rate is 0.51 crashes per million axle pair km.
- Maintenance costs have increased by 70 percent, 65 percent of this being for barrier repairs.
- Two fatalities and seven severe injuries have been reported involving motorcycles and cable barriers. No indication that the barrier created the accident or worsened the consequence.
- Drivers and public opinion are very positive.

Other Concerns

Schermans and Van der Hoek indicated that the 2+1 concept was being considered for the Netherlands. They noted that there are more motorcyclists in the Netherlands than in Sweden, which may cause a problem [45]. The opposition was already labeling cable barrier systems as "egg cutters." Concerns raised by motorcyclists over the use of wire rope safety barriers (WRSB) included their potential to act as a "cheese cutter" in the event of a collision by a motorcyclist.

Transit New Zealand generated a report to provide general guidance on the use of WRSBs with respect to the needs of motorcyclists [46]. The State Highway Geometric Design Manual, which is based on NCHRP Report 350 and *AS/NZS 3845:1999 Road Safety Barrier Systems*, provides guidance on the placement and layout of road safety barriers for both roadside and median barrier systems. The guide specifically states that unprotected road users, which includes motorcyclists, pedal cyclists, and pedestrians, should be taken into consideration. Crash data involving motorcyclists in New Zealand between 2001 and 2005 shows that only a third of all motorcycle crashes occurred on the state highway network, whereas 70 percent of the fatal crashes that occurred were on these roads. Of the total 3,762 injury crashes involving motorcycles, 54 (1.4 percent) involved collision with a road safety barrier and 2 involved WRSB, but none of the motorcycle fatalities involved WRSB. The two crashes with WRSB resulted in the police reporting one serious injury and one minor injury.

Several tests have been carried out on various types of barriers to assess the severity of injuries to the motorcyclists. Regardless of the various tests carried out, as noted in the 2006 ACEM Guidelines for PTW (Powered Two Wheelers)—Safer Road Design in Europe, "limited research done so far does not warrant the conclusion that cable barriers are more hazardous than other types of barrier" [47].

The report concludes that there is no reliable evidence to indicate that the wire rope barriers present greater or lesser risk than other barrier types, or indeed, no barrier at all [46]. The lack of evidence is due to the limited amount of accurate real world or microsimulation testing, along with the limited number of reported crashes involving motorcyclists and WRSBs. It also concludes that, depending on the use and positioning of WRSBs, they may result in a worse crash than if they had otherwise not been provided. Hence, care is required when specifying the need for road safety barriers, as well as when determining the type and location of such measures.

A coroner's report of an investigation of motorcycle death in Australia after crashing the motorcycle into high-tension cable barrier highlights concerns [48]. The cable barrier system was from Brifen and was installed in accordance with Australian Standards AS/NZS 3845:1999 Road Safety Barrier Systems. The location of the fence was site specific, meaning that it could not be positioned in any other location due to the steep drop on the other side. If the fence had been positioned part way down the embankment, an out-of-control vehicle would more likely travel over the fence. The only way to change the position of the fence would be if major road work was undertaken to change the configuration of the central median strip. From the investigation, it was concluded that the reasons for the death were that the person riding the motorcycle had a blood alcohol level more than three times the legal limit and was going at or about double the 110 km/h (62 mph) posted speed limit. Investigators did not believe that the cable barrier fence was to blame for the motorcycle rider's death.

Szwed presented a summary of the experience with wire rope barriers in Victoria [49]. He concluded based upon 10 years of deployment, a literature review, and a before and after crash analysis, that wire rope barriers are generally the safest type of barriers, and they are very cost-effective.

2.11 Summary

The literature review covered a broad spectrum of information sources and provided a viable snapshot of the current state of the practice. From the literature review, it is possible to conclude the following:

- Cable barriers have a long history of use on highways. Improved designs for cable barrier systems have emerged over the past 10 years.
- There is increasing use of cable median barriers across the country.
- There is a general consensus that cable barrier systems have a high degree of effectiveness and lower crash severity when hit.
- Although the generic low-tension systems are still an option for some, there seems to be a greater interest in high-tension cable systems.
- Five companies are marketing proprietary cable barrier systems. The new cable barrier systems they are marketing vary considerably in their design features.
- The new generation of cable barrier systems has been crash-tested to ascertain that they meet the requirements of NCHRP Report 350 or MASH. In assessing the performance of these barrier tests, it is important to note which criteria were used, because there is a difference in testing requirements between NCHRP Report 350 and MASH.
- Efforts to evaluate the safety performance of cable barrier systems have not been uniform. The data, until recently, were not detailed enough to ascertain whether cross-median events actually resulted in crashes.
- Differences in the data from the states, abilities to effectively isolate cross-median crashes, and limited data about site features resulted in a range of effectiveness estimates.
- There only has been limited effort to analytically or physically evaluate the effectiveness of cable barrier systems to reflect the manner in which they are being used.
- Placement of cable barriers has generally followed the accepted guidance for other barriers. There have been more tendencies to deploy cable barrier on sloped medians, but without analyses or test results to confirm effectiveness. The influences of median configuration, width, and slopes began under some research of the FHWA.
- The heights, number, and arrangement of cables for any barrier system design vary. There is limited data to understand the influences of these cable factors on effectiveness.
- The use of vehicle dynamics analysis (VDA) to assess vehicle-to-barrier interface has been shown to explain the occurrence of override and underride events. VDA tools provide a convenient means to consider the potential for bi-directional impacts of the barrier.
- Issues with cable barrier anchorage failures have led to requirements for site-specific design anchorages. There has been some analysis of the effects of varying lengths of cable barriers. There are practices for setting the tension levels in cable barrier systems.
- The relatively limited experience with cable barrier system deployments and maintenance over time implies that there is little data on initial and maintenance costs to provide clear guidance for selecting systems and ancillary features (e.g., mow strips, socketed posts).
- Guidance is needed for determining where cable median barriers should be deployed, which systems should be selected, the needed design features, and their ultimate maintenance. The literature noted that there is only limited guidance of this nature and even where there is some guidance, like the Roadside Design Guide, it is dated, limited, and not specifically derived to reflect the features and functionality of cable barrier systems.
- Most of the reported efforts are related to median applications, but these results are transferable to roadside applications.
- The international literature noted uses of cable barriers or wire rope safety fences has occurred across the world. In some cases, the use of modern cable barrier technologies predates its use in the United States by more than 10 years.

- The few evaluations of systems deployed in other parts of the world generally have concluded that wire rope systems have been effective in reducing the number and severity of crossover crashes. They have been judged to be "cost effective."
- The success with median applications has inspired the use of cable barriers in other applications. Most notably, in Sweden, Australia, and New Zealand, applications on 2+1 roads with narrow medians have been reported with good results.
- There seems to be limited formal guidance or guidelines developed in other countries, and differences in basic road design practices render these guidelines of limited value to U.S. needs.

CHAPTER 3

Cable Barrier Current Practices

In order to establish an up-to-date picture of current agency efforts to utilize the emerging cable barrier technology, a survey was conducted at the outset of the project. To maximize the potential to capture information, the survey was similar to the one used in an earlier study. In 2007, the Texas Transportation Institute (TTI) completed work on NCHRP Project 20-7(210), "Guidelines for the Selection of Cable Barrier Systems (Generic Design vs. High-Tension Design)," which included a comprehensive survey of all state agencies to gather detailed information on the selection and use of cable barrier systems and on the effectiveness of these barriers in the field [1]. Responses were received from 29 states. This survey provided a snapshot of the extent of cable barrier usage and of the state of the practice relative to the design, selection, installation, and maintenance through 2005. This approach allowed updating the information from the earlier survey, and it offered states that did not respond to the TTI survey an opportunity to provide input on their experiences with cable barrier systems.

The questionnaire was designed to acquire information about the use of cable barriers in the states and the guidelines, if any, that were used in the design and construction process. A copy of the survey questionnaire is included in Appendix A of the contractors' final report. Initially the survey was sent to the states in November 2008, and 16 responses were received. In August 2010, the survey was re-sent to states that had not responded to the initial request, and 24 additional responses were received. The survey of the states was supplemented with requests to high-tension cable barrier manufacturers to get their estimates of barrier-miles installed. The summary of the survey results is presented in the following sections.

3.1 Extent of Cable Barrier System Use

The first question on the survey asked the states to indicate approximately how many miles of cable barrier had been put in place or were currently being installed in their state. Based on the responses from 40 states, 3 states did not have any installed cable barriers, 7 states had less than 10 mi (16 km) of installations, 15 had less than 100 mi (160 km) of cable barriers, and 15 states had several hundreds of miles of cable barriers. Figure 3.1 shows the extent of cable barrier usage by state. The majority of cable barriers, 58 percent, were high-tension systems, and 35 percent were generic low-tension systems. The remaining 7 percent were reported as other systems by the states (this included cases where a decision to install cable barrier has been made but the choice of system has not been finalized). Figure 3.2 shows the percentage of different high-tension, low-tension, and other systems. Figure 3.3 shows the total miles of cable barrier obtained by summing reported numbers from the 37 states using cable barriers.

Figure 3.4 shows the total installed miles of high-tension barriers reported by two of the manufacturers. The mileage reported by the states was less than that reported by the manufacturers.

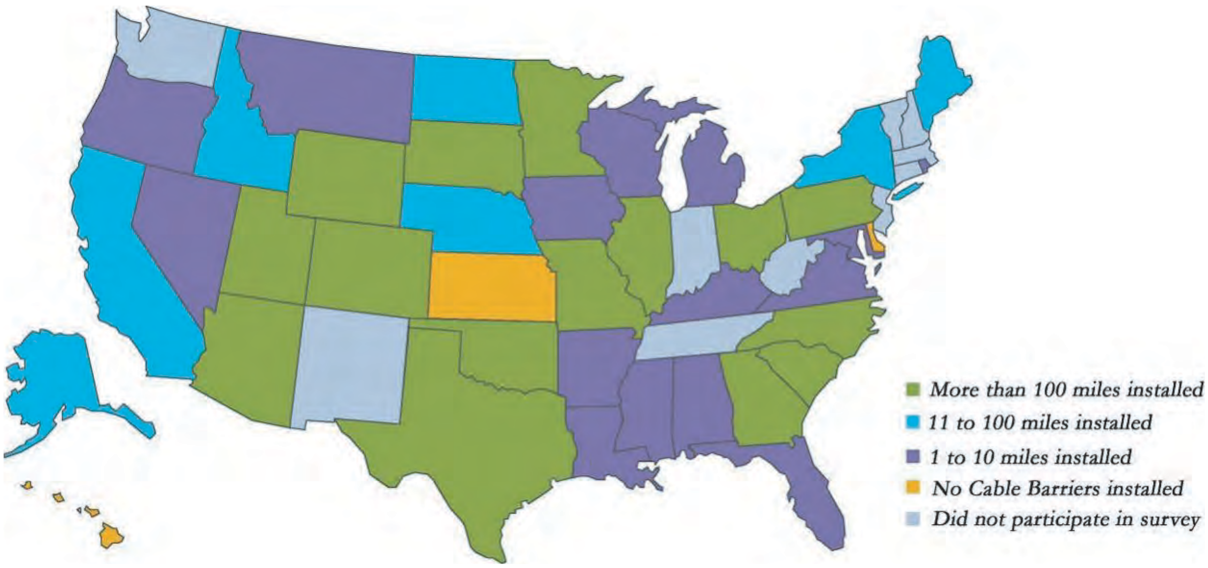


Figure 3.1. Map of cable barrier usage by state (as of November 2010).

The difference could be a result of errors in the approximations made by some states and/or the lack of data from 10 states that did not respond to the survey.

Ninety-seven percent of cable barrier systems were placed in the median while only 3 percent were used on the side of the road. Most of the barriers, 70 percent, were TL3 systems while the remaining 30 percent were TL4 systems. Overall, 79 percent of installed barriers had three cables and the remaining 21 percent had four cables.

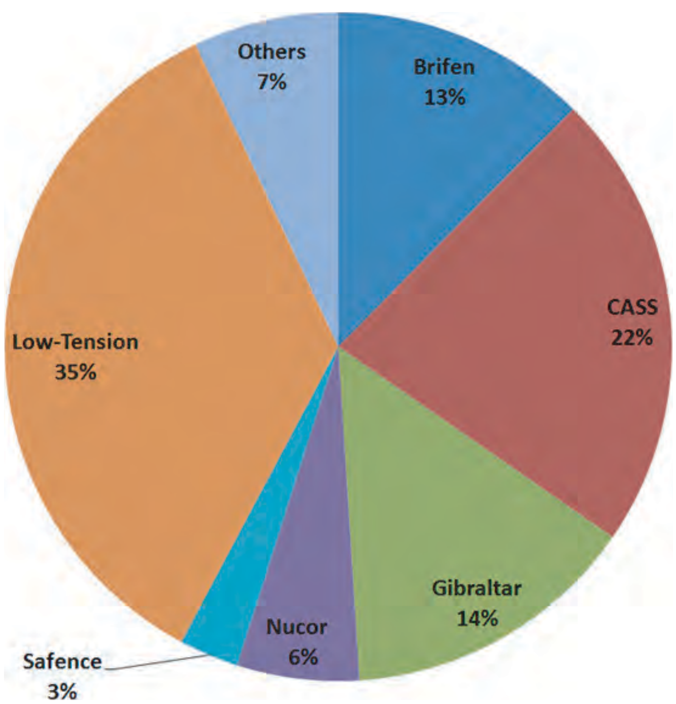


Figure 3.2. Percentage of states using different types of cable barriers.

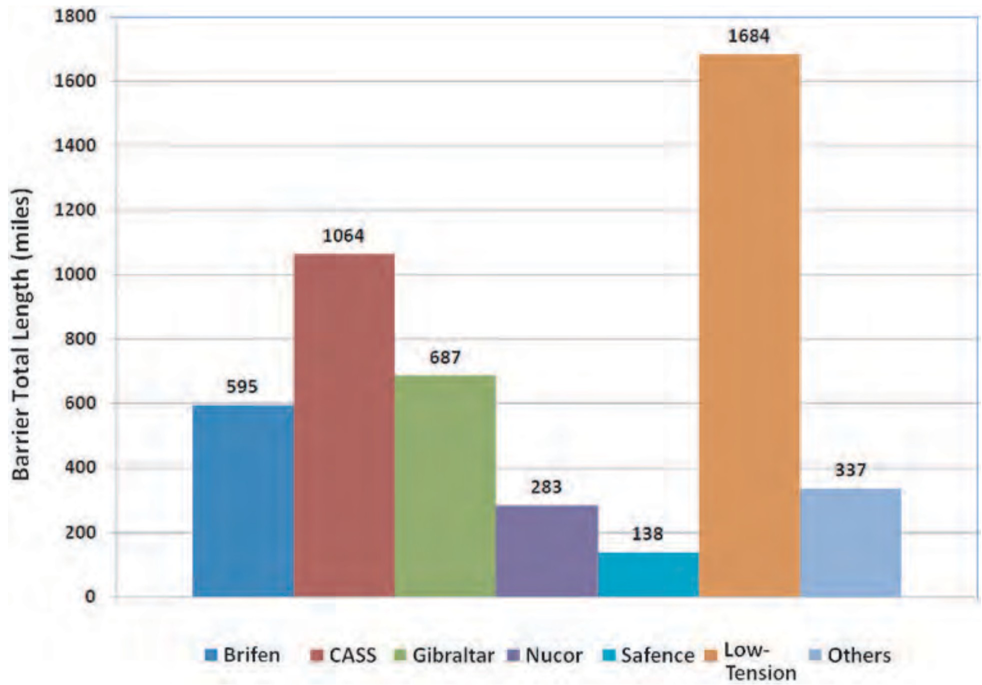


Figure 3.3. Total miles of cable barrier by manufacturer as reported by 37 states.

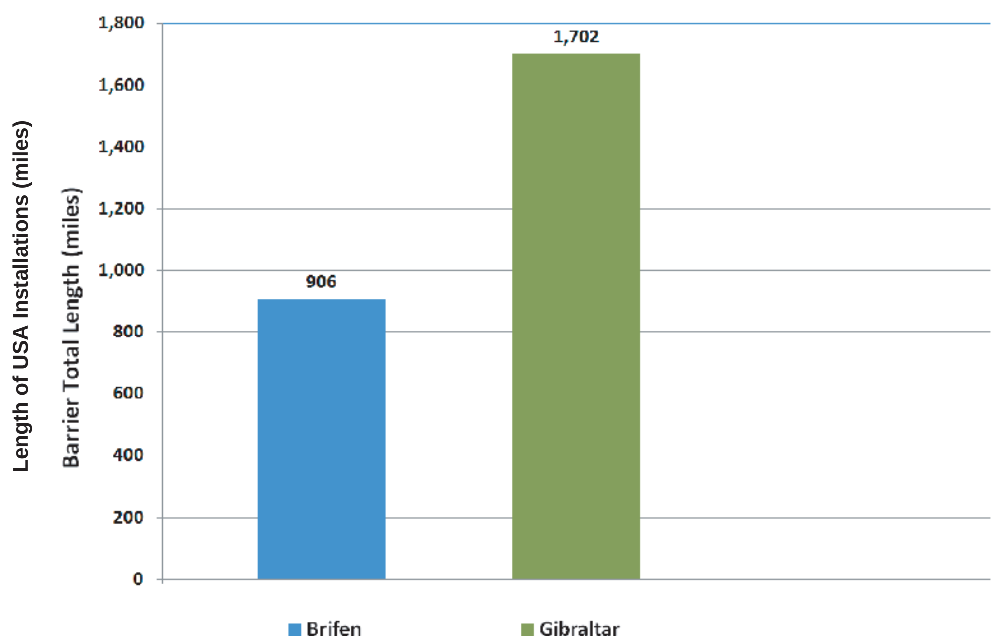


Figure 3.4. Total miles of cable barrier installation reported by manufacturers.

3.2 Median Conditions for Cable Barrier Installation

The survey next posed four questions about the conditions or configurations of the medians where cable barrier systems were installed. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 2: Please estimate the median slopes that exist in your state for which cable median barriers have been, or are planned to be, installed to reduce cross-median crashes.
- Question 3: Please indicate the typical median geometry used in conjunction with the different cross slopes used in your state. If available, cite the number of miles for each case.
- Question 4: Please estimate the median widths (from one break or hinge point to the other) associated with the different cross slopes used in your state.
- Question 5: For the flat-bottom and rounded-bottom median configurations (if used), please specify the typical width of the flat/rounded section.

The survey responses were based on the total mileage reported by the states. The majority of barriers, 55 percent, installed in the median had 6H:1V side slopes and 15 percent had 8H:1V slopes. Steep sloped medians of 4H:1V or 5H:1V represented 20 percent of the medians and 8 percent had flat, 10H:1V slopes. Figure 3.5, based on reported mileage where cable barriers have been installed, shows the distribution of median side slopes.

The different median shapes queried in the survey included the V-shape, flat-bottom, rounded-bottom, non-symmetric, and other. Figure 3.6 shows usage by state for various combinations of median shape and slope for medians where cable barriers are installed. The V-shaped median with a 6H:1V slope is used by 21 states, while the second most common configuration, the flat-bottom-shaped median with a 6H:1V slope is used by 14 states. The V-shaped median with a 4H:1V slope is used by 11 states. Overall V-shape is the most common median shape followed by flat-bottom.

Survey responses showed a wide range of median widths existed among the states. Three states, two of which used cable barriers, reported a minimum median width that is less than 3 m (10 ft), which was significantly lower than the other 23 states that answered Question 4. To avoid unduly distorting the data, these states were excluded from the analysis. The minimum, maximum,

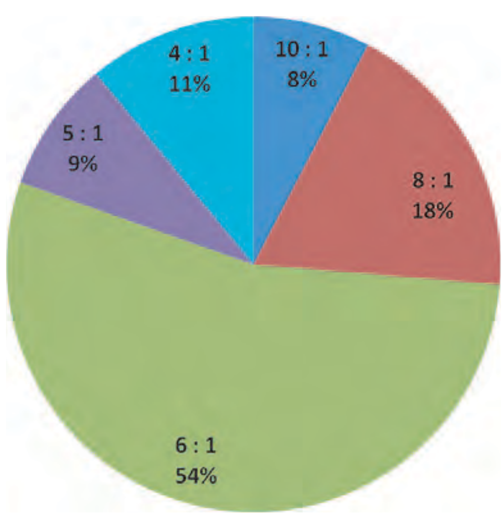


Figure 3.5. Distribution of median side slopes based on total miles reported.

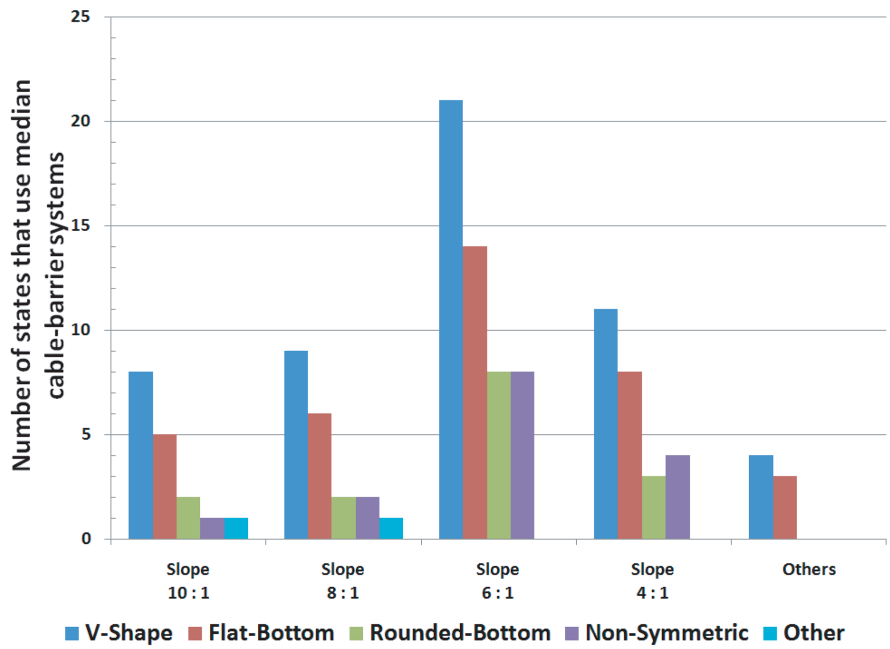


Figure 3.6. Median shape and slope combinations used by states.

and average median widths reported from the 23 states by side slope are shown in Table 3.1. The minimum median widths ranged from 3.5 to 8.5 m (12 to 28 ft), the maximum median widths ranged from 24 to 32 m (80 to 104 ft), and the average ranged from 11.2 to 14 m (37 to 46 ft).

Table 3.2 shows the minimum, average, and maximum width of the flat/round section of flat-bottom and rounded-bottom medians for the 14 states that responded to Question 5.

Table 3.1. Median width with respect to slope grade.

Slope	10H:1V	8H:1V	6H:1V	4H:1V	Other
[1]Minimum Median Width in m (ft)	4.6 (15)	7.3 (24)	6.1 (20)	3.7 (12)	8.5 (28)
[2]Maximum Median Width in m (ft)	30.5 (100)	24.4 (80)	31.2 (104)	24.4 (80)	21.3 (70)
[3]Average Median Width in m (ft)	14.0 (46)	11.2 (37)	14.0 (46)	11.2 (37)	12.8 (42)

[1]Minimum of all minimum widths reported
[2]Maximum of all maximum widths reported
[3]Average of all average widths reported

Table 3.2. Round/Flat median section width with respect to slope grade.

	Slope	[1]Minimum Width Reported in m (ft)	[2]Average Width Reported in m (ft)	[3]Maximum Width Reported in m (ft)
Flat/Round Bottom Width	10:1	1.8 (6)	3.4 (11)	4.6 (15)
	8:1	0.9 (3)	2.1 (7)	3.0 (10)
	6:1	0.6 (2)	6.1 (20)	21.3 (70)
	4:1	0.6 (2)	3.7 (12)	3.0 (10)
	Others	1.2 (4)	9.8 (32)	18.3 (60)

[1]Minimum of all minimum flat/rounded section widths reported
[2]Average of all average flat/rounded section widths reported
[3]Maximum of all maximum flat/rounded section widths reported

3.3 Factors Considered in Selecting Cable Barriers

The survey posed four questions about the factors or criteria considered in determining that cable barriers would address the safety needs for a given situation. The intent was to determine if warrants, state experience with cable barriers, and/or existing standards provided an impetus or direction for specific decisions. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 6: What criteria are used to decide if a barrier is warranted: For median application? For roadside application?
- Question 7: What criteria are generally used to select a cable barrier system over a rigid or semi-flexible system in locations and conditions where any system can be used: For median application? For roadside application?
- Question 8: What criteria, if any, are generally used to select a specific cable barrier system, i.e., Brifen, CASS, Gibraltar, Nucor, Safence, or generic low-tension?
- Question 9: Does your state have specific standards/guidelines for the system design, alignment, construction, and/or maintenance of cable barriers?

For median applications, the states reported the following warranting factors, although not all cited a specific warrant:

- Median width (19 states)
- Crash history data and analysis (19 states)
- Vehicles crossover frequency (11 states)
- Traffic volume (8 states)
- Roadway geometry (slopes and vertical alignment) (6 states)
- AASHTO Roadside Design Guide & Highway Design Manual (5 states)
- Speed (3 states)
- Benefit/cost ratio and analysis (2 states)
- Other (clear zone, maintenance, trucks percentage, etc.)

For the roadside application, 13 states indicated that they do not use cable barriers in this type of installation while 22 noted the following considerations:

- AASHTO Roadside Design Guide (7 states)
- Clear zone and distance to hazard (7 states)
- Crash history data (7 states)
- Fixed objects (5 states)
- Roadway geometry and alignments (3 states)
- Other (speed, traffic volume, maintenance, snow drifting, etc.)

For median applications, the top two selection criteria for cable barriers over other types of longitudinal systems (rigid and semi-rigid) were median width and cost. These and the other criteria mentioned are summarized as follows with the number of responses indicated:

- Median width (23 states)
- Cost (21 states)
- Allowable deflection (8 states)
- Slopes (8 states)
- Roadside features, terrain (7 states)
- Accident crash data (5 states)
- Ease of installation and maintenance (5 states)
- Crossover accidents (4 states)
- High traffic volume (3 states)
- Other (snow drifting, drainage, FHWA, and speed)

Selection criteria for cable barriers over other longitudinal barriers in roadside applications were provided by 33 states as follows:

- Allowable deflection (10 states)
- Distance to hazard (8 states)
- Cost (5 states)
- Slope (5 states)
- Snow drifting (5 states)
- Ease of installation and maintenance (4 states)
- Accident crash data (3 states)
- Other (high traffic volume, roadside features, crossover)

The criteria used to select a specific cable barrier system (i.e., Brifen, CASS, Gibraltar, Nucor, Safence, or the generic low-tension) are shown in Figure 3.7. Fifteen states indicated that the bid is restricted to low-bid that is open to all NCHRP Report 350-approved systems. Ten states used previously specified vendors, while five states used system-specific bid documents. Additionally, 12 states reported other criteria, and these are grouped in four categories that follow:

- Use a low bid for at least 2 approved systems (4 states)
- Use a low bid for a preapproved system (3 states)
- Use experimental or proprietary systems (3 states)
- Use a bid document for a system with specified features (e.g., post spacing, type of post installation, type of anchors, etc.) (3 states)

Based upon the premise that cable barriers would be more often considered as a safety option, the survey attempted to determine how many states already had design and construction standards. There were 21 states that reported having cable barrier design standards and 15 states that did not. These standards typically include soil testing and properties, end-terminal requirements, etc. Twenty-eight states have alignment guidelines that cover lateral placement and adjustment at drainage structures. Thirty states have construction guidelines for post and anchor foundations, tolerances, and other requirements. Only 18 states reported having maintenance guidelines

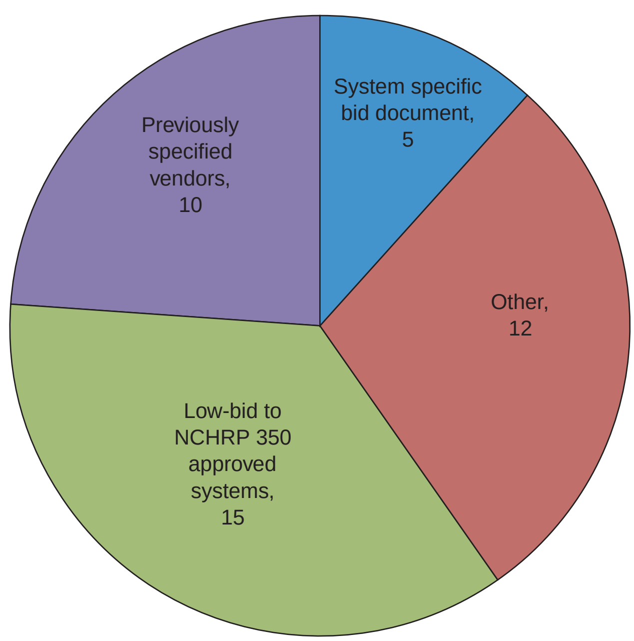


Figure 3.7. Criteria used to select a specific cable barrier system.

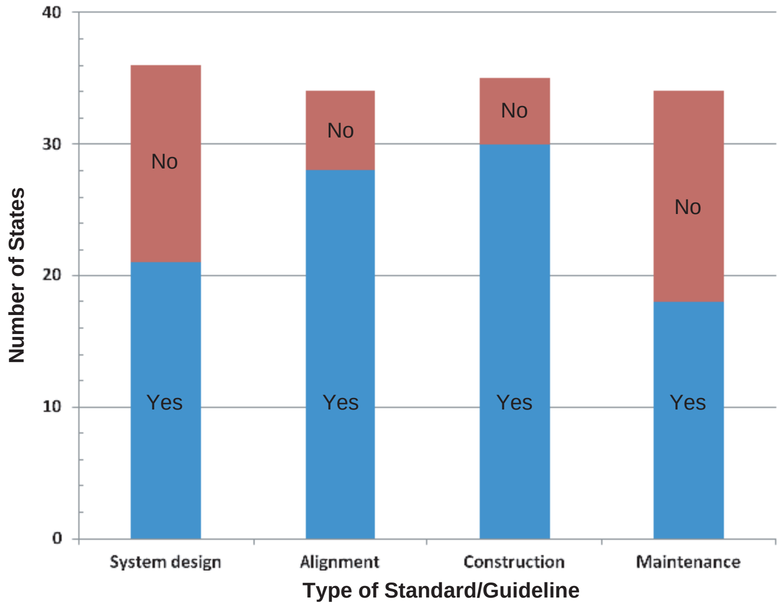


Figure 3.8. Number of states having cable barrier standards.

for tasks such as retensioning, anchor monitoring, and reinstallation and for keeping the cable barrier system in operating condition.

Figure 3.8 shows the number of states having cable barrier standards for system design, alignment, construction, and maintenance.

3.4 Cable Barrier Impacts, Penetrations, and Crashes

The survey posed questions about barrier impacts, penetrations, and crossover crashes for medians where cable barrier systems were installed. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 10: Approximately, every year, how many reported impacts (i.e., crashes) into cable barriers occur on average in your state?
- Question 11: Approximately how many of these reported cable barrier impacts resulted in vehicular penetration? (Penetration is defined as an impact where the vehicle completely passed through the system.)
- Question 12: How many cable barrier penetrations have resulted in crashes into opposite-direction traffic?
- Question 13: Based on the penetrations you experienced, is there a factor or factors that most likely contributed to the penetrations (e.g., barrier type, median feature, impact condition, barrier placement, etc.)?
- Question 14: Are you aware of any crashes into cable barriers by motorcyclists? If so, please summarize the number, circumstances, and severity of such crashes.
- Question 19: Please indicate (yes/no) if the cable barrier failure modes below occurred in your state.

Participants were asked a number of questions about their experiences with cable barrier crashes. Twenty-three states provided information on their yearly average number of reported crashes into cable barriers. Three states did not have any recorded accidents while five states had less than one crash per mile per year. Thirteen states had average accidents between one and six crashes

Table 3.3. Opposite-traffic crashes per year from cable barrier penetrations in 7 states.

Vehicle Penetrations Resulting in Opposite-Direction Crashes							
Year	2003	2004	2005	2006	2007	2008	2009
Number of Crashes	38	31	38	21	35	26	20

per mile per year. Additionally, two states, which have a total cable barrier length of less than 15 miles, reported a higher rate of about 25 crashes per mile per year.

Vehicle penetrations, defined as an impact where the vehicle completely passed through the cable barrier system, were reported by 17 states to have occurred in a combined total of 178 crashes. All but one of the penetrations occurred in the median. There were 25 crashes that involved overrides, 28 crashes were underrides, and the remaining 124 crashes were reported as "other" or unknown. The number of "unknown" crashes is high because some states do not have in-depth details about each accident.

For the 17 states reporting cable barrier penetrations, 10 states had no opposite-direction crashes. The other 7 states reported, on average, a combined total of 30 opposite-direction traffic crashes per year. The combined length of the cable barrier systems reported by these 7 states is 1,434 miles. Table 3.3 shows the combined yearly number of opposite-direction crashes occurring in these 7 states for the period from 2003 to 2009. The number of crashes for 2008 and 2009 years might be lower because of data unavailability for recent years.

It is important to note that the fatalities reported by North Carolina for the years from 2003 to 2005 represent the majority of the fatalities listed in Table 3.3. This is attributed to the fact that North Carolina had data from a comprehensive study conducted on 255 miles of cable barrier systems from January 1, 2003 through December 31, 2005. Of the 2,635 total crashes 96 (3.6 percent) involved penetrations of the median barrier in which the vehicle actually reached the opposite-direction travel lanes. Of these 96 crashes, 38 occurred in 2003, 31 in 2004, and 27 in 2005.

Twenty-two states provided information on possible factors that contributed to median cable barrier penetrations as follows:

- Unstable impact conditions before hitting the barrier caused by, but not limited to, wet conditions, travelling over irregular terrain in the median, or interacting with other vehicles (6 states)
- Severe impact angle and speed (5 states)
- Vehicle's shape and its interaction with different cable heights (5 states)
- Lateral barrier location within the median (3 states)
- Median slope (2 states)
- Others (commercial vehicles and trucks, braking applied at impact point, snow, quality of construction, etc.)

Only 7 states provided information on motorcyclist crashes into a cable barrier. Their responses are as follows:

- One state had one crash where the motorcycle slid under the cables with a low injury severity.
- One state reported two crashes. The first was at a high speed on a curve and the motorcyclist was killed. The other crash involved a motorcyclist who ran off the roadway, laid the bike down, and skidded between posts. The motorcyclist had serious injuries.
- One state reported three fatal crashes where speed was the major contributing factor.

- One state had one crash where the motorcyclist came upon stopped traffic and decided to go into the median rather than hit the rear of a stopped vehicle. The driver was thrown off the motorcycle and took out two of the support posts. The driver appeared okay to the reporting officer, but was taken to the hospital and died three days later.
- One state reported approximately 100 crashes. Two of these crashes were fatal, the first involved speed, and the other one involved alcohol. These two fatalities occurred in locations where the cable barrier was placed near the inside shoulder.
- One state reported a total of 24 cable median barrier hits by motorcyclists over an 8-year period. Of these 24 crashes, 6 were fatal, 5 had A-Injuries, 8 had B-Injuries, 4 had C-Injuries, and 1 was a property-damage-only crash.
- One state reported one injury crash where the motorcyclist was forced off the road into the median cable barrier by a pickup truck that changed lanes and did not see the motorcyclist.

In an effort to understand the possible causes of cable barrier penetrations and crashes, a question on failure mode was posed. The responding states indicated the following:

- Cable failure during impact (6 states yes, 22 states no)
- Failure at end of cable connections (cable extension) (7 states yes, 24 states no)
- Failure at connection between cables and end anchors (8 states yes, 22 states no)
- Excess barrier deflection during impact due to horizontal curvature (9 states yes, 21 states no)
- Excess barrier deflection due to long anchor-to-anchor segments (4 states yes, 25 states no)
- Penetrations/excess deflection due to long post spacing (6 states yes, 24 states no)
- Penetration/excess deflection due to cable spacing or number cables (7 states yes, 22 states no)
- End-anchor pull-out due to soil condition (14 states yes, 16 states no)
- Post foundation pull-out due to soil condition (12 states yes, 18 states no)

3.5 Repair or Maintenance Concerns

The survey next posed two questions about repair and maintenance concerns and practices related to cable barrier systems. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were

- Question 15: Have you experienced any significant or recurring repair or maintenance concerns? If so, please elaborate by cable barrier type as appropriate.
- Question 18: Please describe your maintenance practices.

Thirty-three states responded to this, seven of which did not have any major repair or maintenance concerns. Below are the reported repair and maintenance concerns.

- Weak soil, motion of post foundation especially after spring thaws, crack in foundation (5 states)
- Foundations break upon impacts even when concrete strength tested exceeds manufacturing specifications (4 states)
- Wet or icy median conditions delay repairs since it is hard to get maintenance vehicles to the cable barrier, and posts get frozen into the sockets in winter (4 states)
- Anchors creep, progressive movement of cable end-anchor blocks (3 states)
- Posts gradually lean over as a result of repeated snowplow shoving, spacer blocks collapse on snow loads (2 states)
- Unreported crashes and nuisance hits create repair expenses without the ability to file claims against insurance companies (2 states)
- For curvature hits, cables end up near travel lanes (2 states)
- Maintenance costs, especially when median is narrow, because it gets hit more frequently (2 states)
- Posts twist with cable tensioning (1 state)

- Posts shearing off instead of bending during crashes cause some difficulty in removing the remaining post from the socket (1 state)
- Frequent hits make it difficult to keep up with repairs by contractors (1 state)
- Repair more than a mile stretch of cable (1 state)
- Repair costs are higher with short post spacing (1 state)
- Safety concerns and maintenance difficulties when cable barriers are installed without use of a "mow strip" (1 state)
- Lack of maintenance guidelines for different systems (especially, low tension) (1 state)
- Others (rusting or oxidation of components that are galvanized due to cutting or punching, sockets have been pulled out by severe accidents, end-terminal of a cable barrier system is not crashworthy).

The request for information on maintenance practices yielded the following responses:

Typically, how often do you inspect cable barrier systems?

- Once a year (10 states)
- Twice a year (8 states)
- Once a month (2 states)
- Once every two weeks (1 state)
- Once a week (2 states)
- No inspections (3 states)

Typically, how long after impact is the barrier repaired?

- Less than 2 days (4 states)
- Within 3 or 4 days (4 states)
- Within 5 to 7 days (5 states)
- Within 8 to 14 days (6 states)
- Up to a month (3 states)

Typically, how many posts are replaced per impact?

- Fewer than 5 posts (5 states)
- From 6 to 8 posts (11 states)
- From 8 to 12 posts (4 states)
- Twenty posts (1 state)
- Do not know (5 states)

What is a typical cost of repair per impact?

- Less than $500 (5 states)
- Less than $1,000 (12 states)
- From $1,000 to $2,000 (4 states)
- From $2,000 to $3,000 (2 states)
- More than $3,000 (2 states)
- Do not know (4 states)

Do you use mow strips? If yes, what is the additional cost?

- Yes, $6 to $25 per linear foot for asphalt, $12 per linear foot for concrete (15 states)
- No (19 states)

Do you utilize used parts in repairs? If yes, has this caused problems?

- Yes, some problems (8 states)
- Yes, no problems (5 states)
- No (21 states)

3.6 Other Critical Issues

The survey next posed two questions regarding general concerns about the deployment of cable barrier systems. These addressed basic issues as well as concerns related to procurement, design, and addressing regional conditions. As such, they represent topics that new guidelines might try to address. The detailed versions of these questions are provided in Appendix A of the contractors' final report, but the basic questions were as follows:

- Question 16: Please list the most critical issues that you believe need to be addressed in the guidelines for design, selection, installation, and maintenance of cable barriers. List the most critical first.
- Question 17: Please answer the following design/construction-related cable barrier questions.

Thirty-three states indicated the following critical issues for the design, selection, installation, and maintenance of cable barriers:

- Placement guidelines including median configuration, placement location, cable barrier offset from the roadway, minimum and maximum median width (21 states)
- Different slopes and their impact on barrier effectiveness for 4H:1V and 6H:1V slopes (15 states)
- System performance differences between field data and NCHRP Report 350 tests; a comparison between systems tested under MASH and NCHRP Report 350; standardize test requirements (9 states)
- Cable heights and cable spacing to accommodate small and large vehicles (8 states)
- Geotechnical properties (soil conditions) and creep (8 states)
- Minimum post spacing, recommend post spacing, and a chart for deflection vs. post spacing (7 states)
- Costs and benefits (6 states)
- Recommendation between three vs. four and TL3 vs. TL4 cable barrier systems (6 states)
- Foundation design for terminals, concrete collars, and end terminals (6 states)
- Maintenance guidelines that contain easy repair procedures, especially during winter, as well as budget guidance (6 states)
- Transition to other barrier systems and crashworthiness (5 states)
- Recommended frequency of retensioning for high-tension barriers and force level to pre-stretched cables (4 states)
- Warrants for a new system (3 states)
- Effect of sharp angle and high-speed impacts on deflection, as well as vehicle dynamics (3 states)
- Spacing between anchors and its effects on cable performance (how far apart can the anchors be spaced before the cable performance goes down?); address the effects on deflection of anchor-to-anchor barrier length differences between field applications and crash test installations (2 states)
- Barrier performance on curved alignments (2 states)
- Ways to eliminate penetration, and if a single run is to be installed, which side of roadway is ideal? (2 states)
- Weaved vs. parallel cable barrier systems (2 states)
- Cable systems that do not allow cables to separate and act individually or in subgroup(s) can result in underride or override (1 state)
- Barrier's ability to work after being struck (1 state)
- Deflection degradation over time without pretensioning (1 state)
- Other (crash history, crash risk, motorcycle safety, design criteria and tolerances, trucks, non-proprietary designs, drainage)

One state recommended not installing breakaway signs and luminary support of any kind within the zone of deflection of a cable barrier system. Also, if cable barrier is used in shoulder applications, reduce post spacing to 4 ft and provide 4 ft behind barrier before the slope break point for steep slopes (such as 2H:1V). Another state suggests that AASHTO Roadside Design Guide Figure 6:18 does not apply to flexible cable barrier systems.

The general design, procurement, and deployment concerns questions revealed the following:

Do you have typical guidelines for cable barrier placement?

- Have placement guidelines (26 states)
- Have placement guidelines in draft form (4 states)

Is barrier performance better when placed near the shoulder instead of in the median area?

- Unknown (11 states)
- Yes, better near shoulder (9 states)
- No consensus (4 states)
- Equally effective in either location (2 states)

Do you have requirements for placement near median ditches, drainage inlets, and dikes?

- Yes (23 states)
- No (9 states)
- Use FHWA recommendations (3 states)
- Use AASHTO recommendations (2 states)

Do you provide soil data during request for procurement?

- Have soil data requirements (19 states)
- Do not have soil data requirements (12 states) [many rely on the contractor or manufacturer to do its own testing]

Do you require contractor to repair/replace anchors when excess movement of anchor occurs?

- Yes (25 states)
- No (5 states)
- Do not have this problem (3 states)

Do you have requirements on the type of ends used on the cables?

- Yes (19 states)
- No (9 states)
- Require end terminal to be NCHRP Report 350 accepted (6 states)
- Follow manufacturer's recommendation (6 states)

Do you require pull testing of fully fitted splices to determine breaking strength?

- Yes (10 states)
- No (22 states)

Do you require expected deflection values when anchor-to-anchor length is greater than the crash-tested length?

- Yes (12 states)
- No (19 states)
- Do not install systems longer than what was tested (6 states)
- Other states add a factor of safety, or define maximum deflection values, or do not allow a cable length of more than 2,000 ft.

Do you have inspection requirements?

- Yes (22 states)
- No (7 states)

- Use construction requirements included in the contract specifications and state's standards (5 states)
- Use only the manufacturer's recommendations (3 states)

Do you have construction tolerance limits?

- Yes (24 states)
- No (5 states)
- Use the manufacturer's recommendations (6 states)

What design and placement considerations are complementary with effective maintenance?

- Mowing strips (5 states)
- Keep the barrier at least 10 ft away from roadway (7 states)
- Place the cable barrier as far as possible from the roadway but not in the ditch (4 states)
- Place the cable barrier at the edge of the paved roadway since it eliminates the possibility of erosion and slope problems in front of the cable rail (3 states)
- Require cable barriers to have cast-in-place foundations with embedded sleeves for the posts (4 states)

What practices have you found to make maintaining the roadside around where cable barriers are installed easier?

- Use mowing strips (8 states)
- Use herbicides around posts (4 states)
- Widening the pavement shoulder to cover under the cables (3 states)
- Use vegetation control mats (2 states)
- Use rock liner (1 state)
- Keep the barrier out of the ditch bottom (1 state)

3.7 Summary

Based upon the agency survey the following can be concluded:

- Cable barrier systems are being used by many states, and the extent of use seems to be expanding.
- Low-tension systems were reported for 35 percent of the applications, but at least 58 percent of the applications select high-tension systems from one of the various vendors. Agencies select both three- and four-cable systems and many opt for TL4 systems.
- There is considerable variation in the approaches used to determine if cable barriers should be used. The responses indicated that 54 percent place cable barriers on 6H:1V or flatter slope medians. Placement on 4H:1V sloped medians was reported by 11 percent of the respondents.
- The current practices of states vary relative to the width of median and the slopes that are considered appropriate for the placement of cable barriers. The basic median configurations (i.e., cross-sections) also vary. The requirements for barrier placement in any median configuration also vary.
- Only about a quarter of the states have formal standards for cable barrier design, alignment, construction, and/or maintenance.
- There are varying factors that serve as the basis for the selection across the agencies. These include median configuration, deflections, costs, crash data, traffic levels, ease of maintenance, and potentials for snow accumulation. The number and relative importance of these factors in the selection process is not the same among agencies.
- Impacts, penetrations, and crossover crashes are occurring, but the rate and causes (i.e., failure modes) have not been fully established.

- Less than half the states provided information about the possible factors attributed to barrier penetration. The factors cited included wet conditions, vehicle type and shape, severe angle and speed, lateral position of the barrier, the slope conditions, soil conditions, and commercial vehicles.
- There was limited information available on the contribution of failures of the cable barriers when penetrations occurred.
- Maintenance concerns for cable barriers included weak soil, foundation breaks, repair delays caused by wet or icy medians, anchor creep, post lean, unreported nuisance hits, and costs.
- The agency practices for inspection and routine maintenance vary considerably.

CHAPTER 4

Descriptions of Available Cable Barriers

Six types of NCHRP Report 350-accepted cable barrier systems are currently available for use on U.S. highways, as follows:

- Weak-Steel Post Cable (3-Strand) Guardrail (low-tension)
- Brifen Wire Rope Safety Fence (high-tension)
- Gibraltar Cable Barrier System (high-tension)
- Nucor Steel Marion Cable Barrier System (high-tension)
- Safence Cable Barrier System by Gregory Industries Inc. (high-tension)
- Trinity CASS Cable Barrier System (high-tension)

Several full-scale crash tests have been conducted to evaluate these systems and, based on these tests, Acceptance Letters have been issued by FHWA. Table 4.1 lists the different systems and the corresponding FHWA Acceptance Letters. A more detailed list of these systems is presented in Appendix B of the contractors' final report. Each of these systems is available in a variety of configurations with variations in the number of cables, cable heights, post spacings, post sizes, post embedments, test levels, etc. The following sections give a general description of the different available systems.

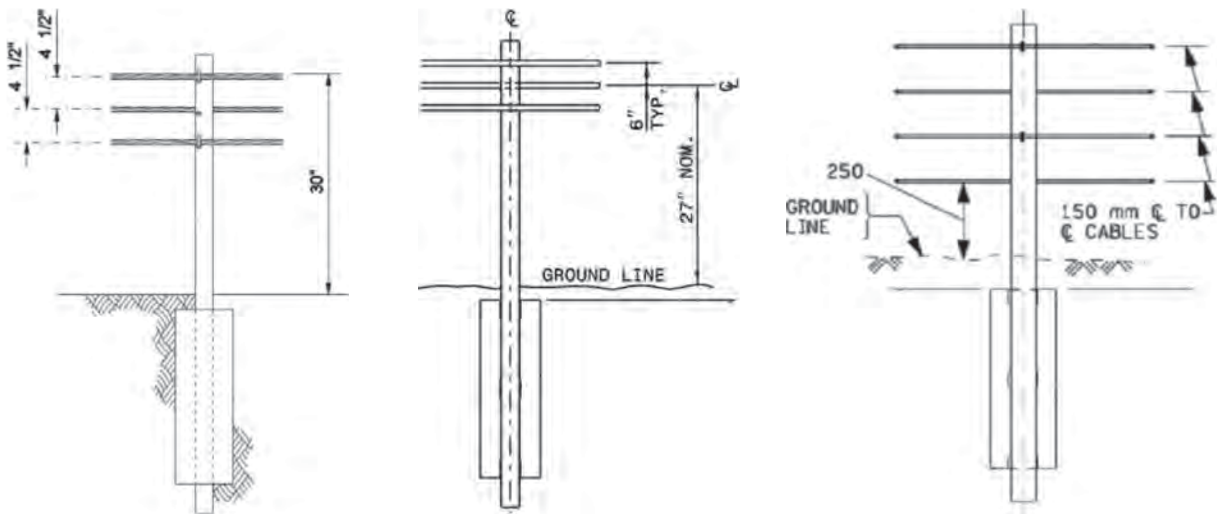
4.1 Weak-Steel Post Cable (Three-Strand) Guardrail

Prior to the recent advances in cable barrier technology, the most common design was the generic cable guardrail, also known as a low-tension system. A low-tension cable system, based on the Washington State design, has been tested in accordance with the NCHRP Report 350 TL3 recommendation at the Texas Transportation Institute [50]. The tested system consisted of three 19 mm (0.75 in) 3 × 7-steel-strand galvanized wire rope cables having a minimum tensile strength of 110 kN (25 kips). The cables were supported at the appropriate heights above ground by S75 × 8 rolled steel posts, 1,778 mm (70 in.) in length, using hook bolts. The hook bolts open up to permit the cable to release from the post when a force ranging from 2,240 N (500 lb) to 4,450 N (1,000 lb) is applied normal to the longitudinal axis of the post. The posts were spaced 4.9 m (16.0 ft) apart.

Steel soil plates, 203 mm × 610 mm × 6 mm (8 in. × 24 in. × ¼ in.) in size, were connected (welded) to the posts at a height of 100 mm (4 in.) from the lower end. The posts, with the welded soil plates, were embedded 851 mm (33.5 in.) in soil. The cable ends were connected to the ground by cable anchors attached to large concrete blocks. The concrete blocks were about 1450 mm × 1150 mm × 990 mm (57 in. × 45 in. × 39 in.) in size. The cables were pretensioned using turn-buckles attached to spring compensator end-assemblies. The spring compensators had a spring rate of 2,000 ± 222 N/mm (450 ± 4.5 lb/in.). The tension in the cables is set based on the atmospheric temperature (about 4,450 N [1,000 lb] at 18°C [65°F]).

Table 4.1. Currently available cable barrier systems.

Manufacturer/Product Name	Acceptance Letter No.	NCHRP 350 Test Level
Generic Weak-Post Cable Guardrail	B-64, B-64 Sup, B-161	TL3
Brifen Wire Rope Safety Fence	B 82 B82 A, B, B1, C, C1,D	TL3, TL4
Gibraltar Cable Barrier System	B-137 B137 A, A1, B, C	TL3, TL4
Nucor Steel Marion Cable Barrier System	B-96, B96A, B167	TL3, TL4
Safence Cable Barrier System by Gregory Industries Inc.	B-88, B-88A-E	TL3, TL4
Trinity CASS Cable Barrier System	B-119,A,B B-141,A,B,C,D,E,F B-157	TL3, TL4



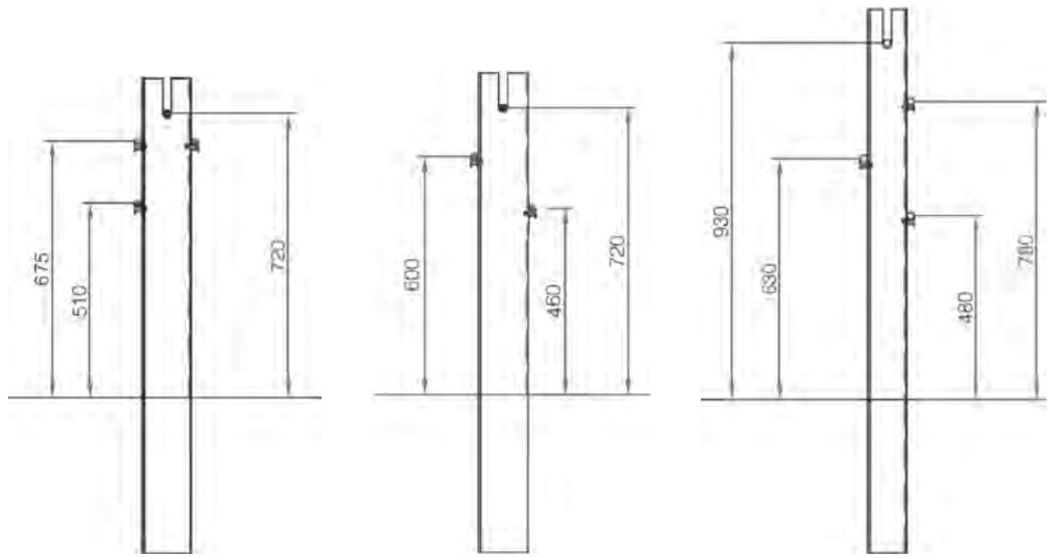
(a) three cables, 4.5" spacing (b) three cables, 6" spacing (c) four cables, 6" spacing

Figure 4.1. Sample cable heights for generic cable barriers.

Generic cable barrier systems are available in different configurations. Three different posts are used with these systems: S75 × 8 steel I-beam (Acceptance Letter B64—SGRO1-a), flanged steel U-channel (Acceptance Letter B64—SGRO1-b), and weakened rounded timber post (Acceptance Letter B64 sup–SGRO1-c). Additionally, different cable setups are used. For roadside applications, all cables are placed on the same side of the post, the side closer to the road. When the barrier is placed in the median, two cables are placed on one side of the post and the other cable is placed on the opposite side. The heights of the cables relative to ground level also varied for different generic cable barrier installations. The most common cable heights are similar to the tested configuration. The lowest cable in this design is set at 533 mm (21 in.) from the ground with the other two consecutive spaces at 114 mm (4.5 in.) above (see Figure 4.1a). In other cable barrier designs, the heights for the three cables are set at 533 mm (21 in.), 686 mm (27 in.), and 838 (33 in.) from ground level (see Figure 4.1b). New York State recently introduced a four-cable barrier design (Acceptance Letter B-161). The heights of the four cables in this design are set at 254 mm (10 in.), 406 mm (16 in.), 559 (22 in.), and 712 mm (28 in.), as shown in Figure 4.1c.

4.2 Brifen Wire Rope Safety Fence

The Brifen Wire Rope Safety Fence (WRSF) system is available in different configurations. The distinctive characteristics of the system are the Z-shaped post and the interweaving of the cables between adjacent posts. Three- and four-cable configurations are available. For



(a) TL3 – four cable (b) TL3 – three cable (c) TL4 – four cable

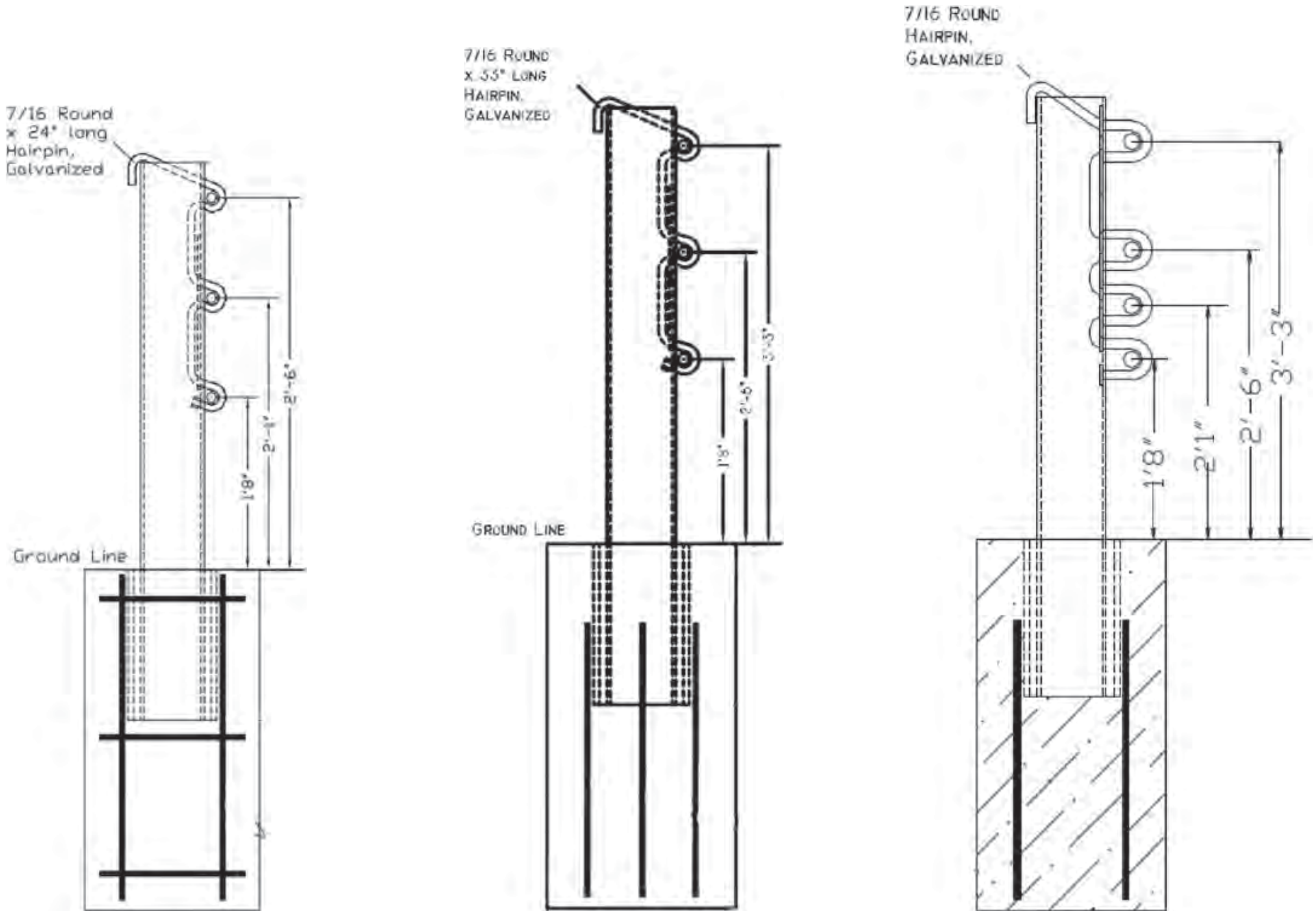
Figure 4.2. Cable height configurations for Brifen WRSF systems.

both configurations, the top cable is placed in a slot at the center of the post. The other two or three cables are woven around the posts. Different cable height configurations have been tested and accepted as TL3 and TL4 roadside barriers. The first system tested was a TL3 four-cable design as shown in Figure 4.2a (Acceptance Letter B-82). In this design, the top cable is placed at a height of 720 mm (28.4 in.) from ground level. The bottom cable is placed at a height of 510 mm (20 in.). The middle two cables are placed at a height of 675 mm (26.57 in.). A three-cable design is also available and has been tested for TL3 condition, as shown in Figure 4.2b (Acceptance Letter B-82C). The heights of the three cables for this system are 460 mm (18 in.), 600 mm (23.5 in.), and 720 mm (28.4 in.). A third design, a TL4 system with four cables, has also been tested and accepted by FHWA (Acceptance Letter B-82B). The heights of the cables for this design, as shown in Figure 4.2c, are at 480 mm (18.9 in.), 630 mm (24.8 in.), 780 mm (30.7 in.), and 930 mm (36.6 in.).

The Brifen WRSF designs are high-tension systems. The cables are tensioned based on the ambient temperature. This tension varies from 14.0 kN (3.1 kips) at 30°C (86°F) to 36.0 kN (8.1 kips) at 10°C (50°F). The posts are typically placed inside a tubular steel socket embedded in a 305 mm (12 in.) diameter × 760 mm (30 in.) deep concrete footings. Driven posts or posts set in driven steel sleeves are also acceptable with the Brifen systems. Typical post spacing of the Brifen system is 3.2 m (10.5 ft). Post spacing of 2.4 m (7.87 ft) and 6.4 m (21 ft) were also tested in accordance with NCHRP Report 350.

4.3 Gibraltar Cable Barrier System

The Gibraltar high-tension cable barrier system is available in different configurations. The distinctive characteristic of the system is that the cables are attached to the post using a single 30 mm (7⁄16 in.) diameter steel hair pin. The system consists of three or four 19 mm (0.75 in.) 3 × 7-steel-strand galvanized wire rope cables. Prestretched and non-prestretched cables can be used with the system. The cables are connected to C-channel posts that are 83 × 63.5 × 3.8 mm (3.25 × 2.5 × 0.15 in.) in cross section. The posts are placed such that adjacent posts are on opposite sides of the cables. The posts are typically connected to the ground through steel sockets that are embedded in reinforced concrete cylinders. Other connections, such as driven posts, have been accepted by FHWA. Varied post spacing can be



(a) TL3 – three cable (b) TL4 – three cable (c) TL4 – four cable

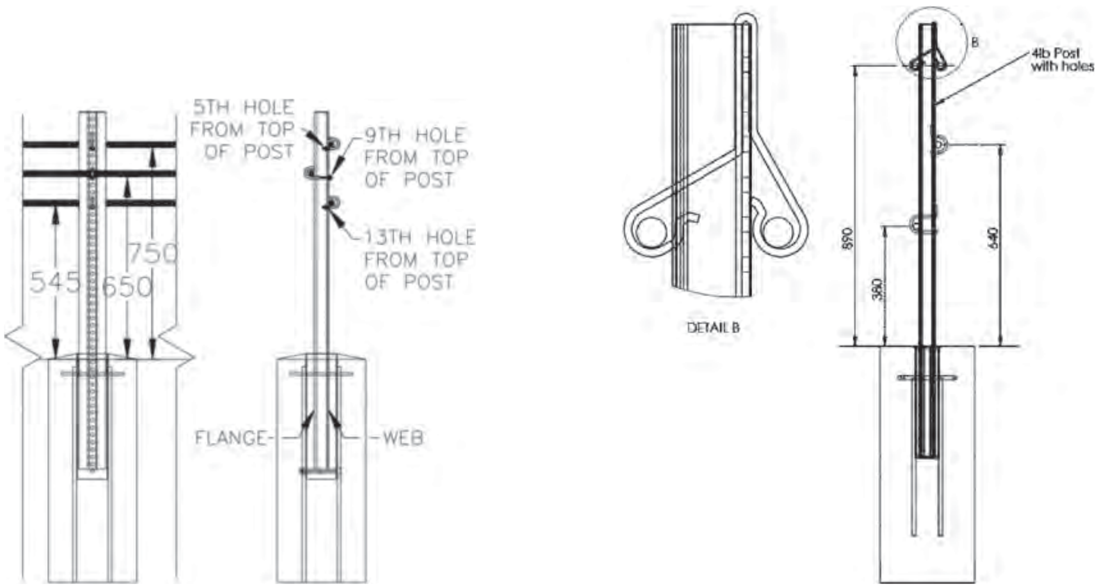
Figure 4.3. Cable height configurations for Gibraltar cable barrier systems.

used with the Gibraltar cable barrier system. Spacing from 3 m (10 ft) to 9 m (30 ft) can be used with the system.

The Gibraltar cable barrier system has been tested in accordance with NCHRP Report 350 and is accepted for TL3 and TL4 conditions. The main difference between the TL3 and TL4 systems is cable spacing and length of the posts. For the TL3 three-cable system, the cable heights are set at 508 mm (20 in.), 635 mm (25 in.), and 762 mm (30 in.) from ground level, as shown in Figure 4.3a (Acceptance Letter B137). For the TL4 three-cable system, the heights are 508 mm (20 in.), 762 mm (30 in.), and 990 mm (39 in.), respectively, as shown in Figure 4.3b (Acceptance Letter B137a). A third system with four cables has also been accepted at TL4 condition (Acceptance Letter B137b). The heights of the cables from ground level are 508 mm (20 in.), 635 mm (25 in.), 762 mm (30 in.), and 990 mm (39 in.), as shown in Figure 4.3c.

4.4 Nucor Steel Marion Cable Barrier System

Two Nucor high-tension cable barrier systems are accepted for use on the National Highway System: a three-cable TL3 system (Figure 4.4a—Acceptance Letters B96 and B96A) and a four-cable TL4 system (Figure 4.4.4b—Acceptance Letter B167). Both systems use 19 mm (0.75 in.) 3 × 7-steel-strand wire rope cables. Prestretched as well as non-prestretched cables can be used



(a) TL3 – three cable (b) TL4 – four cable

Figure 4.4. Cable height configurations for Nucor cable barrier systems.

with these systems. The cables in both systems are attached to 6 kg/m (4 lb/ft) U-channel steel posts. Locking hook bolts, 6.4 mm (.25 in.) in diameter, are used to connect the cables to the posts.

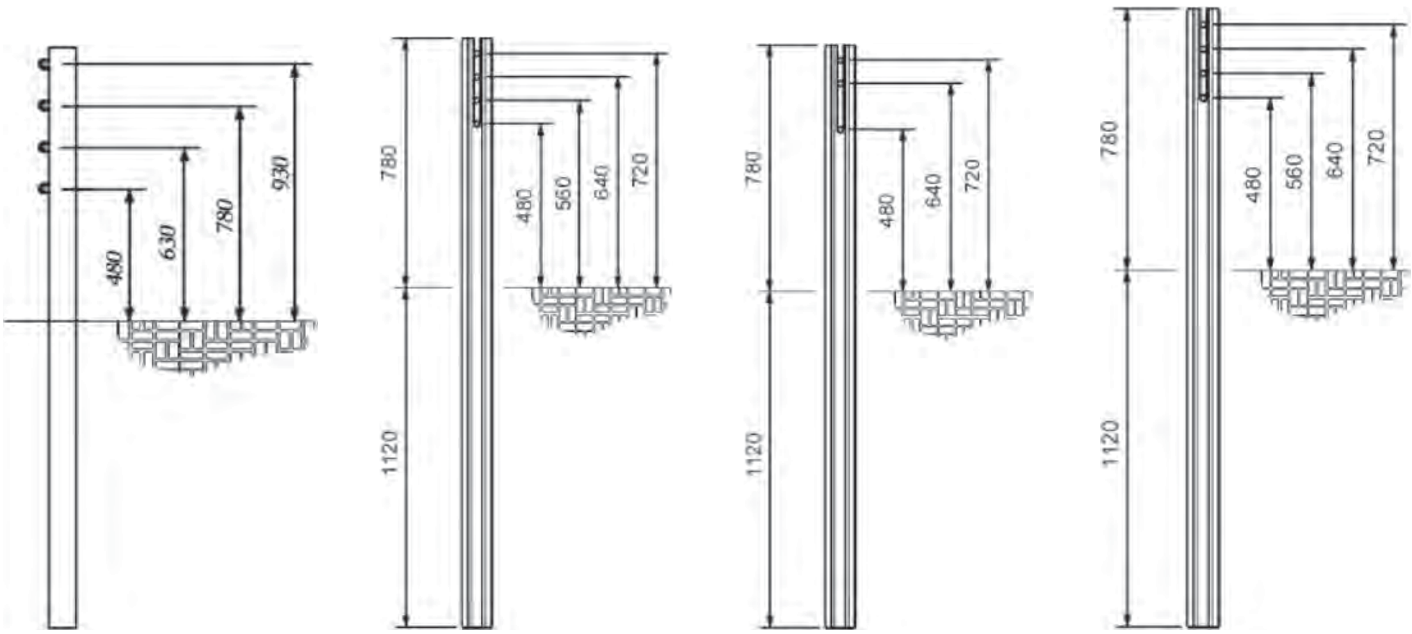
For the TL3 design, the three cables are placed at heights of 545 mm (21.5 in.), 650 mm (25.6 in.), and 750 mm (29.5 in.), as shown in Figure 4.4a. The top and bottom cables in this design are placed on one side of the post while the middle cable is placed on the opposite side. The TL3 design was tested with three different post spacings: 2 m (6.5 ft), 3.8 m (12.5 ft), and 5.1 m (16.7 ft). All tests met the NCHRP Report 350 criteria with variation in barrier deflections. Two different post embedment types were used in the TL3 tests: Direct driven posts with a trapezoidal soil plate, and a socket steel sleeve set in a 300 mm (12 in.) diameter concrete cylinder are available.

For the TL4 design, the bottom cable is placed at 380 mm (15 in.), the top two cables are placed at 890 mm (35 in.), and the remaining cable is placed at 640 mm (25.2 in.) from ground level as shown in Figure 4.4b. Two of the four cables are placed on one side of the post and the other two are placed on the opposite side. Each post is fixed to the ground by means of a plastic socket that is embedded in a 300 mm (12 in.) diameter concrete foundation. The spacing between the posts is 6.1 m (20 ft).

4.5 Safence Cable Barrier System

Safence high-tension cable barrier systems have been tested under TL3 and TL4 conditions. The cables in these systems consist of 19 mm (0.75 in.) 3 × 7-steel-strand prestretched wire rope cables. Systems with three different types of line post have been tested. These post types include an elliptically shaped steel post, an I-shaped post (41 mm flange width and 80 mm web width), and a C-shaped post (95 mm × 30 mm). All three posts have a thickness of 4 mm.

The elliptical posts were used in the original TL3 Safence design (Acceptance Letter B88). This system had four cables that are placed at heights of 480 mm (18.9 in.), 630 mm (24.8 in.), 780 mm (30.7 in.), and 930 mm (36.6 in.) from ground level, as shown in Figure 4.5a. All four cables in this system are placed on the same side of the post and attached using twisted hooks.



(a) 1st TL3 design four cables

(b) 2nd TL3 design four cables

(c) 1st TL4 design three cables

(d) 2nd TL4 design four cables

Figure 4.5. Cable height configurations for Safence cable barrier systems.

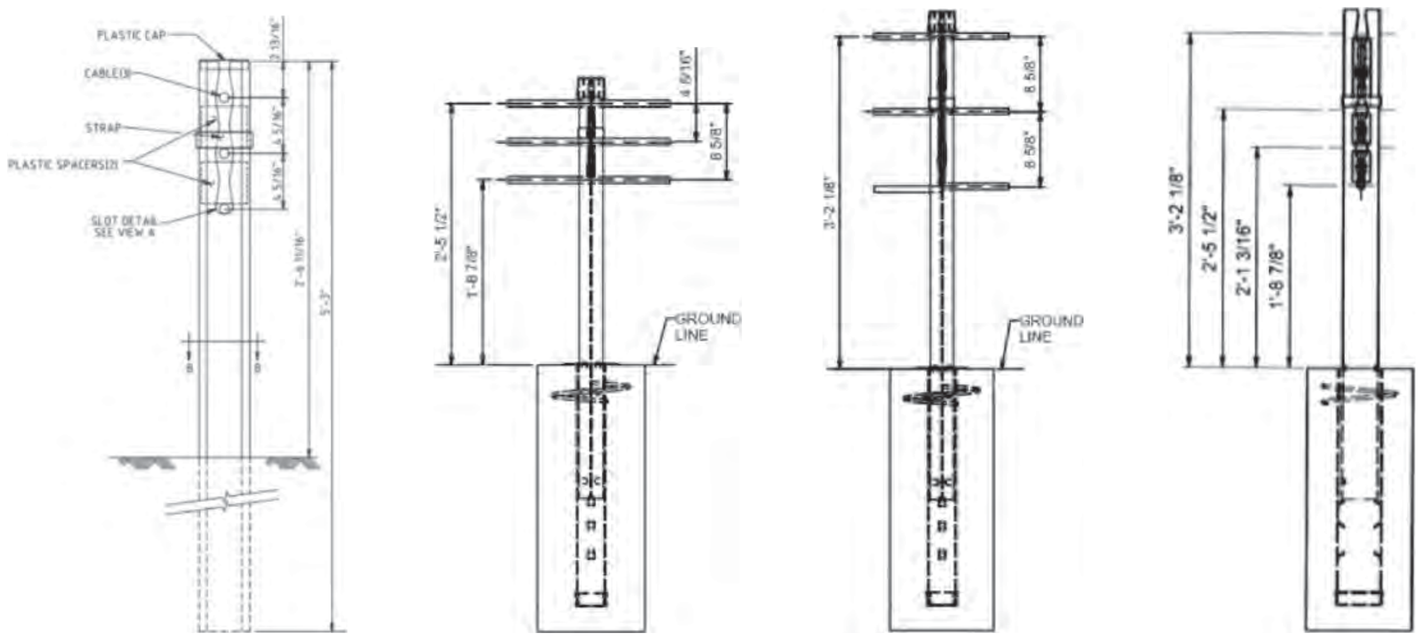
This system is intended for non-median applications (roadside application only). The posts in this design are spaced at 2.5 m (8.2 ft) and embedded 1.11 m (3.6 ft) in soil.

The I-shaped post was used in the second TL3 Safence cable barrier design (Acceptance Letter B88-a). In this design, the four cables are placed at heights of 480 mm (18.9 in.), 560 mm (22 in.), 640 mm (25.2 in.), and 720 mm (28.3 in.) from ground level, as shown in Figure 4.5b. All four cables are inserted in a slot at the center of the post and separated by plastic spacers. This design can be used for both median and roadside applications. A similar design, using C-shaped posts instead of the I-shaped post, has been accepted by FHWA (Acceptance Letter B88c). The posts, in both designs, can be driven directly into the ground or embedded in 200 mm (8 in.) diameter by 600 mm (24 in.) deep concrete footings. Additionally, post spacings of 2 m (6.5 ft) or 3 m (9.8 ft) can be used with this TL3 design.

Two Safence designs have been accepted by FHWA at the TL4 level (Acceptance Letter B88d and B88e). Both designs are similar except for the number of cables. The first design uses three cables placed at heights of 480 mm (18.9 in.), 640 mm (25.2 in.), and 720 mm (28.3 in.) from ground level, as shown in Figure 4.5c. The second design has an additional cable at 560 mm (22 in.) height, as shown in Figure 4.5d. The TL4 designs are similar to the second TL3 design. The posts, however are made stronger, ATSM A50 steel is used instead of the A36 steel used in TL3 designs. Each post was also stiffened at the ground line by adding a steel plate inside the C-post. Additionally, a steel hook was added to the top of each post to delay the release of the cables from the posts during the impact.

4.6 Trinity CASS Cable Barrier System

The Trinity CASS high-tension cable barrier systems have been tested under TL3 and TL4 conditions and are available in different configurations. The cables in these systems consist of 19 mm (0.75 in.) 3 × 7-steel-strand prestretched or non-prestretched steel wire ropes. Three and four cable systems are available. The cables are placed in a slot at the center of the post and



(a) 1st TL3 design
C-Post - three cables

(b) 2nd TL3 design
I-Post - three cables

(c) 1st TL4 design
I-Post - three cables

(d) 2nd TL4 design
I-Post - four cables

Figure 4.6. Cable height configurations for Trinity CASS cable barrier systems.

separated by plastic spacers. The posts can be anchored to the ground using steel sockets that are cast into concrete cylinders, steel tubes driven in soil, or posts directly driven in the soil. Different post spacings, ranging from 2 m (6.5 ft) to 10 m (32.5 ft), can be used with the CASS systems.

The original CASS design uses cold-formed C-shaped posts and has been accepted at TL3 condition (Acceptance Letter B-119). The cable heights relative to ground level in this design are 530 mm (21 in.), 640 mm (25.2 in.), and 750 mm (29.5 in.), as shown in Figure 4.6a. The second CASS TL3 design uses hot rolled posts (Acceptance Letter B-141). The posts in this design are weakened by drilling two 17.5 mm (11⁄16 in.) diameter holes through each flange at ground level. The cables were kept at the same heights as the original design, as shown in Figure 4.6b. A TL4 design, using the same weakened S4 × 7.7 posts, has been tested and accepted by FHWA (Acceptance Letter B-141). This design uses three cables placed at heights of 530 mm (21 in.), 750 mm (29.5 in.), and 968 mm (38 in.) from ground, as shown in Figure 4.6c. A second CASS TL4 design that uses four cables instead of three, has been accepted by FHWA (Acceptance Letter B-157). The cables, in this design are set at heights of 530 mm (21 in.), 750 mm (29.5 in.), 640 mm (25.2 in.), and 968 mm (38 in.).

4.7 Other Designs

A new generic high-tension cable barrier system is in development at the MwRSF and is currently being tested in accordance with MASH. The tests are selected such that the system would be placed anywhere along the lateral direction of 4H:1V or shallower sloped medians.

The system uses four 19 mm (0.75 in.) steel wire ropes (Figure 4.7). The cable heights are at 343, 610, 876, and 1,143 mm (13.5, 24, 34.5, and 45 in.). The four cables are attached to S3 × 5.7 steel posts via specially designed keyway brackets. The brackets are designed to fracture at a certain load level and allow the cables to separate from the posts. The brackets are connected to the posts using 8 mm (5⁄16 in.) diameter bolts, washers, and nuts (two per cable). The posts,

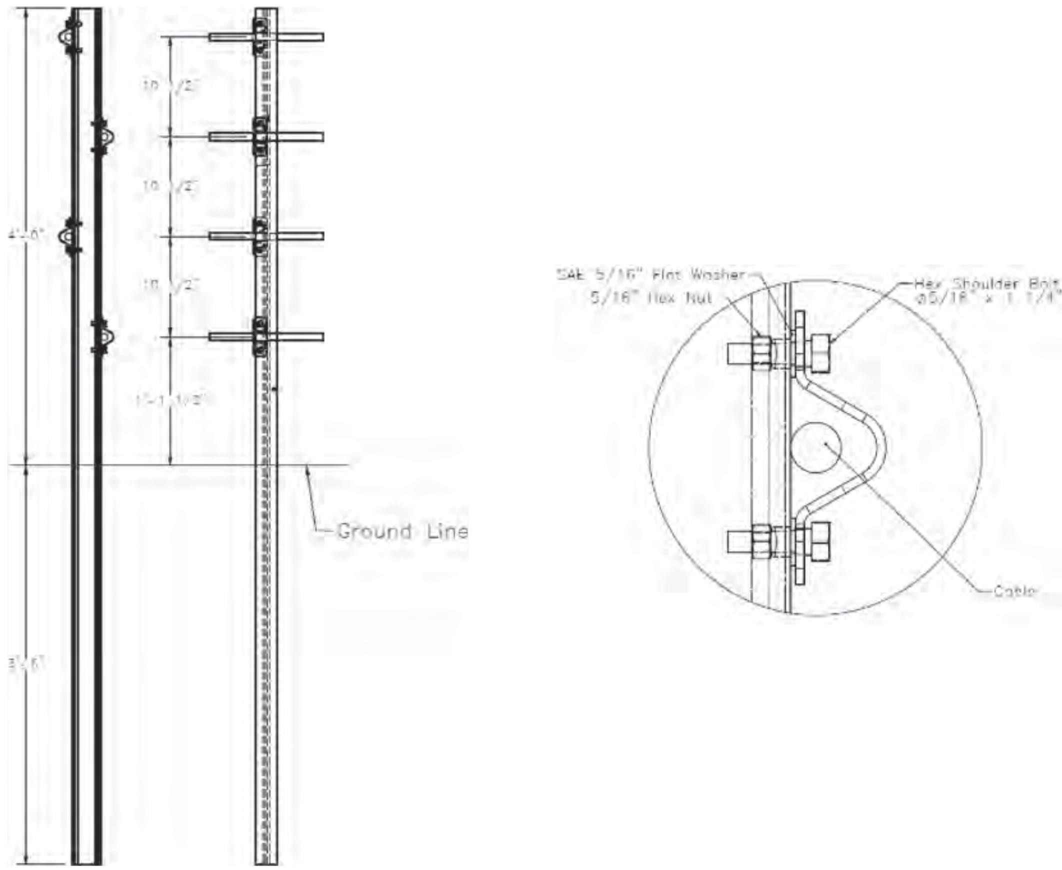


Figure 4.7. MwRSF generic high-tension cable barrier system.

in the tests, are imbedded 1.0 m (3.3 ft) in the ground. The installation length in the tests was 183 m (600 ft), which is the minimum length required under MASH. Even using this length, load cells placed at the end anchors showed a 136 kN (30 kips) increase in cable tension force due to an impact with the 2270 P vehicle. This leads to the conclusion that higher deflection would be observed for longer installations.

Four full-scale crash tests have been conducted on this system, and three additional tests are planned in the near future. The tests vary in vehicle type (1100C, 1500A, and 2270P), barrier location (near side, far side, placement relative to the median), and soil strength (weak and strong soil). A matrix of tests for barrier systems that would be placed anywhere in 4H:1V sloped median will be finalized based on observations from the tests conducted on this system.

CHAPTER 5

Analyses and Results

As noted in Chapter 1, the panel directed the contractor to pursue analyses in the seven areas outlined in Table 1.1. This chapter will provide the details about the approaches used, the factors considered, and the results obtained for the following seven areas:

- Cable barrier placement
- Cable barrier deflection
- End-anchoring and post-anchoring systems
- Interconnection with other systems
- Horizontal curvatures
- Construction and maintenance tolerances
- Installation and maintenance costs

The intent of conducting the analyses in these areas was to derive science- and data-based insights on the influence of various factors with the subsequent translation of these findings into guidelines that would facilitate the deployment of effective cable barrier systems for median and roadside applications.

As one ventures into these analyses, it is necessary to be cognizant of the many factors associated with cable barriers that may need to be considered.

There are many variations in cable barrier system designs, placement, and maintenance. These variations include the following:

- Cable barrier system design
  - Number of cables
  - Cable positions (i.e., heights)
  - Cable placement on posts
  - Cable connectors
  - Post design
  - Post spacing
  - Post embedment including driven vs. placement in foundations
  - Anchorage features
  - Anchor spacing
  - Tensioning elements
  - Cable type
  - Tension levels
  - Transition options
- Placement considerations
  - Median cross-section
  - Changes in median cross-section

  - Tangent and curved roadway sections
  - Obstacles in the median or roadside
  - Shoulder/slope design
  - Drainage requirements
  - Soil conditions
  - Seasonal effects
  - Transitions to other barriers
  - Installation operations
- Maintenance considerations
  - Probability of nuisance hits
  - Anchor movement
  - Post foundation failures
  - Retensioning
  - Maintenance cycles
  - Ease of repair
  - Requirements for lane closure

These factors can have different types and degrees of effects on cable barrier performance. The need exists to assess the implications of the factors to identify the critical ones and translate them into generic guidance. The following sections describe the analyses performed under this study to investigate the effects of some these factors and address the identified cable barrier issues. The results of these analyses were used to develop guidelines for the selection, use, and maintenance of cable barriers.

5.1 Cable Barrier Lateral Placement

One of the most critical factors that affects the performance of cable barriers is the lateral placement relative to configuration (i.e., width, slope, shape) of the roadside or median. On flat terrain, almost all currently available/accepted cable barrier systems will perform adequately and can safely redirect most errant vehicles departing the roadway under nominal conditions. However, this is usually not the case when the cable barrier is placed on a sloped median/roadside. The sloped terrain affects the relative height at which the vehicle impacts the cable barrier, i.e., the vehicle could impact the barrier at a higher or lower vertical position compared to that on flat terrain. This phenomenon could lead to a vehicle not fully engaging the cables and consequently underriding or overriding the barrier. It is, therefore, critical to ensure that the barrier is placed at a location where it can capture and/or redirect the majority of vehicles successfully.

To investigate the full effects of terrain profiles on cable barrier performance and to develop guidelines for a barrier's optimum placement, a comprehensive analysis was performed. Vehicle dynamics simulations were conducted to compute the trajectories of vehicles as they traverse a median on a diagonal path. Two commercially available vehicle dynamics programs were used to conduct the simulations and generate data and animations reflecting the trajectories. For each vehicle type considered in these analyses, two points were defined to represent the primary interface (engagement) region on the front of the vehicle. These points are labeled 1 and 2 in Figure 5.1. A trace of these two points viewed from a position standing in the center of the median downstream from the point a vehicle leaves the roadway is shown as the dark lines in Figure 5.2.

These same data points can be plotted on a diagram of the median cross-section (as shown in the lower part of Figure 5.2). It can be noted that in moving from left to right, after passing the breakpoint between the shoulder and the median onto a sloped surface, the vehicle will be airborne or at least have a low compression load on its suspension system. At some point the

Figure 5.1. Critical interface points.

vehicle will land (or return to a distribution of weight on all wheels), and the suspension will compress to absorb the dynamic load. As the vehicle continues its movement across the median there will be a rebound of the suspension as it dissipates energy. Thus, as the vehicle traverses the median, the height of its interface area will vary depending on the state of the vehicle's suspension system and the slopes of the median. Effective lateral placement of the barrier involves finding the locations where the vehicle's interface area matches the barrier's cable heights. For median applications, finding these locations is complicated by the need to have an effective interface for impacts from either direction.

The vehicle dynamics programs that were used in this study included HVE (Human Vehicle Environment, by the Engineering Dynamics Corporation) [51] and CarSim (by Mechanical Simulation Corporation) [52]. The programs were developed for use by engineers and safety researchers to study interactions among humans, vehicles, and their environment. They are high-level simulation tools aimed at creating three-dimensional models of vehicles and environments and allow the study of their dynamic interaction under selected conditions. Physical and

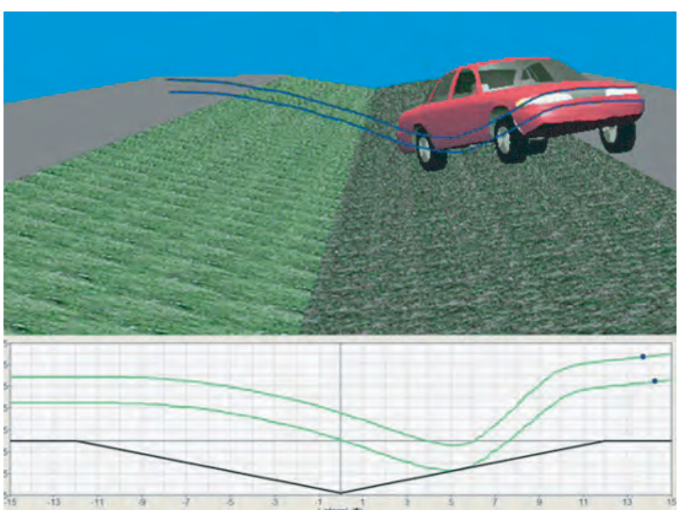


Figure 5.2. Trajectory of interface points as the vehicle crosses the median.

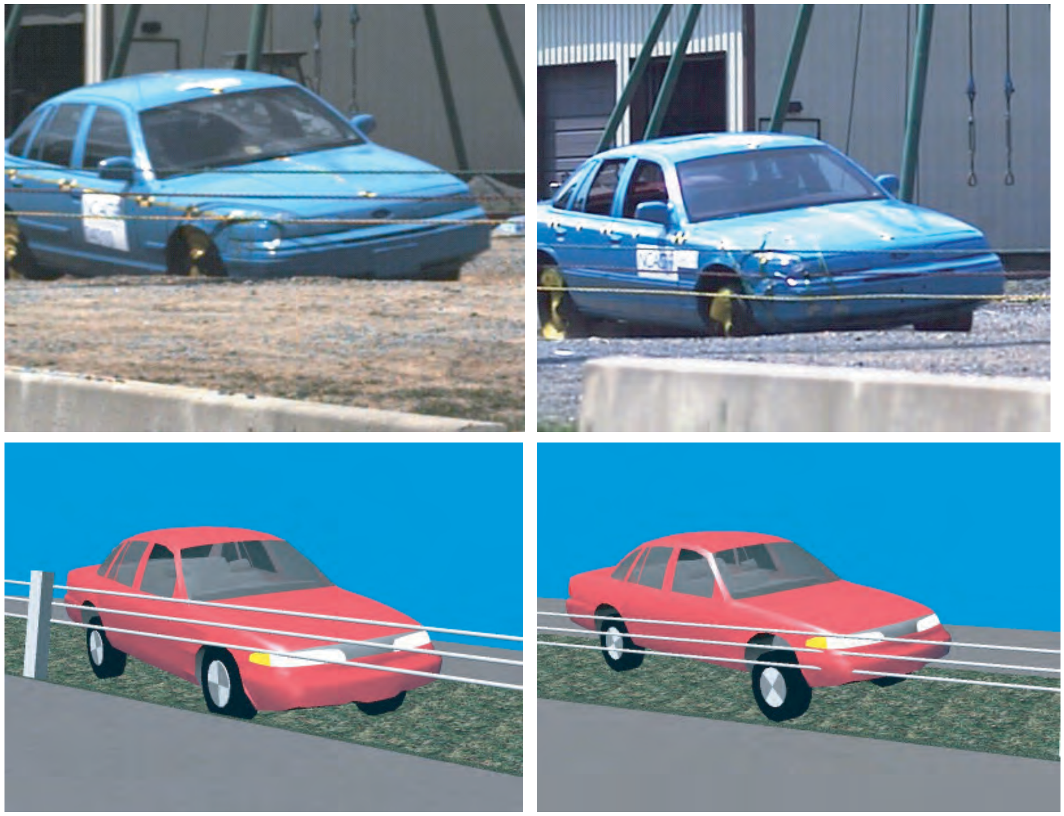


Figure 5.3. Comparisons of HVE predictions and full-scale crash test results.

mathematical models provide a detailed description of a motor vehicle that considers the influence of weight, suspension system, and other vehicle factors. Available databases include a wide range of high-fidelity vehicle models that can be used in dynamic reconstructions and simulations. HVE and CarSim provide physical and visual environment models to simulate selected conditions. Weather attributes, road geometry, and pavement friction properties can be computed and their effects on vehicle dynamics analyzed. Driver's action (e.g., throttle, brakes, steering, and gear selection) can also be simulated. The models have been thoroughly validated and are capable of predicting accurately a vehicle's trajectory for different terrain profiles. NCAC used these programs in several cable barrier research studies, and the results were compared to full-scale crash tests. The predictions were a close match to the full-scale crash tests. Figure 5.3 shows predictions from HVE at the start of impact compared to two full-scale crash tests.

The research considered a broad set of influencing factors as shown in Figure 5.4. This figure shows a typical divided highway where the median is the green area between the shoulders. The median can be of different widths and cross-sections. The cable median barrier is placed somewhere in the median and can be hit from either side. For the situation shown in Figure 5.4, a vehicle leaving the bottom roadway would have a "nearside" hit on the barrier. From the upper roadway, the vehicle would have a "farside" hit. A cable median barrier has to be located such that it functions effectively for both nearside and farside hits.

Today's vehicle fleet is a heterogeneous mix of vehicles with varying shapes and sizes. Figure 5.5 shows a sample assortment of vehicles from the fleet and the variations in the heights of their bumpers and primary structures. To address the effect of vehicle type on barrier performance, several vehicle models were used in the analyses to create an envelope of vehicle trajectories.

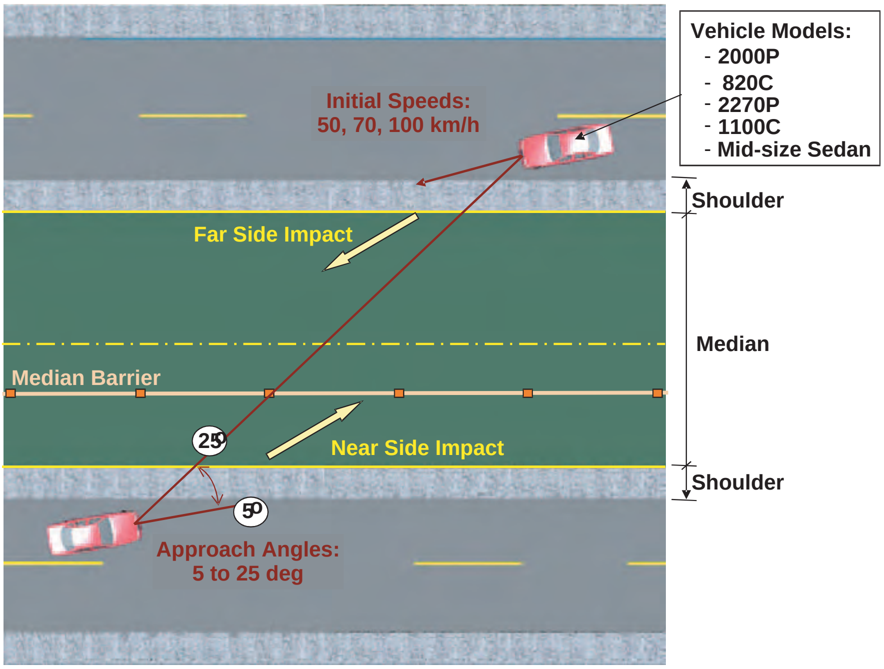


Figure 5.4. Factors considered in cross-median events.

These vehicle models included a pickup truck (Chevrolet C2500) and a small car (Honda Civic) to represent the two NCHRP Report 350 required test vehicles. A large sedan (Crown Victoria) was also included in the analysis. This vehicle type has been found in previous studies to be critical for cable barrier performance due to its front profile (similar to a small car) and its mass (similar to a pickup truck). Additionally, a larger pickup truck and a sedan representing the new MASH 2270P and 1100C vehicles, respectively, were included in the vehicle dynamics analyses.

Defining "effective interface conditions" for any cable barrier design and any median configuration can be accomplished in various ways. For this analysis, effective interface conditions were determined by the following:

- Assessing relative positions of the vehicle to the barrier such that
  - To minimize the potential for override, the top cable should contact the vehicle above Point 1 (lower critical point in Figure 5.1).
  - To minimize the potential for avoid underride, lower cable should contact the vehicle below Point 2 (upper critical point in Figure 5.1).

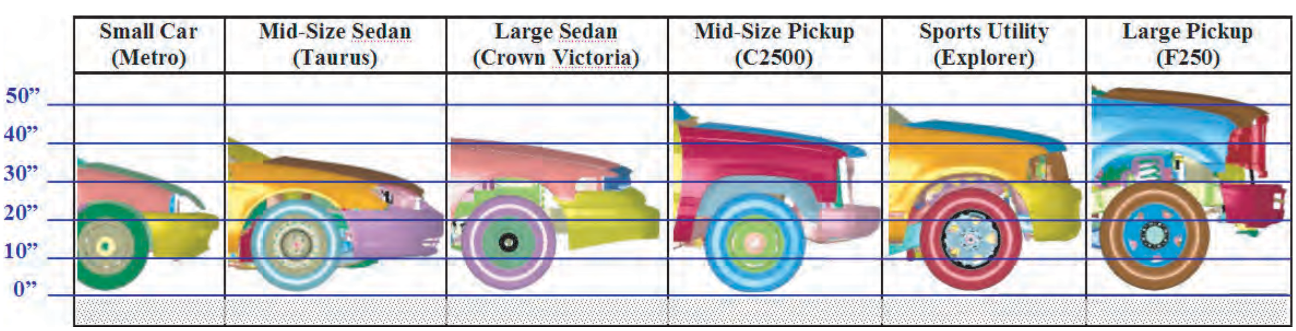


Figure 5.5. Variation in vehicle front profile.

- Defining the impact conditions to be considered. One approach would be to follow NCHRP Report 350 or MASH requirements. In this analysis, a broader view was taken requiring that the conditions should reflect a broader range of approach angles, speeds, and vehicle types.
- Associating interfaces with specific median configurations (i.e., width, shape, side slopes, and depth).

Two critical points (Points 1 and 2) were used for each vehicle to assess its interface with the barrier when placed at different locations along the lateral direction of the median. These critical points were selected based on the geometry of the front structure of the vehicles and by examining full-scale crash tests of these vehicles impacting different cable barrier systems. (Please note that references to colors in the following text will be clear in the color figures which are available in the online version of the report which can be found by searching the TRB website for *NCHRP Report 711.*) Using the results of vehicle dynamics simulations, trace paths of Point 1 for vehicles crossing a median from both directions were plotted in Figure 5.6 with each individual trace representing a specific vehicle, speed, impact angle, and crossing direction. These curves are "normalized" to relate the relative heights of individual cables in the barrier, or the height of the effective interface area on the front of a vehicle to a horizontal plane. For any position across the median, the vertical height of the normalized plot to actual sloped surface is equivalent. Normalization is useful for comparing various types and features of medians and cable barriers. The array of lines represents the broader set of impact cases for the specified parameters. The heavy blue line represents the overall maximum heights for Point 1 for the set of impact cases associated with this particular median configuration. Similarly, plotting all cases for Point 2 yielded the array of lines in Figure 5.7 for the set of impact cases for a given median configuration. The heavy green line represents the overall minimum heights for Point 2. These plots were generated for different median profiles and can be used to define vehicle-to-cable-barrier engagement based on cable barrier lateral position and its cable heights.

Comparing the resulting blue (minimum) override limit and green (maximum) underride limit lines for a given median provides a means of determining the interface effectiveness across all lateral positions for any given barrier design. The three yellow lines in Figure 5.8 represent the coverage of a particular barrier design (in this case a generic three-cable barrier). Where the blue

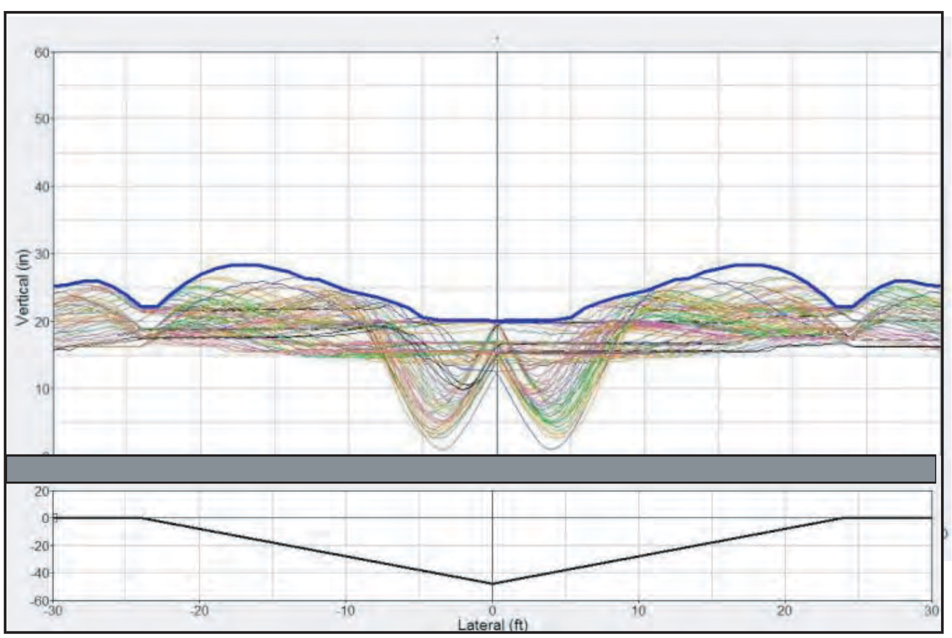


Figure 5.6. Sample override limit curve.

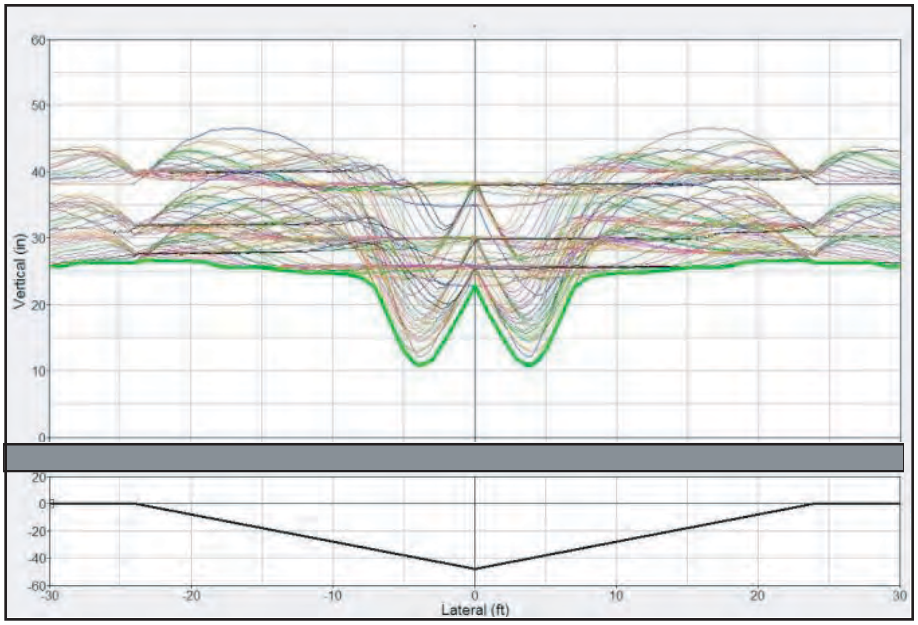


Figure 5.7. Sample underride limit curve.

line goes above the highest yellow line there is an opportunity for an override to occur. Where the green line falls below the lowest yellow line, the possibility of an underride exists.

This approach is used to determine the potential effectiveness for varying cable barrier systems (e.g., number of cables, relative heights) across all possible lateral positions for a given median configuration. The following figures show more specific examples of how this metric can be applied.

Figure 5.9 shows an example of the results for a specific median. The upper portion shows the normalized representation of the interface envelope, the minimum upper cable height curve, the maximum lower cable height curve, and the relative position isobars for a specific type of cable barrier (i.e., generic, low-tension, 3-cable system). The Barrier Interface Envelope is the gray shaded area that surrounds all of the trace bars for different vehicles traversing the median at varying angles and speeds from both directions.

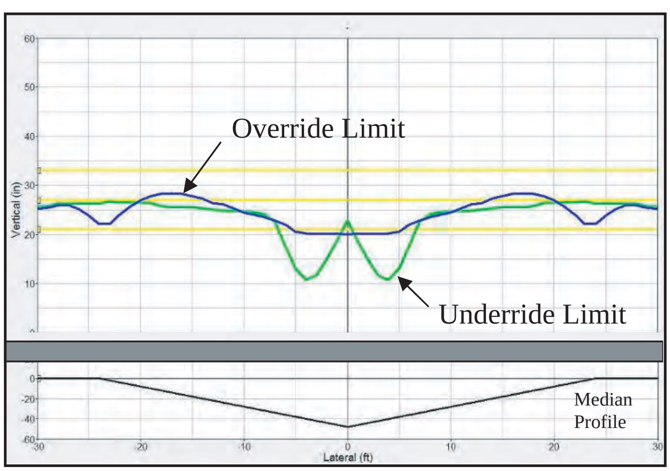


Figure 5.8. Sample override and underride limits plot.

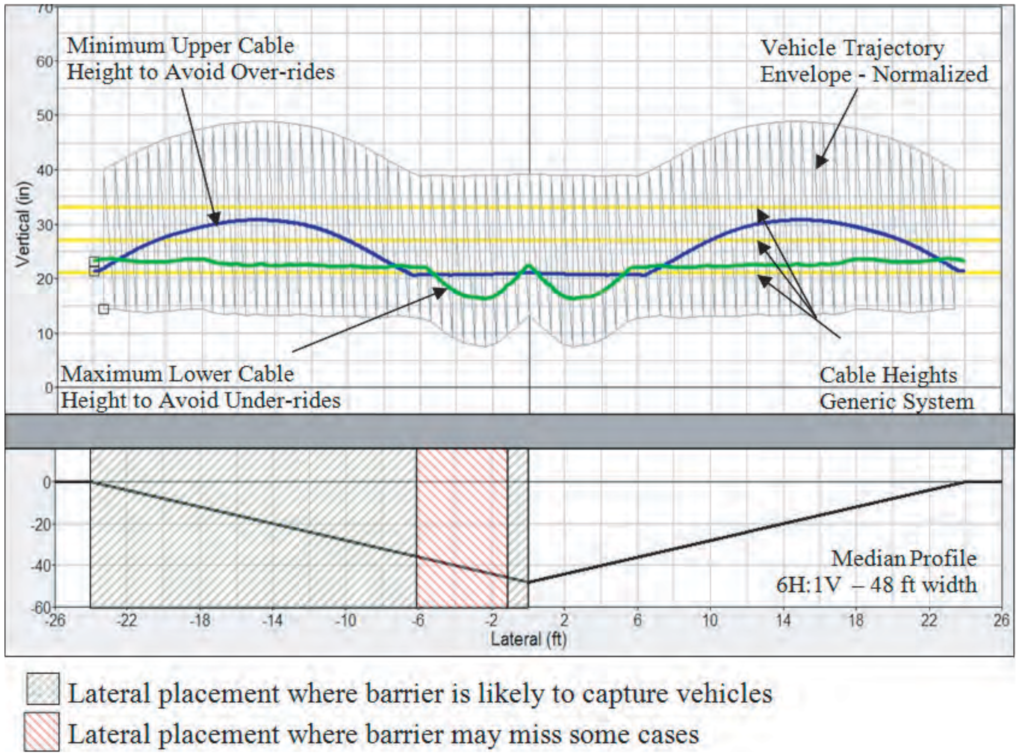


Figure 5.9. Sample plot generated using the results of vehicle dynamics analysis.

The lower portion of Figure 5.9 shows the profile or cross-section of the median related to the upper graph. The green hatched portions indicate the lateral positions where this specific barrier will be effective. Since the median in this case is symmetric, the effectiveness regions are a mirror image on the opposite side. The red hatched area defines the lateral positions where the specific barrier has a cable arrangement that has a lower cable above the maximum lower cable height curve (green) and/or an upper cable below the minimum upper cable height curve (blue). Effective lateral placement occurs where both criteria are met. It can be noted that for this specific barrier system, the red region corresponds to the lateral placement range where the maximum lower cable curve height falls below the lowest cable in the system. This plot would indicate that for this 14.6 m (48 ft) wide median (measured from hinge point to hinge point of median) with 6H:1V side slopes, there is an area from about 0.3 to 1.8 m (1 ft to 6 ft) from the center of the median where placement of this generic cable barrier system is not recommended because of the risk of underriding. Numerous plots of this type for different median profiles were generated and were used in developing the guidelines. Some of these plots are included in Appendix C of the contractors' final report.

In this research, a number of different possible conditions for a median crossing were considered. The following conditions were assumed in the analyses:

- Median has firm surface. Ploughing (or furrowing) into the surface by tires is negligible. Modeling the ploughing condition is beyond the capability of current computer simulation software. This condition has not been incorporated in all previous related research studies (using full-scale tests or computer simulations) and is considered beyond the scope of this project.
- Vehicles are "tracking" as they enter the median (i.e., vehicle's initial speed vector is in the same direction at its longitudinal axis). Even though it is possible to investigate non-tracking conditions using the vehicle dynamics programs, incorporating all non-tracking scenarios would render the number of simulations impractical. Different vehicle types, impact angles, and initial speeds are considered in this study, which should account for most vehicle/barrier interface situations.

- Initial velocity occurs when the vehicle leaves the shoulder. Some deceleration is expected to occur (3–5 mph was noted in the research) for vehicles as they cross the median.
- There are no driver inputs (e.g., steering, braking) that affect the vehicle trajectory.
- No edge rounding was considered in this study. Based on previous investigations, edge rounding reduces the potential of overrides with no significant effect on the underrides.
- A vehicle must have effective engagement with a minimum of one cable to be captured by the barrier.

It is important to note that review of full-scale crash testing has indicated that for low-tension systems an engagement with one cable is sufficient to capture the small car but may not be sufficient to redirect mid-size and larger vehicles. Engagement with one cable was shown to be sufficient for the small vehicle and pickup truck for high-tension systems. This difference could be attributed to the fact that the connection between the cables and posts is stronger in high-tension systems than in low-tension systems. Additionally, the green hatched regions in the generated plots indicate barrier lateral placement where a minimum of one cable would engage the vehicle. This is a minimum condition that has to be satisfied but does not ensure a successful redirection or controlled stopping of the vehicle. In addition to this engagement condition, the barrier needs to have adequate strength to withstand the vehicle impact forces. This can be achieved through full-scale crash testing. At the time that this report was written, a matrix of full-scale crash tests that evaluate cable barrier systems when placed on sloped medians was being developed. These tests will ensure that the cable barrier design (e.g., the strength of connection between cables and posts, the post spacings, the cable vertical spacings, etc.) is adequate to capture and redirect the vehicle without leading to rollover, override, underride, or penetration in between the cables.

The approach described in the previous sections allows for identifying optimum placement of cable barriers for specific median configurations. To develop generalized guidelines that can be used for a wider range of median geometries, the analysis was taken a step further. This was achieved by superimposing (i.e., overlaying) results from median profiles with varied widths. As an example, to evaluate the overall cable barrier performance on 4H:1V slope V-shaped medians, the results from all simulations from this type of median with varied widths are combined.

Figure 5.10 shows the lower cable maximum limits from 4H:1V slope V-shaped medians with varied median widths (5 to 17 m, 16 ft to 56 ft). The minimum of all curves is computed (shown in thick green line in the figure). Similarly, Figure 5.11, shows the upper cable minimum limit

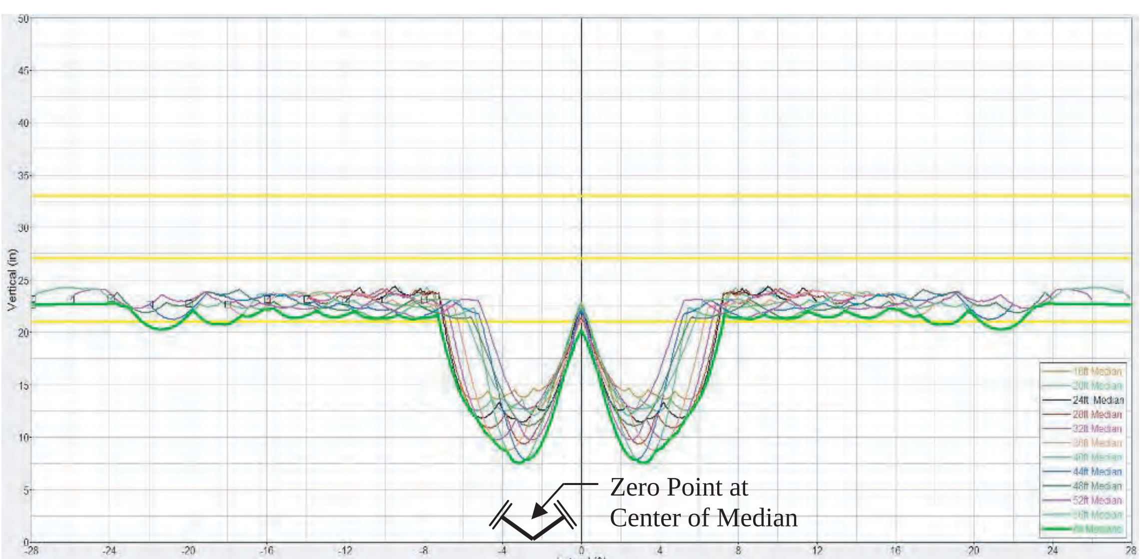


Figure 5.10. Normalized underride limit plot for 4H:1V V-shaped medians, varied widths.

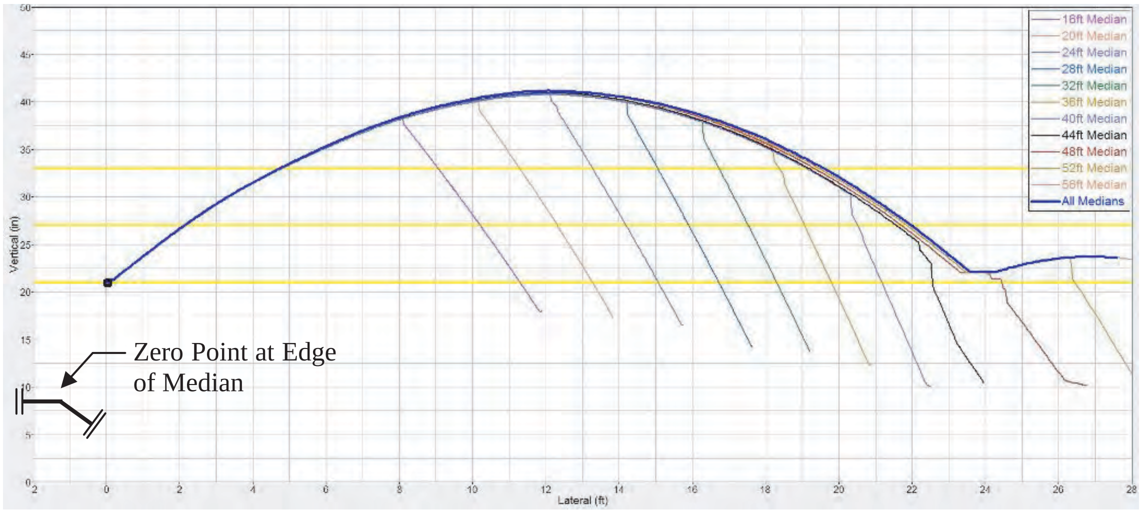


Figure 5.11. Normalized override limit plot for 4H:1V V-shaped medians, varied widths.

for the same medians with varied median widths (5 to 17 m, 16 ft to 56 ft) and the combined maximum curve (thick blue curve). Together, the minimum and maximum curves can be used to assess barrier performance on any 4:1 V-shaped median.

The research considered a wide range of median profiles. The medians varied in shape, slope, and width. For each median profile, simulations with different vehicle types traversing the median at different speeds (from 50 to 100 km/h, 31 to 62 mph) and angles (from 5° to 25°) were performed, and the vehicle trajectory was determined. These trajectories were used to assess vehicle-to-barrier interface when the barrier is placed at different locations across the median. Figures 5.12 and 5.13 present summaries of the results for symmetric V-shaped medians. Figure 5.12 shows the underride limit plots for medians with slopes of 4H:1V, 6H:1V, 8H:1V, 10H:1V, and 12V:1H (with median widths from 5 to 17 m, 16 to 56 ft—not including shoulders). Cable heights of 533, 686, and 838 mm (21, 27, and 33 in.) are included in the plot to assess vehicle engagement

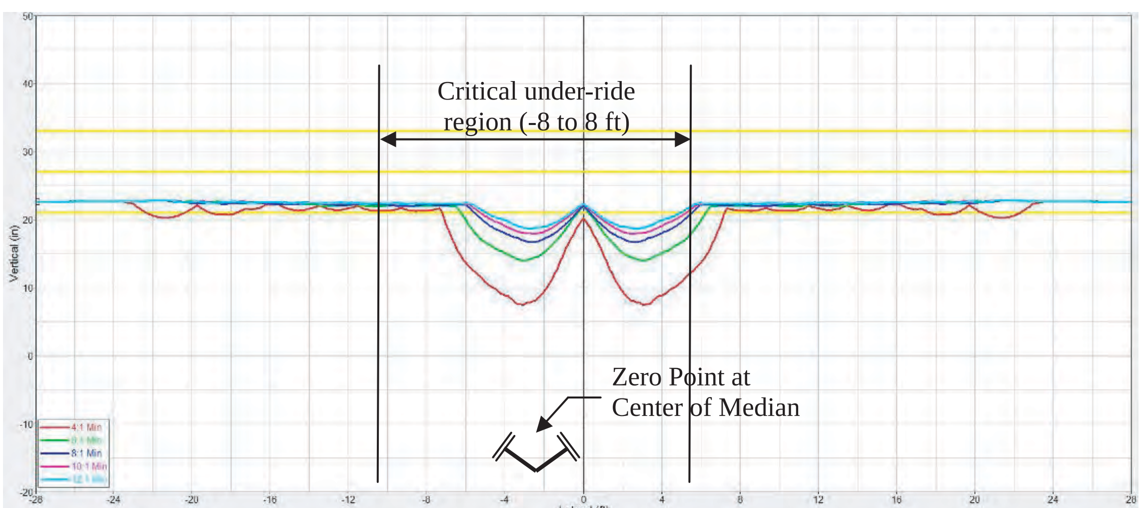


Figure 5.12. Normalized underride limit plot for V-shaped medians 4H:1V to 12H:1V slope, varied width.

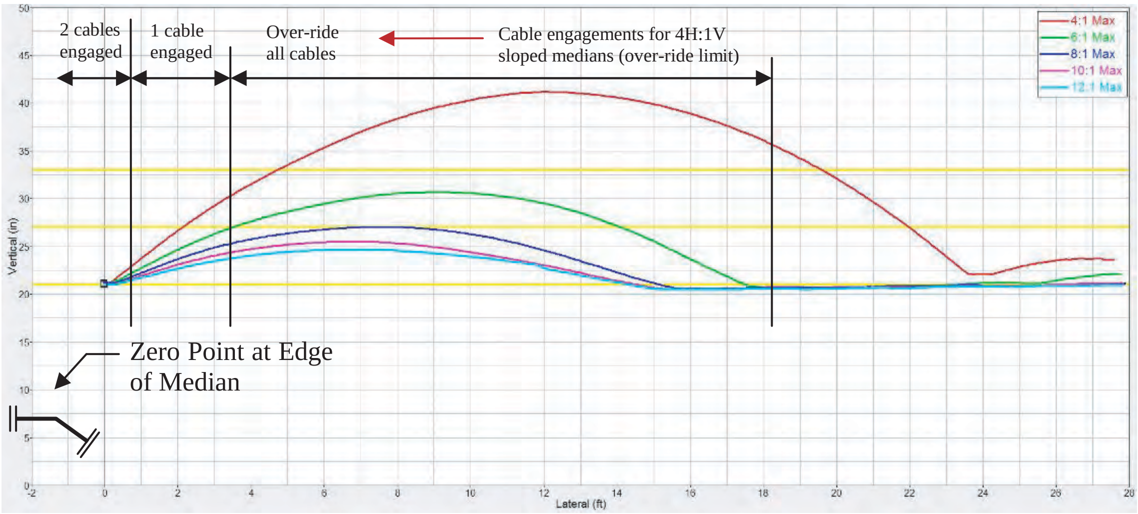


Figure 5.13. Normalized override limit plot for V-shaped medians 4H:1V to 12H:1V slope, varied width.

for systems where the top cable is at least 838 mm (33 in.) and the bottom cable is no higher than 533m (21 in.), which covers the majority of available and installed cable barriers. It can be noticed from the plots that there is potential for underride in the region between 0.3 and 2.4 m (1 ft and 8 ft) from the median center. The plot shows that even for shallow (12H:1V slope) medians there is potential for underride near the bottom of V-shaped medians. In the outer region, farther than 2.4 m (8 ft) from the median center, the results indicate that the vehicle is likely to engage at least one cable if the cable height is at 533 mm (21 in.) or lower. For the center region, between –0.3 and 0.3 m (–1 ft and 1 ft) from the center of the median, the plot shows that the barrier would engage one cable for 6H:1V and shallower slopes, while there is a potential for underride with the 4H:1V slope.

Figure 5.13 shows the override limit plots for symmetric V-shaped medians with slopes of 4H:1V, 6H:1V, 8H:1V, 10H:1V, and 12H:1V. For 4H:1V sloped medians, the results indicate that there is potential for override in the region between 1.2 and 6.0 m (4 ft and 20 ft) from the edge of the median. In the region between 0.6 and 1.2 m (2 ft and 4 ft) and between 6.0 and 6.7 (20 ft and 22 ft) from the edge of the median, the vehicle would likely engage only the top cable. In the region between 0 and .6 m (0 and 2 ft), the vehicle would engage two cables. Similarly, in the region farther than 6.7 m (22 ft) from edge of the median, two cables would be engaged. For medians with slopes flatter than 6H:1V, the plot shows that there is no potential for override, i.e., the vehicle would engage a minimum of one cable if placed anywhere in the median.

Similar plots were generated for flat-bottom medians. The plots; shown in Figures 5.14 through 5.16, include flat-bottom medians with slopes of 4H:1V, 6H:1V, and 8H:1V. For each slope, three depths, 0.6, 1.2, and 1.8 m (2 ft, 4 ft, and 6 ft), were analyzed. A third parameter that was varied is the width of the flat-bottom section, which was varied from 1.2 to 12.2 m (4 ft to 40 ft). The trajectories from all cases (i.e., different flat-bottom median profiles, vehicle type, speed, and angle) were included when generating the underride and override limits. Figure 5.14 shows the underride limit for the three slopes analyzed. The plot shows that for the 4H:1V slope profiles, there is potential for underride in the region between –1.8 and 3 m (–6 ft and 10 ft) from the flat-bottom breakpoint. In the outer region, farther than –1.8 m (–6 ft) in the up-sloped region and farther than 3 m (10 ft) in the flat region, the results indicate that the vehicle is likely to engage at least one cable if the bottom cable height is at 533 mm (21 in.) or lower. For 6H:1V

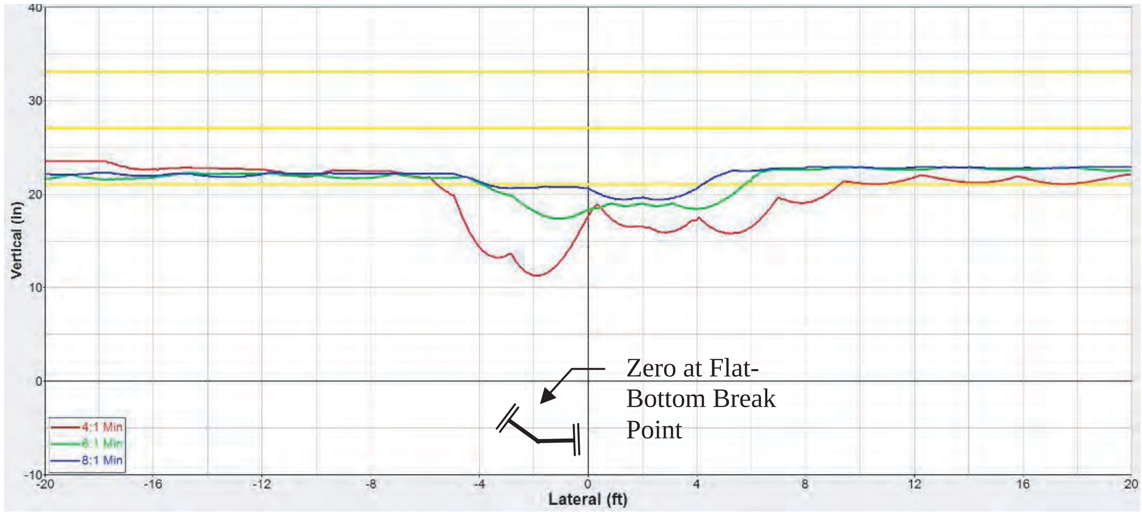


Figure 5.14. Underride limit plot for flat-bottom shaped medians 1.2 to 12.2 m (4 ft to 40 ft) flat-bottom width.

sloped profiles, the underride region is smaller (−1.2 m to 1.5 m [−4 ft to 5 ft] for 6H:1V and −1.2 m to 1.2 m [−4 ft to +4 ft] for 8H:1V).

Figure 5.15 shows a plot similar to Figure 5.14 except that only medians with the flat-bottom section wider than 2.4 m (8 ft) are included. If the flat-bottom section is wider than 2.4 m (8 ft), the plot shows that the barrier will engage the vehicle if it is placed at the flat bottom breakpoint for medians with 6H:1V slopes and shallower.

Figure 5.16 shows the override limit plots for symmetric flat-bottom medians with slopes of 4H:1V, 6H:1V, 8H:1V. The results are very similar to the V-shape profiles. For 4H:1V sloped medians, the region between 1.2 to 6.0 m (4 ft and 20 ft) from the edge of the median shows potential for override. In the regions 0.6 to 1.2 m (2 ft to 4 ft) and 6.0 to 6.7 m (20 ft to 22 ft) from the edge of the median, the vehicle would likely engage the top cable only. In the region between 0 to 0.6 m (0 to 2 ft), the vehicle would engage two cables. Similarly, in the region farther than

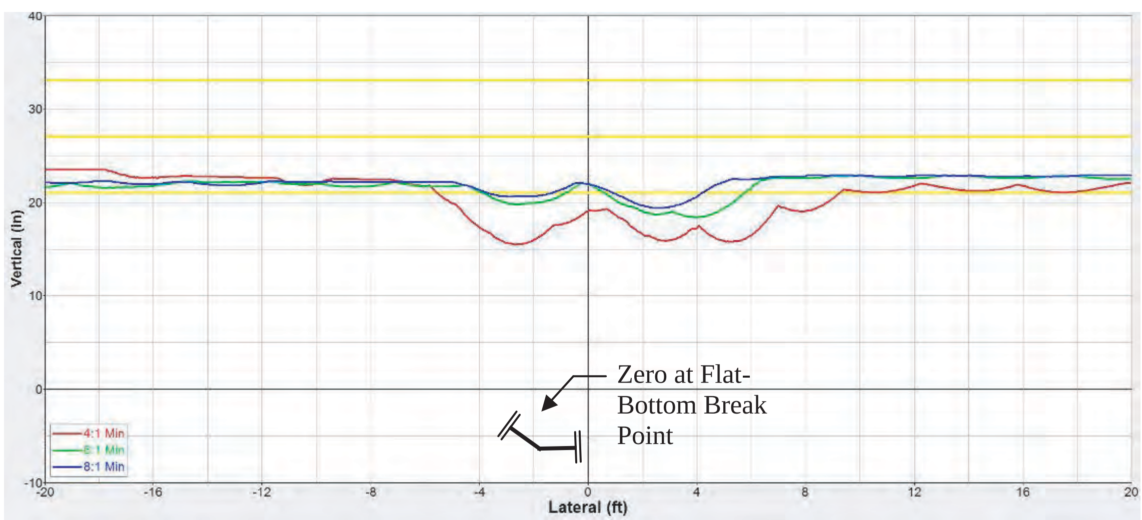


Figure 5.15. Underride limit plot for flat-bottom shaped medians 2.4 to 12.2 m (4 ft to 40 ft) flat-bottom width.

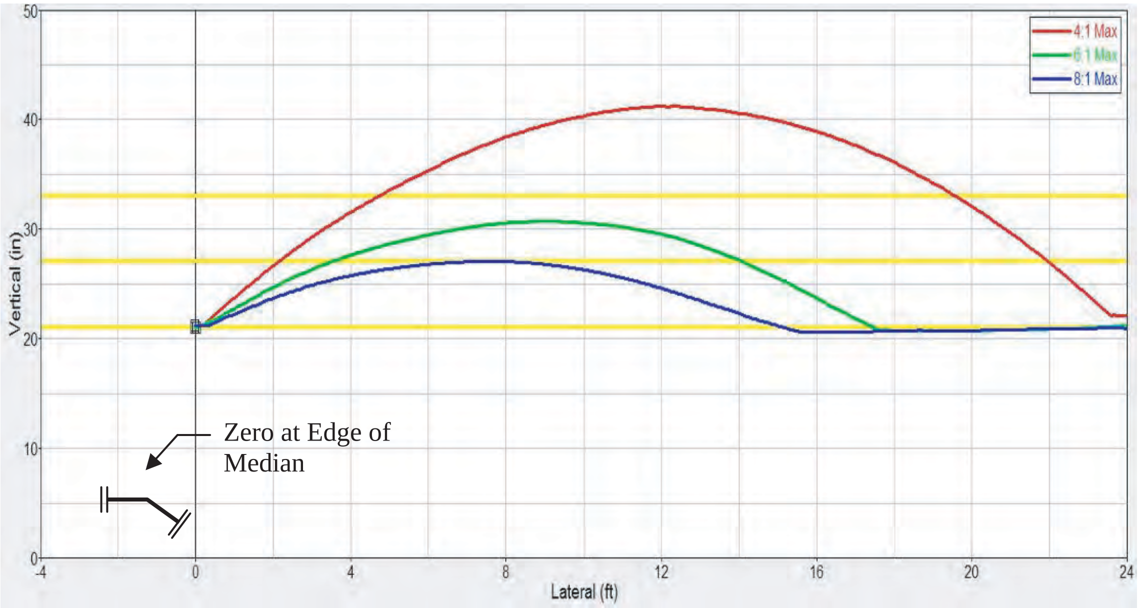


Figure 5.16. Override limit plot for flat-bottom shaped medians.

6.7 (22 ft) from the edge of the median, two cables would be engaged. For medians with slopes flatter than 6H:1V, the plot shows that there is no potential for override, i.e., the vehicle would engage a minimum of one cable if placed anywhere in the median.

Vehicle dynamics analyses were conducted to investigate vehicle-to-barrier interactions on non-symmetric medians. Figure 5.17 depicts a typical override and underride plot from these analyses. The plot shows that the side with the shallower slope is less susceptible to overrides. The underride region is similar on both sides of the median. Comparing this plot to symmetric medians, similar observations can be made for the critical override and underride regions.

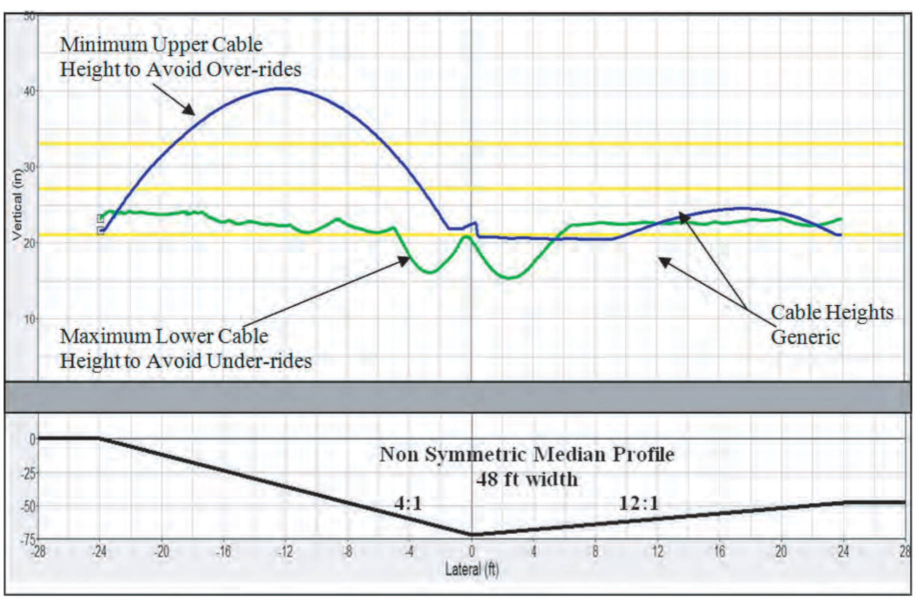


Figure 5.17. Sample underride and override limit plot for non-symmetric medians 4H:1V and 12H:1V slope—14.6 m (48 ft) median width.

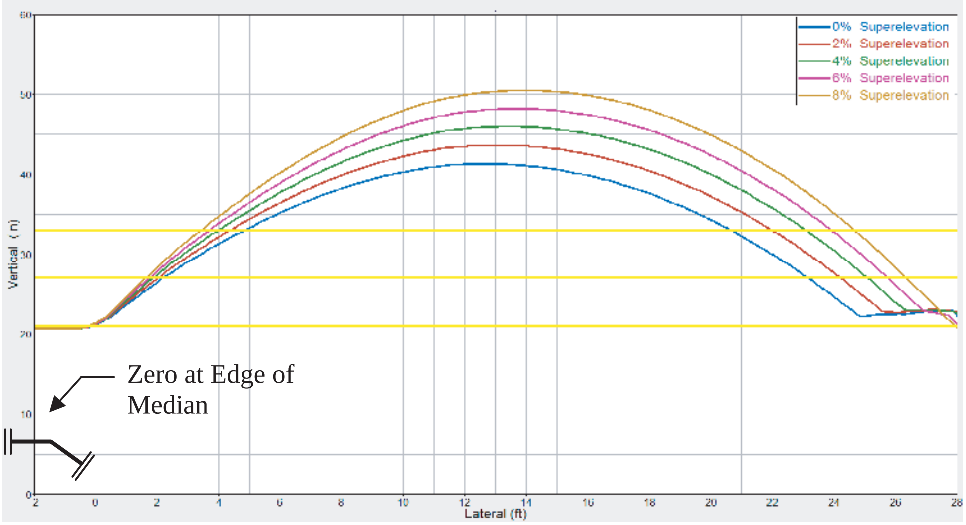


Figure 5.18. Override limit plots for 4H:1V slope medians at varied superelevations.

To investigate the effects of superelevation on vehicle to barrier interface, vehicle dynamics simulations with varied superelevations (0 percent, 2 percent, 4 percent, 6 percent, and 8 percent) were conducted. Two symmetric V-shaped medians, with 4H:1V and 6H:1V side slopes, were used in the analysis. The width of both medians was 17 m (56 ft), from break point to break point (similar results are expected for other median types and widths).

Simulations with varied vehicle types, initial speeds, and approach angles were performed to investigate the superelevation effects on the vehicle trajectories. The simulation results showed that higher superelevation increases the chance of overrides. This is especially critical for medians with steep side slopes (steeper than 6H:1V). Figures 5.18 and 5.19 show the normalized override limit plots for the 4H:1V and 6H:1V sloped medians, respectively. It can be noticed from the figures that the vehicle height relative to ground level increased with increased superelevation. The simulation results showed that the superelevation had negligible effects on the underride limit plots.

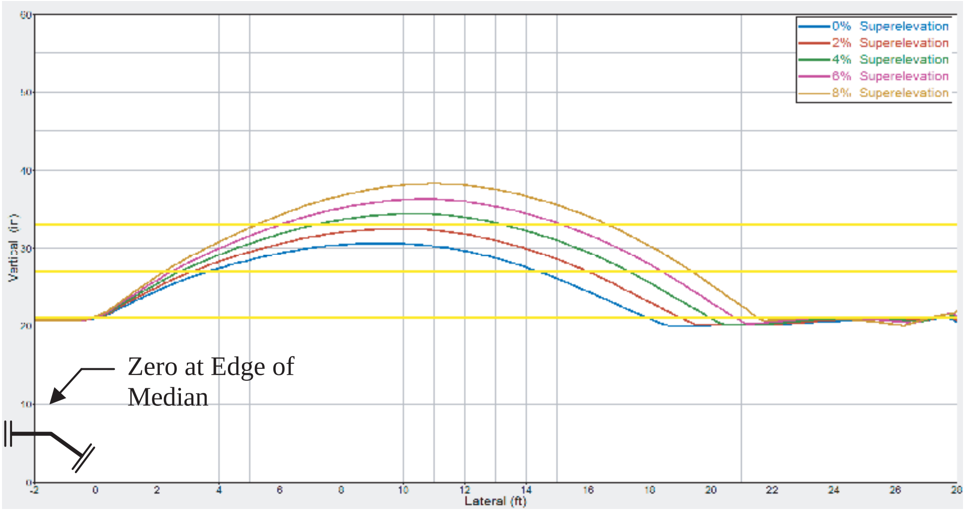


Figure 5.19. Override limit plots for 6H:1V slope medians at varied superelevations.

5.2 Cable Barrier Deflection

The dynamic deflection of a cable barrier during impact is an important characteristic for many reasons. Compared to semi-rigid W-beam barriers and rigid concrete barriers, cable barriers have greater deflections, which is the reason that cable barriers typically are more forgiving to the impacting vehicle's occupants. For the barrier to be safe, adequate space behind the barrier that is clear of hazards must be provided to accommodate the expected deflections. If deflections exceed the space provided, the errant vehicle could impact rigid objects behind the barrier, or worse yet, in median applications on divided highways, cross into opposing traffic.

Various cable barrier systems have been crash-tested successfully and accepted for use on U.S. highways. High-tension cable systems, when compared to low-tension systems, have lower deflection during impacts and reduced maintenance costs. NCHRP Report 350 and MASH require that dynamic deflections observed in the crash tests be reported. These requirements do not standardize all of the test installation features for cable barrier systems. For example, cable barriers are typically tested at 90 to 180 m (300 to 600 ft) installation lengths with the cables anchored at both ends. However, field installations on U.S. highways are typically much longer with anchor-to-anchor distances more than 10 times longer than the ones used in crash tests. With longer anchor-to-anchor spacing, the deflection of the barrier could be significantly higher and could lead to higher likelihoods of barrier penetration. Barrier deflection is also affected by the spacing between the posts, the strength of the posts, the connection between the cable and posts, and the amount of tension in the cable. Understanding the influence of these features on deflection during impact is critical to making effective design decisions about the features of cable barrier systems.

To evaluate the influence of critical installation parameters, such as end-anchor spacing, cable tension, post spacing, etc., on cable barrier deflection, crash scenarios with varied configurations have to be analyzed. To conduct such analyses using only full-scale crash tests would be very costly. Additionally, conducting full-scale crash tests with very long cable barrier installations (300 m [980 ft] and longer) is often not practical and beyond the capabilities of most test facilities. The approach used in this study is based on the coupling of full-scale crash testing with computer simulations using the LS-DYNA finite element program [53]. First, the cable barrier modeling approach was validated using previously conducted full-scale crash tests. Several full-scale crash tests with varied barrier design, barrier length, and post spacing were used in the validation process. Upon completing the validation of the modeling approach, a matrix of simulations with varied design parameters and installation configurations was run to investigate the effects on cable barrier deflection. The installation configuration variations included the following:

- End-anchor spacings—Anchor spacings of 100 m (328 ft) (typical spacing used for NCHRP 350 crash tests), 200 m (656 ft), 300 m (984 ft), 500 m (1,640 ft), and 1,000 m (3,280 ft).
- Initial cable tensions in the system before impact—Cable tensions, 15 kN (3.4 kips) and 24 kN (5.4 kips). These tensions approximately represent typical hot weather (38°C, 100°F) and average weather (10°C, 50°F) conditions, respectively, for high-tension cable barriers.
- Post spacings—Post spacings of 1.6 m (5 ft), 3.2 m (10 ft), 4.8 m (15 ft) and 6.4 m (20 ft).

Five systems were selected for the analyses: Brifen Wire Rope Safety Fence, Gibraltar Cable Barrier System, Nucor Steel Marion Cable Barrier System, Safence Cable Barrier System, and Trinity CASS Cable Barrier System. Information was collected for these five systems, including design drawings, crash test reports, crash test video clips, test data, and acceptance letters. The information for these five proprietary systems was obtained from the manufacturers. These systems are available in different configurations. One system from each cable barrier manufacturer was selected. To assist in the selection, the team contacted the manufacturers to get their feedback on which system should be selected. When selecting the systems, emphasis was placed on choosing systems that are most commonly installed and have multiple full-scale crash test data available. This process ensured that the computer models could be validated fully with crash test data and that the analyzed systems would represent the majority of installed systems.

NCAC models for standard NCHRP Report 350 test vehicles were used in the simulations. These included the Chevrolet C2500 pickup truck (2000P) model and the Geo Metro (820C) vehicle models. These vehicle models were originally validated and subsequently updated over years of application in many crash simulation efforts [54, 55, 56]. These models conformed to the test vehicles reflected in the available crash test data. Since maximum dynamic deflections were the metric of interest, impacts with the 2000P vehicle at 100 km/h (62 mph) and 25° impact angle were the focus. Similar impact location along the barrier was used for all simulations. The impact location was selected such that the maximum deflection would occur at the center of the barrier installation. Simulations with all of the above-stated installation variations were carried out, and the results are presented to show the effects on deflection of end-anchor spacings, post spacings, and initial cable tensions.

Model Development and Validations

Highly detailed computer models of cable barrier systems were created and used in this study. A sophisticated modeling approach was used in creating these models to ensure that they would accurately capture the barrier response during simulation of the crash. The approach used in modeling the different cable barrier systems is described in the following sections.

To create the finite element models of the cable barrier systems, several key features were examined carefully, and appropriate modeling techniques were used to ensure that the models were accurate representations of the actual systems. First, explicit geometry of all components of the system was incorporated in the model including, for example, the cables, the posts, the sleeves, etc. This step was important to ensure that the correct mass, inertia, and stiffness of the different parts are reflected in the model. The soil and concrete were also modeled explicitly using solid elements. The shape of the post/sleeve was incorporated in the soil or concrete mesh to simulate the post/soil interactions. The cables for the models were created using beam elements with the cross-sectional and material properties of the specified cable. To replicate the cable-to-vehicle and cable-to-post interactions accurately, each beam was surrounded by shell elements with null material properties. The beams were connected to the null shell elements using nodal rigid body connections. The necessary initial stress was applied to the beam elements in the initialization phase of the simulation to simulate the pre-crash tension in the cables. For all systems, the connection between the cables and end anchor was considered rigid.

To validate the modeling approach, computer simulations, setup in a similar configuration to the full-scale crash tests, were conducted and the results were compared to the tests. Full-scale crash tests, with varied barrier design, end-anchor spacing, and post spacing were used in the validations. Some of these validations are described in the following sections.

Gibraltar Cable Barrier System

The three-cable, high-tension median cable barrier from Gibraltar Cable Barrier Systems was accepted by the FHWA for use on U.S. highways [57, 58]. This cable barrier system consists of three 19 mm (¾ in.) diameter steel cables supported by steel 83 × 63.4 × 3.8 mm thick (3.25 × 2.5 × 0.15 in. thick) and 1,500 mm (4.9 ft) long C-posts. The bottom, middle, and top cable heights are set at 508 mm (20 in.), 762 mm (30 in.), and 990 mm (39 in.), respectively. The three cables are locked in place using an 11 mm (7⁄16 in.) diameter galvanized steel hairpin and lock plate that fits inside each post. The finite element model of the Gibraltar cable barrier system was created and validated with two full-scale crash tests. The full-scale crash tests were conducted by Karco Engineering, LLC (Test Report No. TR-P26021-01-B and TR-P26028-01-B). Figure 5.20

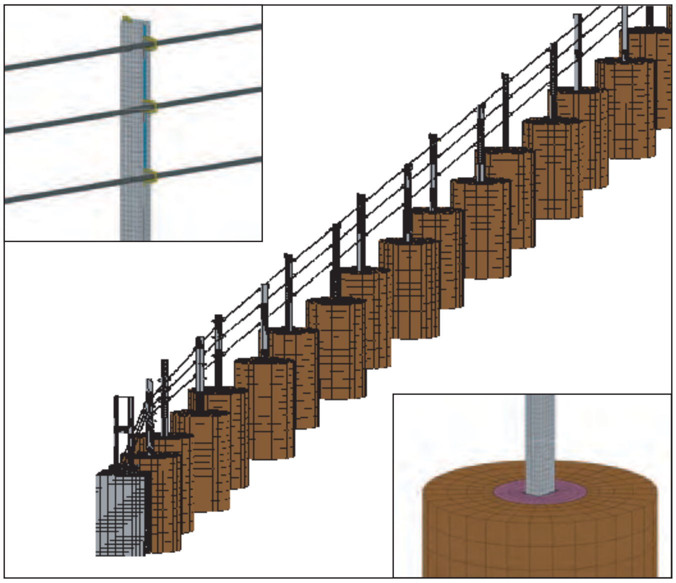


Figure 5.20. Finite element model of the Gibraltar cable barrier system.

shows the details in the finite element model of the Gibraltar cable barrier system. The geometry and design details of all components were obtained from FHWA acceptance letters. The total installation length for both tests was 93 m (305 ft), and the cables were tensioned to 25 kN (5.7 kips). For the first test, the line posts were set on 3 m (10 ft) centers and for the second test, 9.1 m (30 ft) centers. For both tests, a 2000P C2500 vehicle was used, the impact angle was 25°, and impact speed was 100 km/h (62 mph).

Figure 5.21 shows side-by-side comparisons of sequential images from the first crash test and its simulation. In the simulation, the two top cables engaged and redirected the vehicle with a maximum dynamic deflection of 1.9 m (6.4 ft), and the maximum dynamic deflection for the crash test was 2.0 m (6.8 ft). Figure 5.22 shows side-by-side comparisons of sequential images from Crash Test 2 and its simulation. In the simulation, the two top cables engaged and redirected the vehicle with a maximum dynamic deflection of 2.9 m (9.5 ft), and the maximum dynamic deflection for the crash test was 2.8 m (9.3 ft).

Safence Cable Barrier System

The Safence Wire Rope Barrier produced by Blue Systems was accepted as an NCHRP Report 350 TL3 traffic barrier in 2001 [59]. The original design consisted of four 19 mm (¾ in) diameter steel cables supported on 2.1 m (83 in) long elliptically shaped posts spaced on 2.5 m (8.2 ft) centers. In its current design [60], the cables are supported using Safence C-shaped posts embedded in concrete footings. Each post was stiffened at the ground line by adding a steel plate inside the C-post to increase its resistance to bending, and a steel hook was added to the top of each post to retain the cables within the post center slot for a longer time upon barrier impact.

The finite element model of the Safence system was developed and validated using a VTI crash test (Test Report No. 56649). The design drawings and details were obtained from the FHWA acceptance letter [61] and manufacturer's drawings. Figure 5.23 shows details of the finite element model of the Safence cable barrier system.

The overall dynamics of the vehicle in the finite element simulation were similar to those reported in the crash test. The maximum dynamic deflection for the simulation was 3.6 m

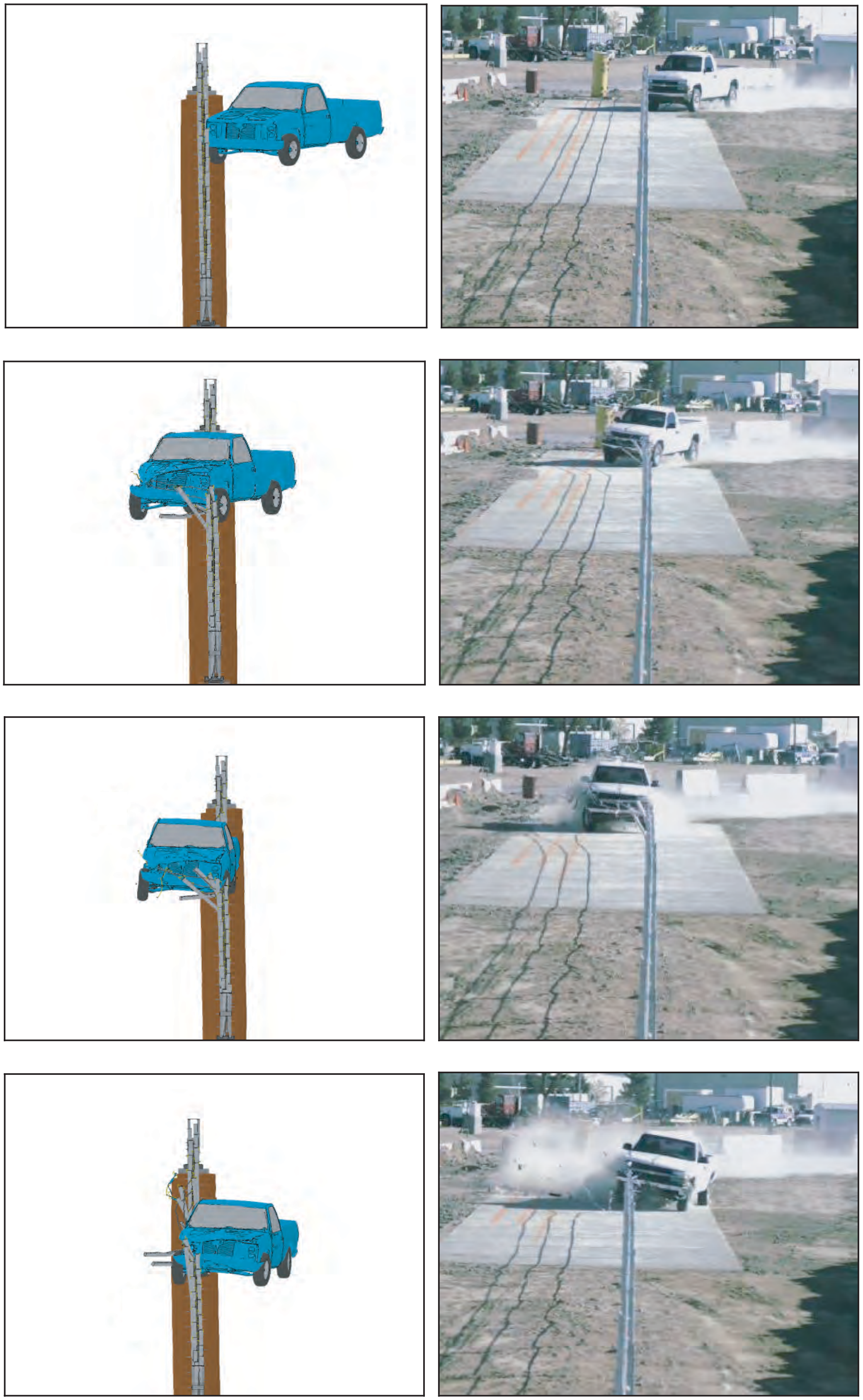


Figure 5.21. Comparison of sequential plots; Gibraltar Test 1.

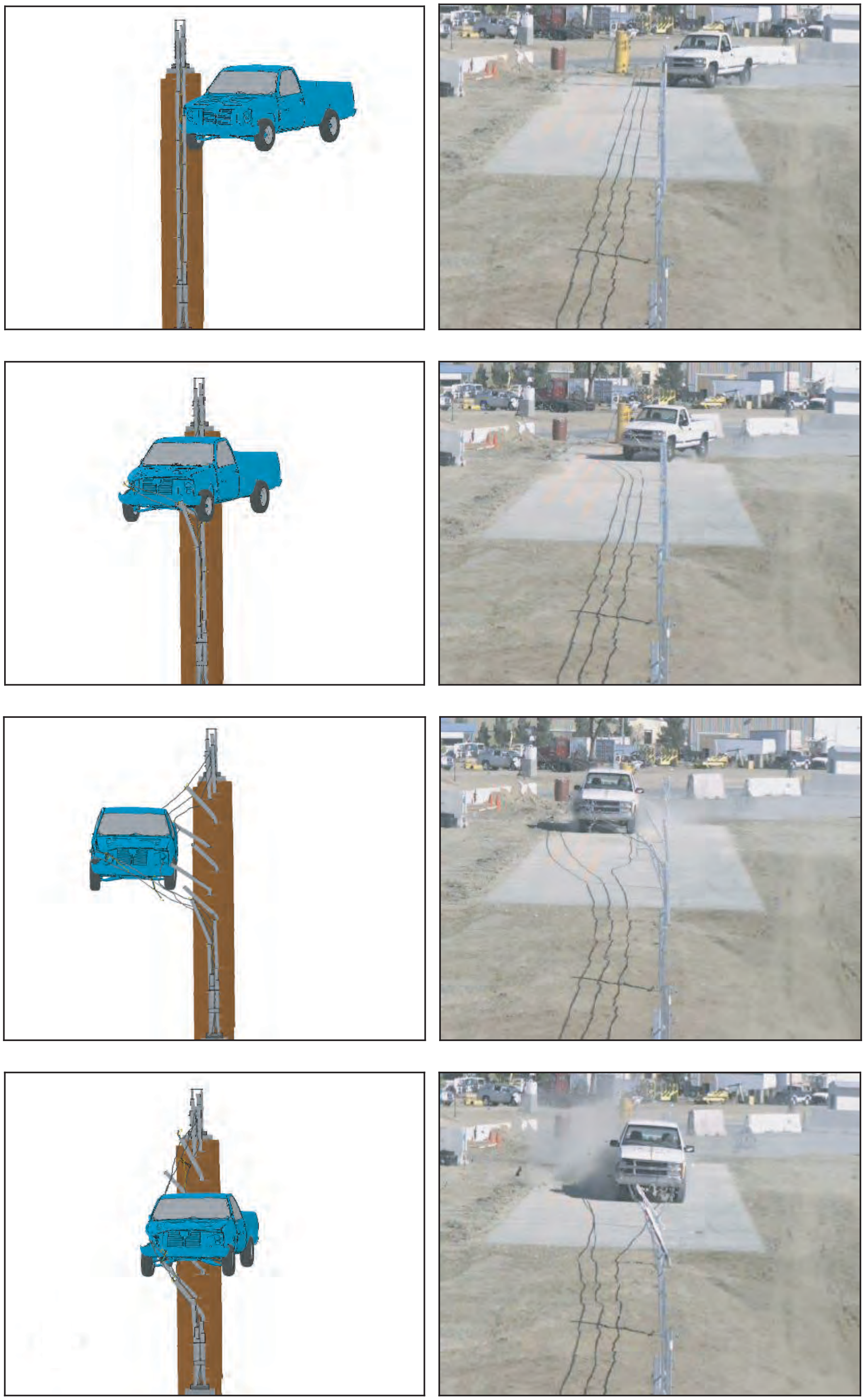


Figure 5.22. Comparison of sequential plots; Gibraltar Test 2.

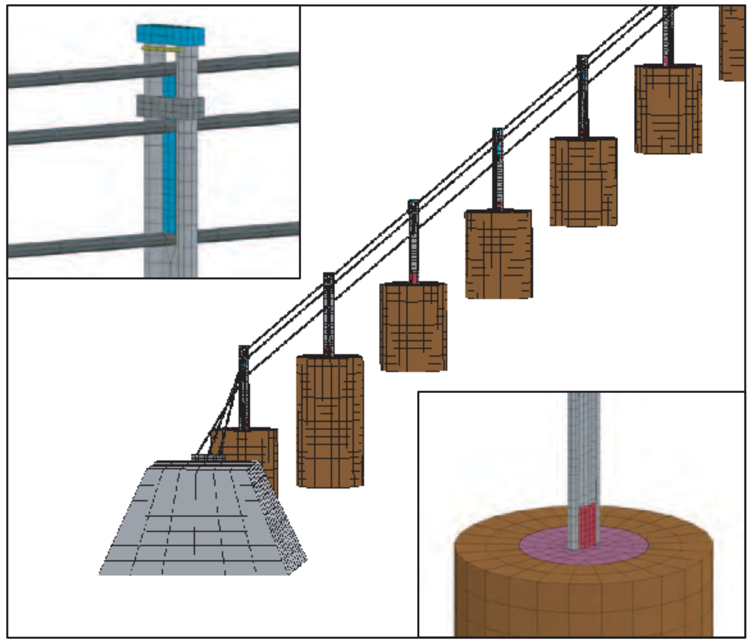


Figure 5.23. Finite element model of the Safence cable barrier system.

(11.7 ft) and for the crash test, 3.7 m (12.1 ft). Side-by-side comparisons of sequential images of the test and simulation are shown in Figure 5.24.

Brifen Cable Barrier System

Brifen Cable Barrier Systems incorporate a proprietary interweaving concept. The systems have 19 mm (¾ in) cables supported by S-shaped posts that are 100 mm × 55 mm × 4.55 mm thick (4 in. × 2 in. × 0.18 in.) and manufactured from ASTM A-36 steel. The top cable is set in a 101 mm deep × 22 mm (4 in. × 1 in.) wide slot cut into the top of each post and bottom cables (two in case of a 3-cable system and three in case of a 4-cable system) are interwoven between the posts.

Figure 5.25 shows the details of the finite element (FE) model of the Brifen wire rope system. The FE model was validated using two full-scale crash tests (Test B-USA-C-2 and Test BCR-1).

In the first test, the test vehicle was a 2000P C2500 pickup truck impacting a 3-cable system at a 25° angle and 100 km/h (62.1 mph). The test article, installed on flat terrain, had a total length of 278 m (912 ft) and post spacings of 3.2 m (10.5 ft). Figure 5.26 shows side-by-side comparisons of sequential images from the test and simulation. In both cases, the top two cables engaged and redirected the vehicle. Maximum dynamic deflection observed in the test was 2.6 m (8.6 ft) and, in the simulation, 2.7 m (8.9 ft). The overall dynamics of the vehicle showed a good correlation with the test. Figure 5.27 shows the comparison of vehicle CG yaw between the test and simulation.

In the second test, the vehicle was a 2000P C2500 pickup truck impacting a 3-cable system at a 25° angle at 100 km/h (62 mph). The test article, installed on flat terrain, had a total length of 111 m (365 ft) and post spacings of 3.2 m (10.5 ft). Figure 5.28 shows side-by-side comparisons of sequential images from the test and simulation. Vehicle behavior in the simulation showed

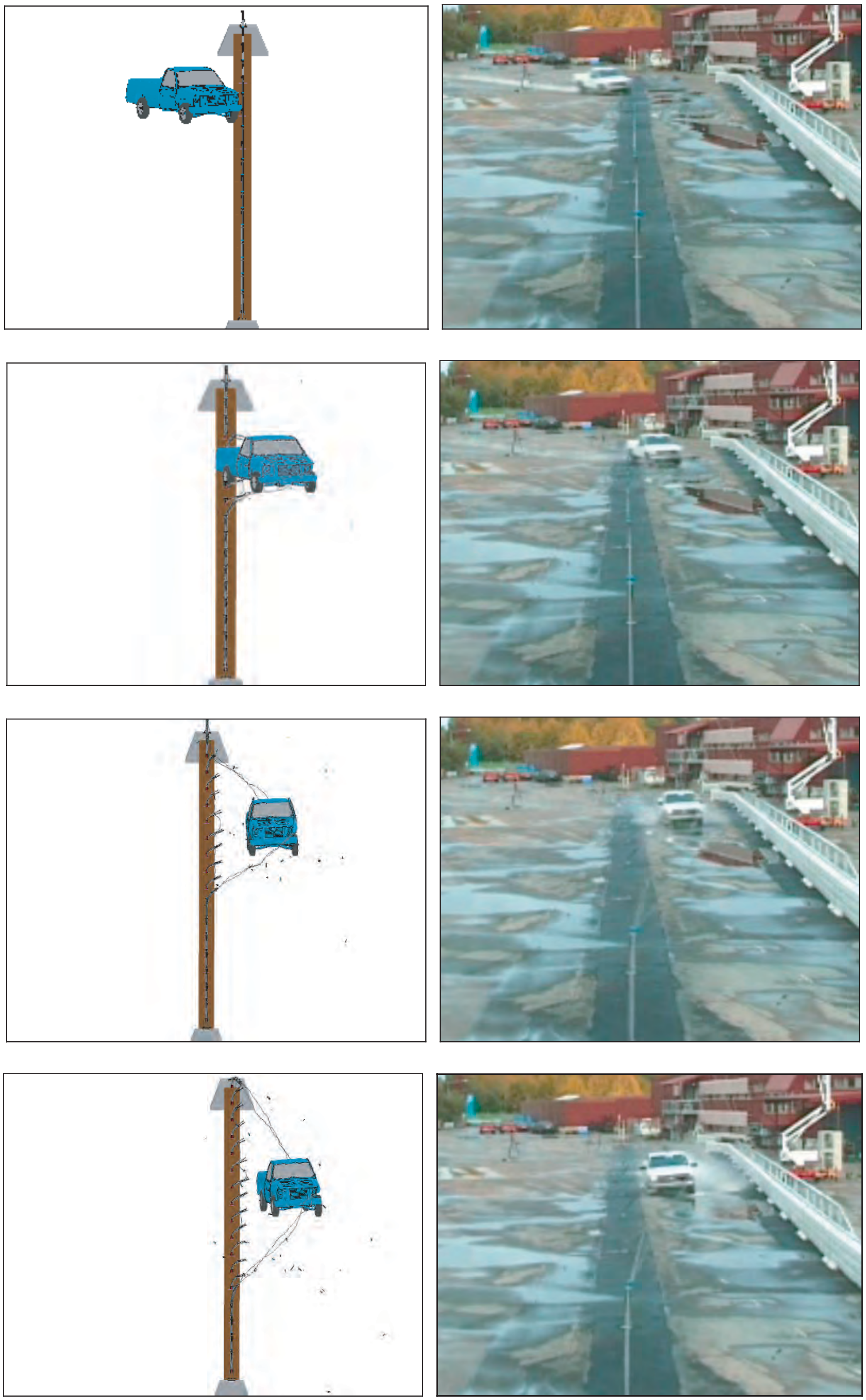


Figure 5.24. Comparison of sequential plots; Safence cable barrier system.

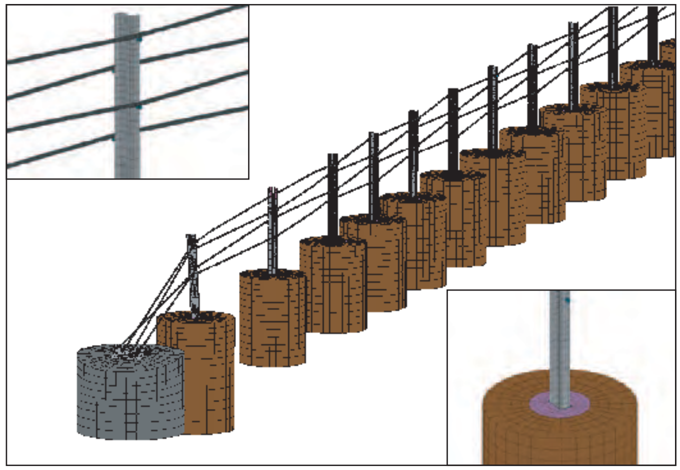


Figure 5.25. Finite element model of the Brifen wire rope system.

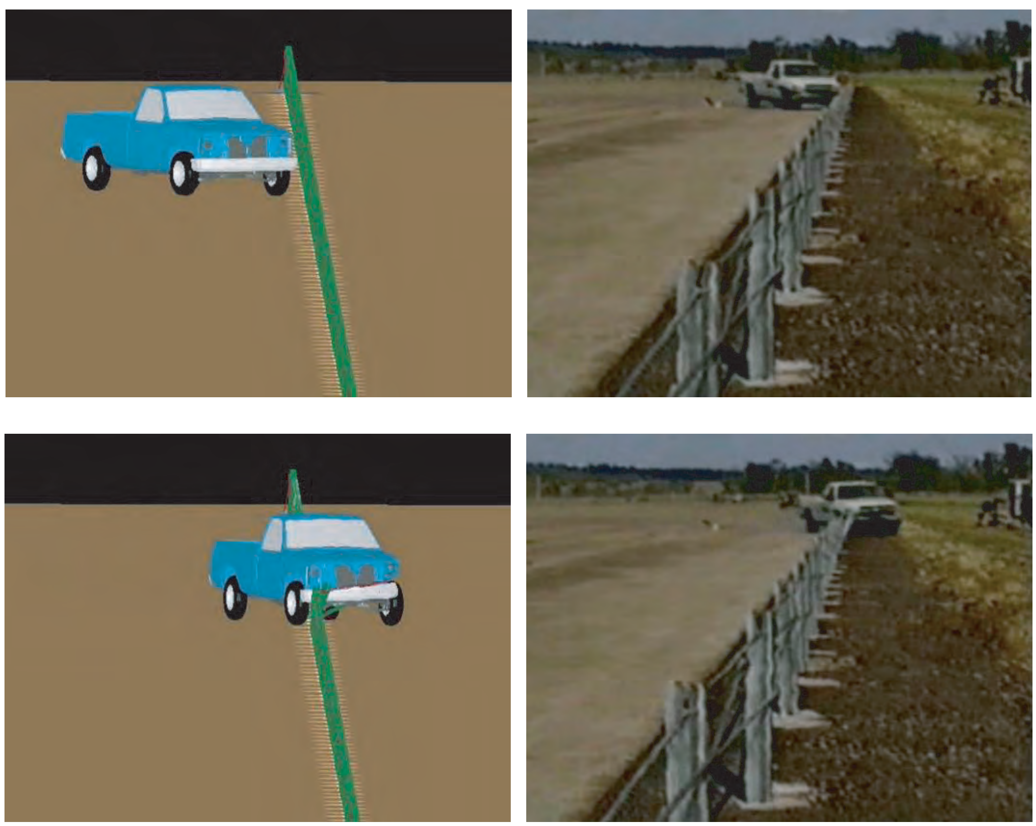


Figure 5.26. Comparison of sequential plots; Brifen Test 1.

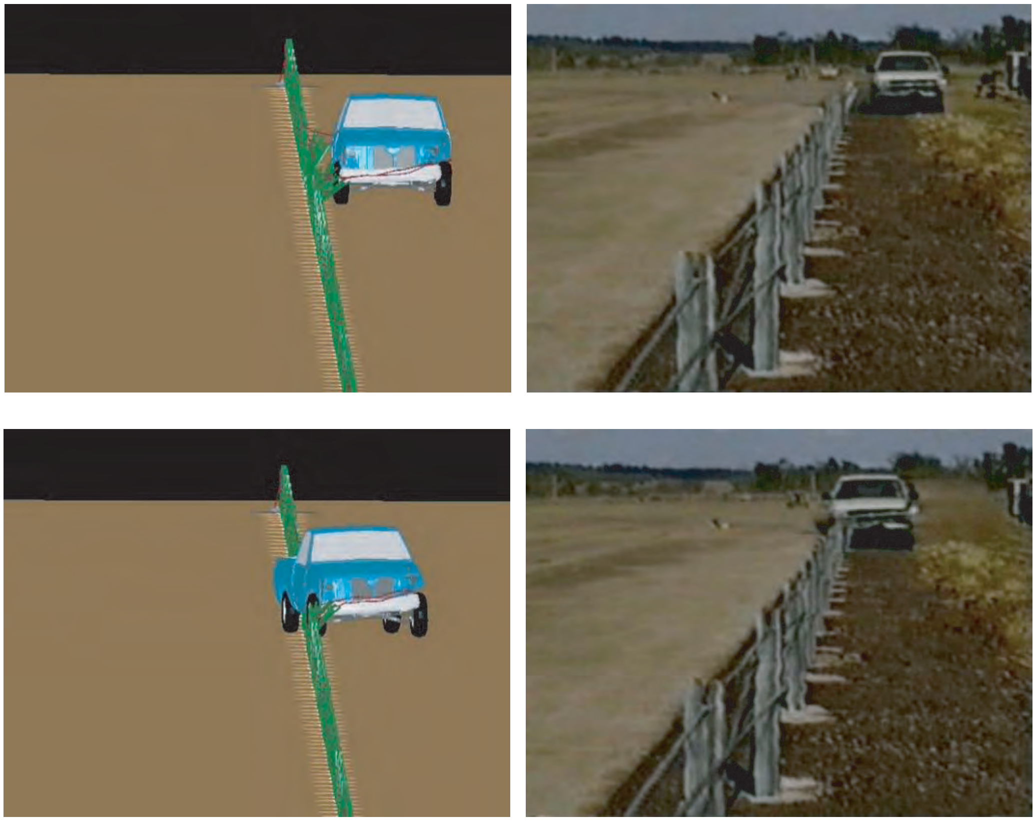


Figure 5.26. **(Continued).**

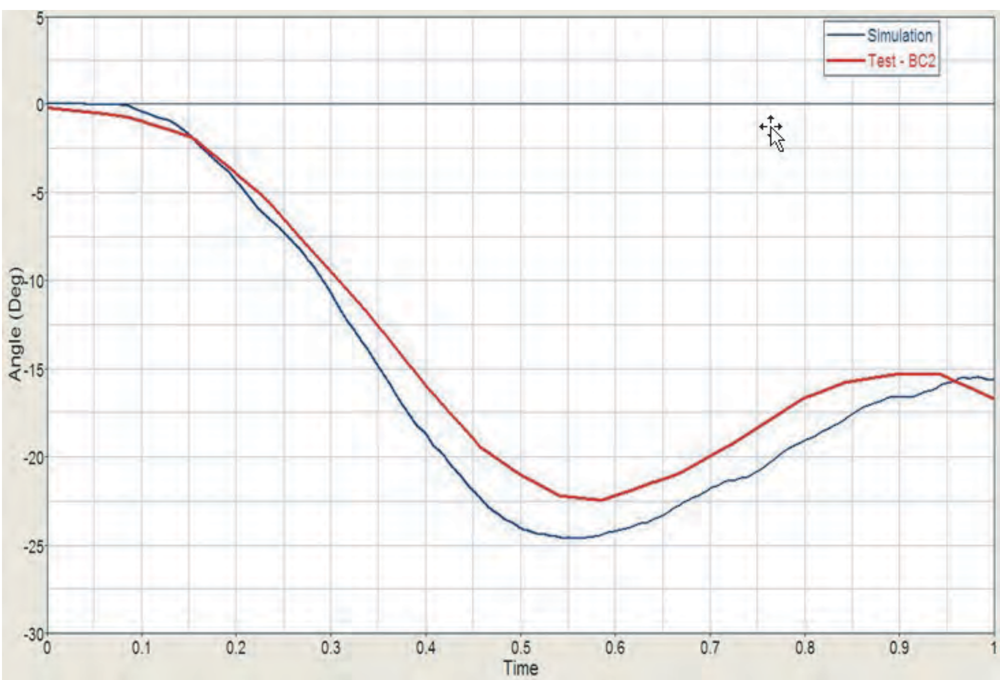


Figure 5.27. Vehicle yaw comparison; Brifen Test 1.

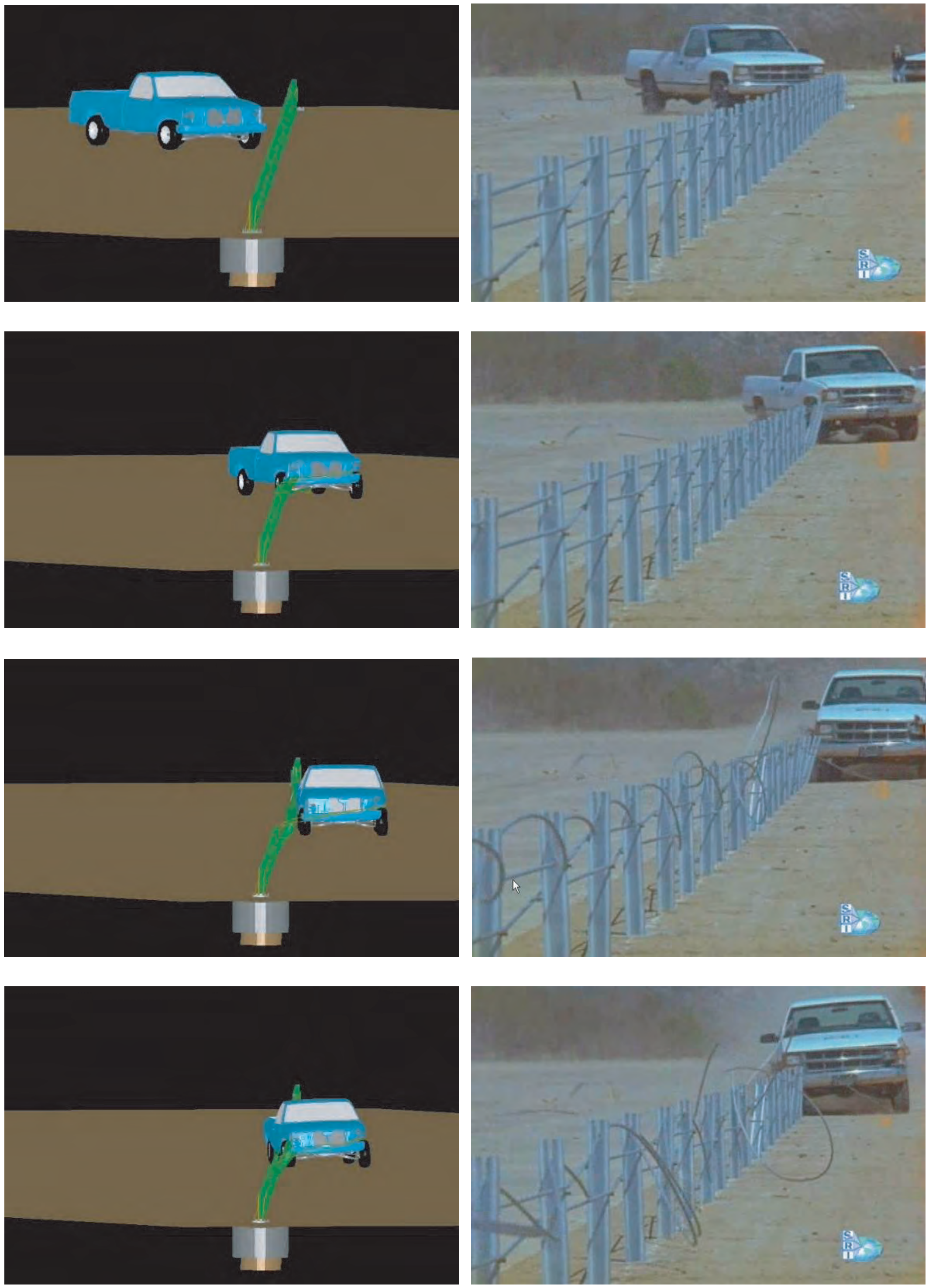


Figure 5.28. Comparison of sequential plots; Brifen Test 2.

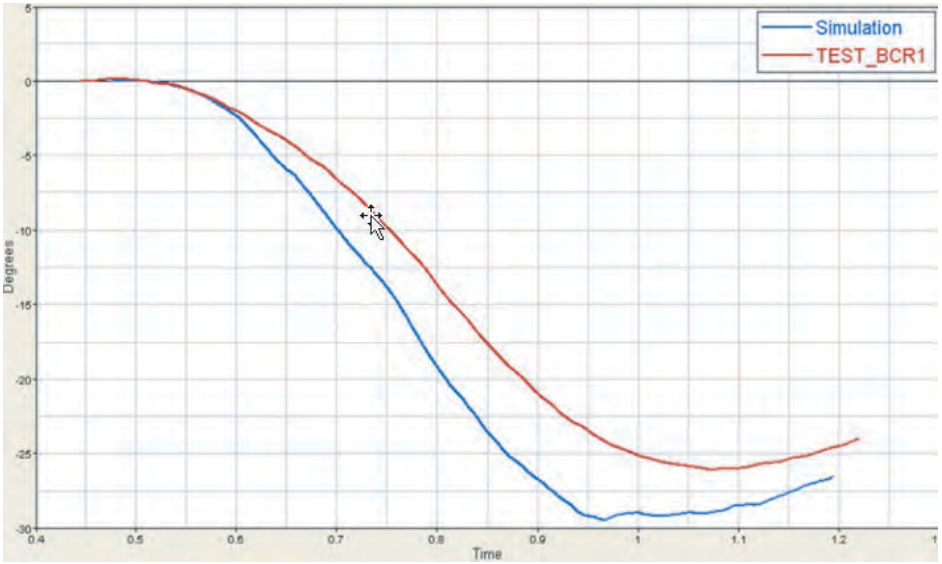


Figure 5.29. Vehicle yaw comparison; Brifen Test 2.

a good correlation with the test. Maximum dynamic deflection observed in the test was 2.1 m (6.9 ft) and, in the simulation, 2.2 m (7.3 ft). Figure 5.29 shows the vehicle yaw comparison between the test and simulation.

Trinity CASS Cable Barrier System

The details of the finite element model of the Trinity CASS Cable Barrier System are shown in Figure 5.30. The system consisted of three 19 mm (3/4 in) steel cables supported on posts that were spaced 3 m (10 ft) apart. The posts were installed in concrete foundations that were 300 mm (1 ft) in diameter and 760 mm (2.5 ft) deep. The test vehicle was a 2000P C2500 pickup. The impact speed was 100 km/h (62 mph), and the impact angle was 24.2°. The total installation length was 102 m (335 ft).

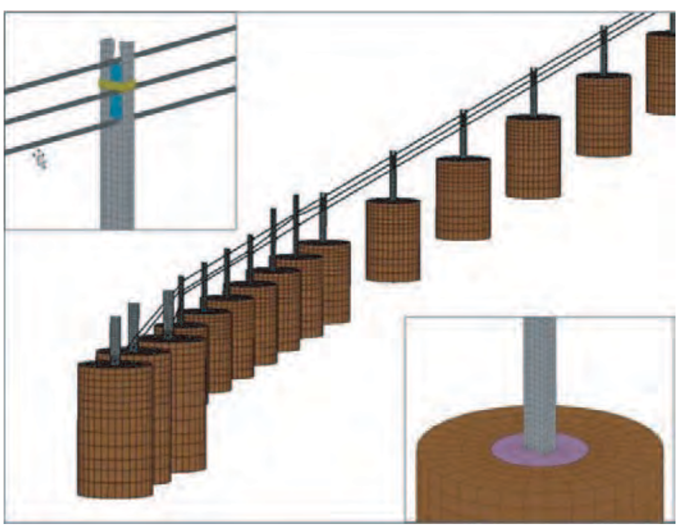


Figure 5.30. Finite element model of the CASS cable barrier system.

In both the test and simulation, the top two cables engaged the vehicle and redirected it. The maximum dynamic deflection for the simulation was 2.5 m (8.1 ft) and, for the crash test, 2.4 m (7.9 ft). Comparisons of the limited sequential plots are shown in Figure 5.31. The vehicle trajectories in the crash test and simulation show good comparison.

Nucor Cable Barrier System

The details of the finite element model of the Nucor cable barrier system was created and used for validation (Figure 5.32). This system uses three 19 mm (0.75 in.) steel 3 × 7 cables. The cables are attached to 6 kg/m (4 lb/ft) U-channel steel posts using locking hook bolts, 6.4 mm (0.25 in.) in diameter. The three cables are placed at heights of 545 mm (21.5 in.), 650 mm (25.6 in.), and 750 mm (29.5 in.). Two of the cables (top and bottom) are placed on one side of the posts while the other cable (middle) is placed on the opposite side. The posts are spaced at 3.8 m (12.5 ft) and anchored using 100 mm (4 in.) diameter 12-gauge steel pipe sockets embedded in a 300 mm (12 in.) diameter by 760 mm deep reinforced concrete footing and embedded in soil with a trapezoidal soil plate. The barrier length was 101.4 m (333 ft).

In both the test and simulation, the top two cables engaged the vehicle and redirected it. The maximum dynamic deflection for the simulation was 1.9 m (6.2 ft) and, for the crash test, was 1.8 m (5.9 ft). Comparisons of sequential plots from the simulation and test are shown in Figure 5.33.

Simulation Results

After completing the development of finite element models of the available cable barrier systems and validating them by comparison to previously conducted full-scale tests, computer models reflecting various post spacings, end-anchor spacings, and cable initial tensions were created. In all cases, the barrier was set up on flat, level terrain and impacted with the 2000P (Chevrolet C2500) pickup truck at 100 km/h (62 mph) initial speed and 25° impact angle. The posts in all systems were placed in sockets embedded in concrete foundations. The systems used in these simulations do not have the exact design as the ones used for the validations. The designs were chosen based on consultations with the cable barrier manufacturers to select the systems that are most commonly installed and most crash-tested. It is important to note that not all systems selected for the analysis use the same number of cables.

Cable Initial Tension Effects

Figure 5.34 shows barrier deflections for two different systems at two initial tension levels (15kN and 24 kN, 3.4 and 5.4 kips) and varied barrier lengths (100 to 1,000 m, 328 to 3,280 ft). The simulations showed that lower initial tension leads to increased barrier deflection. However, the magnitude of the increase in deflection is small compared to the actual deflection. The simulations showed that the maximum tension reached in the cables at the end anchors to be four to five times higher than the initial tension. A reduction in initial tension from 24 kN to 15 kN (5.4 to 3.4 kips), 38 percent, would therefore have less of an effect on the significantly higher maximum tension and, consequently, small effects on barrier deflection.

Full-scale crash tests showed that barrier deflections from generic low-tension cable barrier systems are significantly higher (almost twice) than those observed in the high-tension systems. The reason for this difference in deflection between low-tension and high-tension systems seen in the crash tests is attributed more to the cable/post connections than the initial tension. Most high-tension systems have a significantly stronger cable-to-post connection (by weaving the cables, using a splice at the center of the post, etc.) than the low-tension systems (which typically use open

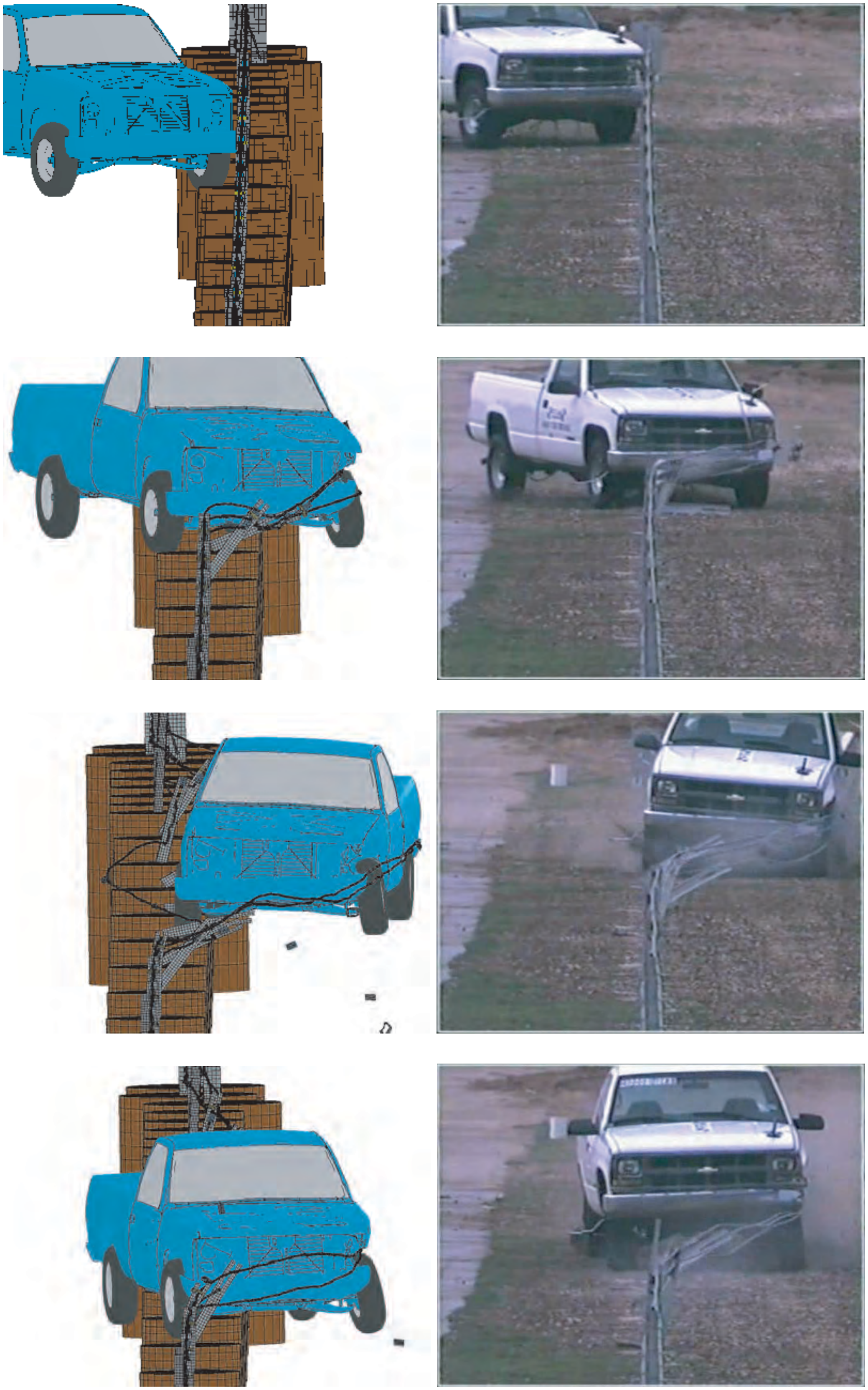


Figure 5.31. Comparison of sequential plots from CASS simulation.

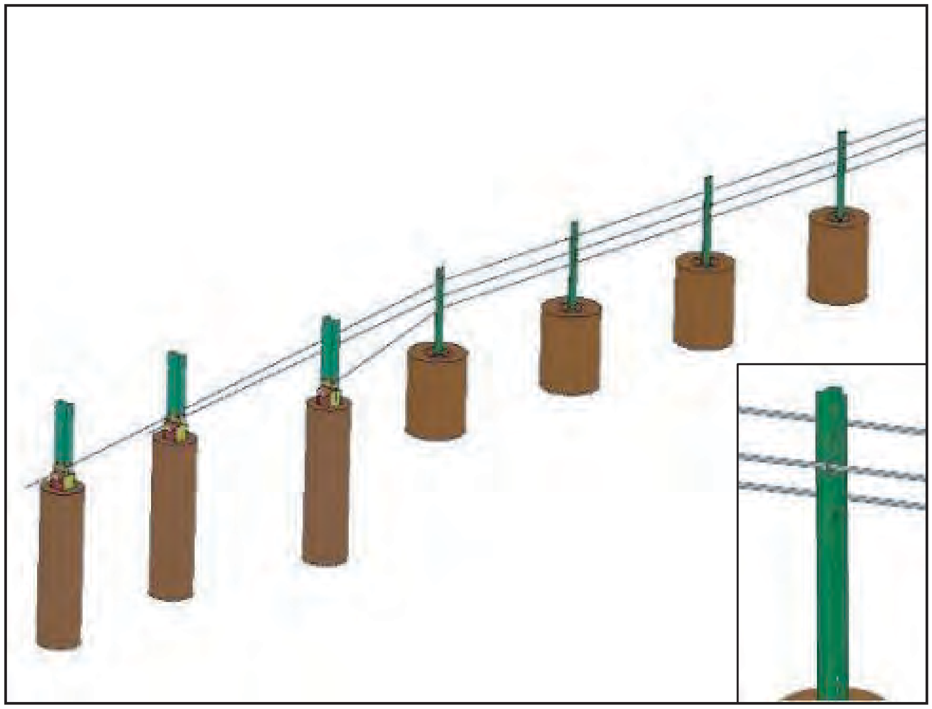


Figure 5.32. Finite element model of the Nucor cable barrier system.

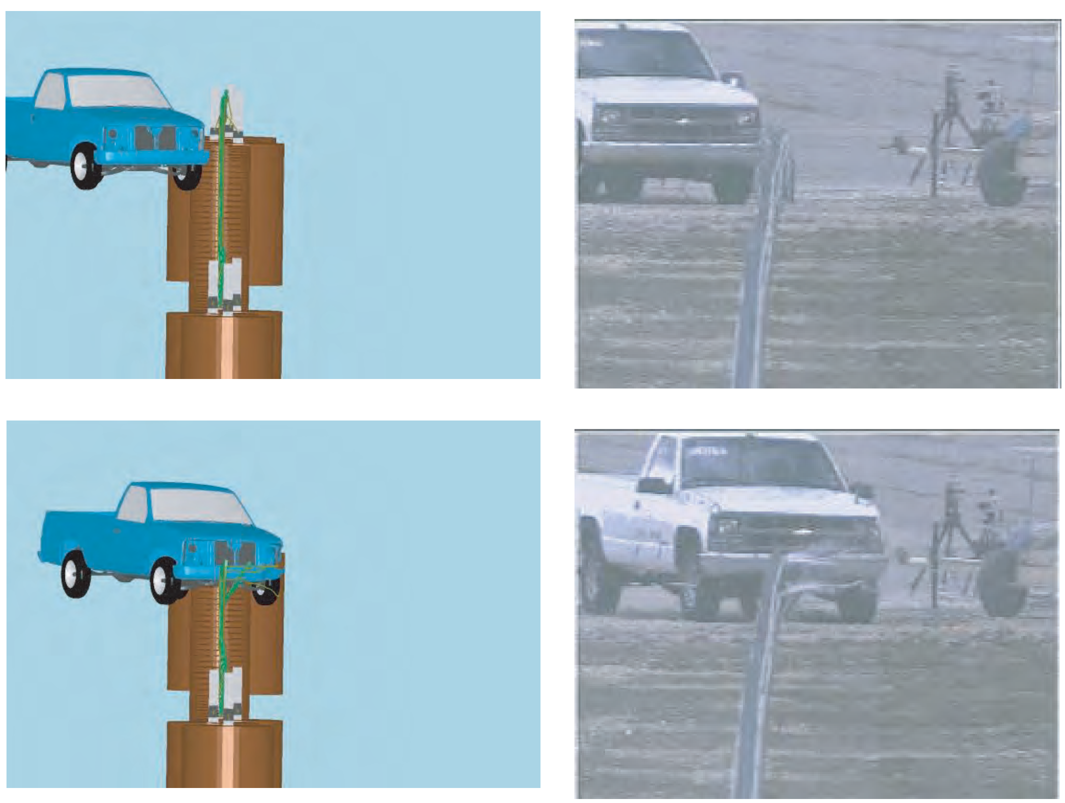


Figure 5.33. Comparison of sequential plots from Nucor simulation.

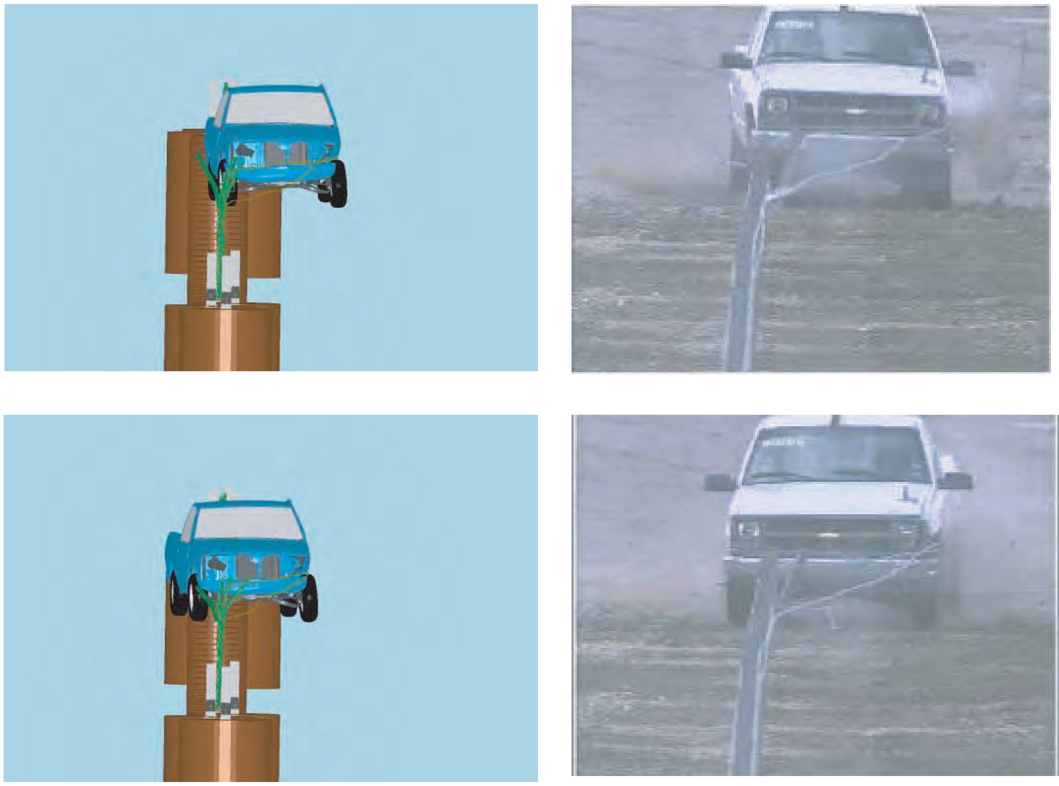


Figure 5.33. **(Continued).**

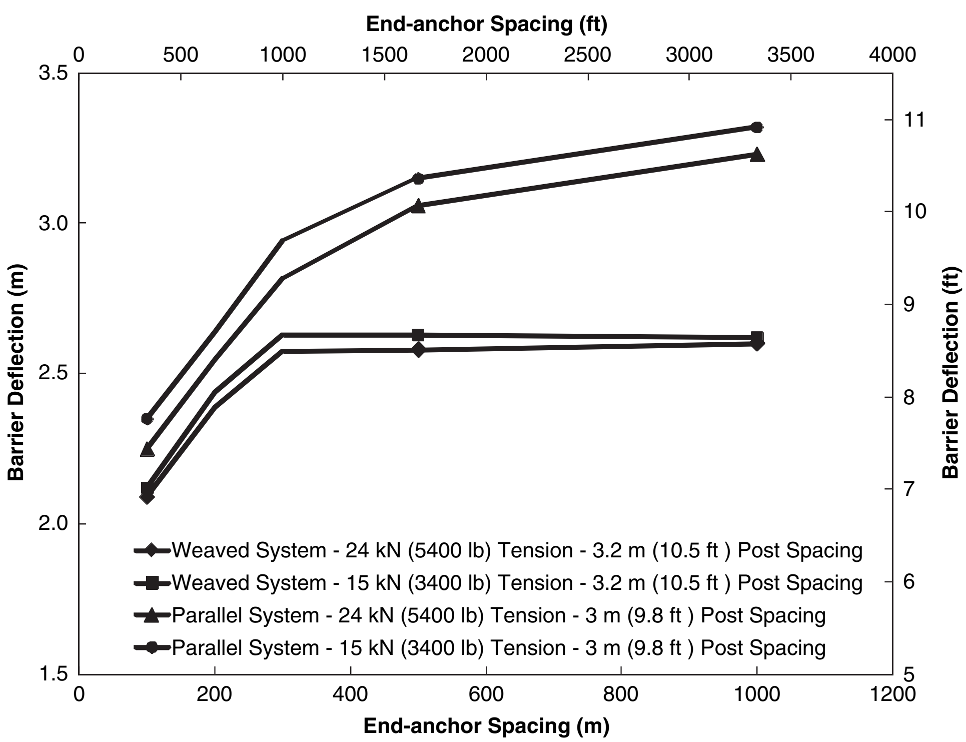


Figure 5.34. Effect of initial cable tension on barrier deflection.

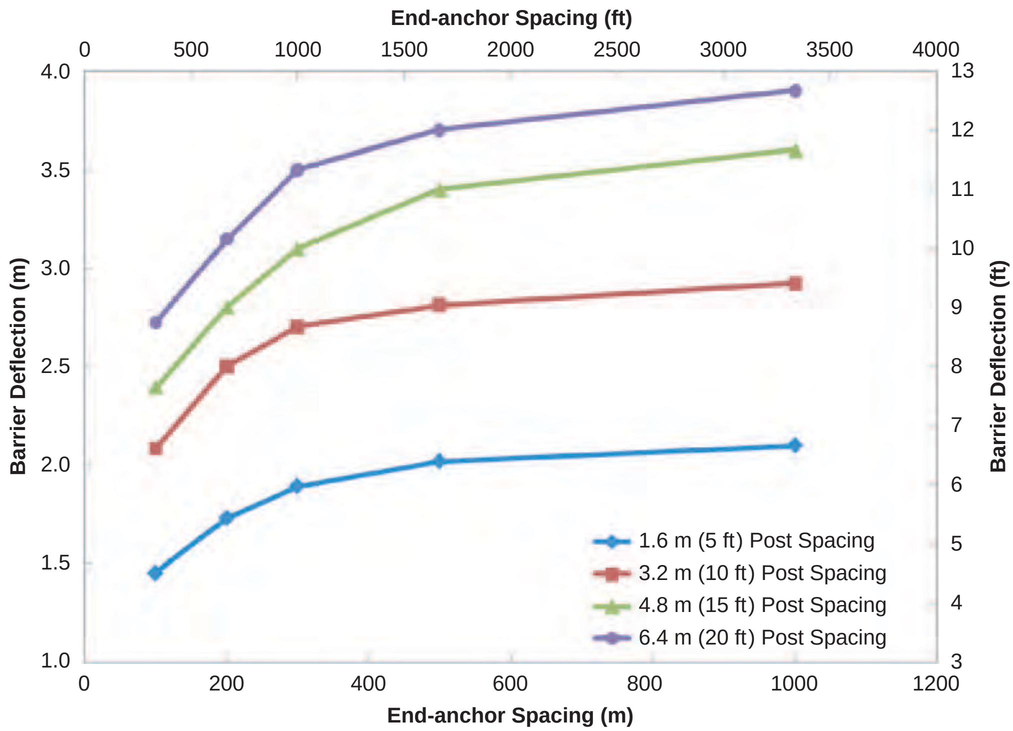


Figure 5.35. Deflection plots for Gibraltar cable barrier system.

hooks to hold the cables to the posts). These stronger cable/post connections delay the release of the cable and lead to reduction in barrier deflection.

End-Anchor Spacing and Post Spacing Effects

To investigate the effects of end-anchor spacing and post spacing on barrier deflection, the simulations with different cable barrier lengths and post spacings were compared. Figures 5.35 through 5.38 show computer-predicted deflections of five cable barrier systems. The figures show the deflections at different end-anchor spacings (100 m to 1,000 m, 328 to 3,280 ft) and post spacings (1.6 to 6.4 m, 5 to 20 ft).

The simulation results show that for all systems the deflection increases as the spacing between the end anchors is increased. The results also show that the effect of end-anchor spacing is different for different cable barrier systems. The difference is mainly attributed to the effect of the cable/post interaction. Systems that restrict the longitudinal sliding of the cables relative to the posts (by engaging the posts or other means) lead to a smaller deflection increase when the end-anchor spacing is increased. The simulations show that the ratio between the increase in barrier deflection and the increase in anchor spacing was less between the 300 m (980 ft) and 500 m (1,640 ft) anchor spacings and even less between the 500 m (1,640 ft) and 1,000 m (3,280 ft) anchor spacings.

For all systems, the simulations show that barrier deflection increases as the post spacing increases. The rate of increase in deflection decreases as the post spacing increases. There was about 30 to 50 percent increase in deflection from 1.6 m (5 ft) post spacing to 3.2 m (10 ft) post spacing, about 10 to 28 percent increase in deflection from 3.2 m (10 ft) post spacing to 4.8 m (15 ft) post spacing, and about 6 to 14 percent increase in deflection from 4.8 m (15 ft) post spacing to 6.4 m (20 ft) post spacing.

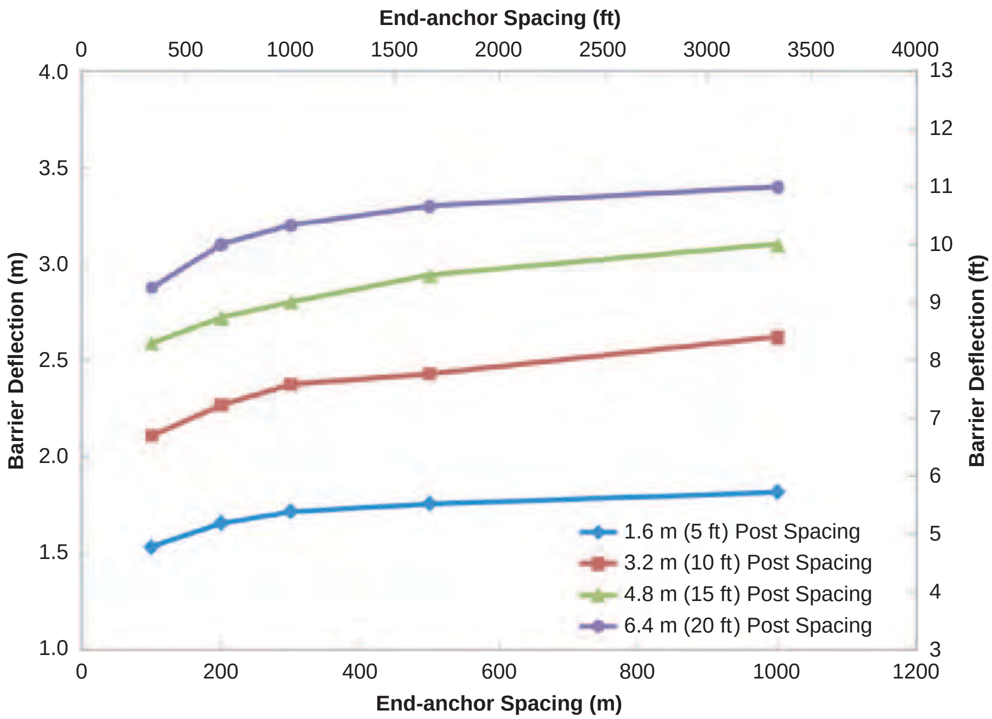


Figure 5.36. Deflection plots for Safence cable barrier system.

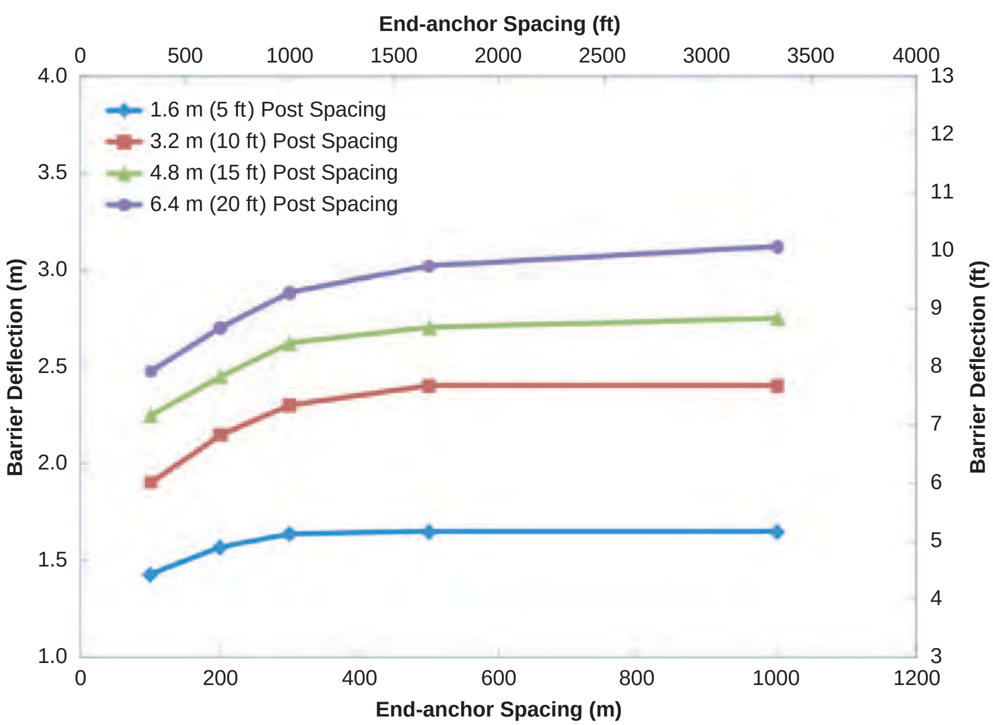


Figure 5.37. Deflection plots for Brifen cable barrier system.

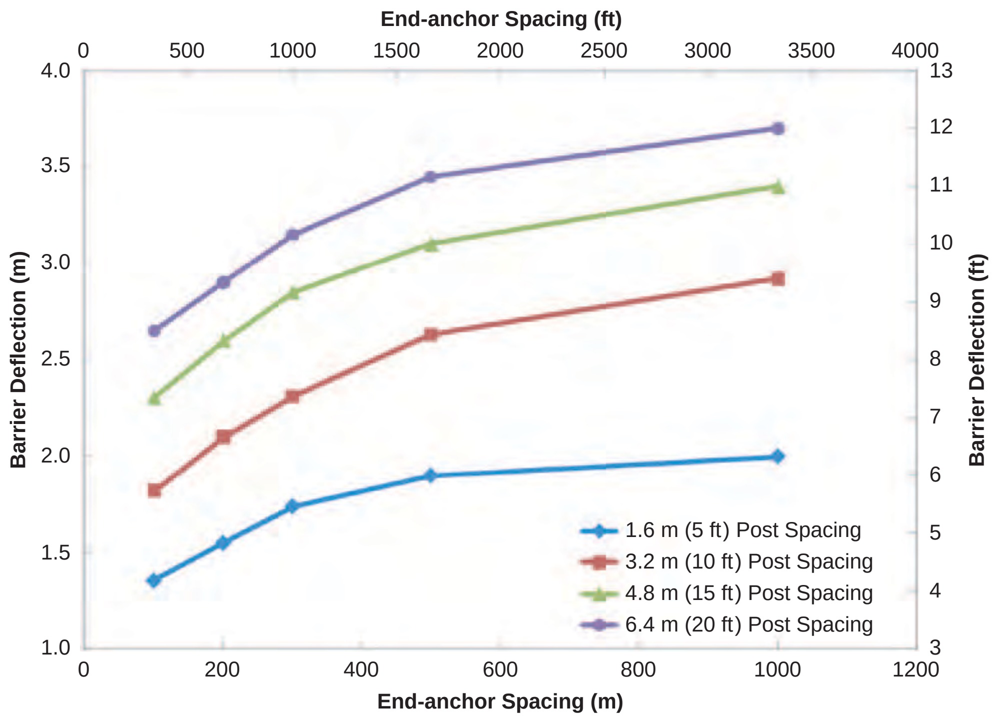


Figure 5.38. Deflection plots for CASS cable barrier system.

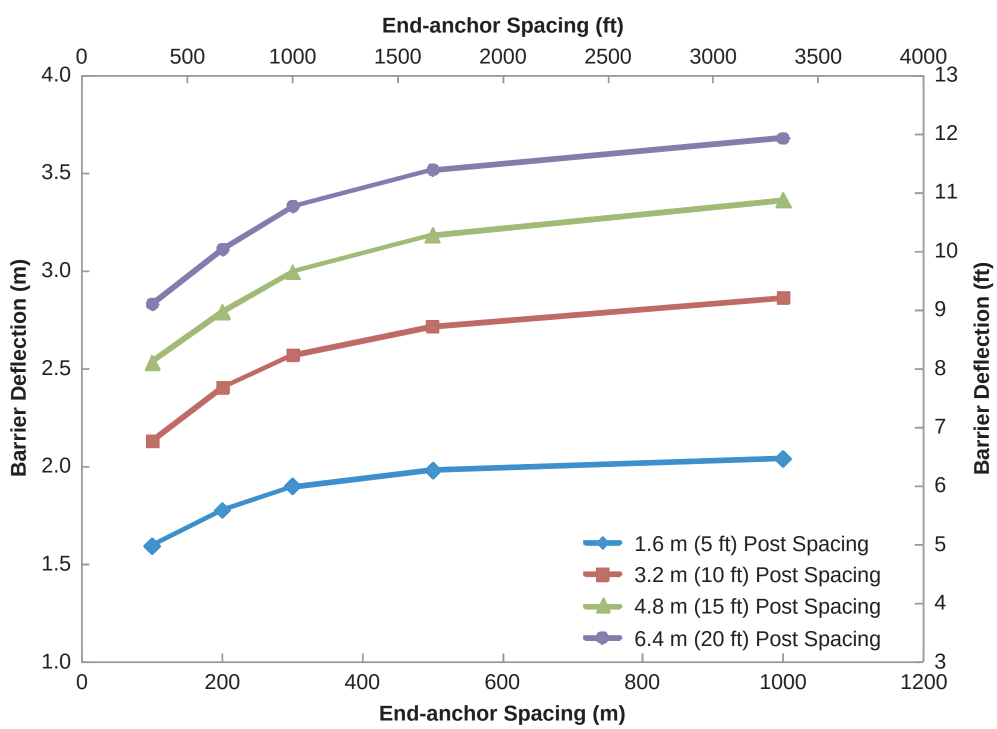


Figure 5.39. Deflection plots for Nucor cable barrier system.

Figure 5.40. End-anchor pull-outs.

5.3 End-Anchoring and Post-Anchoring Systems

Adequate anchoring of the cables is critical to ensure satisfactory barrier performance during impact. Anchor movements lead to lower tension in the cables, which results in larger deflection of the system. The movement could also lead to sagging of the cables, which affects cable heights and consequently affects the barrier's ability to engage the vehicle. Anchor movements are often attributed to weak soil conditions and the substandard-sized anchors. Weather conditions in certain regions of the country can also lead to anchor movement. Temperature decreases lead to higher cable tensions, which, in turn, apply higher forces on the anchors. Anchor pull-outs have been observed in several states, and many state DOTs consider this one of the most critical cable barrier issues. Figure 5.40 shows cases where the anchor has pulled out of the ground.

A recent study conducted at the MwRSF investigated end-anchor movement due to dynamic impact and temperature variation loads [62]. The maximum dynamic impact load used in the analyses was obtained from a MASH Test 3-11 full-scale crash test where load cells were attached to the cables at the end-terminals. The maximum dynamic impact load was found to be 137 kN (31 kips). The maximum thermal load was calculated based on a temperature change of 130°F (from 110 to –20°F). The maximum load due to this change in temperature was computed to be 125 kN (28 kips).

To develop recommendations for end-anchor sizes, the MwRSF researchers used the LPILE software with various sizes and soil strengths [63]. A load of 177 kN (40 kips) was used in the analysis. Figure 5.41 shows the predicted end-anchor movements for different anchor depths,

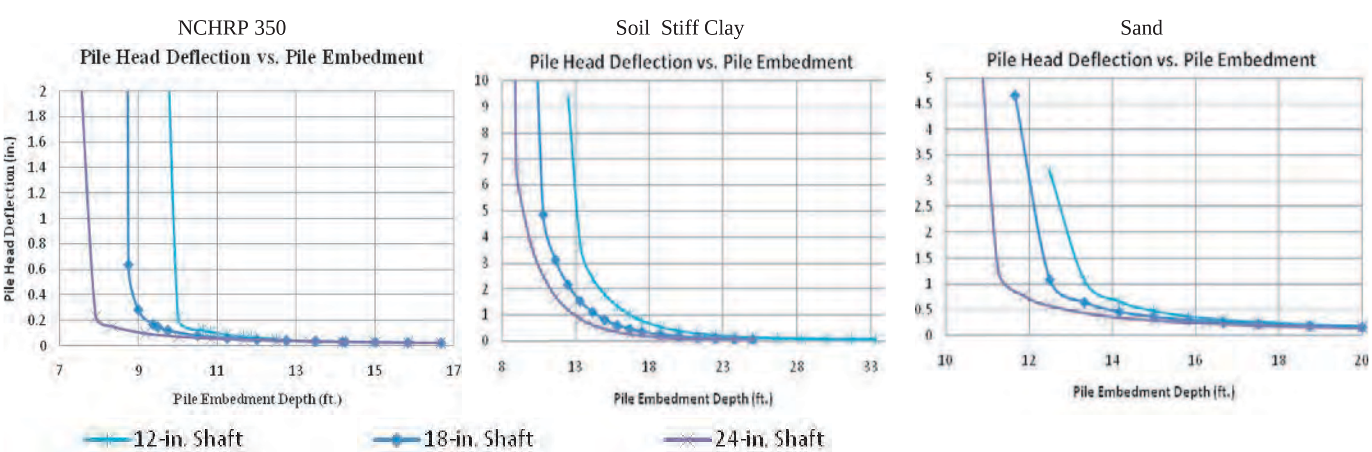


Figure 5.41. Pile deflection for different soil types and end-anchor sizes.

Table 5.1. Recommended end-anchor sizes from MwRSF study [62].

	12-in. Diameter Shaft	18-in. Diameter Shaft	24-in. Diameter Shaft
	Minimum Embedment Depth (ft)	Minimum Embedment Depth (ft)	Minimum Embedment Depth (ft)
350 Soil	10	9	8
Stiff Clay	13	11	9
Sand	13.5	12.5	11.5

anchor diameters, and soil strengths. Based on the assumption that a 50 mm (2 in.) end-anchor movement would lead to complete tension loss in the cables, a recommendation for anchor sizes was developed. Table 5.1 lists the recommended anchor sizes for the different soil conditions. The research indicated these recommendations are very conservative and should not be utilized to indicate the inadequacy of existing foundation designs.

A similar analysis was conducted under this study using the LS-DYNA finite element program. Computer models of cable barrier end anchors with different sizes and geometry were created and subjected to a dynamic load of 140 kN (the 140 kN magnitude was extracted from the simulations performed under Task 5.2 of this study and previously described in Section 5.2). The finite element model setup is shown in Figure 5.42. The soil used in the analysis was based on NCHRP Report 350 strong soil. The soil model was calibrated based on pendulum tests and was used in previous studies and found to give good predictions of the NCHRP Report 350 soil response. Efforts were made under this study to investigate soils with different strengths but, due to lack of test data to calibrate these soil models, the analysis could not be performed. Consequently, the results from this study should be considered as less conservative than the MwRSF results and should be regarded as the minimum size for adequate cable barrier anchoring.

The results from the analysis are shown in Table 5.2. (Readers are reminded that color versions of figures and tables are available in the online version of the report which can be found by searching the TRB website for *NCHRP Report 711*.) End-anchor movement of more than 50 mm (2 in.), shaded in red in the table, are considered inadequate. Movements of 25 to 50 mm (1 to 2 in.), shaded in orange, are considered marginal. Movement less than 25 mm (1 in.), shaded in green, are considered acceptable. It is important to emphasize here that these results are for strong soil and the results do not account for weaker and saturated soils.

Since soil types and conditions vary significantly for different site locations, end-anchor size should be determined on a case-by-case basis. Soil analysis, using similar approaches to the two methods presented above, should be conducted based on the soil data and climate information. Likewise, many designs use posts set in concrete foundations to facilitate removal and replacement of damaged posts. These foundations too must be sized properly based on existing soil and climate conditions so they are not damaged or pulled out of the ground in a crash.

Figure 5.42. End-anchor computer model setup.

Table 5.2. End-anchor movement for different foundation sizes.

Anchor Movement In mm (in.)		Anchor Diameter in m (ft)			
		0.3 (1)	0.6 (2)	0.9 (3)	1.2 (4)
Anchor Depth in m (ft)	0.6 (2)	>55 (2)	>55 (2)	>55 (2)	>55 (2)
	0.9 (3)	>55 (2)	49 (1.93)	20 (0.79)	14 (0.55)
	1.2 (4)	29 (1.14)	24 (0.94)	11 (0.43)	9 (0.31)
	1.5 (5)	19 (0.75)	12 (0.47)	7 (0.28)	6 (0.24)
	1.8 (6)	16 (0.63)	7 (0.28)	5 (0.20)	5 (0.20)
	2.1 (7)	13 (0.51)	6 (0.24)	5 (0.20)	4 (0.16)
	2.4 (8)	11 (0.47)	5 (0.20)	4 (0.16)	4 (0.16)

5.4 Interconnection with Other Systems

There have been accepted systems for the interconnection of cable barriers with strong post guardrail systems. These designs are reflected in FHWA acceptance letters B-147 and B-147A. The letters list several cable-to-W-beam transition designs as meeting NCHRP Report 350 test conditions at Test Level 3. The designs are accepted based on one full-scale crash test. The test was conducted using a South Dakota design wherein a U.S. generic 3-cable barrier was carried over and under a W-beam guardrail and anchored independently behind the metal beam rail. Subsequent to this testing, several of the manufacturers of proprietary cable systems proposed similar transitions, with the basic difference being the cables were attached directly to the W-beam rail element, thus eliminating the need for a separate anchor for the cables. Because the low-tension design performed adequately, there was no reason to suspect that the high-tension proprietary designs would not function as well (or better). Thus, these designs were accepted without full-scale testing. Figure 5.43 depicts a few of these cable barrier to W-beam guardrail transition designs.

In the cable barrier to W-beam transition test, the end terminal of the W-beam guardrail was flared 1.22 m (4 ft) behind the cables. Figure 5.44 shows the vehicle behavior during the impact. As seen in the figure, the vehicle exhibited significant roll due to the impact with the end terminal. The vehicle did not roll over in the test and the transition met the NCHRP Report 350 requirements. Based on the results from this test, 1.22 m (4 ft) should be considered as the minimum flare of the end of the guardrail behind the barrier to avoid vehicle rollover.

Another critical issue with cable barrier transitions is the force between the cable barrier and the system it is connected to (often a W-beam guardrail). It is important to ensure that the cable barrier static tension forces (due to temperature variations) and the impact forces do not lead to pull-out the W-beam barrier from its anchors or failure of the connections between the cables and the W-beam rail. This is especially critical for high-tension cable systems. The W-beam barrier must be long enough and adequately anchored at its downstream end to resist the tension in the cables.

Under this study, simulations were conducted to identify the minimum length needed for strong post W-beam systems when connected to cable barriers. Sections of a G41S W-beam guardrail system were subjected to a longitudinal load of 140 kN (31 kips). This loading was obtained from the simulations performed under Task 5.2 of this study and previously described in Section 5.2. The section length was varied until a movement of the end-post (last post) of the W-beam barrier was less than 25 mm (1 in.). The simulation setup is shown in Figure 5.45. The end-post movement at different G41S section lengths is listed in Table 5.3. The minimum section length was found to be 22.9 m (75 ft).

(a) Generic

(b) Brifen

(c) CASS

(d) Gibraltar

Figure 5.43. Sample cable to W-beam barrier transitions [64].

Figure 5.44. Sequential images from cable barrier to W-beam transition.

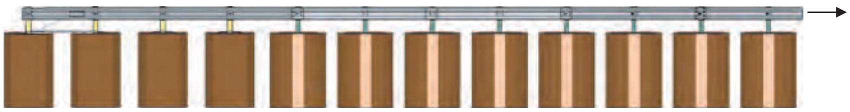


Figure 5.45. Simulation setup for G41S section subjected to a longitudinal load.

Similarly, the connection between each cable and W-beam rail should be designed such that it can withstand 90 kN (20 kips), the maximum load on the cables observed in the simulations under Section 5.2 of this study.

In some installations, the transition was accomplished by placing the cable barrier behind the W-beam guardrail. Figure 5.46 shows a post-crash picture of one of these installations. The picture depicts a case where the vehicle hit the cable system and went between the two barriers. After rebounding from the cable barrier, the vehicle hit the back of the W-beam guardrail. It is therefore recommended that this type of transition should not be used until further analyses and/or testing is conducted to ensure adequate performance is achieved [64].

5.5 Horizontal Curvature

Limited research has been conducted on the performance of cable barrier systems on horizontal curves. Impacts on the convex side of a curved cable barrier will result in larger deflections due to the slackening of the cables that occurs when posts are removed and the cables follow the alignment of a chord rather than the arc. To investigate this effect for high-tension cable barrier systems, finite element simulations were performed.

The models in this study were based on the high-tension, 4-cable CASS system used in the analysis described in Section 5.2. Computer models with varied curve radius and the post spacing were used in the analysis. Curve radii of 150 m (500 ft) (12° curvature), 300 m (1,000 ft) (6° curvature), 450 m (1,500 ft) (4° curvature), and straight alignment were incorporated in the models. For each curve radius, barriers with post spacings of 1.6 m (5 ft), 3.2 m (10 ft), and 6.4 m (20 ft) were created. A total of 12 simulations were performed for the four different horizontal curvatures and three different post spacings. A barrier length of 200 m (650 ft) was used, which provides sufficient length for the barrier to redirect the vehicle. The cable heights were set at 530 mm (21 in.), 640 mm (25.2 in.), 750 mm (29.5 in.) and 968 mm (38 in.). In all simulations, a 2000P Chevrolet C2500 pickup truck impacted the barrier at 100 km/h and 25° angle to the tangent of the curve. In all cases, the barrier was set up on flat, level terrain. Figure 5.47 shows the plan views for the three curves with one of the post spacings, 6.4 m (20 ft).

The maximum deflections of the barrier in the simulations were determined by measuring the distance from the impact side of the vehicle to the original alignment of the barrier. Figure 5.49 shows the location of the initial impact and the deflections for the 150 m (500 ft) (12° curvature), 300 m (1,000 ft) (6° curvature), 450 m (1,500 ft) (4° curvature) simulations for 0.4, 0.6, and 0.8 second time intervals. The deflection results are shown in Figure 5.48.

Table 5.3. W-beam movement for different section lengths.

Section length in m (ft)	17.4 (57)	19.2 (63)	21.0 (69)	22.9 (75)	24.7 (81)
End-post movement in mm (in.)	30 (1.2)	27 (1.06)	26 (1.02)	24 (0.94)	22 (0.87)

Figure 5.46. Post-crash picture of overlapping cable barrier to W-beam guardrail transition.

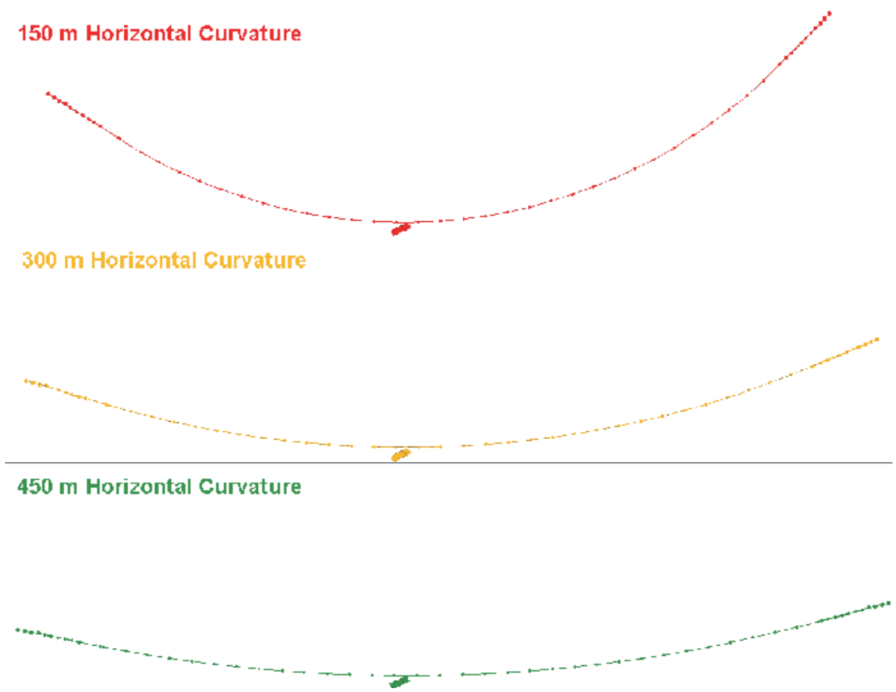


Figure 5.47. Plan views for the three convex curve simulations, 4-cable CASS system.

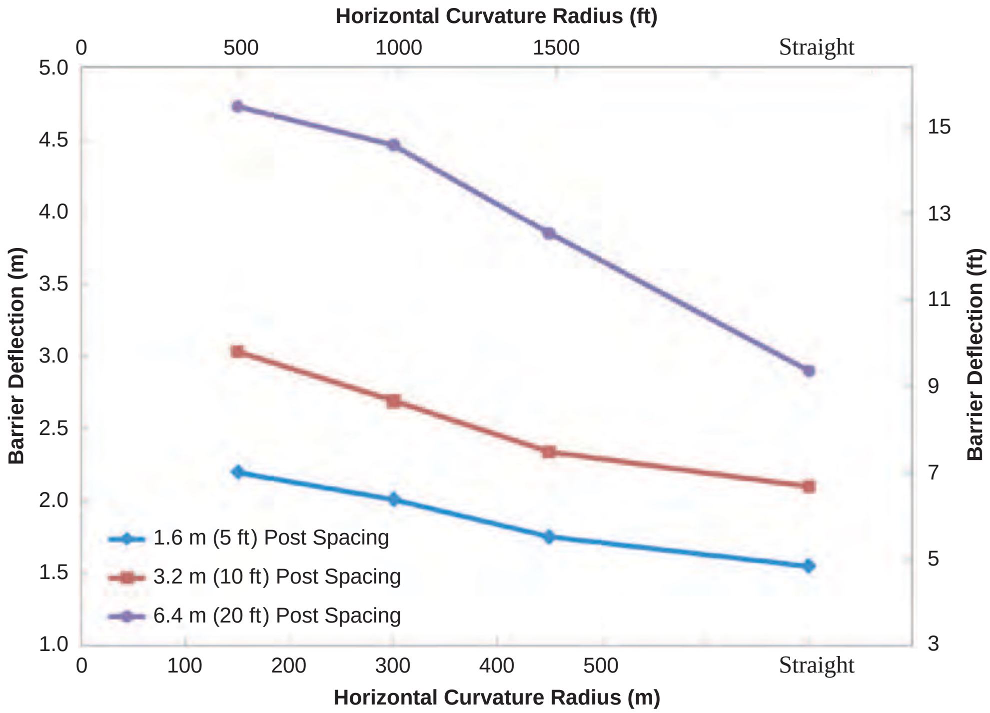


Figure 5.48. Deflection plots for different horizontal curvatures for convex-side impacts.

Figure 5.50 shows the percentage increase in deflection due to horizontal curvature for the three different post spacings. The base deflection is from the simulations using a straight alignment, i.e., zero degree curvature. The results were nearly identical for post spacings of 1.6 m (5 ft) and 3.2 m (10 ft), but going to a wider post spacing of 6.4 m (20 ft) shows a significant increase in deflection. For a curve with a 450 m radius (1,500 ft) (4° curvature), the increase in deflection is only about 10 percent for close post spacings but is 33 percent greater for post spacings of 6.4 m (20 ft). For this level of curvature, the maximum design speed is approximately 100 km/h (62 mph). For the sharpest curve simulated, 150 m radius (500 ft) (12° curvature), the deflection is 63 percent higher for a wide post spacing of 6.4 m (20 ft) and about 43 percent greater for the close post spacings. This level of curvature is associated with a maximum design speed of approximately 70 km/h (43 mph).

These findings suggest that wide post spacings for cable barriers should not be used on horizontal curves where convex hits are possible and the curve radius is less than 400 m (1,300 ft) (degree of curvature greater than 4°). Even if adequate clear area is available, the greater deflection could adversely affect the barrier's ability to capture and redirect impacting vehicles. Also, in median applications on sharp curves, placing barriers on each side of the median should be considered to reduce the likelihood of vehicles impacting the convex side of the barrier and intruding into on-coming traffic.

5.6 Installation Costs

The selection of any roadway element should be made considering the associated life-cycle costs. Life-cycle costs include the costs of installation and costs associated with both routine periodic maintenance and occasional repair costs. The following sections describe the process and available data for life-cycle cost analyses for cable barrier deployments.

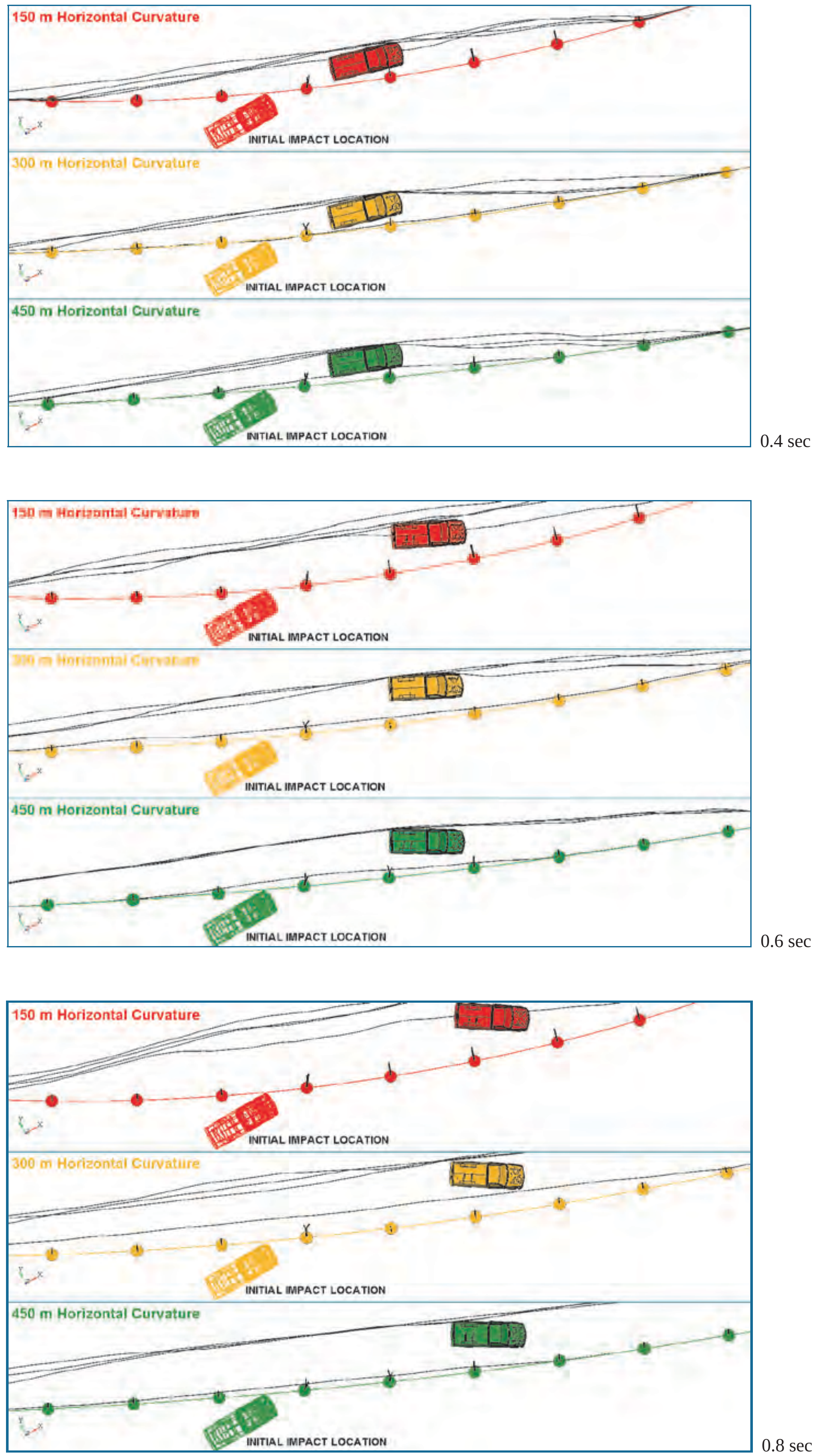


Figure 5.49. Sequential plots from convex-side impacts for different horizontal curvatures.

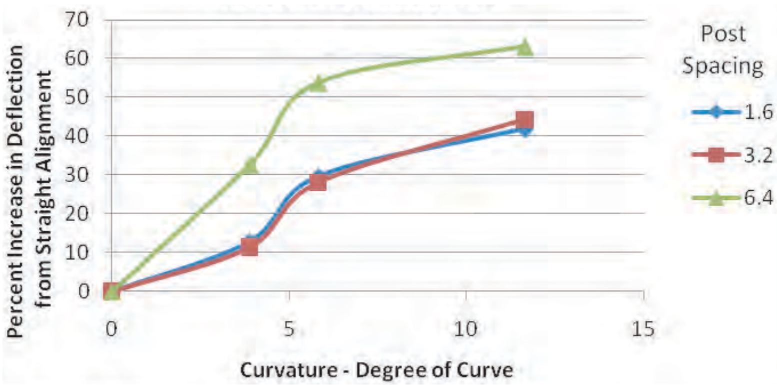


Figure 5.50. Influences of horizontal curvature and post spacing on deflection in convex-side impacts.

Installation Costs

Installation costs for cable barriers include the cost of the barrier and its end anchors as well as costs for modifications to the median or shoulder area. In some cases, the preparatory costs can exceed the cost of the barrier, particularly when major grading work is done and mow strips are constructed. This section of the report addresses costs for only the barrier and its end anchors.

Installation costs for high-tension cable barriers vary widely from state to state. Some factors contributing to these variations could be associated with the length of the installation, cable barrier type, soil condition, and weather environment. Recent (2010) costs for TL3 systems in Texas average less than $5 per linear foot (LF, 0.3 m) but average costs in South Dakota in 2009 were over $15 per LF. An analysis of bid tabulations from Colorado for 2009 through 2011 showed that for 11 projects totaling 151,388 LF (29 mi, 46 km), the average and median winning bid for high-tension cable barriers was $11.69 per LF and $11.10 per LF, respectively. Among the 57 bids for these 11 projects, the unit bid price ranged from $6.10 to $27.00.

Ignoring competitive factors, installation costs for high-tension barriers should depend on post spacing, anchor spacing, number of cables, soil conditions, and type of post foundation. The least expensive system would be a 3-cable system with driven posts, wide post spacing, and wide anchor spacing located in an area with very good soil conditions. The most expensive system would be a 4-cable system with posts in concrete foundations with short anchor spacing located in poor soil conditions.

In general, lowering installation costs by increasing post and anchor spacing will be offset by decreased barrier performance. Barrier deflection during impact would likely be higher and the potential for barrier penetrations would possibly increase. Similarly, installation cost savings achieved by using driven posts instead of concrete foundations with inserts will be offset by increased impact repair costs.

Life-cycle cost analysis provides a way to combine the effects of the tradeoffs mentioned above. For cable barrier systems, life-cycle costs include installation costs, maintenance costs, repair costs, and disposal costs at the end of the system's useful life. The time value of money (i.e., discount rate) needs to be included in the analysis for it to be valid. Performance reductions and barrier failures also need to be included in the analysis.

Data are not available to allow complete life-cycle analyses for the various cable barrier systems. Detailed cost and in-service performance data are needed to perform these analyses, and many state DOTs have not collected this information or accumulated enough data to have meaningful averages. However, it is possible to provide information on some aspects of cable barrier costs that can be used to estimate life-cycle costs.

Effects of Service Life and Discount Rate

Service life of cable barriers is long, which reduces the impact of installation costs on total life-cycle costs. The longer a barrier is in use, the lower the average annual cost of installation will be since these costs are spread over more years. The discount rate determines how future costs are "discounted" so that the average annual costs reflect the time value of money and the opportunity costs associated with the initial investment. Higher discount rates increase the annual cost of installation costs.

Service life for cable barriers can be very long if the roadway where they are installed is not modified in a way that requires the barrier to be moved or removed. For example, cable barriers in medians may have to be removed if the highway is widened by taking land from the median. The width of the modified median may be too narrow to accommodate cable barriers because of the relatively large dynamic deflections associated with flexible cable barriers. Shoulder improvements, pavement overlays, and alignment adjustments are other highway modifications that could shorten the service life of a cable barrier installation. Service lives of 5 to 50 years are used in the analysis to cover the expected range for cable barriers.

The discount rate is primarily affected by interest rates, now and in the future. Interest rates in 2010 are at historic low levels because of the current economic situation. Since interest rates are effectively zero today, the only way they can move is up. During times of high inflation, such as the early 1980s, interest rates were in the high teens. Forecasting future interest rates is difficult, so analyses have been done on a wide range of interest rates from 0 to 14 percent, which should cover the likely range of future rates.

As mentioned above, installation costs for cable barriers vary widely. To allow for the wide variation in costs, calculations have been done for a $1 unit installation cost per linear foot of barrier. Thus, to determine the equivalent average annual cost for an installation costing $10 per linear foot, the numbers in the Table 5.4 need to be multiplied by 10.

Table 5.4 shows how significant the effect of service life and discount rate can be on the contribution of installation costs to total life-cycle costs. For a barrier that costs $1 per linear foot to install, the average annual cost for 1 mile of barrier can range from $106 for a service life of 50 years and a 0 percent discount rate to $1,538 for a 5-year service life and a discount rate of 14 percent.

Table 5.4. Effect of service life and discount rate on life-cycle costs—installation costs.

	Annual cost ($ per mile) per $1.00 of installation cost per linear foot									
Discount Rate	Service Life of Cable Barrier (years)									
	5	10	15	20	25	30	35	40	45	50
14%	1,538	1,012	860	797	768	754	747	743	741	740
12%	1,465	934	775	707	673	655	646	640	637	636
10%	1,393	859	694	620	582	560	547	540	535	533
8%	1,322	787	617	538	495	469	453	443	436	432
6%	1,253	717	544	460	413	384	364	351	342	335
4%	1,186	651	475	389	338	305	283	267	255	246
2%	1,120	588	411	323	270	236	211	193	179	168
0%	1,056	528	352	264	211	176	151	132	117	106

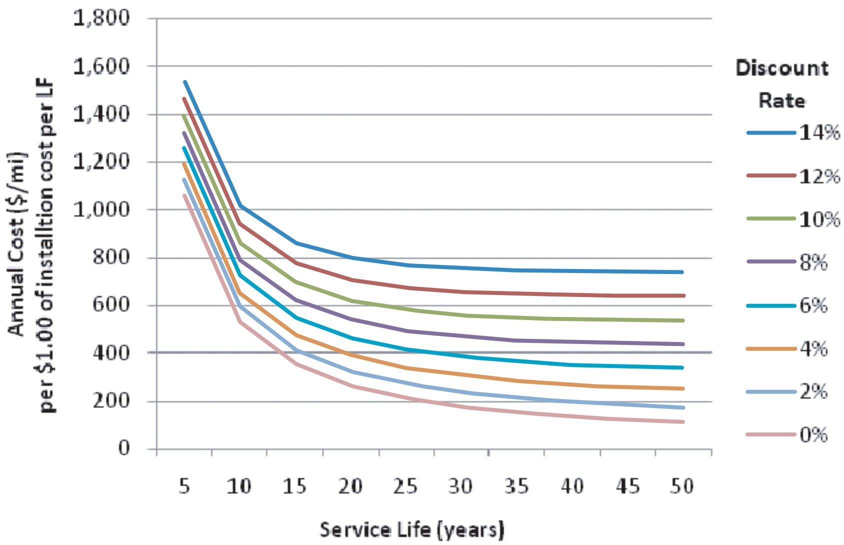


Figure 5.51. Effect of service life and discount rate on life-cycle costs—installation costs.

The data in Table 5.4 is shown graphically in Figure 5.51. This figure shows that for higher discount rates the average annual cost is insensitive to changes in service life beyond 20 years. For discount rates in the "normal" range of 6 to 10 percent, insensitivity to service life occurs around 25 to 30 years. This analysis suggests that using a service life of 25 years for cable barrier projects is appropriate unless it is known that the service life of the system will be shorter because of planned or expected roadway modifications.

Effects of Anchor Spacing on Installation Costs

The spacing of anchors for high-tension cable systems varies widely from project to project. The impact of anchor spacing on barrier performance is discussed elsewhere in the report. Wider spacing of anchors reduces the cost of the system since fewer anchors are needed. If an anchor is destroyed in an impact, the longer the anchor spacing, the greater the length of barrier that is out of service until the anchor is replaced and the system is retensioned.

Anchor cost varies widely because of different designs used by the manufacturers and because of soil condition variations. Undersized anchors have been a significant problem, particularly for states that have not required soil-specific designs. Several anchors have pulled out of the ground during periods of cold weather. Recent average TL3 anchor costs in Texas were $1,512 from December 2009 to February 2010 and $2,300 from October 2009 to December 2009. In 2009, TL3 anchors in South Dakota cost an average of $3,881. Part of the difference in costs between Texas and South Dakota can be attributed to the larger anchors required in northern climates. Stricter specifications in South Dakota may also be responsible for part of the higher costs.

For the previously mentioned 11 recent projects in Colorado, the average and median winning bid for the 127 anchors in these projects was $2,718 and $2,500, respectively. In only 4 of the 11 projects was the unit price of the low bid (contract winner) the lowest price for the anchors. The overall average for the 57 anchor bids was $2,388 and individual bids ranged from $1,500 to $6,000.

For the Colorado projects, the average spacing between anchors ranged from 74 m (241 ft) to 507 m (1,663 ft) with a median of 160 m (525 ft). One long 2010 project in Kentucky totaling 26.6 km (16.5 mi) of high-tension cable barrier used only 24 anchors, giving an average anchor spacing of 2,213 m (7,260 ft). The bid prices (9 contractors) averaged $2,621 per anchor and

Table 5.5. Effect of anchor spacing on installation cost.

Extra Cost ($) per linear foot due to end anchors							
Anchor Spacing (ft)	Cost per end anchor ($)						
	1,000	1,500	2,000	2,500	3,000	3,500	4,000
200	10.00	15.00	20.00	25.00	30.00	35.00	40.00
500	4.00	6.00	8.00	10.00	12.00	14.00	16.00
1,000	2.00	3.00	4.00	5.00	6.00	7.00	8.00
2,500	0.80	1.20	1.60	2.00	2.40	2.80	3.20
5,000	0.40	0.60	0.80	1.00	1.20	1.40	1.60
7,500	0.27	0.40	0.53	0.67	0.80	0.93	1.07
10,000	0.20	0.30	0.40	0.50	0.60	0.70	0.80
15,000	0.13	0.20	0.27	0.33	0.40	0.47	0.53
20,000	0.10	0.15	0.20	0.25	0.30	0.35	0.40

ranged from $2,000 (winning bidder) to $3,200. Two recent projects in Oklahoma had average anchor spacings of 2,500 m (8,200 ft) and 2,256 m (7,400 ft). Anchor costs were $3,900 for the first project and $2,000 for the other.

To allow for the wide variation in anchor costs, a range of costs from $1,000 to $4,000 has been used in the anchor analysis. Using these anchor costs, the extra cost that the anchors add per linear foot of barrier is shown in Table 5.5 for anchor spacings of 61 to 6,100 m (200 to 20,000 ft).

End-anchors can add a lot to the cost of a cable barrier system; but without adequate anchors, high-tension cable barrier systems are ineffective. The dynamic deflection from an impact increases with increased anchor spacing, and the increase in deflection varies for different cable barrier systems. Also, anchors that are undersized cost less, but can lead to failures of the system and costly repairs. Effective end anchors must be designed for site-specific soil and climate conditions. The values highlighted in the table represent typical values for many states and systems: anchor spacings from 300 to 1,500 m (1,000 to 5,000 ft) with anchor costs of $1,500 to $3,000. The impact on barrier installation cost ranges from minor for low-cost anchors separated by 1,500 m (5,000 ft) to major for higher-cost anchors separated by only 300 m (1,000 ft). There is a 10-fold difference in unit cost between these two conditions.

Effects of Post Spacing on Installation Costs

For most installations of high-tension cable barriers, post spacings vary between 10 and 20 ft. Post spacing narrower than 10 ft is used where deflections need to be low to avoid obstructions close behind the barrier. Post spacings greater than 20 ft have been used, but concerns about the increased risk of penetrations at wide post spacings have discouraged states from using very wide post spacings.

Post costs depend on the cost of steel, the amount of steel in the post, the accessories (lock plates, hair pins, spacers, stiffeners, caps, etc.) required by the particular design, and the installation method (concrete foundation, steel sleeves, or driven). Most often these costs are included in the unit bid price for the barrier so that actual post costs are difficult to identify.

Table 5.6 shows the impact of post spacing and post cost on cable barrier installation costs. The table covers a wide range of post costs from $20 to $90. These costs include the material costs for the post and foundation as well as the installation costs. Driven steel posts are the least expensive, and steel posts in concrete foundations designed for poor soil conditions in cold climates are the most expensive. Material costs for posts also vary among the manufacturers due to post size and design.

The post spacings in Table 5.6 range from 1.2 m (4 ft), which is used only in special, low-deflection cases, to 6.4 m (20 ft) which is the upper limit of post spacings for most new installations. Common post spacings are 3.0 m (10 ft) and 4.9 m (16 ft).

Table 5.6. Impact of post spacing and post cost on cable barrier installation costs.

Post Spacing (ft)	Cost ($) per linear foot due to posts and foundations							
	Cost ($) per installed post and foundation							
	20	30	40	50	60	70	80	90
4	5.00	7.50	10.00	12.50	15.00	17.50	20.00	22.50
6	3.33	5.00	6.67	8.33	10.00	11.67	13.33	15.00
8	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25
10	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
12	1.67	2.50	3.33	4.17	5.00	5.83	6.67	7.50
14	1.43	2.14	2.86	3.57	4.29	5.00	5.71	6.43
16	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63
18	1.11	1.67	2.22	2.78	3.33	3.89	4.44	5.00
20	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50

Posts are a major component of overall barrier installation costs, but they are less variable than anchor costs. For the highlighted values in Table 5.6, which represent typical values, the highest value is 2.4 times the lowest value. However, in the case of typical anchor costs as shown in Table 5.5, the highest value is 10 times the lowest value. Coincidentally, the highest typical unit value for post costs is exactly the same as the highest typical cost for anchor costs indicating an equal contribution of post and anchor costs to installation cost. However, the lowest typical post cost is more than 4 times as high as the lowest typical anchor cost.

Effects of Cable Costs on Installation Costs

Cable cost is the most predictable of all of the cable barrier components. Galvanized wire rope used for the cables is a standard commodity; the price varies mostly with the cost of steel. Now that so much prestretched wire rope is being used for highway barriers, there is no significant difference in cost between prestretched and regular wire rope.

Installed cost for cable is approximately $1.00 per linear foot per cable, plus or minus 20 percent. All high-tension cable barriers have either three cables or four cables. The 4-cable systems provide coverage for a wider range of vehicles for a small incremental increase in cost over 3-cable systems.

For barriers with 4.9 m (16 ft) post spacing, the cable costs and post costs are approximately the same. For barriers with closer post spacings, the cable costs are less than the post costs. End anchor costs are usually less than the cable costs except when anchor spacing is less than 610 m (2,000 ft).

Increasing anchor spacing is a way to reduce cable barrier installation cost, but it does have a significant effect on barrier performance. Cable barriers have typically been crash-tested at anchor spacings of approximately 100 m (328 ft) under NCHRP Report 350 guidelines and at 183 m (600 ft) under MASH guidelines. Research discussed in Section 5.2 indicates that an anchor spacing of 305 m (1,000 ft) will result in increases in deflection of approximately 25 percent from crash-test-reported values. Going to an anchor spacing of 1,524 m (5,000 ft) will result in increases in deflection of up to 50 percent from crash-test-reported values, depending on the cable barrier system.

Increasing post spacing is another way to reduce installation costs, but deflection is increased, which affects barrier performance. Increases in deflection resulting from increases in post spacing appear to be independent of anchor spacing. Increasing the post spacing from 3.2 m (10 ft) to 4.8 m (15 ft) can lead to an increase in deflection of approximately 20 percent. An increase of post spacing from 3.2 m (10 ft) to 6.4 m (20 ft) can result in an increase in deflection of approximately 30 percent.

Many states have opted for 3-cable systems instead of 4-cable systems for cost reasons. Also, it may not be clear to these states that 4-cable systems provide greater safety than 3-cable systems for very little extra cost. Penetrations of barriers are caused when vehicles go under, through, or over cable barriers. By adding a fourth cable, a wider range of heights can be achieved, as well as a closer vertical spacing of cables to reduce the likelihood of penetrations.

The inflation-adjusted 2010 societal cost of a highway fatality is estimated to be approximately $3.575 million by FHWA. The average annual cost of adding a fourth cable to a 3-cable barrier is $413 per (1.6 km) mile for a barrier with a 25-year service life and a 6 percent discount rate (see Table 5.4). Adding the fourth cable to 1,600 km (1,000 miles) of barrier has an average annual cost of $413,000. Thus, if the added cable would reduce the number of fatalities by 1 over this 1,600 km (1,000 mi) of highway over an 8-year period, it would offset the cost of the extra cable.

The small incremental cost of adding a cable opens the possibility of designing barriers with more than four cables particularly when used on steep slopes within medians. As mentioned earlier in the report, the wide range of trajectories of vehicles on steep median slopes makes it difficult for a conventional 3-cable or 4-cable barrier to capture all vehicles. Adding one or two cables increases the range over which the barrier can capture vehicles, allowing the barrier to be located in more areas of the median and reducing the probability of penetrations.

5.7 Cable Barrier Maintenance: Tolerances, Repairs, and Systemwide Maintenance

Tolerances: Construction and Maintenance

Variations in cable barrier dimensions, especially cable heights, could affect the ability of the barrier to perform adequately. Additionally, variations in the terrain shape and slope could also affect barrier performance. The vehicle dynamics and finite element simulations performed under this study, as well as findings from the literature, were used to develop suggested tolerances for cable barrier installations. Table 5.7 lists these tolerances. The tolerances were established such that the variations within the suggested limits should not have significant effects on cable barrier performance.

Based on vehicle dynamics analyses, increasing the height of the lowest cable or decreasing the height of the highest cable could adversely affect the barrier's ability to engage a vehicle and lead to underrides or overrides. Thus, a zero tolerance is suggested for the lowest and highest cables for the critical side (upper for lowest cable and lower for highest cable). Cable heights affect a barrier's ability to engage and capture an impacting vehicle so tolerances must be tight to insure that the barrier will perform as designed. For the middle cables and non-critical side of the top and bottom cables, a tolerance of 25 mm (1 in.) is suggested. This tolerance may be difficult to achieve on vertical curves without having post connections that resist vertical movements of the cables. In particular, extra care is needed around drainage inlets to insure that the cables have the correct heights to reduce the probability of underrides.

Table 5.7. Suggested cable barrier tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in)
Bottom Cable Height	-25,+0 mm (-1, +0 in)
Middle Cable(s)	±25 mm (±1 in)
Barrier Lateral Position	±150 mm (±6 in)
Average Post Spacing	±150 mm (±6 in)
Consecutive Post Spacing	±600 mm (±2 ft)
Cable Tension	±2 kN (±0.45 kips)

The lateral position of the barrier relative to the roadway or median centerline is important for several reasons. These reasons were explained in detail in Section 5.1. Small deviations from the design alignment may be needed to accommodate issues in the field such as imbedded rocks, drainage facilities, and other construction constraints. The suggested tolerance for lateral position is 150 mm (6 in.), which should never be exceeded if the barrier is being placed near the centerline of the median because of the sensitivity of barrier performance to location as discussed in Section 5.1.

Post spacing is less critical since it primarily affects the magnitude of deflection and not the ability to engage a vehicle unless the post spacing is very wide (wider than the maximum spacing used for the crash tests). Most cable barriers have been crash-tested and accepted for more than one post spacing, confirming that barriers can perform adequately at varied post spacings. The suggested tolerance for consecutive post spacings is 600 mm (2 ft). This tolerance should provide enough flexibility to account for field obstacles that prevent a post from being installed in the exact location specified on the plans. The suggested tolerance on average post spacing, in the region free of obstacles, is 150 mm (6 in.).

Cable tension makes cable barriers work, particularly for high-tension systems. However, cable tension changes with temperature, increasing in cold weather and decreasing in warm weather due to thermal contraction/expansion. Simulations of cable barriers at different tensions were discussed in Section 5.2. Minor changes in tension do not have significant effects on deflection. Lower tensions allow some increase in deflection, but higher tensions exert higher static loads on anchors, particularly during cold weather. Because of the day-to-day variations in tension due to climatic changes, specifying a tight tolerance on tension would increase the need for barrier maintenance without a commensurate increase in safety. Therefore, the suggested tolerance for cable barrier tension (as measured against the design tension for the given cable temperature) is 2 kN (450 lb).

Cable Barrier Repairs

Most maintenance costs associated with cable barriers result from crash damage. Since cable barriers are often placed where they can be hit frequently, these costs can be significant. In police-reported crashes, it is usually possible to get the offending driver's insurance company to reimburse the highway agency for these costs. But, because cable barriers are so "forgiving," drivers often are able to drive away after a crash, which makes it difficult to collect from an insurance company. Data from a few states indicates that police reports are usually available for slightly more than half of the crashes. However, non-reported crashes are less severe, which means their repair costs will be lower. Kentucky found that non-reported crashes had approximately half as many damaged posts as the more severe crashes where a police report was filed.

Frequent inspections are needed to identify crash damage, but these inspections can be accomplished by highway agency and police personnel reporting damage they observe as they drive by the barriers during their normal work activities. In addition, periodic inspections should be conducted to identify unreported damage. In the state survey conducted for this study, the frequency of inspections ranged from daily to annually. Previous crash history can be used to determine how frequently inspections should be conducted for each highway. Crash frequency depends on the average daily traffic (ADT), speed limit, location of the barrier relative to the edge of pavement, and weather conditions.

In most crashes, only the posts are damaged. It is rare for the cable to be damaged unless a vehicle gets tangled in the cables or the cables are cut by emergency response personnel. In the majority of crashes, the cables can be reinstalled on the replacement posts without the need to retension. If enough posts have been destroyed to cause the cables to be on the ground, then the tension in the repaired system should be checked. If any of the individual cable wires has been broken or if significant kinks in the cable are visible, the cable should be evaluated to determine if it needs to be replaced. In the rare case of an extremely large deflection caused by a heavy vehicle impact, the cable should be examined to make sure that plastic deformation of the cable has not occurred.

The number of posts damaged in a crash depends on a number of factors including the velocity and mass of the impacting vehicle, impact angle, post spacing, cable tension, barrier type, and vehicle-barrier interactions. Most states have found that the average number of posts damaged in a crash is between four and eight. A few crashes with tractor trailers have resulted in more than 50 posts being damaged.

The cost to repair posts depends on a number of factors. Driven posts are more expensive to replace than posts in socketed concrete foundations. Post repairs in winter can be more expensive if the posts are frozen in the sockets. Little data is available on the difference in cost of using driven posts rather than socketed posts. Many states now use socketed posts routinely because of the ease of post replacement after crashes. Ohio, one of the first states to install high-tension cable barriers, purposely installed some of each kind of post to be able to observe the differences. Shortly into the program they began to replace all damaged driven posts with socketed posts because of the difficulty associated with repairing driven posts. Data from Oklahoma shows an installation cost savings of approximately $3 per LF for driven posts. For a 25-year service life and a 6 percent discount factor this savings is about $1,240 per 1.6 km (1.0 mi) per year. Texas data shows an average of about 6 crashes per 1.6 km (1 mile) per year on their highways with cable barriers while 2007 data from Oklahoma shows an average of about 14 crashes per 1.6 km (1.0 mi). Using the more conservative Texas crash rate, the savings in cost for driven posts is approximately $200 per crash. In Oklahoma, the savings is only $90 per crash. Repairs for driven posts require post-driving equipment, which often requires a lane closure. The extra cost for driven-post repairs will easily exceed the $200 saving per crash. Thus, the added cost of including posts with socketed concrete foundations may be justified except possibly for very lightly traveled roads where the expected crash rates are low.

Repair costs, on a per-post basis, are useful for forecasting future repair costs. Some states have collected good information on repair costs for cable barriers at least for the first couple of years of service.

In the state survey, responders were asked to give the average number of posts damaged per impact and the average cost per impact. The 18 responses for cost per impact fell into two groups of nine, the first being rather precise numbers ranging from $240 to $870 and the other having what appeared to be estimates with all numbers rounded to the closest $100 and most rounded to the closest $1,000. These values ranged from $1,000 to $10,000. It appears that the numbers in the first group, which averaged $520 per crash, were probably based on studies while the numbers in the second group, which averaged $2,320 per crash, were rough estimates. Almost all the state in-service performance studies, primarily on the Brifen system, provided results similar to the first group. For example, Oklahoma DOT kept track of the cost of each of the crashes on the Lake Hefner Parkway during its first year the cable barriers were in service, the first high-tension cable barrier installation in the United States. This 4-cable system experienced 126 crashes which, on average, cost $284 (2002 dollars) to repair an average of 4.7 posts per impact. For this system, the average repair cost per post, including traffic control and all other repair costs, was $60.

Repair costs depend partly on how long it takes a repair vehicle to get to the scene. The Lake Hefner Parkway represents a "best case" situation since it is only 11 km (7 mi) long and is located in Oklahoma City close to response units. In rural areas, crash locations may be more than an hour's driving distance from the nearest response unit, which will make repairs more expensive.

The lower repair costs appear to be mostly associated with repairs done by highway agency crews rather than by private contractors. It is possible that some of the states reporting costs included only materials costs and not labor costs. Minnesota reported a total repair cost of $58,500 for 45 crashes and gave a breakdown of the cost for labor, material, and equipment. The average $1,300 cost per crash included $631 for materials, $478 for labor, and $191 for equipment.

A major factor in cable repair costs is the price the highway agency pays for replacement posts. Since the high-tension cable barrier systems are proprietary, once the system is installed the manufacturers have control over the price of replacement posts unless the highway agency has included replacement posts in the initial (or follow-up) contract. Since it is known that a significant number of posts will be damaged in impacts, agencies should consider including a sufficient number of replacement posts in the original construction contract.

Typically six posts are damaged in an average impact into a high-tension cable barrier. If posts are socketed in concrete foundations, their repair is usually quick and relatively inexpensive. Often, the repairs can be done in less than an hour without traffic control. Repair costs depend on the extent of the damage, the remoteness of the crash location, and whether highway agency crews or a contractor does the repairs.

Systemwide Maintenance

On-going, maintenance issues for cable barriers are discussed separately from crash-related repairs since they are systemwide issues rather than site-specific crash-related needs. On-going issues include inspecting and maintaining specified cable heights and correct cable tension, as well as ensuring proper functioning of cable connectors and end anchors. Line posts and their foundations may occasionally need maintenance.

Determining if maintenance is needed requires that the cable barriers be inspected. Modern high-tension cable barriers require little on-going maintenance if they have been designed and installed correctly. Problems can occur when end anchors and post foundations have not been designed for in situ soil and local climate conditions. Under-designed anchors and foundations often rotate out of the ground or move enough to cause reductions in cable tension. Inspections are needed to identify these problems as well as to locate damage to the barrier caused by non-reported crashes.

Annual inspections to identify non-crash-related issues should be sufficient unless design flaws in anchors and post foundations are known to exist or if extreme weather events have occurred. Flooding can cause erosion, which will affect the heights of the cables, and very cold weather will exert heavy static loads on the anchors, which could cause anchor movement. If non-prestretched cables were used when the barrier was installed, cable tensions should be checked and adjusted every 6 months for the first several years. Once the wires in the cables have seated themselves, semi-annual retensioning should not be needed.

Cable heights should be checked at the bottom and top of vertical curves to make sure the cables have not moved up or down from their specified heights. On sharp horizontal curves, cable heights can be affected by leaning line posts. Cable heights are also affected by discontinuities in the ground under the cables. Erosion, winter maintenance, crashes, and other activities around the cable barriers can cause ruts or mounds that will affect the effective height of the cables. These discontinuities should be removed if they cause the cable heights to be out of tolerance. Mow strips, as described below, can be effective in minimizing these problems.

Maintaining adequate tension in cable barriers is important particularly for high-tension systems. Cable tension is affected by temperature changes. When the temperature drops, the cable contracts, which increases its tension. Increases in temperature cause the cable to expand,

Table 5.8. Hours of labor savings/mile/year required to justify mow strip.

25-Year Service Life and 6 percent Discount Rate					
Labor & Equip Cost per Hour	Cost of Mow Strip per Linear Foot ($)				
	5	10	15	20	25
$20	103	207	310	413	516
$30	69	138	207	275	344
$40	52	103	155	207	258
$50	41	83	124	165	207
$60	34	69	103	138	172

which lowers its tension. Each cable barrier manufacturer has a temperature-tension table that gives the required tension as a function of cable (not air) temperature. Most manufacturers also sell tension meters to measure cable tension. Friction between the cables and posts, particularly for interwoven systems, can delay the migration of tension changes along the barrier. After retensioning, the cable tension should be checked at several different locations along the barrier to make sure the tension has equalized and that the system has the correct tension. As discussed above, a suggested tolerance for tension is ±2 kN (±0.45 kips) from the specified tension given in the manufacturer's table.

High tensions resulting from cold weather could cause improperly manufactured/installed cable connections to fail. Strength specifications and testing requirements for turn buckles, swaged-on fittings, and other cable connectors should be included in contract documents. For example, Kansas requires a minimum tensile strength of 164 kN (36.8 kips). The strength of the connection should be at least as strong as the breaking strength of the cable.

Mow strips are used by some states to reduce the cost of mowing grass around the cable barriers and to strengthen the post and anchor foundations. Mow strips are expensive and can cost as much or more than the cable barrier itself. In the survey of states, 15 indicated that they use mow strips and 19 indicated they did not. Costs ranged from $6 to $25 per LF (0.3 m). Mow strips can also strengthen the embedment of line post foundations and end anchors, which lessens the chance for anchor/foundation failure. Mow strips also reduce the discontinuities in the natural ground, which should help to maintain proper cable heights. It is difficult to estimate the monetary value of the strengthening of the posts and foundations and reducing ground discontinuities, but they are significant.

Table 5.8 shows how many hours of labor need to be saved each year for 1 mile of highway to justify the addition of a mow strip solely on grass cutting benefits. This table is based on a 25-year life for the mow strip and a discount rate of 6 percent. For example, if a mow strip costs $15 per LF and labor and equipment costs for grass mowing is $40 per hour, to justify a mow strip, a total of 155 hours of labor would have to be saved each year for each mile of highway where the mow strip is installed. These hours should be reduced by anticipated benefits from the strengthening of the posts and anchors and reducing ground discontinuities.

CHAPTER 6

Guidelines for Cable Barriers

Although strong-post cable barriers were in use in some states as early as the 1950s, New York pioneered the development and testing of the weak-post design in the 1960s. This design, included in the 1977 AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers* as the G1 Cable Guardrail, may have been the first design guidance for a cable barrier system. This system was originally used primarily as a roadside barrier in a few states that were concerned with snow collecting in front of more solid barrier systems such as the W-beam guardrail. In the 1990s, several states became aware of an increase in cross-median head-on crashes along sections of freeways and began to install cable barriers to minimize the likelihood of these severe crashes. Today, there are several thousand miles of cable median barriers in the United States – both the initial low-tension generic designs and the more recent proprietary high-tension designs. The following sections summarize the principal findings of this research effort and translate them into guidelines that can be used by highway agencies to design cable barrier projects or formalize their own policies and procedures.

6.1 Warrants

Barrier warrants address the need for, and cost-effectiveness of, any type of traffic barrier system for specific highway situations. This study made no attempt to assess, develop, or revise any existing warrants for either median barriers or roadside barriers. Current warrants, either as recommended in the AASHTO *Roadside Design Guide* or individual state guidelines, were considered appropriate and adequate for determining if a barrier is needed. Once the decision to install a barrier has been made, the next step is to select the most appropriate barrier type to use. In this regard, cable barrier is often a cost-effective choice for installation in wider medians because it is relatively lower in cost than other designs, can be installed on non-level terrain (within limitations), and can often be maintained relatively easily.

6.2 Structural Details and Crash Performance Characteristics

Over the years, various cable barrier designs have been developed for use in medians and on roadsides. Early designs, known as generic, low-tension cable barriers, were adopted by state DOTs such as New York, Washington, North Carolina, Missouri, and others. These designs were found to be an effective means of preventing most median crossover events where deployed. The designs had limitations that prompted efforts to develop the several proprietary designs that emerged in the early 2000s. These new designs, known as high-tension systems, have higher cable tension, stronger cable-to-post connections, and, consequently, lower barrier deflection than generic systems. These new designs were also found to be a cost-effective means for reducing run-off-the-road fatalities and severe injuries. High-tension cable barrier systems are available from five manufacturers: Brifen, Gibraltar, Nucor Steel Marion, Gregory Industries (Safence systems), and Trinity (CASS systems).

The available cable barrier systems vary in number of cables, cable heights, post size and geometry, cable-to-post connections, post spacing, and end-anchoring systems. Descriptions of these systems are presented in Chapter 4 and Appendix B of the contractors' final report. A summary of the full-scale crash tests conducted on cable barrier systems is presented in Appendix D of the contractors' final report.

6.3 Cable Barrier Guidelines

The cable guardrail guidelines developed under this project addressed seven areas of concern: barrier lateral placement on sloped surfaces, influences of post spacing and end-anchor spacings on barrier deflection, post and terminal anchoring, interconnection with other barrier systems, construction and maintenance tolerances, placement along horizontal curves, and installation and maintenance costs. The principal recommendations or guidance that evolved for each of these areas are discussed below. A summary of the developed guidelines as well as others from the literature are listed in Appendix E of the contractors' final report, which is published herein.

Lateral Barrier Placement

Vehicle dynamics analyses were performed to develop guidelines for effective cable barrier placement on sloped medians. These guidelines were developed for systems where the top cable is at 838 mm (33 in.) or higher and the bottom cable is at 533 mm (21 in.) or lower. This covers most currently available cable barrier systems. For systems that do not meet these requirements, vehicle dynamics analysis for the specific median profiles and specific barrier systems, following a similar approach to the one described in Section 5.1, can be used to find the effective placement locations. Nomographs for many basic median configurations and barrier designs are provided in Appendix C of the contractors' final report and can be used to determine effective locations where there are consistent conditions. Additionally, similar analysis can be performed to determine effective cable barrier placement if this cannot be achieved based on the following guidelines.

The analysis showed that changes in slopes are the main factors contributing to median barrier penetrations and vehicle intrusion into opposing traffic lanes. A negative change in slope (down slope), typically located at the edge of the median or roadside, can lead to vehicle overrides for high-speed and high-angle impacts. A positive change in slope (upward slope) typically located near or at the center of the median, can lead to vehicle underrides. The greater the change of slope, the more critical effect it has on barrier performance. The guidelines listed below provide recommendations for reducing vehicle underrides and overrides. Because these guidelines were based on a relatively limited number of vehicle types, impact speeds, and impact angles, and do not factor driver inputs such as braking and steering, it is important to note that adherence to these guidelines will not prevent all penetrations of the barrier.

General Placement Guidelines

- Cable barrier systems should not be placed on slopes steeper than 4H:1V (unless the system has been designed for and successfully crash-tested under these conditions).
- Cable barrier systems can be used on 4H:1V or shallower sloped medians or roadsides (6H:1V or shallower sloped medians or roadsides are preferable), provided the placement guidelines listed below are followed.

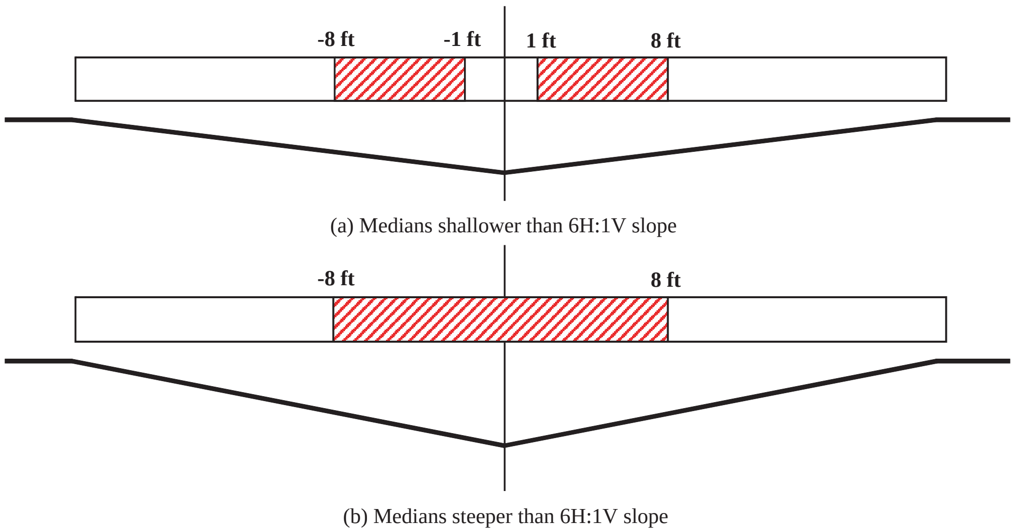


Figure 6.1. Underride criteria for V-shaped medians.

- The gentler the slope, the lower the effects on the trace of the vehicle interface area and the greater the potential for an effective vehicle-to-barrier interface.
- Wider medians offer more effective lateral placement options.
- Median cross-section shape influences the effective lateral placement areas.

Symmetric V-Shaped and Rounded-Bottom Medians

- To avoid underrides of small and mid-size vehicles, the barrier should not be placed in the region between 0.3 m (1 ft) and 2.4 m (8 ft) from either side of the center of the V-shaped section (Figure 6.1a). For medians with slopes steeper than 6H:1V, the region between –0.3 m (–1 ft) and 0.3 m (1 ft) from the center of the median should also be avoided (Figure 6.1b). The cross-hatched areas in the figures indicate the lateral positions where the cable barrier may not be effective.
- To avoid override of larger vehicles (SUVs and pickup trucks), the barrier should not be placed in a region between 1.2 m (4 ft) and 6.0 m (20 ft) from the edge of the median (breakpoint) when the median slope is steeper than 6H:1V (Figure 6.2).

Symmetric Flat-Bottom Medians

- To avoid underrides of small and mid-size vehicles, the barrier should not be placed in the region between 0.3 m (1 ft) and 2.4 m (8 ft) from either side of the flat-bottom breakpoints (Figure 6.3a). If the median slope is steeper than 6H:1V or if its flat-bottom section is less than 2.4 m (8 ft) in width, the region between –0.3 m (–1 ft) and 0.3 m (1 ft) from the flat-bottom breakpoint should also be avoided (Figure 6.3b).

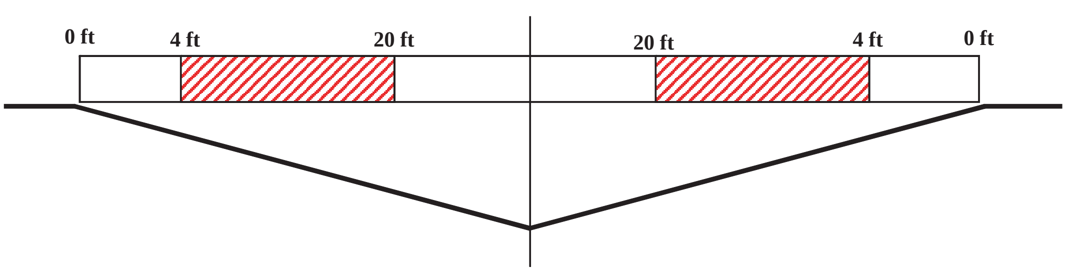


Figure 6.2. Override criteria for V-shaped medians steeper than 6H:1V slope.

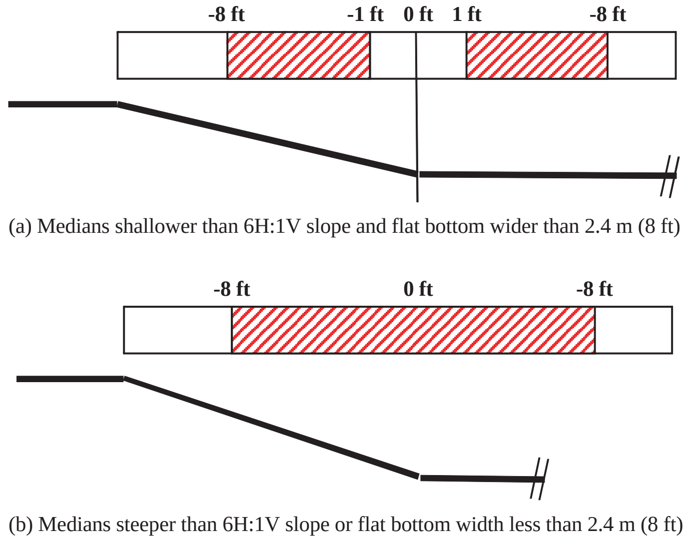


Figure 6.3. Underride criteria for flat-bottom medians.

- To avoid override of larger vehicles (SUVs and pickup trucks), the barrier should not be placed in a region between 1.2 m (4 ft) and 6.0 m (20 ft) from the edge of the median (breakpoint) when the median slope is steeper that 6H:1V (Figure 6.4).

Non-Symmetrical Medians

- It is preferable to place the cable barrier on the side of the median with the shallower slope.
- The guidelines for V-shaped and flat-bottom medians should be followed to avoid vehicle underrides or overrides.

Shoulders and Superelevations

- Shoulders with slopes of 6 percent or flatter do not lead to any negative effects on vehicle-to-barrier engagement and consequently do not affect barrier performance.
- For roads with superelevation steeper than 3 percent, the barrier should be placed not farther than 0.6 m (2 ft) from the edge of the median for medians steeper than 6H:1V slope and not farther than 1.5 m (5 ft) for medians shallower than 6H:1V. The barrier could be placed on the opposite side of the median (away from the superelevation).

Cable Barrier Deflection

Computer simulations using validated cable barrier models were conducted to study the effects of end-anchor spacing and post spacing on the dynamic deflection. The simulation

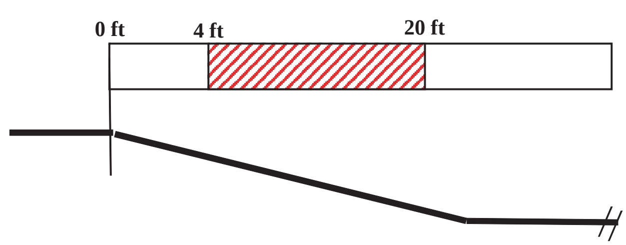


Figure 6.4. Override criteria for flat-bottom medians steeper than 6H:1V slope.

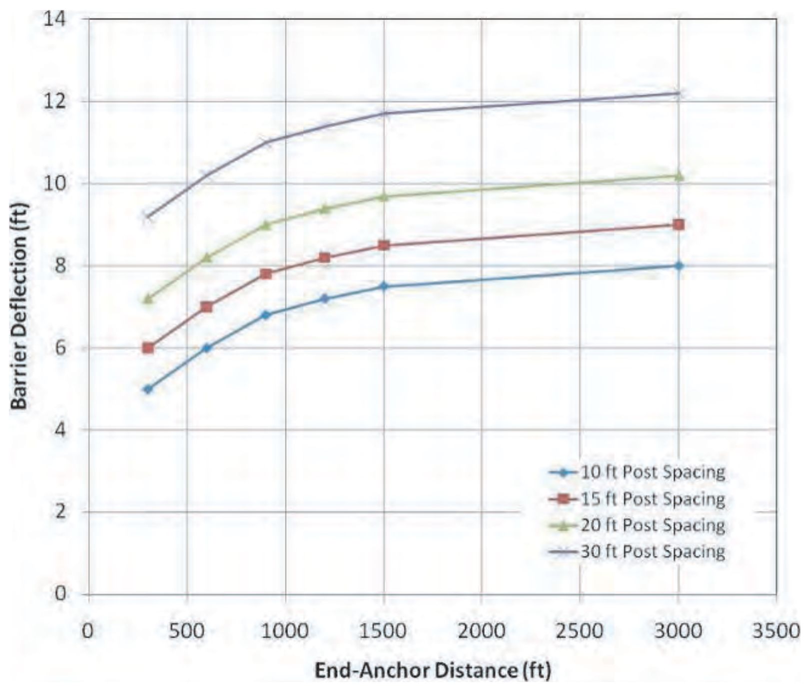


Figure 6.5. Hypothetical plot of barrier deflection vs. end-anchor and post spacings.

results, as expected, indicated that in impacts with cable barriers, the maximum dynamic deflection is affected significantly by the end-anchor spacing and post spacing. Greater end-anchor spacing leads to increased barrier deflections. The rate of increase in deflection is greater for end-anchor spacing of less than 500 m (1,640 ft). Similarly, the results showed that post spacing affects the barrier deflection with longer post spacing leading to increased deflection. The results indicate that these effects vary for different types of cable barrier systems. Based on these findings the following guidelines are recommended.

- Design deflection should not be based solely on deflection data from full-scale crash tests.
- Highway designers should investigate the differences in deflections associated with a specific design (e.g., end-anchor spacing, post spacing, post type, cable-to-post connection) of a cable barrier system.

It is important to know that the "design deflection" distances noted by each manufacturer are based on the deflection that resulted from a 100 km/h (62 mph), 25° test with a pickup truck impacting a cable barrier with specific post and end-anchor spacings. In the field, deflections can be greater depending on the specific impact conditions that occur and the installation setup.

A hypothetical plot, showing the effect of end-anchor and post spacings on barrier deflection, is shown in Figure 6.5. Similar plots should be generated for the different cable barrier systems. It should be the individual manufacturer's responsibility to ensure that such plots are available for each of its systems.

End Anchors and Post Embedment

End anchors perform a critical function for cable barriers by keeping the cables in tension to minimize deflection upon impact by a vehicle. Some problems have been noted in the field when these anchors have moved in the soil, either because of initial cable tension, increased cable tension caused by lower temperatures, or as a result of crashes into the barrier. Movement of the anchor in the soil decreases the tension in the cables which, when extreme, may result in unsatisfactory barrier performance. Therefore, anchors should be designed based upon an analysis of the soil where the cable barrier will be placed. Based on the soil data and climate information, static and dynamic geotechnical analyses or testing should be performed to determine the appropriate size for the end anchor. Likewise, many designs use posts set in concrete foundations to facilitate removal and replacement of damaged posts. These foundations also must be sized properly, based on existing soil and climate conditions, so they are not damaged or pulled out of the ground in a crash. Below are guidelines to ensure adequate size for the end-anchor and post footings.

- Soil analysis must be performed to determine the appropriate size for the end-anchor and post footings.
- The anchors should withstand a dynamic and static load (due to temperature variation) of 140 kN (31 kips) if all cables are connected to a single anchor or 90 kN (20 kips) if the cables are individually anchored. The anchor should not be damaged, and anchor movement should be less than 50 mm (2 in), preferably less than 25 mm (1 in.) under this load.
- Fitting hardware used to connect the cable ends to the end terminal and/or end anchors should be properly installed to avoid cable pull-out from the connector during impact.
- When a concrete footing is used for the posts, the footing should be designed to withstand a load higher than the plastic capacity of the post (i.e., the post would bend before the post footing breaks or moves significantly).

Interconnection with Other Systems

Because of the deflection distances inherent in a cable barrier, there will often be locations where cable cannot be used to shield a fixed object hazard effectively, such as where bridge piers are set in a narrow median. In such cases, a median cable barrier must be terminated and a semi-rigid barrier introduced.

FHWA has issued acceptance letters for several cable-to-W-beam transition designs as meeting NCHRP Report 350 test conditions at Test Level 3. The designs were accepted based on full-scale crash testing conducted under NCHRP Report 350 with a South Dakota design in which a generic 3-cable barrier was carried over and under a W-beam guardrail (which was anchored separately) and anchored independently behind the metal beam rail. Subsequent to this testing, several of the manufacturers of proprietary cable systems proposed similar transitions, with the basic difference being the cables were attached directly to the W-beam rail element, thus eliminating the need for a separate anchor for the cables.

At this time, only transitions where the cable barrier system is in line with the other system have acceptance letters and all accepted transitions connect to semi-rigid (strong-post W-beam) barriers. Also, all transition acceptance letters are based on one full-scale crash test (South Dakota design). The new transitions have been accepted without additional full-scale crash testing. Based on the findings described in Section 5.4, the following guidelines are recommended:

- Cable barrier should not be transitioned into rigid (concrete) or flexible (weak-post W-beam) barriers unless further analyses and/or testing are conducted and adequate performance is achieved.
- Transitions achieved by overlapping a section of the cable barrier in front or behind semi-rigid systems should not be used until further analyses and/or testing are conducted to ensure adequate performance is achieved.
- The semi-rigid barrier to which the cables are connected must be long enough and adequately anchored at its downstream end to resist the tension in the cables. The semi-rigid barrier should withstand a 140 kN (31 kips) load with less than 25 mm (1 in.) movement of its end

post or end anchor. Under this study, simulations were conducted to identify the minimum length needed for strong-post W-beam systems, and it was found to be 23 m (75 ft).

- The connection between each cable and the rail of the semi-rigid barrier should be designed such that it can withstand 90 kN (20 kips).
- The semi-rigid barrier should be appropriately flared back with adequate offset between it and the cable barrier. A minimum of 1.2 m (4 ft) flare is recommended.
- The heights of the cable barrier system should be compatible with the semi-rigid barrier over the length of the transition.
- The cable barrier needs to be transitioned from its lateral position to that of the semi-rigid system.

Cable Barrier Tolerances

The tolerances listed in Table 6.1 are recommended to minimize the effects of installation variations on cable barrier performance (see Section 5.6).

Placement along Horizontal Curves

There are two concerns that must be considered when cable barrier is located along a curved section of roadway. The first is that the high-tensioned cables can exert significant lateral pressure on the support posts and may cause them to bend over time, regardless of whether the barrier is on the inside of a highway curve to the left (convex) or on the outside (concave). The second concern is crash performance. When a convex installation is impacted, the tension in the barrier immediately decreases as the cables are separated from the posts and become slack, resulting in deflections in excess of the barrier's design deflection.

Limited research has been conducted to study the effects of horizontal curvature on the performance of cable barrier systems. To investigate this effect, finite elements simulations were performed. Barrier models with varied curvature radii, 150, 300, and 400 m (492, 984, and 1,312 ft), and varied post spacing, 1.6, 3.2, and 6.4 m (5, 10, and 20 ft), were created. The models are based on one of the high-tension systems used in analysis described in Section 5.2 (a 4-cable CASS system). It is expected that similar results with other high-tension systems would be observed.

The simulations were conducted for impacts with a 2000P vehicle traveling at 100 km/h (62 mph) and 25° angle. The barrier length used for all simulations was 200 m (656 ft). The deflections of the barrier from these simulations were extracted, and the results are plotted in Figure 5.48. The simulations clearly indicate that convex curvature leads to increased deflection. The increase in deflection was as high as 70 percent. Thus, it is important to consider this effect when selecting barrier location.

The simulation results suggest the following guidelines:

- Shorter post spacings should be used to account for the increase in deflection when cable barriers are placed on horizontal curves with a radius less than 400 m (1,300 ft).

Table 6.1. Suggested cable barrier tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in.)
Bottom Cable Height	-25,+0 mm (-1, +0 in.)
Middle Cable(s)	±25 mm (±1 in.)
Barrier Lateral Position	±150 mm (±6 in.)
Average Post Spacing	±150 mm (±6 in.)
Consecutive Post Spacing	±600 mm (±2 ft)
Cable Tension	±2 kN (±0.45 kips)

- Shorter post spacings should also be used to reduce the bending of the posts over time due to lateral forces applied by the cables on the posts.
- The lateral placement guidelines developed under Section 5.1 should be followed to ensure adequate vehicle-to-barrier interface.
- The barrier should be placed as close as possible to the convex side to allow more space behind the barrier for the added deflection. This will also reduce the number of cable barrier hits since it is placed farther away from the more frequent impacts with vehicles coming from the concave side [1].
- For narrower medians, the use of two cable barriers (one on each side of the median) or a more rigid barrier should be considered to reduce the likelihood of vehicles impacting the convex side and intruding into on-coming traffic.

Placement on Vertical Curves

Placing cable barriers on vertical curves also creates potential concerns for barrier performance. In such installations, the tensioned cables exert upward vertical forces on the posts, which are significantly lower in elevation than the end anchors, particularly at the bottom of the vertical curve. Depending on the specific design details of the barrier, i.e., post embedment and cable-to-post connections, these upward forces could pull the posts out of the ground, pull the posts out of the sockets, or pull the cables off the posts, resulting in less cable tension and cables at the incorrect height in relation to the ground. Designers should be aware of this possibility.

Placing the end anchors as close as possible to the minimum and maximum points of the vertical curvature reduces the upward vertical forces. Similarly, placing the end anchors at locations where there is a sudden change in the vertical slope would reduce the vertical variation effects. Another possible solution is to use closer post spacing through sharp vertical curves to reduce the vertical component of force on individual posts. Suggested guidelines for cable barrier when placed on vertical curves are listed below.

- End anchors of the cable barrier should be placed as close as possible to the bottom and top points of the vertical curvature.
- End anchors should be placed at points where there is a sudden change in vertical slope.
- Post spacings should be reduced in sharp vertical curves.
- Regrading short sections of the median that have sharp vertical curvatures should be considered.
- Regular checks should be performed at the bottom and top of vertical curves to ensure that the cables have not moved up or down from their specified heights.

Installation and Maintenance Costs

An analysis of installation and maintenance costs for cable barriers was conducted to ensure effective use of limited safety resources (Section 5.7). Based on these findings, the following guidelines have been developed:

- Life-cycle cost analyses should be used to evaluate cable barrier systems rather than selecting systems on the basis of lowest bid for installation. All FHWA-accepted systems do not perform the same.
- End-anchor and post foundation specifications should require designs based on in situ soil conditions and expected climate conditions that are reflected in the costs.
- If a maximum design deflection has been set for a project, then the combined effects of post spacing and anchor-to-anchor spacing for each specific type of high-tension cable barrier should be considered to ensure that the required maximum deflection will not be exceeded.

- Because of the small marginal cost of adding an extra cable and the likelihood of improved safety performance of the barrier with an extra cable, benefit/cost analyses should be used to determine when a fourth or fifth cable is justified.
- Periodic inspection schedules based on expected frequency of impacts should be established for each cable barrier installation.
- Maximum response times for repairing damaged barriers should be established based on the class of highway and the extent of damage.
- Cable heights on barriers at the bottom and top of vertical curves should be checked periodically to make sure they remain at design heights.
- Post spacings should be reduced for horizontal curves with a radius 400 m (1,300 ft) or less.
- A benefit/cost analysis should be conducted to determine when a mow strip is justified.
- Cable barriers should be inspected after severe weather events, including flooding and extremely cold temperatures, to check for erosion, end anchor movement, and cable heights on vertical and sharp horizontal curves.
- Driven posts should not be used except when the expected rate of impacts is too low to justify socketed posts.
- Manufacturers should provide training on barrier installation, maintenance, and repairs for highway agencies and emergency response crews.

CHAPTER 7

Summary and Conclusions

Following the tasks prescribed under this project, a comprehensive effort to identify and develop guidelines for the use, selection, and maintenance of cable barriers was undertaken. The focus of the effort was to undertake analyses that would provide a sound basis for the guidelines. The efforts included the following:

- A comprehensive literature review of U.S. and international cable barrier studies was undertaken. The focus was to capture all ideas relevant to the design, performance, evaluation, and maintenance of cable barrier systems. Chapter 2 of this report documents the findings of this effort and includes a summary of the conclusions drawn.
- It is noteworthy that there are various "modern" cable barrier systems that are being deployed in a majority of the states. These deployments are proceeding with the best available insights, but the approaches, selection criteria, and design practices vary considerably. Information was gathered related to state guidelines, in-service evaluations (both formal and ad hoc), as well as manufacturer's design, installation, and maintenance documentation for all cable barrier systems. The features of the various systems and their testing outcomes were gathered. This effort involved direct contacts with the states to gather pertinent information. The findings are documented in Chapter 3.
- An interim report that summarized the findings of the background studies was generated to provide a basis for the specific analyses to be undertaken. The interim report proposed 12 candidate work plans for Phase II of the project. Each work plan described the issue to be addressed, provided a detailed outline of the planned approach, and outlined the expected guidelines to be developed. After deliberations with the panel the following seven work efforts were selected:
  - Analyses of impact of lateral placement on cable barrier effectiveness
  - Investigation of cable barrier deflection for varying designs
  - Assessment of end-anchoring systems (anchor size and soil condition)
  - Review of requirements for interconnection with other barriers (transitions)
  - Formulation of construction tolerance for cable barrier systems
  - Evaluation of the influences of roadway horizontal curvature
  - Identification of installation and maintenance costs
- The panel approved these work plans and authorized the contractor to proceed.
- The research efforts were executed in accordance with the plans. This research will help agencies currently moving forward with cable median barrier systems to have additional knowledge on which to base impending decisions. The results of these research efforts are presented in Chapter 5.
- The research was undertaken with a focus on formulating guidelines for cable barrier systems. These efforts were undertaken considering the variations in cable barrier technology, median configurations, potential impact conditions, highway design, operational issues, and other factors. The resulting guidelines were compared to, and supplemented with, existing guidelines reflected in current practices and those proposed in other research.

- After review of the preliminary guidelines by the panel, presented in this draft report, a workshop was held to solicit feedback on the draft guidelines from state agencies, industry representatives, and other practitioners who would be the primary users of the guidelines. The feedback and comments from the workshop participants serve as the basis for updates to the guidelines.
- A final report documenting the updates was prepared. The final report presents the final recommended guidelines, document limitations of the analysis, cite the sources of the material presented, and suggest needs for future research.

7.1 Research Findings

The research efforts led to the following conclusions:

- There is continued growth in the application of cable barriers and accumulating evidence that they are highly effective. Although the newer technologies for cable barriers date back to the 1990s, many agencies may have been cautious about applying the technology due to the lack of experience and limited guidance in doing it effectively.
- Despite interest in understanding the safety problem and the effectiveness of cable barriers, there is still no definitive data for the identification of problem locations and/or the evaluation of treatment effectiveness. Changes in FARS 2008 to define median crossovers as a specific crash type will help to address the need for better data.
- Vehicle dynamics analysis (VDA) reveals useful insights into influences of terrain on barrier performance. It provides the basis for "interface analyses," which should be considered the first issue to be addressed for barriers on slopes.
- There are many factors that influence vehicle dynamic response when traversing sloped terrain. Primary factors include vehicle mass, speed, angle of departure, and slope. Secondary factors include the distribution of vehicle load, condition of vehicle subsystems (e.g., suspension), surface conditions, driver control inputs, and surface friction.
- The design of any barrier and its placement influence interface effectiveness for any sloped conditions (i.e., design and placement sensitivity).
- Median or roadside conditions can vary widely, even along a particular highway. Median configuration is a function of width, shape, slope, and depth. Median analysis must include bi-directional crossings.
- This research builds upon efforts that were initiated by FHWA and expanded to cover a wider range of median profiles: V-shaped, flat-bottomed, rounded, and asymmetrical medians from 5 to 30 m (16 to 100 ft) wide.
- The interface analyses were undertaken for a broader set of conditions than is normally used to evaluate roadside hardware. More specifically, the analyses considered the following conditions/factors:
  - Impact speeds of 50 to 100 km/hr (31 to 62 mph)
  - Impact angles of 5 to 25 degrees
  - Vehicle types 820C, 1100C, 2000P, and 2270P
- VDA was used to generate bi-directional trace paths for each vehicle type, speed, angle, and median configuration. Individual trace paths were aggregated to define interface envelopes. The interface envelopes provided the basis for establishing override and underride limits for each median configuration.
- Aggregation of the override and underride limits across varying median configurations provides a basis for establishing functional design requirements.
- Finite element models of the major proprietary cable barrier systems were developed to reflect their design differences. These models were compared to the acceptance crash tests for each system to provide validity for the analysis.

- Crash simulations were conducted to analyze the influences of post spacing on dynamic deflection. There was a uniformity of increase in deflection for all systems with greater post spacing.
- Simulation was used to analyze the effects of distance or lengths between anchorages on cable deflections. It was noted that deflection increases rapidly up to distances of about 300 m (1,000 ft) and then increases continually but more slowly up to the 1,000 m (3,300 ft) modeled.
- The change in cable barrier deflection due to end-anchor spacing variation is different for different barrier systems.
- Anchorage design requirements were noted to be critical to system functionality. The need to design anchorages for local conditions was highlighted.
- Construction tolerances were cited based upon the results of the various analyses.
- Interconnections were noted to be necessary for situations where the cable barrier system cannot adequately protect some obstacles. Examples of common interconnections were provided.
- Interconnections require that there be adequate offset or overlap flaring of the semi-rigid system. These semi-rigid systems should be designed to withstand the tension forces exerted by the cable barrier. It is also necessary to make sure that the heights of the barriers are consistent and that the cable line is transitioned to the semi-rigid barrier line.
- Analysis of cable barrier performance on horizontal curves noted the greater deflection possible on convex curves and the need to consider shorter post spacing.
- Installation costs were based upon available data where compiled as a basis for estimating the potential costs of new systems. The relative influences of the various components, discount rates, service life, and related factors were discussed.
- Maintenance elements including inspection and routine servicing were identified and, to the extent possible, costs of these activities were cited.
- Repair costs were noted to be hard to estimate because the number and severity of crashes are hard to predict.
- Elements of repair costs and the available data on associated costs were presented.

7.2 Development of Guidance, Guidelines, and Procedures

The results from this research consist of guidelines for the selection, use, and maintenance of cable barrier installations. This information will help highway agencies optimize the performance of cable barriers and decrease serious injuries and fatalities, as well as reduce barrier maintenance costs. These guidelines will have an impact only if they are accepted by FHWA and state DOTs.

The process of developing the guidelines for the selection, use, and maintenance of cable barriers followed a hierarchal approach to the various factors listed above considering the tradeoff between factors. The research team formulated the first draft of the guidelines. At this point, the research team arranged a workshop that included the panel and up to 10 other knowledgeable individuals representing DOTs, industry, and other groups to critique, revise, and enhance the guidelines.

7.3 Future Research Needs

Although this research extended the knowledge about the use, design, selection, deployment, and maintenance aspects of cable median barriers, there remain topics that need further study. In-service evaluations and research investigations identified several key topics/issues that need to be addressed. A few of these topics are listed below.

- Collect detailed in-service performance information for the various cable barrier systems.
- Analyze the relationship between inter-cable spacing and the risk of vehicle penetrations between the cables.

- Conduct further investigations for connecting cable barriers to other systems such as concrete and weak post barriers (transitions).
- Develop guidelines for the steepness of fill-embankment slope behind cable barrier in roadside installations.
- Develop a systematic method for determining end-anchor and post footing sizes for different soil and environment conditions.
- Develop criteria for maintenance actions for damaged sections of cable barrier (to possibly be integrated with the results of NCHRP Project 22-27).
- Develop warrants for using TL4 cable barrier systems rather than TL3 systems.
- Investigate the use of intermediate anchors to maintain barrier effectiveness on long runs of cable barriers.
- Develop guidelines and/or technologies for upgrading of existing systems (e.g., low to high tension, adding cables).
- Develop guidelines for using cable barrier on vertical alignment and in the proximity of intersections and interchanges.
- Investigate the influences of post type, connectors, and embedment (e.g., driven vs. sleeve) on barrier performance.
- Study the crashworthiness and effectiveness of interfaces for trucks.
- Develop improved testing protocols and evaluation criteria to provide a more robust crashworthiness evaluation that would allow the potential effectiveness of cable barriers on slopes to be considered in selecting a specific cable barrier design. Also, develop testing criteria specifically for trucks.
- Revisit the benefit/cost relationships for various types of median barriers relative to traffic to derive an updated set of warrants that reflects the favorable economics of cable barriers.
- Use the cable barrier models developed in this study to test new concepts for improving cable barrier designs.

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Glossary

Acceptance Testing—Crash tests reported to FHWA to obtain a letter accepting a roadside hardware item to be considered acceptable for use on the National Highway System.

Anchor—a mass designed to counter the tension forces in a cable barrier system at either end. These are usually large concrete blocks whose size and depth are a function of the soil conditions.

Anchor Spacing—The distance between end anchors for a continuous length of cable barrier.

Anchorage—See Anchor.

Asymmetric Cross-Section—A median cross-section that has unequal side slopes.

Barrier Interface Envelope—A graph or plot that depicts variations in vehicle vertical position as it traverses the median at different speeds and angles. In some cases, more than one vehicle type is incorporated in the envelope.

Barrier Transition—The device or hardware used to link one type of barrier to another in a fashion that will function safely.

Cable Barrier Technology—Various designs for cable barrier systems.

Cable Tension—The amount of tensile force in the cable.

Cable Post—A semi-rigid steel beam of varying shape used to provide support for cables before and during an impact.

Cable Connector—A device (e.g., hook bolt, hair pin, or similar fixture) designed to hold the cable at a specific height.

Cable Splices—Connection between cable sections that are physically joined to provide the needed continuity.

CarSim—Commercially available software for vehicle dynamics analysis distributed by Mechanical Simulation Corporation.

Central Reserve—Common international term for median. See Median.

Crash Simulation—A computer process that predicts the vehicle and/or barrier response of a crash event.

Cross Median Crash—A crash between two or more vehicles that follows a vehicle crossing over the median from the opposite side of the highway.

Cross-Median Event—An event where a vehicle wholly or partially crosses the median. These may or may not result in a crash.

Crossovers—Points along a divided highway where vehicles can transfer to travel in the opposite direction. Usually restricted to emergency or maintenance vehicles.

Deflection—The amount of lateral displacement of a barrier from its original position to that during or after an impact.

Durability—The ability of a material or device to function effectively over time.

Finite Element Models—Representations of objects created by subdividing the entire item into small pieces for which their geometry, material characteristics, contacts, and failure modes are defined. In time-based simulations, each element is subjected to forces that cause movement, deformation, or failures. Systematic updates of the changes to each element allow replication of impacts or other physical changes.

Furrowing—The sinking into the median soil when wet or very dry causing the vehicle's interface area to be lower at point of impact.

Guidelines—A structured set of guidance statements reflecting a consensus.

Guidance—Statements that provide soundly based directives for undertaking an action.

GWU—George Washington University.

High-Tension—A cable barrier system that has higher initial tension and stronger post-to-cable connection than the original generic cable barrier systems. The high-tension systems experience lower deflection during impacts than the original systems but may require larger anchors.

HVE (Human Vehicle Environment)—Software tool for vehicle dynamics analysis distributed by Engineering Dynamics Corporation.

Interface Trace Plot—A diagram showing the relative position of points defining the interface region of the front of a vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Interface Region—The front area of a vehicle that has sufficient structural integrity to interact with a barrier. This varies by vehicle.

Interface Envelope—The area subtended by the points defining the primary structural region on the front of the vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Lower Trace Limit—See Underride Limit.

Low-Tension—A term used to define the original generic cable barrier system in which the tension in the cables is about 4,450 N (1,000 lb) at 18°C (65°F).

LS-DYNA—Finite element simulation software developed by the Livermore Software & Technology Corporation.

Maintenance Cycles—Repetitive actions in time to keep a device functional.

MASH—Manual for Assessment of Safety Hardware. AASHTO hardware crashworthiness testing protocols and standards.

Maximum Lower Cable Height—The highest a bottom cable can be to allow engagement between the vehicle and barrier to avoid underride for the selected vehicle or set of vehicles.

Median—An unpaved area between opposing lanes of traffic and associated shoulders.

Median Configuration—The features of the median cross-section.

Median Cross-Section—The dimensions, slopes, and shape that result from passing a plane perpendicular to the road at any given point.

Median Profiles—The features of the median cross-section.

Median Shape—See median profiles.

Median, Asymmetrical—A cross-section with unequal side slopes that converge to a central point.

Median, Flat Bottom—A cross-section with equal side slopes that extend to a flat-bottomed area of a given depth.

Median, Multi-Slope/Broken Back—A cross-section with two or more side slopes that converge to a central point.

Median, Raised—Medians have up-slopes from the edge of the shoulder.

Median, Rounded Bottom—A cross-section with equal side slopes that converge to a central point that has a rounded transition from one side to the next.

Median, V-Shaped—A cross-section with equal side slopes that converge to a central point.

Minimum Upper Cable Height—The lowest a top cable can be to allow engagement between the vehicle and barrier to avoid override for the selected vehicle or set of vehicles.

Mow Strips—A paved area along the cable line that eliminates the need for grass mowing around the posts.

MwRSF—Midwest Roadside Safety Facility at University of Nebraska-Lincoln.

NCAC—National Crash Analysis Center at George Washington University.

NCHRP Report 350—Report 350 was adopted as the national standard for roadside hardware crashworthiness testing.

Normalized Trace Plot—A trace plot or interface trace plot in which the vertical height of the reference points above the ground line (or surface) is plotted on a horizontal axis.

Nuisance Hit—A random impact of a cable barrier that results in minor damage but often goes unreported because the vehicle recovers and is able to continue. May also occur from impacts associated with maintenance operations.

Off-Tracking—The path of a vehicle that involves some degree of lateral sliding.

Override—An event where all or part of a vehicle gets over the top of a barrier.

Override Limit—A line (curve) defining the minimum height of the top cable that allows engagement between the vehicle and barrier to avoid overrides. The line defines the minimum height at different lateral placements of the barrier.

Ploughing—See Furrowing.

Prestretched Cable—Cable that is statically loaded after manufacture to reduce the slack in individual strands of the cable before installation.

Primary Structural Region—See Interface region.

Position Isobars—A continuous line that indicates the relative position of the cables for any lateral position across the median.

Post Embedment—The method used to place a post to support the cables including direct driven, placed in a socket, or installation in a drilled footing with compacted material or concrete.

Retensioning—The mechanical process of increasing the tension in existing cables.

Retrofit—Changing the configuration of the cable barrier design after initial deployment.

Roadside—The area beyond the shoulder adjacent to the highway.

RDG—AASHTO Roadside Design Guide.

Sleeve—A type of footing that allows a post to be readily inserted or removed after installation.

Slope Rounding—The process of regarding sloped medians such that the edges at the breakpoint are curved with a certain radius.

Socket—A concrete foundation for posts that allows them to slide in or out. Sockets greatly facilitate rapid repair of damaged cable barrier posts after an impact.

Socketed Posts—See Socket.

Spring Response—The incremental dampening of forces by a spring directed toward restoring equilibrium.

Strand—A single wire in the bunch of twisted wires that constitutes the cable or wire rope component. Sometimes used to refer to the bunch of cables (e.g., three-strand, low-tension system).

Safety Fence—Common international term for guardrail or cable barrier system.

Trace Plot—The diagram showing the relative position of a point on a vehicle as it traverses a specific path as viewed from a downstream point perpendicular to the centerline of the road.

Tracking—See Off-Tracking.

Tension Compensators—A device that incorporates springs to regulate the tension in the cables. These devices are used in generic, low-tension cable barriers.

Tolerances—The permissible range of variation in construction and installation of cable barriers (these could be dimensions, mechanical properties, measurements, etc.).

Transitions—See Interconnections.

TTI—Texas Transportation Institute at Texas A&M University.

Underride—An event where all or part of a vehicle goes under the lowest longitudinal element of a barrier.

Underride Limit—A line (curve) defining the maximum height of the bottom cable that allows engagement between the vehicle and barrier and avoids underrides. The line defines the maximum height at different lateral placements of the barrier.

Upper Trace Limit—see Override Limit.

Validation—The process of determining how well a model represents the real situation.
Vaulting—See Override.
Vehicle Dynamics—The physics of the forces acting on a vehicle as it moves across a surface considering the features of the vehicle.
Vehicle Dynamics Analysis (VDA)—The analysis of the physics of a moving vehicle with specific design characteristics (e.g., mass, suspension features, length) that is influenced by the loaded mass, speed, and direction of the vehicle and surface conditions (e.g., slope, surface firmness, friction) of the vehicle's path.
Vehicle Trajectory—the path a vehicle takes as it traverses across roadway and roadside features.
Verge—International term for shoulder or gore area at on- or off-ramps of highways.
Wire Rope Safety Fence—International term for cable barrier. See Cable Barrier.

APPENDIXES

Appendixes A through D of the contractors' final report are not published herein but are available on the TRB website by searching for *NCHRP Report 711*. Appendix E is published herein and follows.

APPENDIX E

Summary of Recommended Guidelines

In NCHRP Project 22-25, Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems, a comprehensive review of the state of the art relative to cable barrier systems was undertaken. These efforts included a review of the literature, a survey of highway agencies, and discussions with knowledgeable professionals from government, industry, and academia. These efforts identified current practices and the rationale behind them, as well as issues that needed attention. In research efforts that followed, various analyses were undertaken in an attempt to address the issues and provide a sound basis for additional guidance. For example, thousands of vehicle dynamics simulations were run to understand the trajectories for various vehicles traversing different median configurations to establish criteria for lateral placement that would maximize the effectiveness of the vehicle-to-barrier interface. The following sections provide a summary of the guidance derived from all of these efforts. The guidance was vetted in a 2-day meeting that involved the project panel and invited professionals from government, industry, and academia. The consensus guidance is outlined below. It is believed to provide a solid basis for agencies that have been using cable barriers to update their practices to enhance safety performance or cost effectiveness as well as to aid agencies interested in considering the use of cable barriers for the first time.

1. Planning and Feasibility (Use)

The process of deploying a cable barrier system begins with planning and feasibility studies for a given highway corridor to determine whether a barrier is needed and whether a cable barrier system is an appropriate type of barrier. The safety history of the corridor is often the primary consideration followed by considerations of the highway features, traffic conditions, system considerations, available products, and environmental factors. Guidance on the things that need to be considered at the planning and feasibility stage are cited below. These were derived from information documented in the research report.

1.1. Safety Needs

1.1.1. Numerous studies have shown that cable barriers are one of the most effective means of reducing median crossover fatalities and serious injuries.

1.1.2. An analysis of cross-median crash history should be conducted to determine those sections with the greatest need. State crash records and/or FARS data provide a basis for analyzing cross-median crashes. The 2008 improvements to FARS provide a specific data item of cross-median crashes to facilitate the capture of these types of crashes.

1.1.3. Crashes should be characterized by environmental, traffic, road features, contributing causes, and other factors to determine candidate countermeasures.

1.1.4. Crash rates should be compared to appropriate (e.g., national or state) benchmarks to prioritize sites.

1.2. Facility Features

1.2.1. Median configurations should be inventoried because placement is influenced by changes in width, variations in alignment, cross section, and other features.
1.2.2. Obstacles in the median that require special barrier treatment should be identified (e.g., bridge piers, lighting structures, drainage elements).
1.2.3. Aerial images, video logs, or other digital data sources to capture relevant median configuration and obstacles information should be used.
1.2.4. Requirements for median crossover points should be determined considering emergency management, operations, and maintenance.
1.2.5. Soil conditions and implications for cable barrier end-anchors and post embedment should be considered.

1.3. Traffic Considerations

1.3.1. Posted and actual speeds for the highway should be considered as they will have implications for barrier effectiveness.
1.3.2. Roadway facilities with higher truck percentages should receive greater consideration for the use of TL4 cable barriers systems. (See criteria in *NCHRP Report 638*.)
1.3.3. The level and nature of traffic to prioritize candidate projects should be determined on the basis of exposure. Assess the implications of directional flows.
1.3.4. Projected future traffic levels should be considered in the context of the expected project life.
1.3.5. Possible changes in the types of median encroachments that may occur along a highway corridor (e.g., lane change actions near interchanges) should be considered.

1.4. General System Considerations

1.4.1. Barriers should be used where the need exists and a cost-effectiveness traffic barrier system can be deployed.
1.4.2. The AASHTO Roadside Design Guide or applicable state guidelines for deployment considerations should be followed.
1.4.3. Cable barrier is often the cost-effective choice for installation in wider medians because of its lower cost, adaptability to non-level terrain (within limitations), and relative ease of maintenance.
1.4.4. Proper placement, installation, and maintenance is necessary to assure full effectiveness of cable median barriers after deployment.

1.5. Barrier Systems

1.5.1. Only cable barrier designs that have been accepted for use on the National Highway System should be used. Any limitations cited within the acceptance should be considered when selecting the barrier.
1.5.2. Compatibility of the design with other systems in use by the agency should also be considered. This has implications for the number of items in the parts inventory, interconnection options, and staff training.
1.5.3. Consideration should be given to the harmonization of procurement and addressing bid processes as well as related issues.

1.6. Environmental Factors

1.6.1. The prospect for problems with snow accumulation for various types of barriers on their winter performance should be considered.

1.6.2. Drainage needs and the median/roadside soil conditions relative to post and anchorage requirements should be taken into consideration.
1.6.3. Frequency of wet soil conditions should be considered for barrier installation and maintenance.

2. Cable Barrier System Design

There are generic and proprietary cable barrier systems available with varying features. Effective use of cable barrier systems necessitates an understanding of these features and how they influence the performance of the system in a given application as well as how they influence cost, installation, and maintenance requirements over time. Guidelines related to features such as number of cables, post design and spacing, cable-to-post connections, and cable tension and anchorages are listed below. The available options in each case have cost and performance implications. There are a variety of approaches to transition cable barriers into other barrier systems and ancillary features, such as mow strips, that facilitate maintenance. A fundamental requirement for deployment of these systems is that they pass the established crashworthiness requirements to be considered acceptable for use on the nation's highways.

2.1. Number of Cables

2.1.1. Research has shown that the interface area provided by the barrier is increased with additional cables.
2.1.2. There are greater placement options for the increased number of cable options.
2.1.3. Due to the potential for slight variations in lateral placement that may be needed to accommodate changes in the median configuration and/or obstacles, the cable design that offers a greater amount of effective placement area (e.g., with increased number of cables) should be selected.

2.2. Posts and Spacings

2.2.1. Soil conditions need to be assessed to assure that the posts will be able to adequately support the system and provide the necessary resistance when impacted.
2.2.2. Moisture in the soil will influence the functionality of cable barrier posts. Wetter soil conditions may increase the potential deflection.
2.2.3. Placing cable barrier posts in sockets reduces repair time and costs relative to posts driven in soil.
2.2.4. Cable barrier deflection is a function of post spacing. Generally the greater the post spacing, the higher the potential deflection.
2.2.5. MASH requires that cable barriers be evaluated for a minimum 200 meter installation. Longer installations may result in greater deflection.
2.2.6. Soil conditions will influence long-term post maintenance costs; therefore, an appropriate design should be selected.
2.2.7. Post spacing can be reduced where lower deflection is needed or horizontal/vertical curvature may affect cable integrity.

2.3. Cable Tension and Anchorages

2.3.1. Pre-stretched cables reduce the number of times the system needs to be retensioned, which may be an advantage over non pre-stretched cable.
2.3.2. Cable tension needs to be maintained over the length of the barrier run.

2.3.3. An anchorage designed for the local soil conditions is needed for each run of cable barrier. Since anchorages can be expensive, a minimum run of 1,000 feet may be considered. There is no physical maximum length of run, but practical considerations may apply (e.g., need for openings, other features).

2.4. Acceptance Testing

2.4.1. Determine whether the barrier was tested to NCHRP Report 350 or MASH criteria. Systems tested under MASH are subjected to higher impact severity conditions (heavier test vehicle, longer installation, sloped medians, etc.). Also, MASH requires a longer test article length, so cable barrier deflections will be different. Hence the use of MASH tested systems has advantages over Report 350 tested systems.

2.4.2. Assess the variations in side slope conditions, if any, from the test conditions relative to the anticipated slope placement.

2.4.3. Determine whether the testing was for TL 3 or TL 4 and associated slope conditions.

2.4.4. The "working width" established in testing of the system provides a useful rule of thumb for estimating cable barrier deflection.

3. Deployment

The deployment process involves taking a preferred cable barrier system and fitting it into the specific environment of a highway corridor. Many applications of cable barriers are retrofit efforts to address crash problems or the potential for crashes. Often, the existing highway environment was designed for lower traffic volumes and design standards that have been revised to reflect acquired knowledge about highway operations, safety, drainage, and maintenance. The environment may not provide desired widths, side slopes and median configurations may vary, and a variety of other objects may exist in the median or on the roadside. This section provides guidance for deployment related to road alignment, cross sectional features, and other aspects.

3.1. Lateral Placement

3.1.1. General: The potential effectiveness of cable barriers is a function of lateral position in a given median configuration (i.e., width, side slopes, shape, and depth). Basic lateral placement guidelines below are developed for a single run of systems where the top cable is at 33" or higher, and the bottom cable is at 21" or lower. This range covers most currently available cable barrier systems. The guidelines are applicable to all median widths. For systems that do not meet these criteria, or if lateral placement cannot be achieved based on the below guidelines, optimal placement needs to be determined by the use of lateral placement charts or specific vehicle dynamics analyses.

The guidelines are based upon analyses which considered vehicles ranging from 820 kg to 2270 kg, departing the roadway at angles from 5 to 30 degrees, at speeds ranging from 30 to 62 mph. This implies that the guidelines cover a greater range of possible impact scenarios than traditional crashworthiness criteria.

<u>Basic Cable Barrier Placement Guidelines:</u>

- Cable barrier systems should not be placed on slopes steeper than 4H:1V (unless the system has been designed for and successfully crash tested under these conditions).
- Cable barrier systems can be used on 4H:1V, or shallower sloped medians, or roadsides (6H:1V, or shallower sloped medians, or roadsides are preferable), provided the placement guidelines listed below are followed.

- Parallel runs of cable barrier may be appropriate for situations such as differential profile grades, narrow medians, or when objects such as high-mast light poles are located in the middle of the roadway median.
- A minimum clear distance equivalent to the likely deflection of cable barrier should be maintained between the cable barrier system and any obstruction. This should be adjusted for horizontal curve situations.
- A cable barrier system should be placed as far away from the travel lane as practical while maintaining proper orientation and performance of the systems to reduce nuisance hits.
- If the cable barrier switches from one median side to the other and terminals are not protected, overlapping runs of cable barrier are recommended to reduce the risk of crossovers.

<u>Symmetric V-Shaped and Rounded-Bottom Medians:</u>

- To avoid underrides, the barrier should not be placed in the region between –8 ft and 8 ft from the center of the median.
- For medians with slopes 6H:1V or shallower, the barrier may be placed in the region between –1 ft and 1 ft from the center of the median (special treatment, such as a mow strip, may be needed to compensate for poor soil condition in this region).
- To avoid overrides of larger vehicles (SUVs and pickup trucks), the barrier should not be placed farther than 4 ft from the edge (break point) of the median when the median side slope is steeper than 6H:1V.

<u>Symmetric Flat-Bottom Medians:</u>

- To avoid underrides, the barrier should not be placed in the region between –8 ft and 8 ft from the flat-bottom break points.
- For medians with slopes 6H:1V or shallower, the barrier may be placed in the region between –1 ft and 1 ft from the flat-bottom break points (special treatment, such as a mow strip, may be needed to compensate for poor soil condition in this region).
- To avoid overrides of larger vehicles (SUVs and pick-up trucks), the barrier should not be placed farther than 4 ft from the edge (break point) of the median when the median side slope is steeper than 6H:1V.

<u>Nonsymmetrical Medians:</u>

- It is preferable to place the cable barrier on the side of the median with the shallower slope.
- The guidelines for the v-shaped and flat-bottom medians listed above should be followed to minimize the risk of vehicle underrides or overrides.

<u>Shoulders and Superelevations:</u>

- Shoulders with down slopes of 6% or flatter are not detrimental to vehicle-to-barrier engagement and consequently do not affect barrier performance.
- For roads with superelevation steeper than 3%, the barrier should be placed not farther than 2 ft from the edge of (break point) medians when the slope is steeper than 6H:1V, and not farther than 5 ft when the slope is shallower than 6H:1V.

3.2. Deflection

3.2.1. Simulation analysis indicated that in impacts with cable barriers, the maximum dynamic deflection is affected significantly by the end-anchor spacing and post spacing. Greater end-anchor spacing leads to increased barrier deflections. Similarly, wider post spacing leads to higher deflection.

3.2.2. The results indicated that these effects are different for different types of barrier systems.

3.2.3. Cable barrier design deflection should not be based solely on deflection data from full-scale crash tests. Highway designers should investigate the differences in deflections associated with a specific design (e.g., anchor spacing, post spacing, post type, cable-to-post connection) of a cable barrier system.

3.2.4. Deflection plots for different barrier systems were generated under this study and used to investigate barrier deflection based on the barrier system, end-anchor spacing, and post spacing. Similar analyses, or other sources of data, should be used to provide a basis for understanding deflections for cable barrier systems.

3.3. End-anchors and Post Footings

3.3.1. End-anchors perform a critical function for cable barriers by keeping the cables in tension to minimize deflection upon impact by a vehicle. Some problems can occur in the field when these anchors have moved in the soil, either because of initial cable tension, increased cable tension caused by lower temperatures, or as a result of crashes into the barrier. Movement of the anchor in the soil decreases the tension in the cables which may result in unsatisfactory crash performance.

3.3.2. Soil analysis should be performed to determine the appropriate size for the end-anchor and post footings for each installation.

3.3.3. End-anchor and post footings should be designed for site-specific soil conditions.

3.3.4. The anchors should withstand a dynamic and static thermal load of at least 40 kips if all cables are connected to a single anchor, or at least 30 kips if the cables are individually anchored.

3.3.5. Special care and procedures should be used for installation of end cable connectors (terminations) to avoid premature cable pull out during impacts.

3.3.6. Very cold climatic conditions may require higher design loads. Anchors should be designed to limit movement to less than 1 in.

3.3.7. When a concrete footing is used for the posts, the footing should withstand a load higher than the plastic capacity of the post (i.e., the post would bend before the breaking or significant movement of the post footing).

3.3.8. Cable barrier system design should account for the potential of frost heave.

3.3.9. It may be appropriate to design for the durability of post sockets where multiple impacts might be expected. Other elements may be needed to provide adequate movement resistance.

3.4. Horizontal Curve Placement

3.4.1. The use of cable barrier along a curved section of the roadway can exert significant lateral pressure on the support posts and may cause them to bend over time. This occurs for cable barriers on the inside (convex) or outside (concave) of a highway curve.

3.4.2. Decreased post spacing from that on tangent sections may be appropriate for sections of cable barriers on horizontal curves.

3.4.3. Impacts on the convex side of a curved cable barrier will result in larger deflections. This effect was analyzed using simulations and an increase in deflection, even with high-tension systems, was as high as 70%.

3.4.4. With the increased deflection, the chance for loss of engagement is greater when the posts are damaged. Damaged posts should be replaced as soon as practical.

3.4.5. Reduced post spacings should be used to account for the increase in deflection when cable barriers are placed on horizontal curves with a radius less than 1,300 ft. This will also reduce the bending of the posts overtime due to lateral forces applied by the cables on the posts.

3.4.6. The barrier should be placed as close as practical to the convex side to allow more space behind the barrier for the added deflection. This may also reduce the number of cable barrier hits since it is placed further away from the more likely impacts with vehicles on the concave side.

3.4.7. For narrower medians, the use of two cable barriers (one on each side of the median) or a more rigid barrier may be considered appropriate to reduce the likelihood of vehicles impacting the convex side and intruding into oncoming traffic.

3.4.8. Placement of the cable barrier on the convex side (i.e., inside of the curve relative to near traffic) is recommended to allow maximum median space for recovery of vehicles leaving opposing travel lanes.

3.5. Vertical Curve Effects

3.5.1. On vertical curves, an upward force is exerted between the cable and the posts which could pull the posts out of the ground or pull the cables off the posts, resulting in less cable tension and cables at the incorrect height in relation to the ground. These effects adversely affect crash performance.

3.5.2. Manufacturers recommendations for keeping posts on vertical curves properly anchored in the soil should be observed.

3.5.3. End-anchors of the cable barrier should be placed as close as practical to the bottom and top points of the vertical curvature.

3.5.4. End-anchors may be placed at points where there is a sudden change in vertical slope.

3.5.5. Post spacing may be reduced in sharper vertical curves to offset the upward force effects.

3.5.6. Closer end-anchor spacing through extremely sharp vertical curves to reduce the vertical component of force on individual posts should be considered.

3.5.7. Re-grading short sections of the median that have sharp vertical curvatures should be considered.

3.5.8. Placement of cable barrier systems on some sag vertical alignments may be prudent. For example, Texas suggests that they should be avoided where the parabolic factor has a K-value of 11.

3.5.9. Periodic inspections should be performed at the bottom and top of vertical curves to ensure that the cables have not moved up or down from their specified heights.

3.6. Transitions and Interconnections

3.6.1. Cable barrier should not be transitioned into rigid (concrete) or flexible (weak post) barriers until further analyses and/or testing is conducted.

3.6.2. For transitions achieved by overlapping independent systems, the basic principle that each system should protect the hazard should be followed.

3.6.3. For transitions where the cable barrier is directly attached to the adjacent system, the following are recommended:

- The barrier to which the cables are connected should be long enough and adequately anchored at its downstream end to resist the forces from impacts and temperature variations in the cable barrier system. For w-beam strong-post guardrail, a minimum length of 75 ft is recommended. For other systems, the section connected to the cable barrier should be capable of withstanding a minimum of 40 kips of combined force.
- Similarly, the connection between each cable and the barrier should withstand the impact and thermal loads. The connection should be designed so that it can withstand a minimum of 30 kips.

- Adequate offset (flare) should be used between the cable barrier and the other system to prevent vehicle instability during the impact. A minimum of 4 ft offset behind the cable barrier is recommended for w-beam strong-post guardrails.
- The heights of the cable barrier and the other system should be compatible over the length of the transition region.

3.7. Mow Strips

3.7.1. A benefit/cost analysis may be conducted to determine when a mow strip is justified.
3.7.2. A maintenance consideration is the use of mow strips to reduce hand-moving and herbicide operations.
3.7.3. Distance between the edge of the travel lane and the cable barrier should consider mower width, if practical.
3.7.4. Delineation of cable barrier should be at 100 ft spacing, unless otherwise approved by the engineer.
3.7.5. Footing for terminal anchors should be designed to keep static loads well below the ultimate strength.

3.8. Design for Operations

3.8.1. There is a higher probability of high angle traffic conflicts in the vicinity of interchanges and hence the potential for barrier impacts at sharper angles. These concerns might dictate the use of a higher level barrier or reducing post spacing to limit deflection for such impacts.
3.8.2. Cable barrier deployment should consider the needs for turnarounds, crossovers, and access points to accommodate emergencies, enforcement, and maintenance operations.
3.8.3. Crossovers require full end treatments for safety and anchorages since the cable barrier runs are terminated.
3.8.4. Locations should be selected such that the risk of a crossover of an errant vehicle is minimized.
3.8.5. The distance between breaks in the cable barrier system to allow emergency vehicles access should be approximately 2 to 3 miles unless interchanges provide opportunities for emergency vehicles to get to the other side of the median barrier.

4. Costs and Benefits Analyses

Highway agencies seem to always operate with limited resources making costs and benefits critical metrics in justifying cable barrier projects. Cable barrier systems have features that are often thought to make them cost-effective. In this project efforts were devoted to gathering data and outlining a process for analyzing the costs and benefits for a cable barrier project. The guidelines focus on factors that need to be included in the analyses and efforts to compile the time and costs data needed to effectively evaluate periodic maintenance and post-crash repair costs for deployed cable barrier systems.

4.1. Initial Costs

4.1.1. Initial cable barrier system costs will be a function of the median configuration in the corridor, soil conditions, traffic and environmental factors, the barrier type selected, and the options.
4.1.2. Initial costs may vary by the barrier manufacturer, installation contractor, options available, regional cost factors, and other items.

4.1.3. Initial cost estimates should be based upon a clear understanding of the placement of the cable barrier installation, obstacles, environmental factors, associated anchorages, interconnections, and other factors.
4.1.4. End-anchor and post foundations should require designs based on in situ soil conditions and expected climate conditions that are reflected in the costs.
4.1.5. If a maximum design deflection has been set for a project, then the combined effects of post spacing and anchor-to-anchor spacing for each specific type of high-tension cable barrier should be considered to ensure that the required maximum deflection will not be exceeded.

4.2. Repair Costs

4.2.1. Repair costs will be a function of the degree of damage and nature of the elements that need to be replaced.
4.2.2. Some cable barrier options, such as socketed posts, may reduce long-term maintenance costs.
4.2.3. Agencies should maintain databases for cable barrier repair costs to develop improved capabilities to estimate these over time.
4.2.4. Maximum response times for repairing damaged barriers should be established based on the class of highway and the extent of damage.
4.2.5. There is only limited data available for cable barrier repair costs by DOTs at this time.

4.3. Periodic Costs

4.3.1. Periodic inspection schedules based on expected frequency of impacts should be established for each cable barrier installation.
4.3.2. Cable heights on barriers at the bottom and top of vertical curves should be checked periodically to make sure they remain at design heights.
4.3.3. Cable barriers should be inspected after severe weather events including flooding and extremely cold temperatures to check for erosion, end-anchor movement, and cable heights on vertical and sharp horizontal curves.

4.4. Benefits

4.4.1. All accepted systems do not perform the same, which implies that the benefits are not equivalent. Use the best available system-specific performance data in decision making (e.g., severity aspects).
4.4.2. Because of the small marginal cost of adding an extra cable and the likelihood that safety performance of the barrier is improved, the option should be considered.
4.4.3. Manufacturers may provide training on barrier installation, maintenance, and repairs for highway agencies and emergency response crews.

4.5. Trade-off Analyses

4.5.1. Life-cycle cost analyses should be considered to evaluate cable barrier systems, instead of selecting systems on the basis of lowest bid for installation.
4.5.2. Procedures for systematically considering all aspects of the trade-offs for various options should be followed.
4.5.3. The trade-off option of driven posts versus socketed posts requires estimates on expected number of hits and time-to-repair. Agencies should consider capturing such data to enhance the effectiveness of trade-off analyses.
4.5.4. Post spacing options for cable barrier systems can be a trade-off item.
4.5.5. Leaving trade-off items as part of the bid specification may make the selection of a contractor more difficult.

5. Construction

Proper construction of any barrier system is necessary for it to perform properly. This applies to cable barrier systems as well, but given that these systems can be deployed with limited heavy construction some needs may be overlooked. There have been reported problems with the construction of modern cable barrier systems that can be attributed to limited installation experience in many areas. Some guidance generated in this project is summarized below.

5.1. Tolerances

5.1.1. Recommended tolerances for construction are listed in Table E-1:

Table E-1. Cable barrier parameters and tolerances.

Cable Barrier Parameter	Tolerance
Top Cable Height	-0,+25 mm (-0, +1 in)
Bottom Cable Height	-25,+0 mm (-1, +0 in)
Middle Cable(s)	±25 mm (±1 in)
Barrier Lateral Position	±150 mm (±6 in)
Average Post Spacing	±150 mm (±6 in)
Cable Tension	±2 kN (±0.45 kips)

5.2. Median Grading and Slope Rounding

5.2.1. Computer simulations showed that gentler slopes lead to greater potential for effective vehicle-to-barrier interface, increased lateral placement options, and reduced vehicle instability. Hence, designing the median in new construction for a gentler slope (6H:V1 or shallower) is encouraged.

5.2.2. Slope rounding reduces the impulse to the vehicle's suspension and hence the response when negotiating fore and backslopes. Slope rounding occurs to some extent naturally due to erosion over time.

5.2.3. Spot grading may be useful towards enhancement of lateral placement options.

5.3. Field Adjustments

5.3.1. The barrier effectiveness areas for each system and median configuration provide the basis for determining the latitude in making field adjustments.

5.3.2. Cross drainage structures with less than 36 in of cover pose a challenge for placing cable barrier posts. Structures of less than 16 ft can be spanned in order to avoid post placement on the drainage structure.

5.3.3. Field adjustments to anchor locations may necessitate new soil analysis and foundation design.

6. Maintenance and Operations

The responsibility for addressing highway safety needs does not end with the appropriate selection, design, and deployment of a cable barrier in a highway corridor. All barrier systems must be properly maintained to assure that they will effectively perform safety functions over time. That implies the need to inspect, adjust, repair, and/or replace barriers. To some extent, these needs are greater for cable barriers than other types, particularly the more rigid barriers, as one of their features is that they allow deflections that reduce crash severity by sacrificing elements of the system. It is not unusual for vehicles to drive away from impacts with cable barriers after an impact, but it is critical that any damage be repaired before the next impact. There are also design features of

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cable systems that are susceptible to maintenance needs, such as cable tensioning or post pull out on installations on vertical curves. Guidance for maintenance needs is provided below.

6.1. Periodic Maintenance

6.1.1. When developing plans for implementation of new cable barrier projects, the needs for periodic maintenance should be programmed and coordinated within the budget cycle.
6.1.2. Checks on cable tension on at least an annual basis should be undertaken to ensure effective system performance. The tension checks may be less frequent after the system has been in place for several years.
6.1.3. Coordination with other agency personnel to report damaged sections of cable barriers promptly should be considered.
6.1.4. Periodic inspections of critical cable system components, identified by manufacturer, should be conducted on a regular basis. Special attention is appropriate for cable barriers placed on horizontal and vertical curves due to the potential for greater post problems that can increase the degree of deflection.

6.2. Emergency Response

6.2.1. Emergency responders need to be made aware of and trained for rescue efforts where a vehicle is entwined in a cable barrier.
6.2.2. Cutting of the cables should be avoided due to the adverse implications of restoring the system.
6.2.3. Safe cutting procedures need to be defined when they become necessary.
6.2.4. Emergency response agencies should have educational materials to provide them with clear and concise guidance on when and how to safely disconnect or cut cables when a vehicle is entangled after an impact.

6.3. Post-Crash Repair

6.3.1. Accepted practices for cable splicing should be followed to insure adequate strength and to minimize the potential that they will represent a snag point. Splices should be offset on each of the cables.

6.4. Monitoring Performance

6.4.1. Motorcycle and truck crashes into median barriers should be monitored.
6.4.2. Unusual crashes (e.g., motorcycles and trucks) should be monitored to apply appropriate ancillary treatments.
6.4.3. Before and after crashes should be compared for treated sites to determine effectiveness achieved.

Epilogue

The process of planning, designing, operating, and maintaining highways is a constantly evolving effort. Guidance develops incrementally over time and its value is ascertained by safe and efficient movements of people and goods. These guidelines are believed to provide an incremental step in advancing the process. Not all those involved in reviewing this research and the formulation of guidelines agreed on every aspect. Where there was majority agreement the guidelines were retained, but a number of suggested guidelines were excluded. Certainly experience, changing traffic conditions, advances in technologies, adjustments to cost and benefits measures, and alterations in policies and regulations will lead to new insights and guidance that can be incorporated in future versions under the wisdom of national organizations.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation