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UPDATE TO CABLE BARRIER LITERATURE REVIEW

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16. Abstract (Limit: 200 words)
A review of cable barrier testing projects is presented. Historical development of cable barriers is considered, and modern evolution into low-tension and high-tension systems is described. System details were described for each test when available, and the full-scale test results summarized. Simulation of cable barrier impacts with full-scale test vehicles was summarized with a historical perspective. Modern efforts to simulate cable barrier impacts were also discussed.

This report is intended to supplement and update the information in a previously-published Cable Literature Review, MwRSF Research Report No. TRP-03-118-02.

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1 INTRODUCTION

Cable guardrail systems, often consisting of either three or four cables supported by weak posts, have proven to be crashworthy in many impact situations. These systems are often classified as "flexible" since their deflections are typically quite large, resulting in lower occupant risk and less vehicle damage than many "semi-rigid" and "rigid" barriers. Further, state accident experience with cable barriers has demonstrated the capability to redirect passenger vehicles, single-unit trucks, and tractor-trailer vehicles. The full-scale crash testing and simulation efforts that were conducted in support of crashworthy cable barrier system development are presented herein.

1.1 Scope

The scope of this study was to supplement the previous literature review of cable barrier system components and designs conducted by Coon et al. [1], and to increase the existing knowledge base of wire rope barrier crash testing and simulation efforts.

1.2 Methodology

To fulfill the objectives of this study, several tasks were completed: (1) full-scale crash testing data was tabulated; (2) crash testing data was sorted and organized by performance evaluation criteria; and (3) a literature review of cable modeling was conducted. The classifications, corresponding performance evaluation criteria, and approximate time periods are shown in Table 1.

1.3 Terminology

A list of terms used in this report and a brief explanation are provided in Table 2.

Table 1. Referenced Testing Criteria Used for Testing and Approximate Time Period

Classification*	Approximate Time Period	Performance Evaluation Criteria*	Reference
Historical	Pre 1980	NCHRP Report No. 153 TRC 191 Individual Agency Criteria	2, 3
NCHRP 230	1980-1993	NCHRP Report No. 230 DTp and BS6770, BS6579 (England)	4
NCHRP 350	1993-2008	NCHRP Report No. 350 DTp and BS6770, BS6579 (England)	5
Contemporary	2008-Present	MASH	6

* NCHRP – National Cooperative Highway Research Program
TRC – Transportation Research Circular
MASH – Manual for the Assessment of Safety Hardware

Table 2. Wire Rope Terminology

Term	Explanation
Wire Rope Terminology	
Cable / Wire Rope	Used interchangeably. Refers to wire rope utilized in cable guardrail systems. In this report, "wire rope" refers to 3/4-in. (19-mm) diameter 3x7 Wire Rope.
3x7 Wire Rope	Three strands, each containing seven wires, wrapped helically together without an independent core.
6x19 IWRC Wire Rope	Commonly-used wire rope in many applications; consists of 6 strands with 19 wires per strand, and each strand is wrapped helically around an independent wire rope core (IWRC).
Strand	Differentiable unit of wire rope. Consists of units of wires wrapped helically together around a central wire.
Wire	Basic component of strand. Thin steel rod, most often circularly-shaped, extending the length of the wire rope.
Wire Rope Terminations	
Closed Socket	Single cast piece terminating wire rope in a funnel and secured using epoxy or spelter mix. Top of socket has bearing arch for connection to other hardware.
Open Socket	Similar to closed socket. Wire rope is terminated in a funnel and secured usins epoxy or spelter mix. Top of socket consists of a removable bearing rod with a cotter pin, resting in bearing eyelets.
Swage	Mechanical process to interlock a hollow member onto a cable by means of applying pressure until the component plastically deforms around the wire rope.
Thimble	Not often used in cable guardrail systems. Consists of a tear-drop-shaped which holds the wire rope in a grooved valley. Wire rope is fastened to the thimble using cable clips.
Cable Clips	U-bolts with a swage grip fastened to the wire rope using nuts. The swage grip matches the lay of the wire rope and is swaged to the rope.
Cable Barrier System Terminology	
Anchor Bracket	Termination of many cable barrier systems. A construction of plates and members acting to secure tension members (e.g., threaded rods) and initiate slip or failure when impacted.
Bend	Indicates plastic deformation, usually of a steel post, causing a member to be distorted.
Fracture / Rupture	Failure of a component in a cable guardrail system due to tearing and separation into at least two parts.
Rotate	Rigid-body motion of a component about an axis/axes.
Socket	Cable component used to terminate a wire rope using a hard-setting compound, often consisting of an epoxy.
Turnbuckle	Most often constructed of threaded rods connected to the cables and a crank with two thread directions for tightening the system.

2 HISTORICAL CABLE SYSTEM TESTING AND DEVELOPMENT, 1950-1979

The history of the development of wire rope guardrail systems dates back to the 1950s through 1970s, when organizations in California, Michigan, New York, Texas, Canada, and England constructed wire rope guardrail systems. Testing results were evaluated using a variety of performance criteria, including recommendations presented in NCHRP Report 153 [2], TRC 191 [3], and agency-specific criteria. Ad hoc testing and development of the cable barriers was often conducted, and led to the development of components and configurations tested according to the criteria presented in NCHRP Report 230 [4] and 350 [5]. All of the full-scale crash tests are accompanied by system details provided in Appendix A, and test summary details are provided in Appendix B.

2.1 Testing Conducted in the United States

2.1.1 California Department of Highways, 1958-1964

Some of the earliest-recorded tests on wire rope guardrail were conducted by the California Department of Highways between 1958 and 1964. A total of six tests were performed on experimental designs of wire rope barriers incorporating a chain-link mesh as a glare screen [7]. The chain link mesh was constructed from plastic-coated 2-in. (51-mm) square wire mesh, which was 36 to 48 in. (914 to 1,219 mm) tall and placed between 6 in. (152 mm) and 9 in. (229 mm) above the ground, as shown in Figure 1. Posts used in the systems were 2 $^{1}/_{2}$ in. x 4.1 lb/ft (51 mm x 6.1 kg/m) H-section posts spaced 8.0 ft (2.4 m) on center.

The first test conducted on the cable and chain link barrier system, test no. 12, consisted of a 1952 Ford Sedan, weighing 4,002 lb (1,815 kg), with an impact speed and angle of 56 mph (90 km/h) and 27 degrees, respectively. The cables were located 27 and 9 in. (686 and 229 mm)

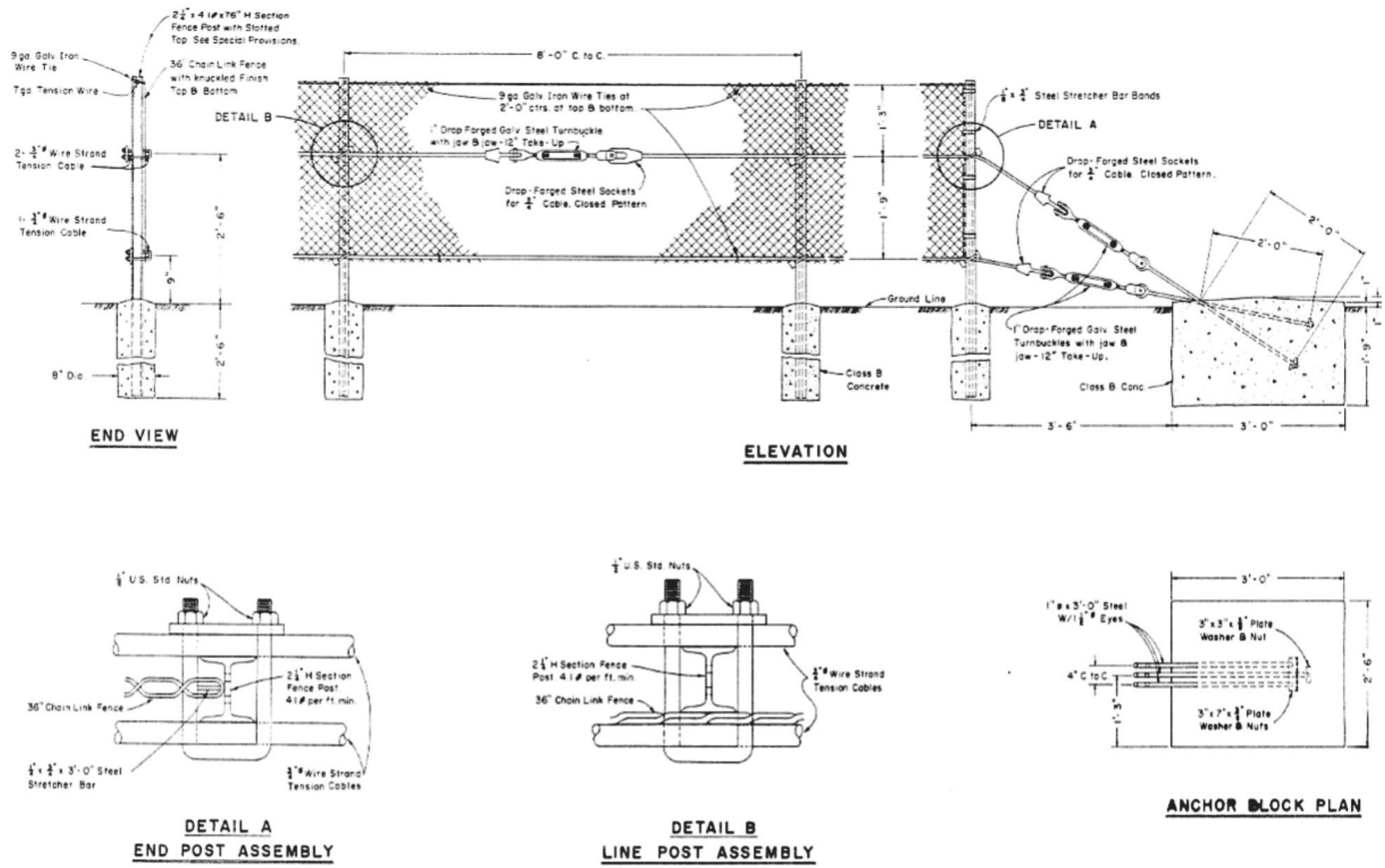


Figure 1. California Cable Barrier and Termination, 1959 [7]

from the ground and were attached to the posts with U-bolts. The test vehicle was redirected and snagged, yawing approximately 90 degrees before coming to rest in contact with the system.

The height of the top cable was increased to 30 in. (762 mm) and the system was tested again. Test no. 14 was conducted with a 1953 Chevrolet Sedan, weighing 4,000 lb (1,814 kg), with a test speed and angle of 61 mph (98 km/h) and 31 degrees relative to the barrier system, respectively. Sequential photographs of test no. 14 are shown in Figure 2. The vehicle was captured by the system but snagged and spun out after redirection. The cables extended into the wheel well of the vehicle and remained engaged with the suspension after coming to rest.

The system was retested in test no. 19 using a 1953 Chevrolet sedan, weighing 3,700 lb (1,678 kg), with a test speed and angle of 41 mph (66 km/h) and 15 degrees, respectively. The test vehicle came to rest in contact with the barrier system.

Based on the acceptable system results, researchers incorporated a turn-down section of the cable guardrail designed as a gate for emergency vehicle access as well as cable anchorage. The barrier gate consisted of a sloped termination of the lower cable into an anchor block and removal of the chain link fence. The upper cable bridged the gap between the posts and above the lower-cable termination. The upper cable contained a turnbuckle which was located above the concrete anchor block. Test no. 20 was conducted using a 1954 Chevrolet sedan impacting the system at 52 mph (84 km/h) and 32 degrees near the center of the emergency gate. Sequential photographs are shown in Figure 3. During the test, the vehicle rode up the lower anchored cable, resulting in spin-out around the cable anchor. The excessive snag and large accelerations were determined to be a significant risk to occupants, even though the vehicle was contained.

Next, the cable barrier was constructed on a 1,200-ft (366-m) radius curve and crash tested. Test no. 21 consisted of a 1953 Chevrolet sedan impacting the convex, or outer side of the

Figure 2. Sequential Photographs, Test No. 14, 1958 [7]

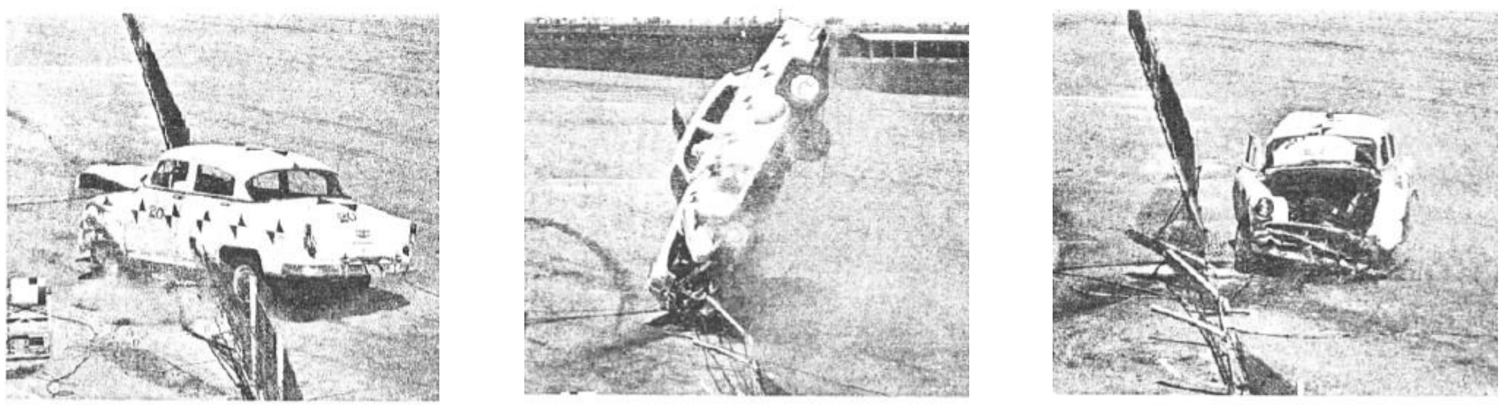


Figure 3. Sequential Photographs, Test No. 20, 1959 [7]

barrier system, with a test speed and angle of 60 mph (97 km/h) and 31 degrees, respectively. The test vehicle was safely captured and came to rest in contact with the barrier.

The final test of the cable and chain link barrier was conducted with a heavy-vehicle impacting the cable barrier system. Test no. 23 consisted of a 1937 40-passenger bus impacting the cable barrier system at 42 mph (68 km/h) and 34 degrees. The bus was captured by the cable barrier system and came to rest in contact with the system.

Researchers determined that the cable barrier system was a safe and low-cost alternative to stiffer barrier systems. Typically, vehicle damage was minimal, though posts and wire mesh required replacement. Researchers stated that vehicles involved in low-severity impacts were often able to drive away from the impact under the vehicle's own power. Plus, the cable system with glare screen was advantageous in reducing reflective glare during the day and headlights at night.

Four additional tests were conducted on the barrier system at high speeds and angles (8). The first system consisted of 2 $^{1}/_{4}$-in.-x 4.1-lb/ft by 88-in. long (57-mm x 6.1-kg/m by 2,235-mm) H-section posts anchored in asphalt sleeves. Steel sleeves were cast in 8-in. (203-mm) diameter by 30-in. (762-mm) long asphalt cylinders. The cylinders were cast into holes drilled in the tarmac. Two cables were used in the system, one on either side of the post, at a height of 30 in. (762mm) from the ground. Cables consisted of 0.75-in. (19-mm) diameter 6x19 IWRC cables and were secured to the posts with 0.75-in. (19-mm) diameter U-bolts. In addition, 2 in. x 2 in. (51 mm x 51 mm) chain link fence was placed on the back side of the posts.

Test no. 1 on the cable barrier system consisted of a 1960 Dodge Sedan, weighing 4,300 lb (1,950 kg), impacting the barrier at 90 mph (145 km/h) and 25 degrees to the barrier system. The vehicle was captured and redirected, but due to snagging on the posts, the vehicle spun out prior to exiting the system. During the test, the cables in the impact section were frayed and damaged, resulting in minor strand separation.

The cables in test no. 1 were repaired with wire rope splices and the damaged posts were replaced. A variation of the turnbuckle used in test no. 1 was used in the second system. Test no. 2 on the modified system was conducted with a 1960 Dodge sedan, weighing 4,300 lb (1,950 kg), with a test speed and angle of 83 mph (134 km/h) and 25 degrees, respectively. During the test, the cable connection with the anchor block failed, and the vehicle penetrated through the guardrail then rolled several times.

Since the failure of the anchor block was believed to be responsible for the failure of test no. 2, the anchor block size was increased and the connection strengthened prior to test no. 3. The third test was a retest of test no. 2 with a test speed and angle of 84 mph (135 km/h) and 25 degrees, respectively, and the system adequately redirected the test vehicle. Following redirection, the vehicle snagged on one of the cable posts and spun out.

The final high-speed test of the cable system was conducted using alternative hardware for cable splices, turnbuckles, and end fitters. The final test consisted of a 1960 Dodge sedan, weighing 4,300 lb (1,950 kg), with a test speed and angle of 87 mph (140 km/h) and 25 degrees, respectively. The vehicle was smoothly decelerated until the front tire snagged and the vehicle spun out.

The high-speed tests were analyzed, and the pipe-type turnbuckles were determined to be the safest and most cost-effective turnbuckles for use in the cable system. It was observed that during redirection, the vehicle passed over the pipe-type turnbuckles without snagging or tearing the cables. During the test with the swaged turnbuckles, the splices were destroyed and the turnbuckles damaged.

After conducting the high-speed tests, the California Department of Highways investigated impacts of low-profile sports cars into raised, flat, and sawtooth median configurations with wire rope-chain link barriers located above the roadway [9]. It was desired that a location could be found that would safely capture or redirect vehicles when impacted on either side of the median. In addition, ramp tests were conducted to evaluate bumper trajectory in median impact conditions.

After considering the median cross-section configurations, researchers selected two median profiles and a cable barrier system for crash testing. The tested cable systems consisted of posts with 2 $^{1}/_{4}$-in. x 4.1-lb/ft (57-mm x 6.1-kg/m) H-sections measuring 88 in. (2,235 mm) long. Two 0.75-in. (19-mm) diameter cables were used in the first two tests, and three 0.75-in. (19-mm) diameter cables were used in the last four tests. All cables were 0.75-in. (19-mm) diameter 6x19 IWRC wire rope. Top cable mounting heights were 26 in. (660 mm) and 27 in. (686 mm) for cables on both sides of the posts in test nos. 91 through 93 and 94 through 96, respectively. The lower cable in test nos. 93 through 96 was located 18 in. (457 mm) from the ground. Cable barrier system details are shown in Figure 4.

The first test on the cable barrier system, test no. 91, was conducted with the cable barrier system located in the center of a raised median with a 6-in. (152-mm) tall curb. The system was tested with a 1960 Ford sedan, weighing 4,138 lb (1,877 kg), with a test speed and angle of 67 mph (108 km/h) and 7 degrees, respectively. The vehicle was contained and redirected, but spun out following redirection.

The system was repaired and retested in test no. 92 with a 1958 Triumph, weighing 2,540 lb (1,152 kg), with a test speed and angle of 67 mph (108 km/h) and 25 degrees, respectively. The test vehicle was captured by the barrier system and brought to a controlled stop.

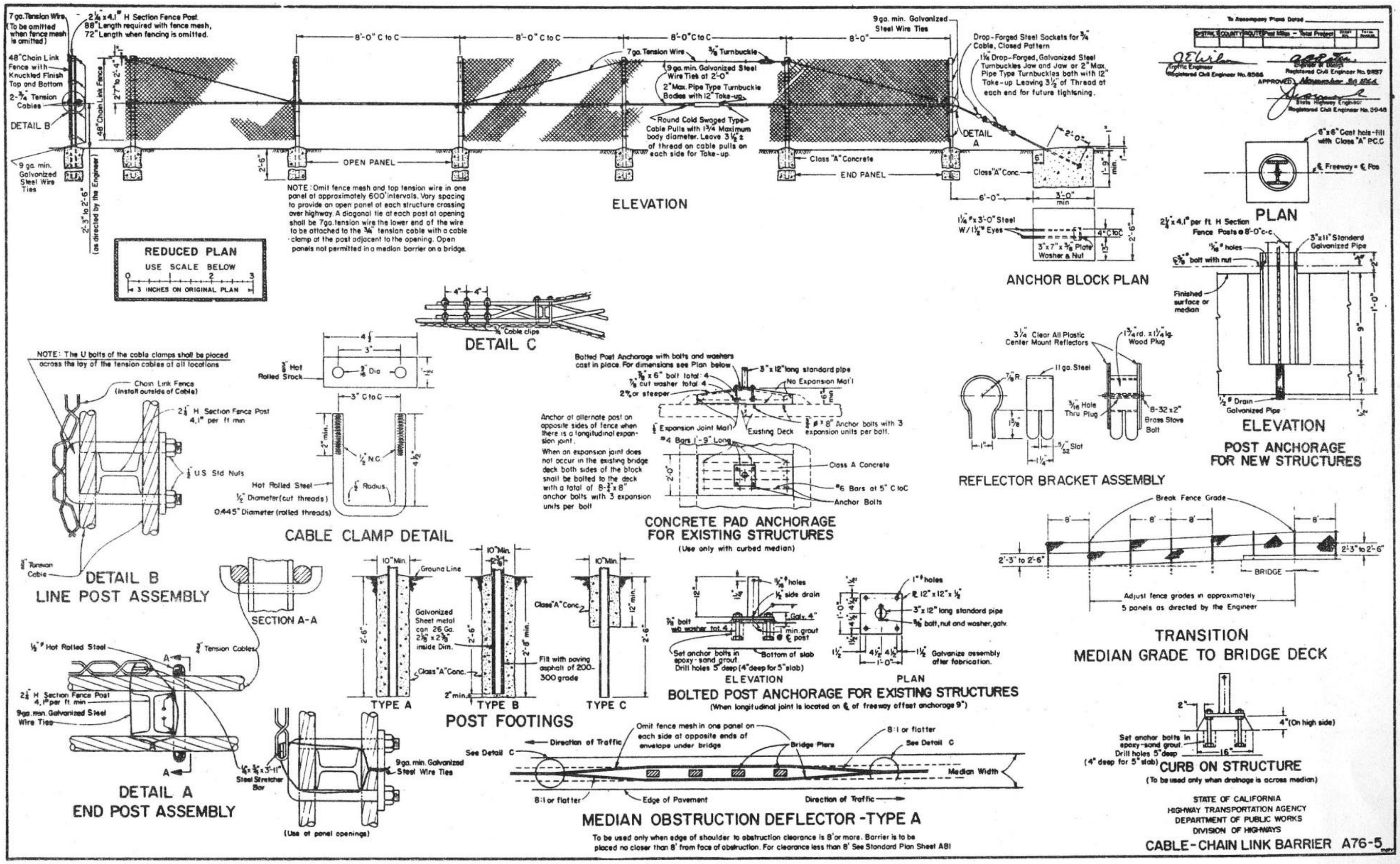


Figure 4. Cable System Details, California Department of Highways, 1965 [9]

Test nos. 93 and 94 were conducted on a cable barrier system installed on a level field with the cable heights lowered to simulate impact occurring on the raised side of a sawtooth median. Test no. 93 consisted of a 1960 Ford Sedan striking the barrier system with a test speed and angle of 65 mph (105 km/h) and 7 degrees, respectively. The front tire overrode the lower cable and the vehicle's roll displacement reached nearly 90 degrees prior to spinning out.

The attachments for the lower cable were redesigned prior to test no. 94 since the cables failed to disengage from the system in previous tests. The cable guardrail system was installed on the shoulder of a set of elevated lanes, at the peak of a raised sawtooth median profile. Test no. 94 was conducted with a 1960 Ford sedan with a test speed and angle of 60 mph (97 km/h) and 7 degrees, respectively. During the test, the lower breakaway cable released from the posts and the vehicle was captured and redirected, then spun out and came to a controlled stop.

Test no. 95 was also conducted on the top of a 2:1 upslope to simulate impact on the side with a high slope rate. The test consisted of a 1958 Triumph impacting the barrier at a test speed and angle of 65 mph (105 km/h) and 25 degrees, respectively. During the test, the vehicle penetrated through the cables and was redirected by the cable on the opposite side of the post from impact, trapping the vehicle and bringing it to an abrupt stop. Additionally, the dummy's shoulder was damaged due to rubbing contact with one of the cables.

Test no. 96 was conducted as a retest of test no. 95 since the cable clips on the lower cable failed to keep the cable attached to the posts during impact. The test consisted of a 1960 Triumph impacting the system with a test speed and angle of 63 mph (101 km/h) and 25 degrees, respectively. The vehicle penetrated through the system with little redirection and vaulted off of the top of the slope break point. During impact, the cables slid over the hood of the test vehicle and struck the dummy in the neck. The cable impact caused a piece of the dummy's clothing to tear free, and a strap was lodged 2 in. (51 mm) in the dummy's neck, possibly resulting in fatal injuries or decapitation of a live driver.

Based on the results of the study, it was determined that while cable barrier installations on flat medians were acceptable for construction, inclined or raised medians typically resulted in override or underride of the vehicle for systems constructed with a single cable height. Researchers determined that the tested two-cable system was not crashworthy and recommended construction of alternative barrier types. Due to the high-traffic volumes and speeds in California, the California Department of Highways recommended slip-forming a concrete barrier over the existing cable-post system [10].

2.1.2 General Motors, 1958-1961

General Motors conducted several tests on guardrail systems in use around the United States during the same time as the California testing. The first series of tests, conducted in 1958, evaluated the 4-cable system consisting of strong-post I-sections supporting four cables on slotted spacers attached to the posts with $^{5}/_{8}$-in. (16-mm) bolts [11]. Test details were not available for the 20 tests conducted.

Based on the results of the full-scale testing, 5 observations were made that were pertinent to cable guardrail systems: (1) posts should be designed such that the cables are not dragged down as the post yields; (2) cable ends must be anchored solidly enough so that the full tensile capacity can be developed in the end section and short installations; (3) the rail should be mounted high enough so that it will remain above the center of gravity throughout the impact; (4) the cable guardrail systems tested caused extensive damage to the vehicles; and (5) all guardrail impacts damage vehicles and may be hazardous to occupants, thus guardrail should only be installed in locations more hazardous than the guardrail itself.

Following the first series of tests, General Motors conducted a follow-up study on additional designs of weak-post and strong-post W-beam, cable guardrail, and convex rail designs [12]. The first cable test was conducted with grooved oblong spacer blocks, as shown in Figure 5. Test conditions for test no. 511 consisted of a 4,137-lb (1,877-kg) sedan impacting the cable guardrail system at 41 mph (66 km/h) and 20 degrees relative to the centerline of post no. 4. The vehicle was redirected with minimal damage to the vehicle or the barrier system.

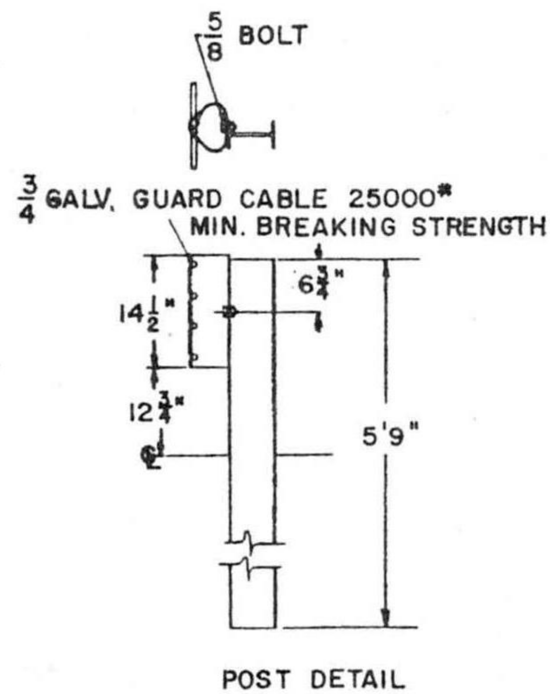


Figure 5. Spacer Block and Post Configuration, 1961 [12]

A subsequent test on the same system, test no. 542, consisted of a sedan impacting at 61.5 mph (99.0 km/h) and 20 degrees to the barrier, resulting in vehicle penetration and cable fracture.

Researchers at General Motors modified the cable system crash tested in California [7] in order to improve cable barrier performance. A 2-in. x 2-in. (51-mm x 51-mm) chain link fence and 2 $^{1}/_{4}$-in. (57-mm) H-section posts were used in combination with two wire ropes, and the posts were anchored in 8-in. (203-mm) diameter concrete footers.

In test no. 591, the test vehicle impacted the barrier system at 65 mph (105 km/h) and 16.7 degrees at an impact location 146 ft (44.5 m) downstream from post no. 3. The vehicle was captured with peak accelerations in the longitudinal and lateral directions of 4.5 g's and 5.0 g's, respectively.

Test no. 593 was a low-angle, high-speed evaluation of the system evaluated in test no. 591. Test no. 593 resulted in spin-out with peak accelerations near 30 g's as a result of snagging on the chain link fence and U-bolts with cable turnbuckles.

Due to spin-out and high accelerations, the cable mounting height was increased by 3 in. (76 mm) from the California design. Test no. 596 consisted of a 1960 Pontiac coupe impacting the barrier at 35 mph (56 km/h) and 8.5 degrees, and the vehicle was safely captured. However, the top cable slid over the vehicle's hood and contacted the A-pillar of the passenger compartment during the test.

2.1.3 New York State

2.1.3.1 Department of Public Works, 1960-1965

The New York State Department of Public Works (NYSDPW) crash tested guardrail systems to generate force-deflection and trajectory plots for pure bending (box beam), pure tensile (cable), and mixed tensile and bending (W-beam) systems [13]. Force-deflection plots were used to develop analytical simulation models of the different systems. Since bending forces in cables were not considered, researchers focused theoretical modeling on the tension in the cables and post motion through the soil.

The first test of the NYSDPW cable guardrail system, test no. 1, was conducted with 6B8.5 (152B12.6) steel posts. The posts were configured with oblong spacer blockouts and four $^{3}/_{4}$-in. (19-mm) diameter cables, which was similar to the system tested at General Motors [12], and the posts were spaced 10 ft (3.0 m) on center. During the test, one cable fractured and another pulled out of a splice. The test vehicle came to rest on top of the cables, and large accelerations were noted.

Due to the unsatisfactory results of the initial test, designers made 11 observations which provided the foundation for modifying all of the NYSDPW guardrail systems. The observations pertinent to cable guardrail included:

- Cables stretch, resulting in large deflections
- Because deflections are large, post contact is inevitable
- Large number of posts are struck at all impact angles
- Cables require strong end anchor to prevent cable pullout
- Cables should not be securely fastened to the posts so that the posts will not pull the cables down during impact

Additionally, two other observations were made with regard to desired improvements to the barrier system and included:

- Cable provides little delineation effect due to small size
- Temperature compensators are necessary to prevent sag

Test no. 12 was conducted on a cable bridge rail incorporating changes from the above comments, consisting of 2 $^{1}/_{4}$-in. x 2 $^{1}/_{4}$-in. by 6-ft long (57-mm x 57-mm by 1.8-m) posts spaced 6 ft (1.8 m) on center. Four cables were interwoven diagonally between the posts, and four longitudinal cables spanned the length of the bridge. The tested sedan impacted the cable barrier bridge rail at 52 mph (84 km/h) and 21 degrees, respectively. The vehicle fractured many of the posts, resulting in penetration of the vehicle and unacceptable performance of the rail.

The cable barrier system was modified prior to test no. 18 to include 2 $^{1}/_{4}$-in. x 2-in. x 4.1- lb/ft by 66-in. long (57-mm x 51-mm x 6.1-kg/m by 1,676-mm) rectangular posts spaced 8 ft (2.4 m) on center, and cable mounting heights of 30, 24, and 18 in. (762, 610, and 457 mm) from the ground. The posts were anchored with 48-in. (1,219-mm) drive anchors attached to the posts and embedded at 45 degree angles underground. The barrier system was located 18 in. (457 mm) in front of the break point of a 2:1 slope. Test no. 18 consisted of a 1960 Plymouth sedan impacting the barrier with a test speed and angle of 62 mph (100 km/h) and 32 degrees, respectively. The vehicle was captured and remained in contact with the barrier system.

The cable barrier system was retested in test no. 20 after adding 24-in. x 8-in. x $^{1}/_{4}$-in. (610-mm x 203-mm x 6-mm) soil plates to the back flanges of 3I5.7 (76I8.5) posts. The system was located 18 in. (457 mm) in front of a 2:1 slope. Additionally, the post lengths and embedment depths were increased to 81 in. and 39 in. (2,057 mm and 991 mm), respectively. The test vehicle, a 1961 Plymouth 2-door sedan, impacted the barrier system with a test speed and angle of 55 mph (89 km/h) and 25 degrees, respectively. The vehicle was redirected but rolled over after exiting the barrier.

Two modifications were made to the system prior to test no. 28: (1) the 2:1 ditch behind the installation was removed; and (2) the system was installed on an 8-degree interior curve. Test no. 28 consisted of a 1961 Plymouth 2-door sedan impacting the barrier at 53 mph (85 km/h) and 25 degrees. The vehicle was redirected smoothly and exited the barrier with a speed greater than 45 mph (72 km/h).

Since it appeared that the failure of test no. 20 occurred due to the rebound of the vehicle off of the 2:1 ditch, it was believed that permitting greater deflection may result in better impact performance of the cable barrier. The system tested in test no. 20 was modified by extending the post spacing to 12 ft (3.7 m), and the post lengths were shortened to 75 in. (1,905 mm) to allow the cables to release off of the top of the posts more quickly when impacted. Additionally, L-angles were attached to the cables with J-bolts between posts to increase visibility. Test no. 33 was conducted with a 1961 Plymouth 2-door sedan impacting at 54 mph (87 km/h) and 25 degrees, respectively. The vehicle was redirected but nearly rolled over, as occurred in test no. 20. The L-angle cable support brackets were thrown in front of the vehicle during the test.

The cable heights were lowered by 3 in. (76 mm) to mounting heights of 27, 21, and 15 in. (686, 533, and 381 mm) prior to test no. 36. Post lengths were also reduced by 3 in. (76 mm). The vehicle, a 1961 Plymouth 2-door sedan, impacted the installation in test no. 36 at a test speed and angle of 43 mph (69 km/h) and 35 degrees, respectively. The vehicle was redirected but spun out before exiting the system. In addition, the attached L-angles were thrown from the system in test nos. 33 and 36.

Since it was believed that the cable heights did not cause the apparent wheel snag in test no. 33, the cables heights and post length were increased by 3 in. (76 mm). Test no. 37 was essentially a retest of test no. 33. The test vehicle impacted the system at 53 mph (85 km/h) and 5 degrees, and was captured by the barrier.

Based on a review of the high-speed film from the previous tests, the system was believed to be too stiff to allow smooth redirection, so the cable heights were adjusted to 27, 24, and 21 in. (686, 610, and 533 mm). Post spacing was increased from 12 ft to 16 ft (3.7 m to 4.9 m), and the post length was decreased again to 69 in. (1,753 mm). A large concrete anchor was installed to prevent anchor movement during impact. The vehicle impacted the barrier at 44 mph (71 km/h) and 25 degrees and was smoothly redirected. The system details of the final cable barrier system tested are shown in Figure 6.

2.1.3.2 New York State Department of Highways, 1970-1976

Following the development and evaluation of experimental guardrail systems in the early 1960s, contractors reported several concerns with the new barriers. Research agencies attempted

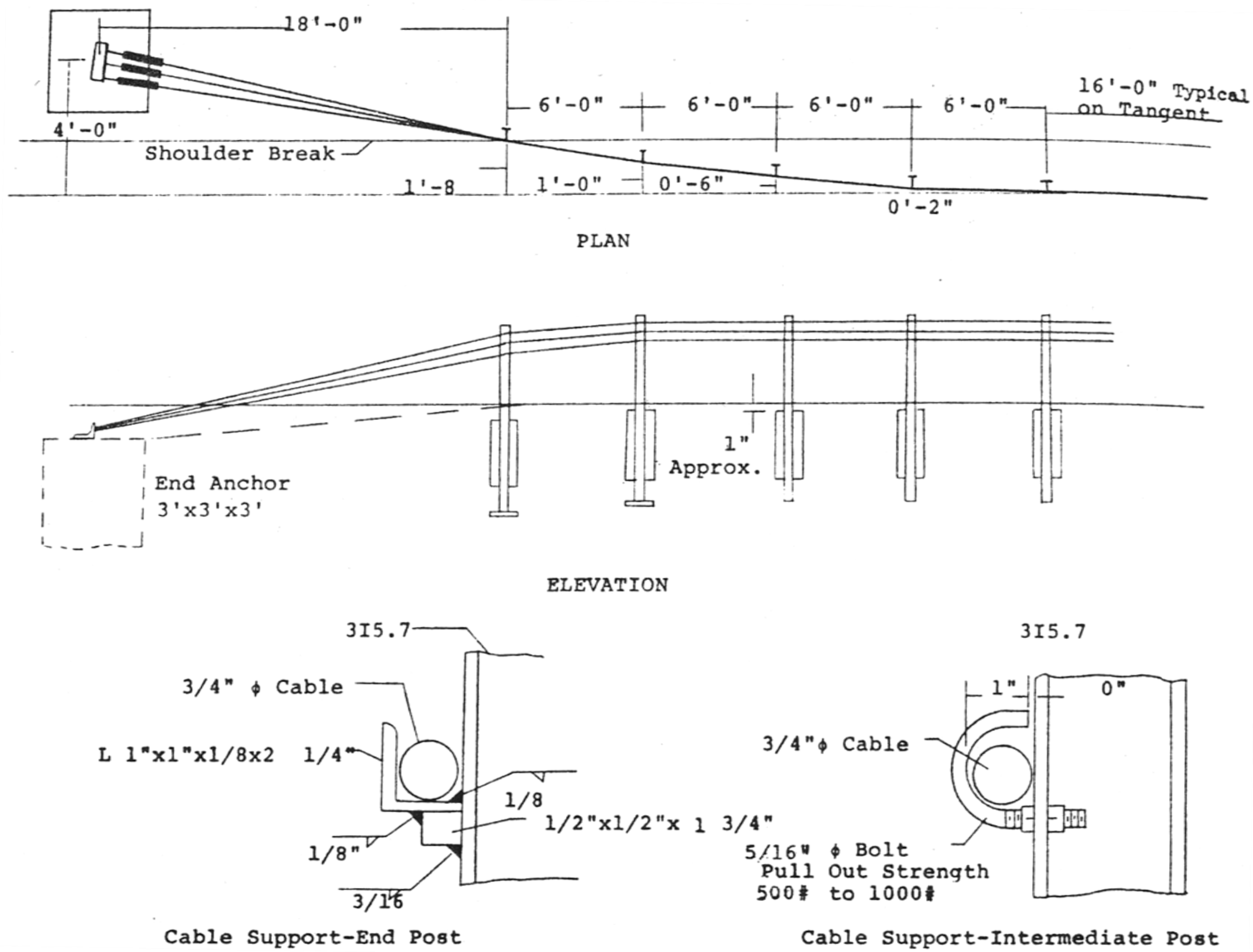


Figure 6. Final Tested Barrier Design, New York, 1967 [13]

to address the problems observed in the field using in-service retrofits for barriers, as well as to update barrier installation standards throughout the state of New York [14].

First, researchers desired to validate a computer simulation model developed previously [13]. Researchers conducted a head-on test of a 3,105-lb (1,408-kg) sedan into a standard cable guardrail installation. Post spacing was 16 ft (4.9 m) on center, and cable mounting heights were 27, 24, and 21 in. (686, 610, and 533 mm). The sedan impacted the cable system perpendicular to the line of posts at a test speed of 28 mph (45 km/h). The vehicle was brought to a controlled stop and rebounded out of the line of posts parallel to the impact direction. Based on photographs from the test, approximately seven posts were bent or damaged after impact. The results of test no. 1 were then compared to simulations to compare dynamic deflection results.

Since cable barrier systems have relatively large dynamic deflections, maintenance and construction crews indicated that the large deflections were problematic, so researchers attempted to develop stiffening retrofits for cable systems. To prevent snag in impacts with large deflections, S3x5.7 (S76x8.5) steel posts were used to support the cables. Therefore, researchers believed that the most practical way to reduce deflections in a cable guardrail system is to increase the number of posts installed in the system.

Researchers examined the relationship of post spacing with dynamic deflection. Four tests were conducted on similar systems, each consisting of S3x5.7 posts supporting the cables with $^{1}/_{4}$-in. (6-mm) diameter hook bolts. Cable mounting heights in test nos. 9 and 10 were 27, 24, and 21 in. (686, 610, and 533 mm). In test nos. 11 and 12, cable mounting heights were 30, 24, and 18 in. (762, 610, and 457 mm). Dynamic deflections recorded in each of the tests are shown in Table 3. Sequentials from test no. 10 are shown in Figure 7.

Table 3. Dynamic Deflections of Cable Guardrail for Different Post Spacings [13]

Test Number	Post Spacing		Vehicle Weight		Impact Speed		Impact Angle	Impact Energy		Deflection	
	ft	m	lb	kg	mph	km/h	deg	kip-ft	kJ	ft	m
9	16	4.9	3500	1588	53	85	25	58.7	69.0	11	3.4
10	12	3.7	3300	1497	56	90	25	61.8	72.6	9.5	2.9
11	8	2.4	3300	1497	58	93	25	66.3	77.9	8	2.4
12	4	1.2	3000	1361	55	89	25	54.2	63.7	7	2.1

*NOTE: Test no. 35 and test no. 12 refer to the same test; thus test results are equivalent

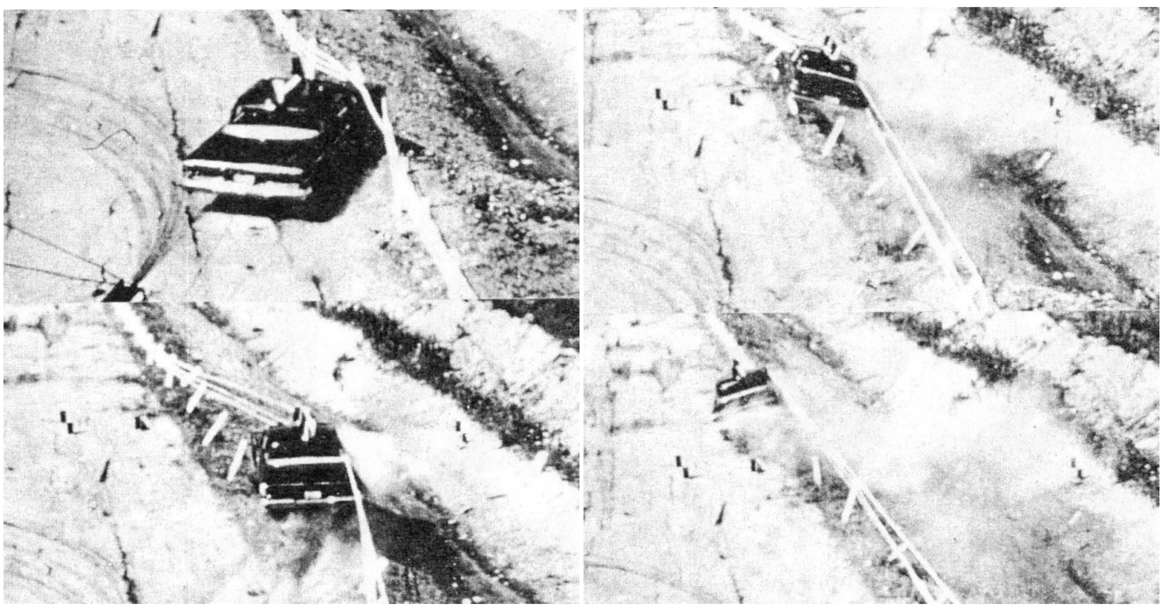


Figure 7. Test No. 10 Sequentials, 1976 [13]

Researchers also desired to develop guidelines for placement of cable barriers near curves. A 50-ft (15.2-m) radius was installed on both ends of a 100-ft long (30.5-m) tangent section of guardrail for test no. 13. A 1965 Plymouth 4-door sedan, weighing 3,105 lb (1,408 kg), impacted the system at the midpoint of the tangent length of guardrail at a speed and angle of 35 mph (56 km/h) and 90 degrees, respectively. The vehicle was smoothly redirected and rebounded away from the system. Dynamic deflection of the cables in test no. 13 was unknown. An estimated nine posts released the cable.

Since the cable system had performed very well in previous full-scale tests, the system was evaluated with a heavy truck and small car to evaluate the cable guardrail system under impact conditions which were likely to occur in field operation. Cable heights in both tests were 27, 24, and 21 in. (686, 610, and 533 mm). Standard cable attachment hardware consisted of $^{5}/_{16}$-in. (8-mm) diameter hook bolts, and the posts had S3x5.7 (S76x8.5) sections. Terminals in both tests were concrete block anchors with rigid anchor rods.

In test no. 17, a 15,000-lb (6,804-kg) dump truck was directed into the cable system at a speed and angle of 39 mph (63 km/h) and 25 degrees, respectively, and was successfully redirected. The maximum dynamic deflection was 14 ft (4.3 m). It should be noted that the impact severity of test no. 17 was 136.2 kip-ft (184.7 kJ).

In test no. 21, a 1,623-lb (736-kg) small car impacted the cable barrier at a speed and angle of 57 mph (92 km/h) and 25 degrees, respectively. The small car was smoothly redirected with a maximum dynamic deflection of 70 in. (1,778 mm). Thus, the cable system was determined to perform acceptably when impacted with small cars, large sedans, and heavy trucks.

2.1.3.2.1. New York End Terminal Development

Test nos. 22 and 23 were conducted on a cable end terminal design. Design details are shown in Figure 8. The end terminal consisted of an S3x5.7 (S76x8.5) routing post with angles welded to the post at ground level for groundline bearing struts. A cable hanger was attached to the routing post to transition the longitudinal cables into the cable anchor bracket. The anchor bracket was fastened to a concrete block anchor with threaded rods and nuts and flared back at a flare rate of 18:1. The angle formed between the ground and cable centerline was approximately 45 degrees at the anchor.

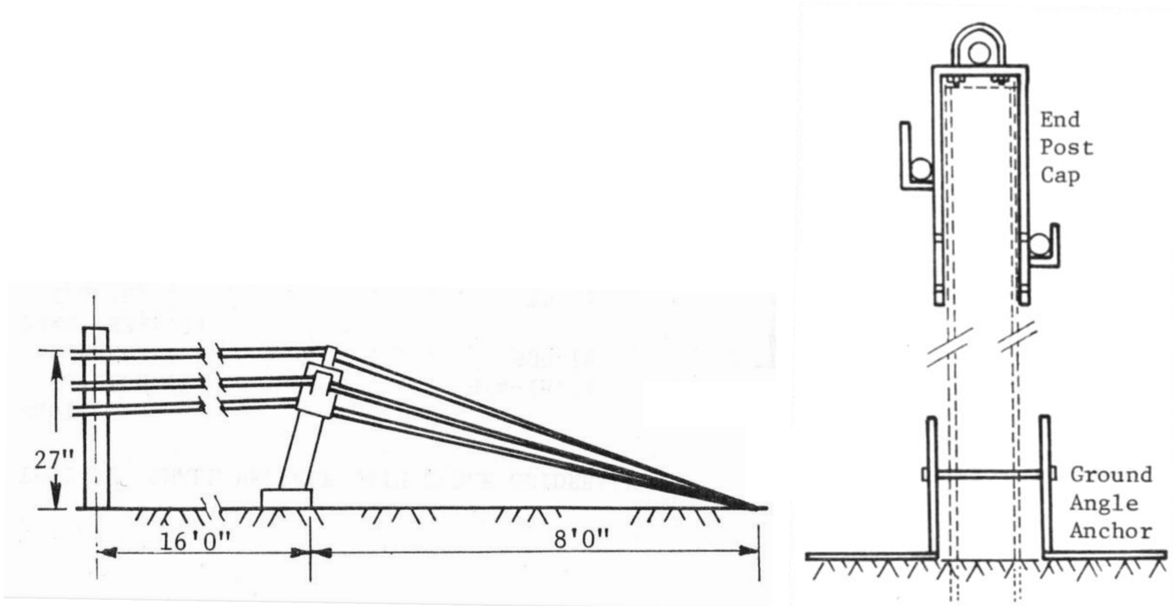


Figure 8. End Terminal Development, NYSDOT, 1976 [13]

Test no. 22 consisted of a 1965 Plymouth 2-door sedan impacting the terminal at 44 mph (71 km/h). The centerline of the vehicle was aligned with the centerline of the first tangent post in the system. As the vehicle ran over the cable ends, the fittings disengaged from the anchor block. The vehicle impacted six posts before redirecting smoothly out of the system.

It was observed that in the tested configuration, the threaded rods at the cable termination may not release as designed. In addition, the terminal may be subject to unnecessary impacts being located near the tangent section of guardrail. Therefore, the system was flared back 4 ft (1.2 m) and upstream 18 ft (5.5 m) to assist in release of the threaded rods from the anchor on impact. Test no. 23 consisted of a 1965 Plymouth 2-door sedan impacting the terminal at 44 mph (71 km/h) with the centerline of the vehicle aligned with the first tangent post in the system. The right-front tire was caught between two cables, causing the lower and upper end fittings to fracture, but the vehicle was redirected out of the system. The snagging caused a peak 50-ms average acceleration of 8.4 g's. Further testing on a cable terminal design was suspended due to unacceptable snagging and high accelerations.

2.1.3.2.2. New York Cable Barrier Transition Development

In addition to the development of a new terminal, researchers also desired to develop transitions for cable guardrail systems. The first transition design incorporated two flares: (1) the cable was flared backwards downstream of the transition point, and (2) the box beam was flared backward downstream of the transition point. The cable and box beam guardrails both utilized posts with S3x5.7 (S76x8.5) sections, and the cable guardrail post spacing was 16 ft (4.9 m) between centers. Cable heights were nominally 27, 24, and 21 in. (686, 610, and 533 mm).

Test no. 30 consisted of a 1964 Ford 4-door sedan, weighing 3,680 lb (1,669 kg), impacting the cable guardrail system upstream of the transition point. The tested speed and angle were 62 mph (100 km/h) and 25 degrees, respectively. The cables deflected with the vehicle, but the vehicle impacted the flared section of box beam guardrail at a high impact angle relative to the angle of the box beam, which caused the box beam to buckle and form a plastic hinge. The vehicle then penetrated through the system, and the box beam was removed from the posts. Extensive damage occurred to the test vehicle as a result of the test.

Researchers made several modifications to the system consisting of an internal box beam transition. This was accomplished by welding C-channels together to form low-stiffness cable transition members. The stiffness was increased twice to match the stiffness of the standard box beam section. Researchers hoped that this would minimize the impact force at the transition point, as well as provide a more aesthetic transition between the cable and box beam.

Test no. 31 consisted of a 1962 Valiant station wagon impacting the cable guardrail upstream of the transition at a test speed and angle of 54 mph (87 km/h) and 25 degrees, respectively. The vehicle impacted the exposed end of the box beam after the low-stiffness box beam elements deflected, resulting in snag and large decelerations. The transition design was therefore determined to be unacceptable.

The system was modified again to incorporate a circular impact head placed on the end of the box beam transition, and a slot was cut in the lower-stiffness box beam sections to transition the cables through the box section. Three beams were used to transition the box beam stiffness, consisting of welded 6x6, 6x4, and 6x2 (152 mm x 152 mm, 152 mm x 102 mm, and 152 mm x 51 mm) sections. The transition length was 36 ft (11.0 m) and the first six posts leading to the transition were spaced at 6 ft (1.8 m) on center.

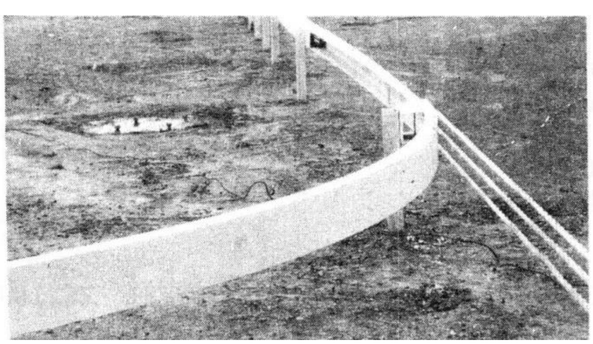
Test no. 32 consisted of a 3,000-lb (1,361-kg) 1964 Plymouth Sedan impacting the cable guardrail upstream of the transition at 40 mph (64 km/h) and 20 degrees. The vehicle was captured and came to rest in contact with the system, but the speed was lower than desired for the test.

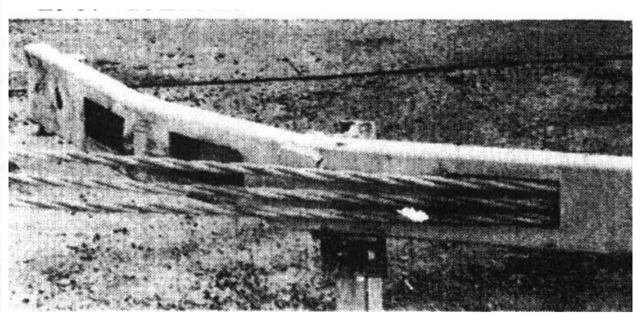
Test no. 33 consisted of a retest of test no. 32 at a higher impact speed. A 1962 Ford station wagon, weighing 3,895 lb (1,767 kg), impacted the system at 55 mph (89 km/h) and 22 degrees. The vehicle was smoothly redirected and exited the system at 8 mph (13 km/h) and parallel with the tangent length of box beam.

Test no. 34 was conducted with an impact point slightly closer to the transition point. A 1965 Plymouth sedan, weighing 3,105 lb (1,408 kg), impacted the cable guardrail upstream from the box beam transition at a test speed and angle of 61 mph (98 km/h) and 25 degrees, respectively. As the cables deformed the left-front corner of the vehicle, the left-front tire extended under the rail and the vehicle snagged at the transition point, which was a result of the close proximity of the cables to the transition such that the vehicle was directed into the cylindrical impact head..

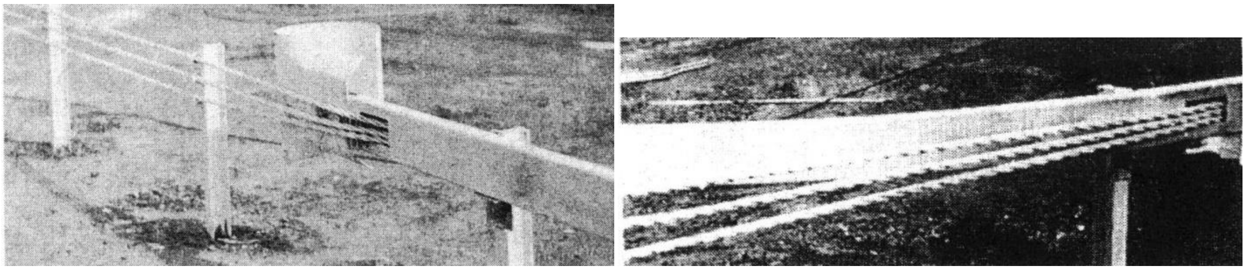
Due to the unsatisfactory performance of the transition design, the system was modified again. The post spacing of the cable guardrail upstream of the transition was reduced, and the box beam was flared back behind the cable guardrail. Instead of transitioning the cable within the box beam, the cable was attached to the box beam using weak U-clamps designed to release the cable on impact. This transition length was 100 ft (30.5 m), consistent with observations that vehicles rarely remain in contact with guardrail systems for more than 100 ft (30.5 m). In this way, snag was expected to be minimized. Cable guardrail post spacing upstream of the transition was 6 ft (1.8 m).

Two test no. 35's were conducted, one with low impact speed which researchers determined was not representative of practical worst-case impact conditions. The retry of test no. 35 was conducted with a 1963 Plymouth sedan, weighing 3,000 lb (1,361 kg), and impacting at 55 mph (89 km/h) and 25 degrees. The vehicle did not impact the box beam guardrail at all, but was redirected with a maximum dynamic deflection of 4 ft-10 in. (1,473 mm). Because the vehicle did not impact the box beam, test no. 35 was also considered in the post-spacing analysis study, and designated test no. 12. The transition designs are shown in Figure 9.





(a) Test No. 30 (b) Test No. 31



(c) Test Nos. 32 and 33 (d) Test Nos. 34 and 35 (35 same as 12)

Figure 9. NYSDOT Transition Designs, 1976 [14]

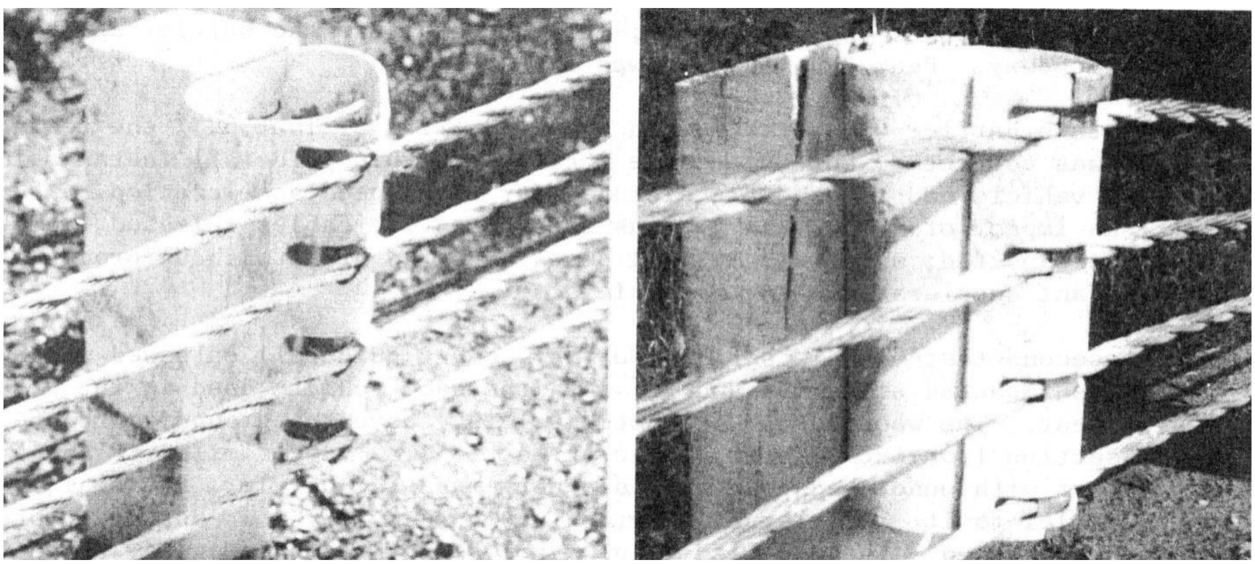
A similar idea was used when designing a cable to W-beam guardrail transition. The cable guardrail was attached to the W-beam using weak U-bolts, and post spacing was 16 ft (4.9 m) prior to the transition. The W-beam guardrail was placed on a parabolic flare upstream of the transition, and the cable was terminated 100 ft (30.5 m) downstream of the transition.

Test no. 36 consisted of a 3,680-lb (1,669-kg) 1964 Ford Sedan impacting the cable system upstream of the W-beam at 59 mph (95 km/h) and 25 degrees. However, unlike the box beam, the W-beam pocketed in front of the vehicle and caused major snag and spin-out. Further, two cable splices released during impact, which was later determined to be due to the low load rating of the splice components. Because of the price similarity between cable and W-beam systems and little need of immediate development, this design was abandoned.

2.1.3.2.3. New York Retrofit of Existing Cable Systems

Lastly, researchers investigated safety retrofit ideas for the existing strong-post 4-cable guardrail systems first developed by General Motors [11-12]. Accident reports with the 4-cable system indicated a relatively low containment rate and unacceptable system performance in general. Maintenance crews also raised concern that the cables fell out of the slotted spacer blocks too easily.

The four-cable guardrail developed by General Motors [12] consisted of 6 in. x 8 in. (152 mm x 203 mm) wood posts spaced 10 ft (3.0 m). Four cables were mounted in slotted-oblong spacer blocks to retain the cable mounting height and to prevent cable entanglement with the posts. These spacer blocks are shown in Figure 10. The system was modified by inserting thin-gauge, V-shaped retainer clips at the front of the spacer block to prevent unnecessary pull-out of the cables. Because of the small thickness of the material, the cables released from the posts when loaded in an impact event, but were retained under normal operating conditions. Furthermore, the clips could be squeezed by hand to fit within the slots of the spacer block.



(a) (b)

Figure 10. Retainer Clips (a) V-shaped Clip (b) Proposed Hanger Plate, 1976 [14]

Test no. 52 consisted of a 1962 Ford station wagon, weighing 3,985 lb (1,807 kg), impacting the system at 40 mph (64 km/h) and 25 degrees. The system successfully captured the vehicle with minimum occupant risk. Maximum system deflection was 66 in. (1,676 mm).

To rectify concerns that the posts were too stiff in bending, the wood posts were sawn to a base dimension of 6 in. x 3 in. (152 mm x 76 mm) in test no. 53. The test consisted of a 1962 Ford station wagon with a weight of 3,985 lb (1,807 kg) impacting the system at 40 mph

(64 km/h) and 25 degrees. The vehicle was successfully brought to a controlled stop, but more posts were fractured during the sawn-post test than with unmodified posts, with little observable difference in occupant risk. Maximum dynamic deflection observed in the test was 72 in. (2,134 mm).

Based on the performance of the thin-gauge V-clips installed in test nos. 52 and 53, an alternative cable retainer mechanism was created. It consisted of a hanger plate that passed through the top of the oblong blockout in front of the cables with a lip to prevent the hanger from dropping through the open-ended blockout. Because the sheet was the same size as the sheet used to make the V-clips, its performance was believed to be comparable, and was also recommended for use in upgrading older cable barrier systems.

The strong-wood post system was determined to be acceptable with the minor retainer clip modifications. Sawing the posts at the base was not recommended, since it did not appreciably reduce occupant risk for the impact. However, it should be noted that the strong-post cable guardrail system was also installed with steel posts. Modifications to this system were not evaluated. However, little money was budgeted for upgrading existing deficient systems, so researchers focused on the system they believed could be most easily and inexpensively improved. An example of a steel-post system installed in the field is shown in Figure 11.

Figure 11. Steel-Post 4-Cable Guardrail System Installed In Field [15]

2.1.1 Texas Transportation Institute, 1974

The Texas Transportation Institute (TTI), located in College Station, Texas, conducted a test on a cable guardrail end terminal in 1974 [16]. Cable system details are shown in Figure 12. The cable barrier end terminal system was composed of 5 $^{1}/_{2}$-in. diameter by 6-ft long (140-mm by 1.83-m) posts with $^{5}/_{16}$-in. (8-mm) diameter cable hook bolts to support the cables. Three $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables were installed with spring compensators and turnbuckles to provide pretension. One bent, threaded rod was inserted into a longitudinal hole in each anchor post, and was fastened to a turnbuckle at the other end. A nut and washer were used to secure it to the post. The cables were terminated in the end posts using a cable bracket and three threaded rods which passed through longitudinal holes in the post. The threaded rods had washers and nuts to secure them to the posts.

The test vehicle for test no. 8330B, a 1965 Oldsmobile 98 weighing 4,490 lb (2,036 kg), impacted the end of the cable guardrail terminal with a tested speed and angle of 58 mph (93.3

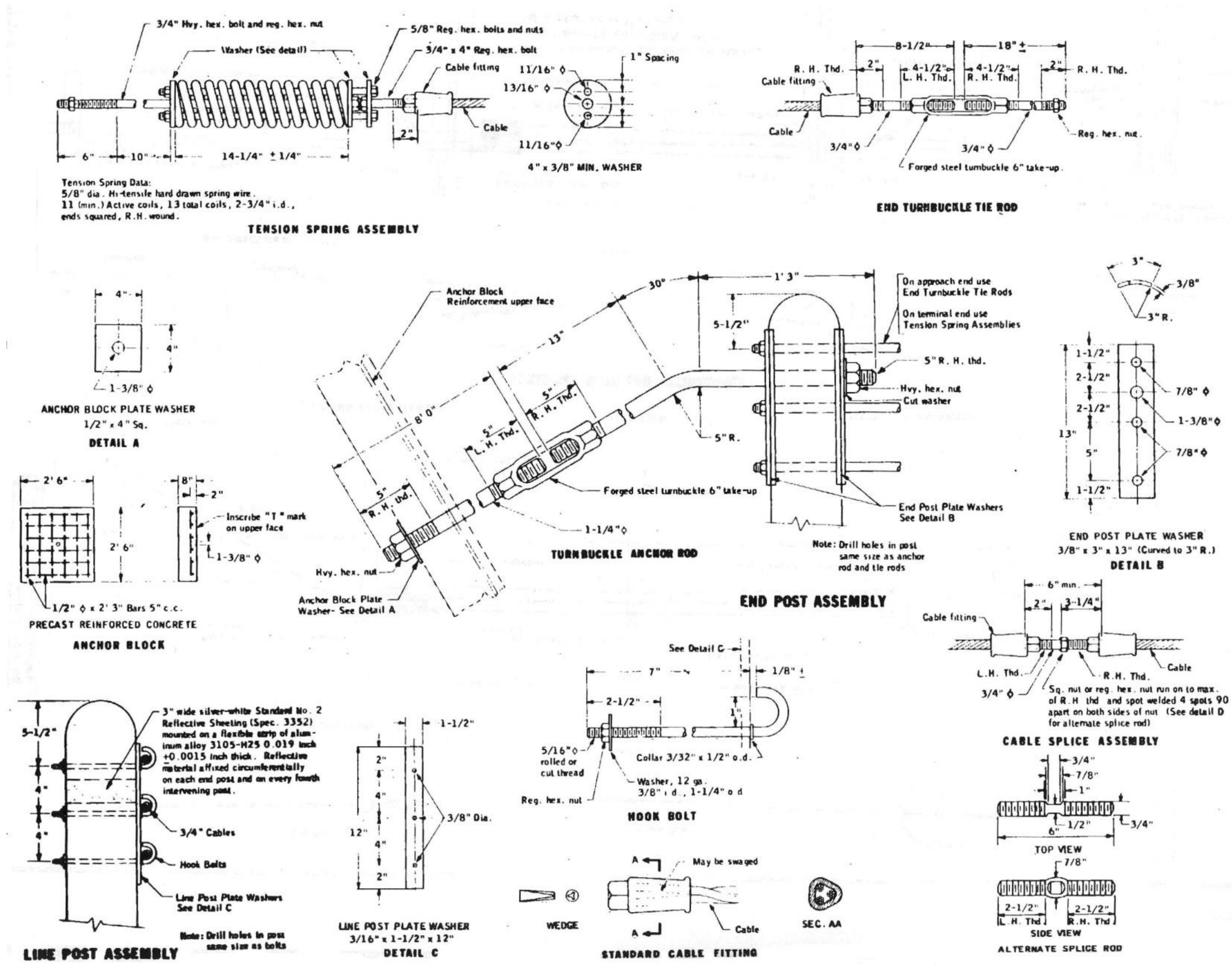


Figure 12. System Details, End-On Test of Cable Guardrail, 1974 [16]

km/h) and 5 degrees, respectively. The vehicle contacted and fractured the first three posts in the system and scraped the fourth post without significant observed roll or pitch motion. The top cable fractured during impact, releasing tension in the cable downstream of the test vehicle. Some snagging occurred when the threaded rod attached to the top cable punctured the front bumper; however, occupant risk criteria were satisfied. Therefore, the test was considered acceptable.

2.2 International Testing

2.2.1 Road Research Laboratories, Crowthorne, England, 1967-1969

Independent testing of cable guardrail systems for use on roads in Canada and England occurred at nearly the same time as research in the United States. Researchers in England tested four-cable and two-cable chain link barriers similar to those tested in California in 1967.

2.2.1.1 Prototype Evaluation

A "Deflector" barrier and an "Arrestor" barrier were evaluated by the Road Research Laboratories [17]. The "Deflector" system consisted of either 3-in. x 1 $^1/_2$-in. (76-mm x 38-mm) or 2 $^1/_4$-in. x 1-in. (57-mm x 25-mm) I-section posts embedded in concrete footers. Two 0.75-in. (19-mm) diameter cables were attached to both sides of the posts with $^1/_2$-in. (13-mm) diameter Tespa U-clips, for a total of 4 cables. The cable mounting heights were 27 and 19 in. (686 and 483 mm) from the ground, and were tensioned to 1,000 lb (4.4 kN). A 2-in. x 2-in. (51-mm x 51-mm) chain link fence with welded horns was attached to the posts, with a top height of approximately 44 in. (1,118 mm) and a lower height of approximately 8 in. (203 mm).

The "Arrestor" system was very similar to the "Deflector" system. Posts utilized in the "Arrestor" system were either 3-in. x 1 $^1/_2$-in. (76-mm x 38-mm) or 2 $^1/_4$-in. x 1-in. (57-mm x 25-mm) I-section posts embedded in concrete footers. One cable was attached to both sides of the post with $^{1}/_{2}$-in. (13-mm) diameter Tespa clips. The cables were both mounted at a height of 24 $^{1}/_{2}$ in. (622 mm). Wire mesh, identical to that in the “Deflector” system, was used in the “Arrestor” system, and was attached to the posts using the Tespa clips.

The first test on the “Deflector” system, test no. 11, consisted of a 3,000-lb (1,361-kg) Vanguard sedan, which impacted the cable guardrail system at 44 mph (71 km/h) and 20 degrees. The test vehicle was successfully redirected at 34 mph (55 km/h) and 12 degrees. The maximum dynamic tension in the cables was 6,000 lb (26.7 kN). During the test, the lower cable, which was designed to release from the posts to prevent wheel snag and roll motion, failed to release from the posts.

Test no. 12 was also conducted on the “Deflector” system, using smaller 2 $^{1}/_{4}$-in. x 1-in. (57-mm x 25-mm) I-section posts. In test no. 12, a 3,000-lb (1,361-kg) sedan impacted the “Deflector” system at 42 mph (68 km/h) and 19 degrees. The lower cables did not release from the posts as designed, and the vehicle experienced a small roll angular displacement toward the barrier during the test. The vehicle was redirected smoothly and exited the system at 35 mph (56 km/h) and 18 degrees.

Test no. 13 was a test of the “Arrestor” system using the larger 3-in. x 1 $^{1}/_{2}$-in. (76-mm x 38-mm) I-section posts. The vehicle impacted the barrier system at 46 mph (74 km/h) and 20 degrees, and was redirected smoothly. The vehicle exited the system at 32 mph (51 km/h) and 13 degrees with a maximum dynamic deflection of 48 in. (1,219 mm).

Test no. 14 was a retest of test no. 13 using the smaller 2 $^{1}/_{4}$-in. x 1-in. (57-mm x 25-mm) I-section posts. The vehicle impacted the barrier at a test speed and angle of 41 mph (66 km/h) and 20 degrees respectively, and was smoothly redirected. The exit speed and angle recorded were 26.9 mph (43.2 km/h) and 17 degrees, respectively.

The “Deflector” system did not perform as expected in test nos. 11 and 12, since the lower cable did not release from the posts. Further development was suspended. Researchers modified the “Arrestor” system by lowering the cable height 2 $^{1}/_{2}$ in. (64 mm) to examine whether a reduction in height, which may lead to better containment of the small car, would result in unacceptable system performance for larger vehicles.

Test no. 15 consisted of a 1,560-lb (708-kg) Austin Minivan impacting the lowered "Arrestor" system at 52 mph (84 km/h) and 20 degrees. A photograph of the vehicle impacting the barrier is shown in Figure 13. The vehicle was redirected and exited the system with a speed and angle of 30 mph (48 km/h) and 15 degrees, respectively. During the test, the cables cut into the side panels of the minivan, and the vehicle experienced roll displacement away from the barrier. Nonetheless, the “Arrestor” system performed satisfactorily.

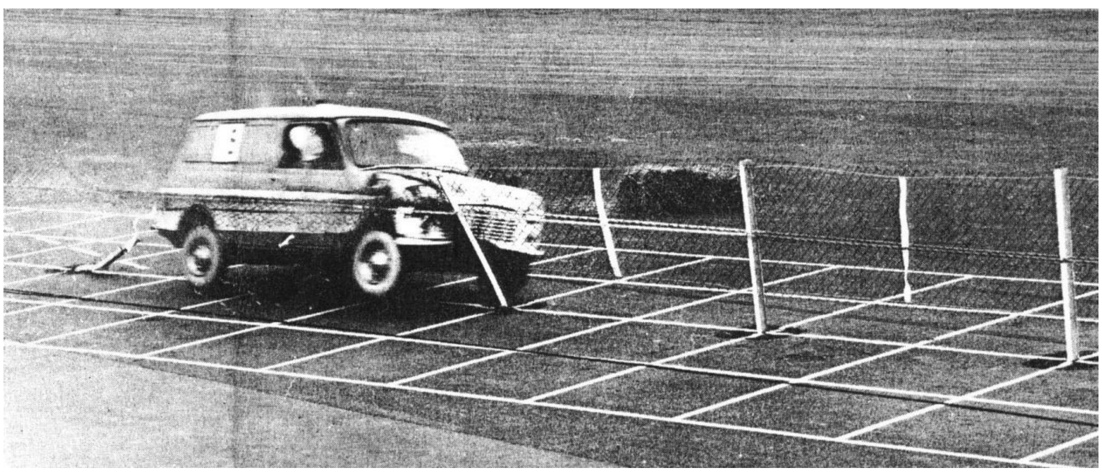


Figure 13. Minivan Impact in Test No. 15, 1967 [17].

The “Arrestor” system was modified by reducing the post heights 15 in. (381 mm) and eliminating the chain link fence since it acted as a snagging component. The modified system was evaluated in test no. 16, which consisted of a 1,950-lb (885-kg) Volkswagen car impacting the barrier at 62 mph (100 km/h) and 19 degrees. The vehicle was redirected smoothly and exited the barrier, but 85 ft (25.9 m) downstream of impact, the vehicle yawed 360 degrees and struck the barrier a second time. It was observed that the steering linkage was damaged due to post contact during the test, and contributed to the yaw motion. The researchers noted that testing in Germany with a similar car, which had a rear-mounted engine, had similar yaw spin-out motion after impact.

In test no. 17, researchers retested the system, which was evaluated in test no. 15 with a 3,000-lb (1,361-kg) sedan, due to the 360 degree yaw motion observed in test no. 16. The sedan impacted the system at 48 mph (77 km/h) and 8 degrees. The vehicle was redirected smoothly and exited the barrier system at 41 mph (66 km/h) and 10 degrees.

Test no. 19 was conducted as a retest of test no. 17 at a higher speed. The vehicle impacted the barrier at 58 mph (93 km/h) and 10.5 degrees. The vehicle overrode the traffic-side cable when the banding clips failed, and the right-front wheels became trapped by the cables. Following redirection, the vehicle yawed and rolled over. The final position of the test vehicle following test no. 19 is shown in Figure 14.

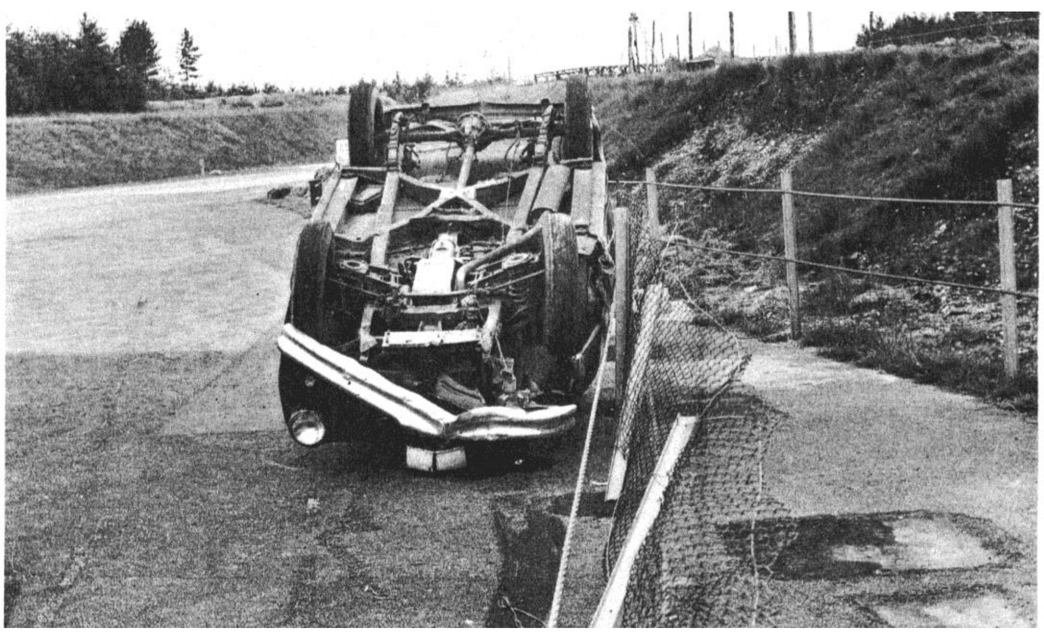


Figure 14. Vehicle Final Position, Test No. 19, 1967 [17]

To prevent the cables from being overrun by the test vehicle, 1 $^{7}/_{8}$-in. (48-mm) square tubes were used as posts, and U-bolts were used instead of the banding clips to attach the cables and the fence to the posts. The test vehicle, a 3,000-lb (1,361-kg) Vanguard, impacted the cable barrier system at 57 mph (92 km/h) and 6 degrees. The vehicle was redirected and exited the system at 49 mph (79 km/h) and 5 degrees. During the test, the vehicle climbed the posts and underwent slight roll angular displacement away from the barrier before stabilizing and coming to a controlled stop.

Since post climb was undesirable, the 2 $^{1}/_{4}$-in. x 1-in. (57-mm x 25-mm) I-section posts replaced the tubular posts, and banding clips replaced the U-bolts. Test no. 21 consisted of a 3,000-lb (1,361-kg) Vanguard impacting at 60 mph (97 km/h) and 10 degrees, and the test vehicle climbed the posts and subsequently rolled over. A photograph of the test vehicle rolling in test no. 21 is shown in Figure 15.

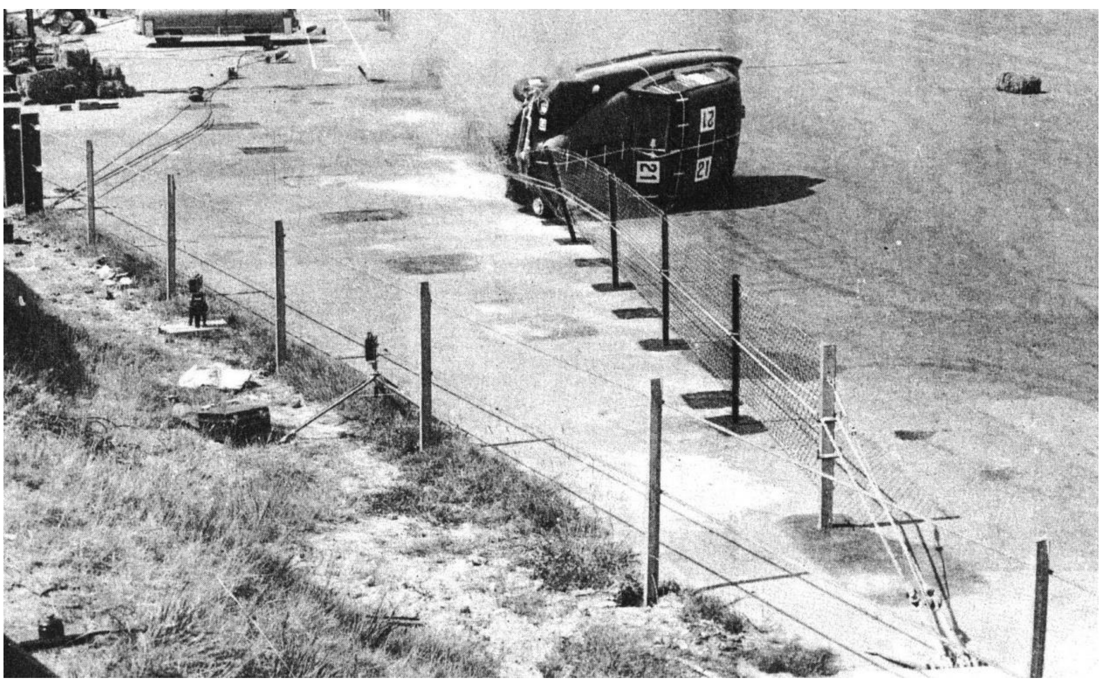


Figure 15. Test Vehicle Rolling Away from Barrier, Test No. 21, 1967 [17]

The researchers reviewed the results of the full-scale crash tests, and made three observations: 1) if two cable heights are used, the lower cables may not be stripped from the posts and may present a hazard if a vehicle overruns the cable; 2) if the cables are held at a single height, low-angle impacts do not allow release of the cables and may cause vehicle rollover; and 3) the chain link fence may cause vehicle instability.

2.2.1.2 Slotted Post Design

Following this study, the researchers at the Road Research Laboratory in Crowthorne conducted an investigation into a new cable barrier, consisting of posts with slots cut in the webs and two cables stacked in the slots [18]. The posts used in the design variations of the new system had 2 $^{1}/_{4}$ x 1-in., 2 $^{1}/_{2}$ x 1-in., and 3 x 1 $^{1}/_{2}$-in. I-sections (57 x 25-mm, 63 x 25-mm, and 76 x 38-mm) and measured between 47 and 57 $^{3}/_{8}$ in. (1,194 and 1,457 mm) long. Each post was placed in sockets set in concrete for rapid post replacement. The slots in the top of the posts were between 2 and 4 $^{1}/_{2}$ in. (51 and 114 mm) deep.

The cables used in the systems consisted of $^{3}/_{4}$-in. (19-mm) diameter 3x7 regular lay wire rope with a nominal breaking load of 37,500 lb (166.9 kN). Pretension in the ropes was varied during the tests, but was observed to have little influence on vehicle redirection or behavior; therefore, the standard tension for most tests was 3,000 lb (13.3 kN).

Test nos. 22 through 25 were conducted on the slotted-post system at increasing impact speeds but at impact angles of approximately 10 degrees. Test results are shown in Table 4.

Table 4. Test Results, Test Nos. 22-25, 1967 [18]

Test Name	Speed		Angle	Post Spacing		Results
	mph	km/h	deg	ft	m	
22	29	47	9	8	2.4	Acceptable
23	31.7	51.0	9	16	4.9	Acceptable
24	43	69	12	16	4.9	Acceptable
25	60	97	10	8	2.4	Acceptable

Test no. 26 was a retest of test no. 25 with a higher impact angle. The test speed and angle were 59 mph (95 km/h) and 20 degrees, respectively. Again, the vehicle was satisfactorily redirected and exited the barrier system at 44.3 mph (71.3 km/h) and 3 degrees.

Two modifications were made to the barrier system prior to test no. 27. The post slot depths were increased from 3 in. (76 mm) to 6 in. (152 mm), and system length was increased to 790 ft (241 m). The test vehicle impacted the barrier at 32 mph (51 km/h) and 8 degrees.

Test no. 28 consisted of a barrier system 100 ft (30.5 m) long, and the vehicle impacted the system at 31 mph (50 km/h) and 9 degrees. In test nos. 26 and 27, the vehicles were redirected, but researchers observed that the cables did not release easily from the posts with 6 in. (152 mm) slot heights. Thus, the slot height was set to 4.5 in. (114 mm) for further testing.

Test nos. 29 and 30 were conducted on the barrier system with 4 $^1/_2$-in. (114-mm) slot depths cut in 2 $^1/_4$-in. x 1-in. by 50 $^1/_2$-in. long (57-mm x 25-mm by 1,283-mm) I-section posts, with an effective two-cable mounting height of 27 in. (686 mm). Test no. 29 consisted of a 3,000-lb (1,361-kg) Vanguard impacting the cable system at 57 mph (91.7 km/h) and 20 degrees. Test no. 30 consisted of a 1,560-lb (708-kg) Austin Minivan impacting the cable barrier system at 67 mph (108 km/h) and 22 degrees. In both tests, the vehicles were smoothly redirected and exited the barrier system with an exit angle less than 40 percent of the impact angle.

Test no. 31 was conducted with a 7,120-lb (3,230-kg) Bedford Pantechnion truck. The vehicle impacted the barrier system with a test speed and angle of 47 mph (75.6 km/h) and 17.5

degrees, respectively. The right-front wheel of the vehicle overran the traffic-side cable, but the vehicle was smoothly redirected and exited the barrier at 31 mph (50 km/h) and 15 degrees.

Since the larger test vehicle overran the traffic-side cable, the slotted-post barrier was modified, and the cables were placed at different heights, in order to redirect different types of vehicles. The posts were modified by adding a welded hook on the front face of the posts so that the cable mounting heights were 30 and 25 in. (762 and 635 mm). The first test on the modified system, test no. 32, consisted of a 1,560-lb (707-kg) Austin Minivan impacting the cable barrier system at 28 mph (45 km/h) and 20 degrees. The vehicle was contained and redirected, but the top cable slipped over the hood and contacted the right-side A-pillar.

Test nos. 33 and 34 were conducted on the modified system using a 3,000-lb (1,361-kg) Vanguard and a 7,120-lb (3,230-kg) Bedford Pantechnion truck, respectively. The vehicles were smoothly redirected, and the truck was captured and brought to a stop in contact with the system.

The effect of cable tension on redirection was investigated in test no. 35. The upper and lower ropes were tensioned to 3.85 kip (17.1 kN) and 5.0 kip (22.2 kN), respectively. The test vehicle, a 3,000-lb (1,361-kg) Vanguard, impacted the barrier system at 34 mph (55 km/h) and 20 degrees. The vehicle was satisfactorily redirected, but with no noticeable change in deflection.

The system was retested in test no. 36 with a cable pretension of 3.0 kip (13.3 kN) and an 8,200-lb (3,719-kg) Bedford Pantechnion truck, and the vehicle was smoothly redirected.

Test no. 37 consisted of a retest of test no. 36 with an 8,200-lb (3,719-kg) Bedford Pantechnion truck impacting at a higher speed of 42.3 mph (68.1 km/h) and 13 degrees. The test vehicle was smoothly redirected and exited the system, but overran the front cable with the right-front tire. A photograph of vehicle redirection in test no. 37 is shown in Figure 16.

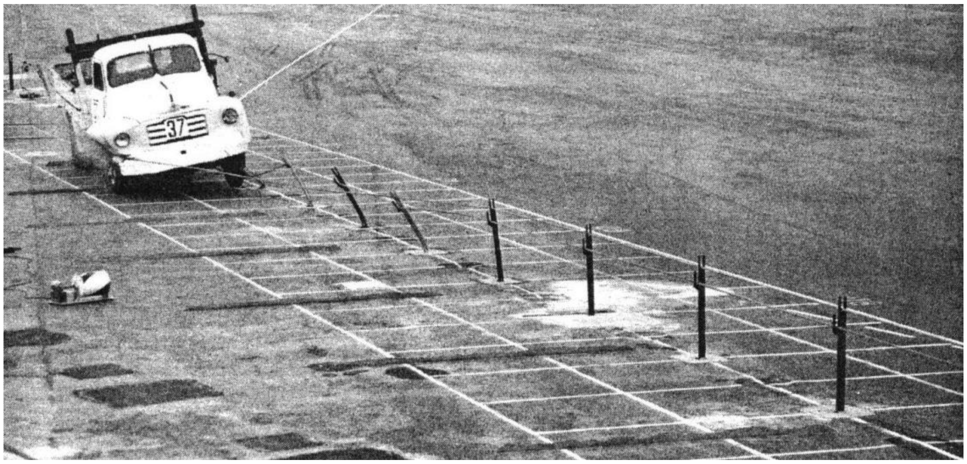


Figure 16. Vehicle Redirection, Test No. 37, 1967 [18]

In test no. 38, researchers evaluated the system under a worst-case vehicle impact. A low-profile sports car impacted the system at 64 mph (103 km/h) and 24 degrees, and the results were unsatisfactory. The upper cable released from the posts and slid over the hood and into the A-pillar, where it caused the windshield to release. The upper cable then impacted the dummy's neck region, and the lower cable slid up the vehicle's hood. The vehicle underrode the system and contacted a fixed object behind the barrier. It should be noted that the path of the vehicle was uncontrolled due to an equipment malfunction prior to impact. The cable impact with the windshield is shown in Figure 17.

Figure 17. Upper Cable Impact Into Windshield, Test No. 38, 1967 [18]

Results of test no. 38 were inflammatory. Researchers indicated that the impact with the low-profile vehicle could have resulted in severe neck or head injuries, or possible decapitation. Furthermore, the vehicle underrode both the upper and lower cables, which was not anticipated. Though this type of impact was not expected to be very common, any impact with a low-profile vehicle could result in similar behavior; thus, the barrier system was modified for further testing.

The barrier was modified prior to test no. 39 by placing both cables in the slot in the web of the post. The post length was increased to 52 $^3/_8$ in. (1,330 mm). A terminal section was created to anchor the ropes, as shown in Figure 18. The lower rope was terminated with an eye socket which connected to a spigot anchored in concrete. The upper rope remained unanchored. Impact with the tested anchorage section is shown in Figure 19. The test vehicle in test no. 39 impacted the barrier system 25 ft (7.6 m) upstream from the anchorage section at a test speed and angle of 55 mph (89 km/h) and 18 degrees. The lower rope upstream of the anchorage released from the spigot as the vehicle approached, and the lower rope on the opposing end of the terminal was overran by the test vehicle and released from the posts. The remaining unanchored cable retained the test vehicle and redirected it. The vehicle exited the barrier 120 ft (36.6 m) downstream of impact at an exit speed and angle of 34.1 mph (54.9 km/h) and 11 degrees. Thus, the cable anchorage system was determined to be acceptable.

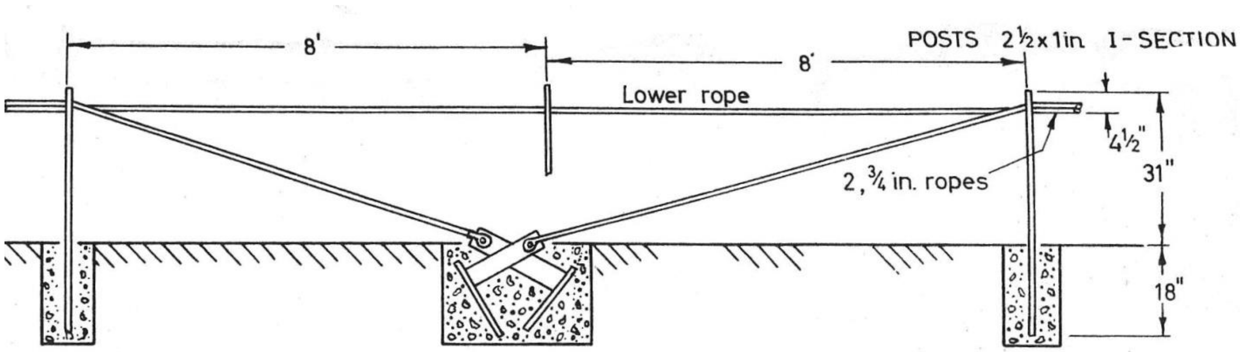


Figure 18. Slotted Post System Details at Gate, Test No. 39, 1967 [18]

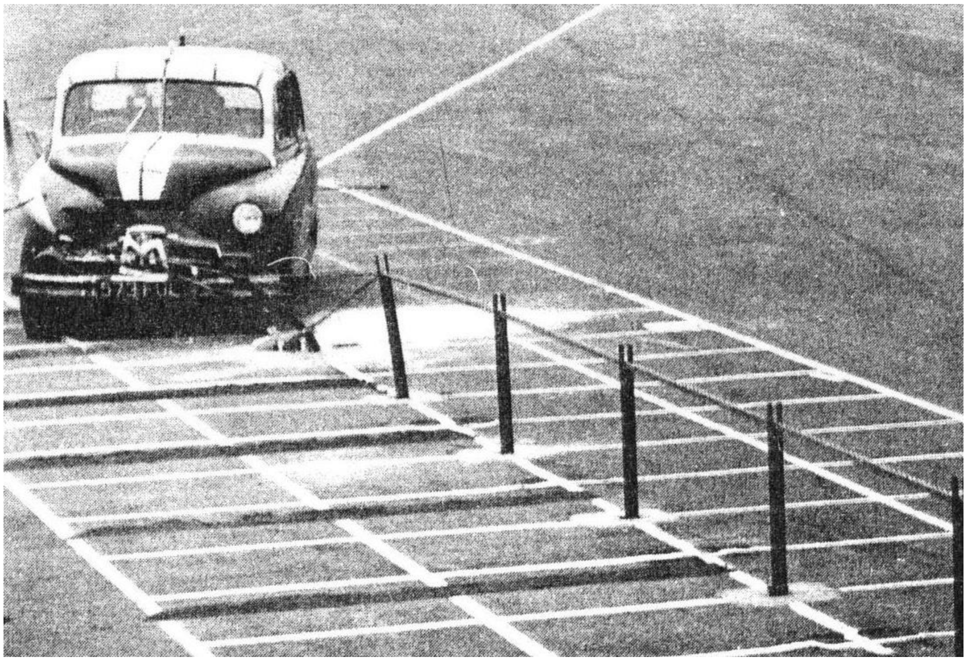


Figure 19. Cable Gate Impact, Test No. 39, 1967 [18]

2.2.1.1 Design Sensitivity Evaluation

The barrier system was further evaluated in test nos. 40, 41, 42, and 43, by installing sections of barrier in lengths of 2,000, 1,000, 500, and 5,000 ft (610, 305, 152 and 1,524 m) on a highway under construction. Both cables in each system were tensioned to 3,000 lb (13.3 kN). The test speeds for these tests were 55, 60, 55, and 50 mph (89, 97, 89, and 80 km/h) at angles of approximately 20 degrees. The maximum dynamic deflections in test nos. 40, 41, 42, and 43 were 144, 150, 76, and 108 in. (3,658, 3,810, 1,930, and 2,743 mm), respectively. All tests were satisfactory.

A correlation was not observed between system length and deflection in test nos. 40 through 43. Therefore, the effect of wire rope pretension was evaluated. The cables were cyclically loaded 8 times to 16,000 lb (71.2 kN) prior to test nos. 44 through 47. Static rope tension at the time of the test was 3.0 kip (13.3 kN). The installation length was 2,000 ft (610 m).

Test no. 44 consisted of a Vanguard impacting at 62 mph (100 km/h) and 20 degrees, and the maximum dynamic deflection was 106 in. (2,692 mm).

Test no. 45 was a retest of test no. 44 with a static rope pretension of 6.0 kip (26.7 kN). The Vanguard impacted the barrier system with a test speed and angle of 58.5 mph (94.1 km/h) and 22 degrees, respectively. Maximum dynamic deflection was determined to be 114 in. (2,896 mm). The vehicle was satisfactorily redirected, and it was observed that rope pretension had little effect on dynamic deflections for the indicated system configuration.

Test no. 46 consisted of a 4,000-ft (1,219-m) long barrier system, and the test vehicle impacted the barrier system at a test speed and angle of 62.5 mph (100.6 km/h) and 19 degrees, respectively. The maximum dynamic deflection was determined to be 159 in. (4,039 mm). Researchers suggested that by doubling the system length, a 50 percent increase in deflection was observed.

The final test on the highway section, test no. 47, was similar to test no. 44, with post spacing doubled from 8 ft (2.4 m) to 16 ft (4.9 m). The test vehicle, a 3,000-lb (1,361-kg) Vanguard, impacted the barrier system at 65 mph (105 km/h) and 17.5 deg, and was smoothly redirected. The maximum dynamic deflection was determined to be 168 in. (4,267 mm). Therefore, researchers postulated that the effect of doubling the post spacing was roughly the same as doubling the system length.

An alternative barrier system was evaluated, consisting of posts that were bolted to the concrete footings instead of being placed in sockets. The system incorporated 3-in. x 1 $^{1}/_{2}$-in. by 32 $^{1}/_{2}$-in. long (76-mm x 38-mm by 826-mm) I-section posts bolted to the tarmac through an anchor plate. The cables were positioned in the bottom of a 6-in. (152-mm) slot in the top of each post, with the top cable resting on the bottom cable. The system was tested in test no. 70 using a minivan with test speed and angle measuring 64.5 mph (103.8 km/h) and 20 degrees, respectively. During impact, the cables slid over the hood and struck the A-pillar of the vehicle. Due to the tripping forces caused by eccentric cable loading and reactions of the stronger posts, the vehicle rolled as it exited the barrier. Therefore, the second alternative system was determined to be unacceptable. Cable impact with the windshield is shown in Figure 20.

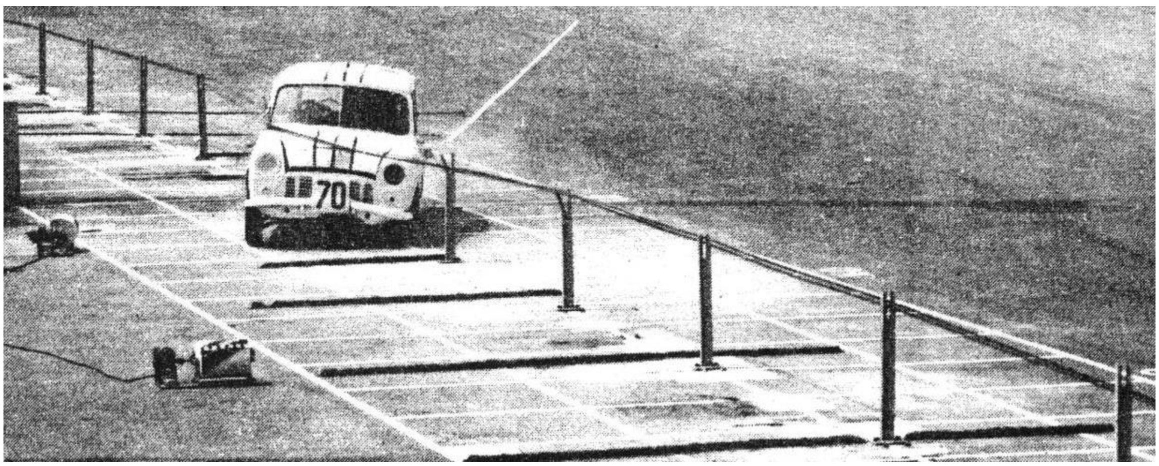


Figure 20. Cable Impact with Windshield, Test No. 70, 1967 [18]

The barrier system was modified by reducing the cable mounting height by 2 in. (51 mm) to 25 in. (635 mm), while retaining the 3-in. x 1 $^{1}/_{2}$-in. by 32 $^{1}/_{2}$-in. long (76-mm x 38-mm by 826-mm) I-section posts. The posts were placed in sockets in concrete footers, similar to previous tests. The system was evaluated in test no. 73 with a 1,560-lb (708-kg) Austin Minivan at 62.6 mph (100.7 km/h) and 12 degrees, and the vehicle was smoothly redirected with no snagging. Thus, the slotted-post barrier system was determined to be acceptable with stronger posts.

As a result of this study, researchers made several conclusions: (1) cable release may be accomplished by setting the cables in shallow slots in the tops of posts; (2) placing cables at two heights may cause hazard to smaller vehicles by sliding over the hood and striking the windshield and the lower height may be run over by larger vehicles; (3) ropes placed at a single height will redirect small and large vehicles if the cable is located above the vehicle bumper; and (4) exit angles from the cable barrier system are typically less than half of the impact angles.

2.2.2 Canada Department of Highways, Ontario, 1967-1970

2.2.2.1 Preliminary Testing

At the same time as the MIRA testing, research on a different barrier system, incorporating three cables in the design, was conducted by the Canadian Department of Highways in Ontario [19]. A total of 22 full-scale tests were conducted to evaluate the required anchor strength, cable strength and size, number of cables, and attachment to the posts. All of the cable systems tested included 6-in. diameter by 77-in. long (152-mm by 1,956-mm) cedar posts, with embedment depths of 42 in. (1,067 mm). Posts were typically at 12 ft (3.7 m) spacing, when used. Four anchors were used in the test series, consisting of the "Standard", "Modified", "Concrete", and "Expanding Steel" cable anchors. Anchor details are shown in Figures 21 through 24.

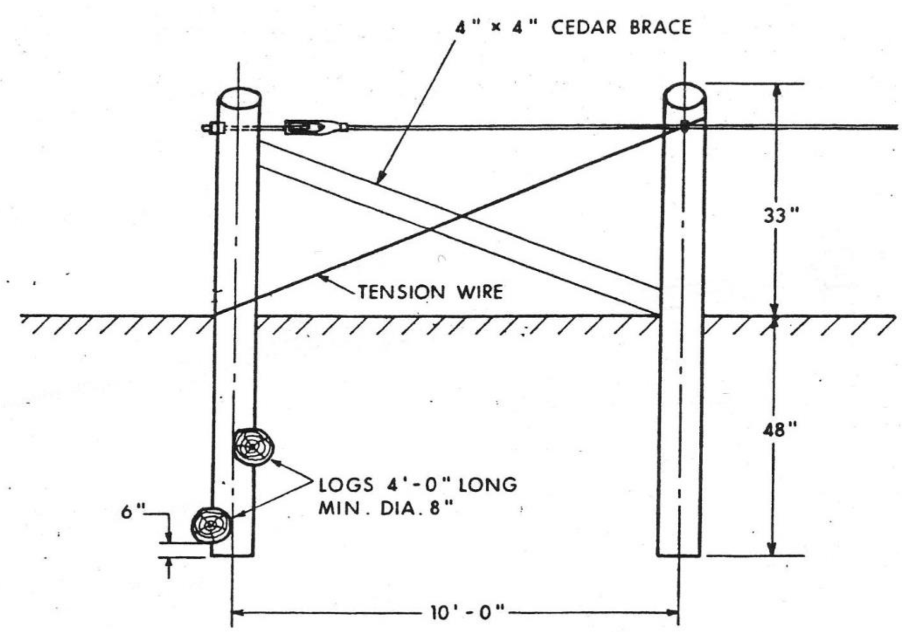


Figure 21. Canadian Department of Highways "Standard" Anchor Details, 1967 [19]

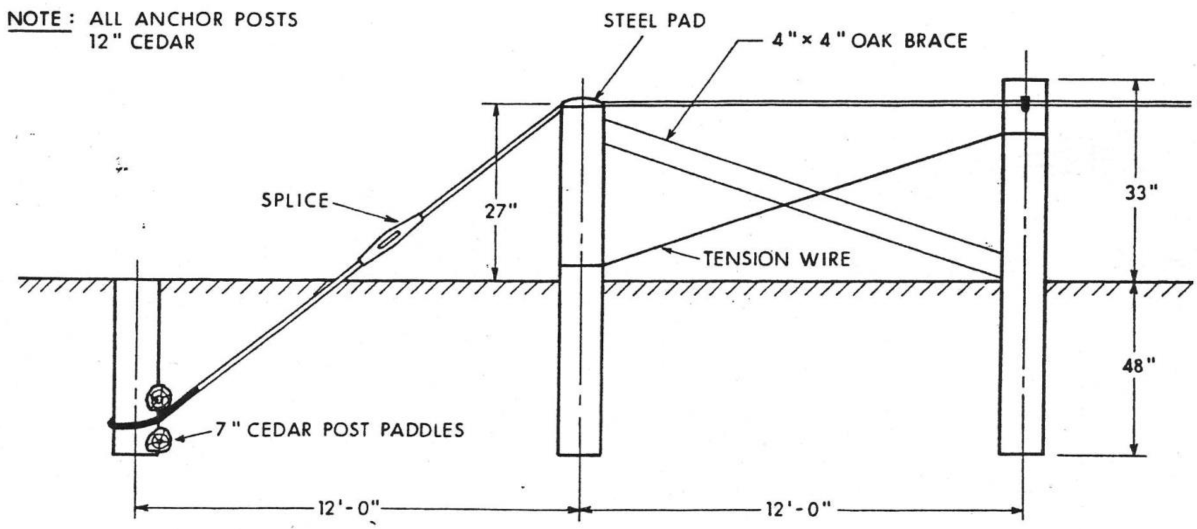


Figure 22. Canadian Department of Highways "Modified" Cable Anchor Details, 1967 [19]

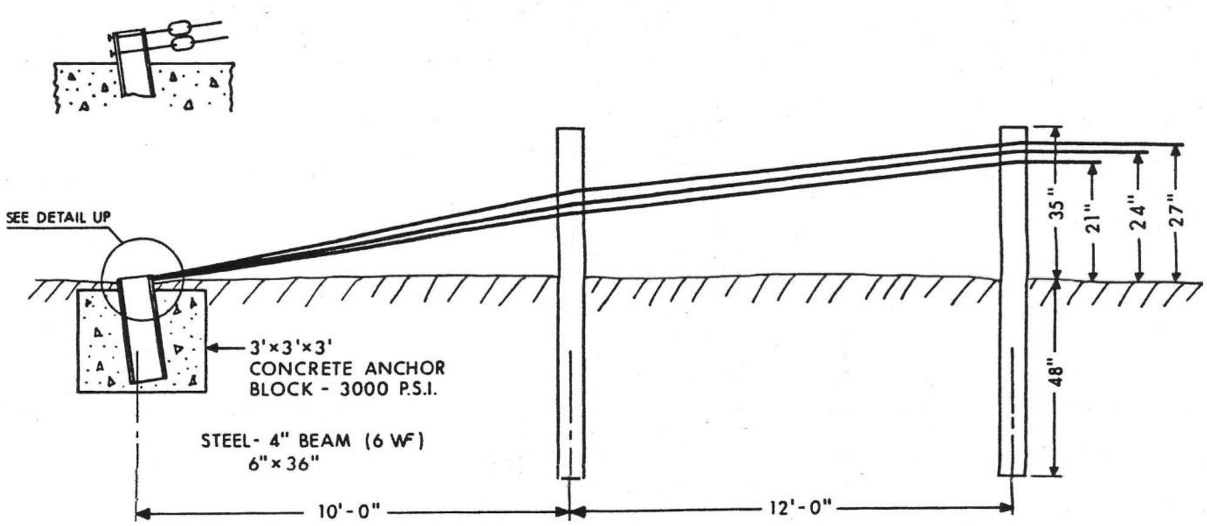


Figure 23. Canadian Department of Highways "Concrete" Anchor Details, 1967 [19]

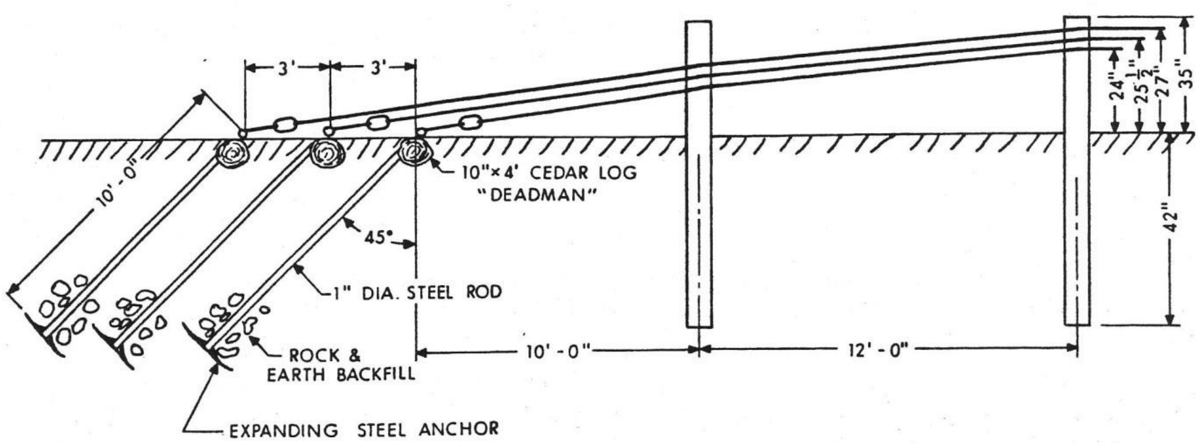


Figure 24. Canadian Department of Highways "Expanding Steel" Anchor Details, 1967 [19]

The Standard cable anchor consisted of two 6-in. diameter by 81-in. long (152-mm by 2,057-mm) cedar anchor posts and two 8-in. diameter (minimum) by 4-ft long (203-mm by 1.2-m) transverse studs located 22 in. and 38 in. (559 mm and 965 mm) below ground, as shown in Figure 21. A single $^1/_2$-in. (13-mm) diameter cable was terminated with a threaded rod, passing through the terminal post. The two anchor posts were braced with a tension wire and a 4-in. x 4-in. by 10-ft 6-in. long (102-mm x 102-mm by 3.2-m) cedar brace.

After viewing the results of the first crash test, researchers at the Canadian Department of Highways modified the "Standard" cable anchor into the "Modified" anchor. It was determined that better anchor performance could be attained by routing the cable into the ground and securing it to an anchor post, as shown in Figure 22. To accomplish this, the end post of the standard anchor was cut 6 in. (152 mm) from the top and a steel bearing pad was attached to the top of the post. The cable was routed over the bearing pad and into the ground where it formed a loop around a 6-in. diameter by 48-in. long (152-mm x 1,219-mm) cedar post fully embedded in the ground. To secure the cable loop, two 7-in. (178-mm) cedar paddles were fastened to the post above and below the cable loop.

Prior to test no. 1-68, the "Concrete" anchor was created. The "Concrete" anchor was similar to the "Modified" anchor, with of 3 cables at mounting heights of 27, 24, and 21 in. (686, 610, and 533 mm), as shown in Figure 23. The "Concrete" anchor sometimes utilized only 2 cables. The cables were routed through holes drilled in the 6-in. diameter by 83-in. long (152-mm by 2,108-mm) cedar posts and were terminated by connecting to a 6-in. x 4-in. by 36-in. long (152-mm x 102-mm by 914-mm) wide-flanged steel beam anchored in a 3-ft x 3-ft x 3-ft (0.9-m x 0.9-m x 0.9-m) concrete block.

An "Expanding Steel" anchor was also proposed which incorporated hinged steel plates attached to 1-in. diameter by 10-ft long (25-mm by 3.0-m) steel rods, as shown in Figure 24. The rods were fastened to 10-in. diameter by 4-ft long (254-mm by 1.2-m) cedar deadman logs, which served as the cable termination points. The three cable mounting heights for the Expanding Steel anchor were 27, 25 $^{1}/_{2}$, and 24 in. (686, 648, and 610 mm).

Test no. 1-67 consisted of one Grade 50 $^{1}/_{2}$-in. (13-mm) diameter 3x7 cable, with a top mounting height of 25 in. (635 mm), attached to the posts with staple hooks. The test vehicle, a station wagon with a weight of 4,000 lb (1,814 kg), impacted the cable barrier system at 51 mph (82 km/h) and 25 degrees. Upon impact, the cable fractured and the vehicle penetrated through the system with no redirection. During the impact, the anchor posts deflected.

Based on the results of the first test, it was determined that the cable strength was insufficient to provide adequate redirection to impacting vehicles. Therefore, the design was modified to include a single $^{3}/_{4}$-in. (19-mm) diameter 3x7 cable instead of the $^{1}/_{2}$-in. (13-mm) diameter cable used in the first test. In test no. 2-67, the test vehicle impacted the cable barrier system at 47 mph (76 km/h) and 25 degrees, and the vehicle was redirected with acceptable ridedown accelerations. The maximum deflection recorded in the test was 6 ft (1.8 m).

Though the single cable design was sufficient to capture the large sedan at a moderate impact speed, it was observed that damage occurred to the cable during impact and that one cable was likely insufficient to capture all sizes of passenger vehicles which may depart the roadway. Two further tests were conducted on the single-cable guardrail system with standard anchor, but were not described in the test report. Since the strength of the single-cable system could be improved by adding additional cables, three $^{1}/_{2}$-in. (13-mm) diameter cables were implemented in test no. 8-67. Three $^{1}/_{2}$-in. (13-mm) diameter cables were observed to be stronger than one $^{3}/_{4}$-in. (19-mm) diameter cable, which successfully redirected the test vehicle in test no. 2-67, but not as strong as two $^{3}/_{4}$ (19-mm) diameter cables. Test no. 8-67 was conducted with a test speed and angle of 56.7 mph (91.2 km/h) and 25 degrees, and the test results were acceptable. Furthermore, the damage done to the vehicle was very slight, and the test vehicle was repaired for further testing.

In test no. 3-68, three modifications were made to the system: (1) the length of the installation was increased to 350 ft (106.8 m); (2) the system was installed at the break point of a 3:1 ditch; and (3) the "Concrete" anchor was utilized. Three $^{1}/_{2}$-in. (13-mm) diameter Grade 110 cables were torqued to 30 lb-ft for an approximate tension of 785 lb (3.50 kN) prior to test no. 3-68. The test vehicle impacted the cable barrier system at a test speed and angle of 50 mph (80 km/h) and 25 degrees, respectively. The vehicle was smoothly redirected but made secondary contact with the barrier system, resulting in cable entrapment in the front wheel well and subsequent spin-out. It was believed that the spin-out behavior observed in the test was related to the extension of the vehicle's suspension as it passed over the ditch. Test results from test no. 3-68 are shown in Figure 25.

Figure 25. Impact 3-68, 1968 [19]

The cable barrier system was modified prior to test no. 1A-68 by incorporating improved connections between the cable and the "Concrete" anchor. Static rope tensions were also increased to approximately 1,180 lb (5.25 kN) by torquing the cable assemblies to 45 lb-ft (61.0 N-m). The test vehicle impacted the system at 48 mph (77 km/h) and 25 degrees and was successfully redirected before spinning out. Furthermore, upon investigation of the snagging problem, it was observed that when the test vehicle extended over the ditch profile, the front suspension relaxed and allowed the lower cables to protrude into the wheel well, which also occurred in test no. 3-68. The vehicle was redirected and made secondary contact with the system 85 ft (25.9 m) downstream of impact. The center cable assembly failed during the test, allowing the center cable to go slack.

In test no. 1-68, the top cable was Grade 110, while the bottom and middle cable were Grade 50 steel. The test vehicle, a 4,000-lb (1,814-kg) station wagon, impacted the cable guardrail system at 52 mph (84 km/h) and 25 degrees. As the vehicle was projected over the ditch, the suspension relaxed and the cables were trapped behind the impacting wheel, resulting in excessive yaw rotations of the vehicle. Furthermore, the top cable slid up the hood and shattered the windshield during impact.

Since entrapment of the cables in test nos. 3-68 and 1-68 caused spin-outs, researchers again tested the single-cable design using the "Modified" anchor, and a single $^{3}/_{4}$-in. (19-mm) diameter 3x7 cable. In addition, the length of the system was increased to 500 ft (152.4 m). Test no. 5-68 was conducted with an impact speed and angle of 50 mph (80 km/h) and 25 degrees, respectively, and the system deflected to allow the vehicle to completely enter the ditch. Nonetheless, the vehicle was redirected with a small exit angle (approximately 5 degrees) with equivalent vehicle damage to that observed in the three-cable tests. Therefore, it was concluded that the 6-in. (152-mm) separation between the top and bottom cables in the three-cable tests may have contributed to vehicle yaw motions and entrapment in the wheel well.

The system tested in test no. 5-68 was retested with a small car in test no. 9-68. The test vehicle impacted the system at 52 mph (84 km/h) and 25 degrees. During the test, the body of the small car separated from the chassis after the cables formed a groove above the headlight. Researchers examined the body of the small car and discovered that it was corroded and held in place by plaster and newspaper in some locations. Despite the failure of the car body, the cables formed a groove above the headlight at the hood level, indicative of acceptable barrier performance. Thus the test was judged to be successful. Test results from test no. 9-68 are shown in Figure 26.

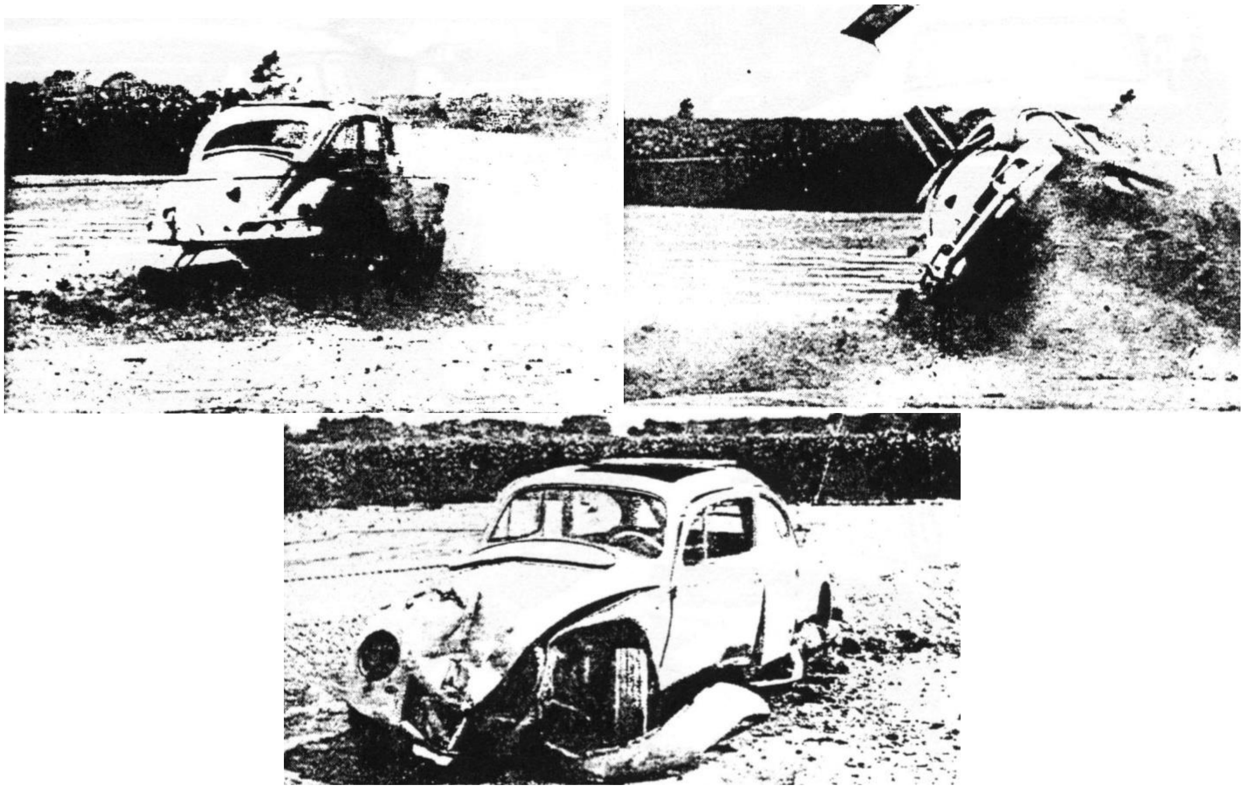


Figure 26. Test No. 9-68, 1968 [19]

To investigate the contribution of posts to cable barrier performance, the system evaluated in test no. 5A-68 was modified such that no posts were present between the two anchors. The test vehicle impacted the system at a speed and angle of 50 mph (80 km/h) and 25 degrees, respectively. During the impact event, the vehicle was partially redirected before fracturing the cable anchor assemblies on both ends and rolling over in the ditch. Since the entire impact load was carried by the end assemblies, it was determined that stronger end assemblies should be used. In addition, the contribution of posts to vehicle redirection was confirmed. Posts contribute via friction with the wire rope, resistance to lateral deflection, and energy absorption.

Researchers attempted several cable spacer designs, in unnamed tests, to reduce the entrapment of the cables in vehicle suspensions when cable systems are installed adjacent to ditches. In test no. 6-68, a 12-ton (106.8-kN) hydraulic press was used to swage large spacers to the cables in order to prevent the spacers from being dragged along the cable by the impacting vehicle as the last and strongest spacer design. The Grade 110, $^{1}/_{2}$-in. (13-mm) diameter three-cable system was again tested with a "Concrete" block anchorage at a system length of 350 ft (106.7 m) on the break point of a 3:1 ditch. The test vehicle impacted the cable barrier system with a test speed and angle of 46 mph (74 km/h) and 25 degrees, respectively, and was captured by the barrier system. A review of the test's high-speed video indicated that the vehicle dragged the swaged spacers as it traversed along the barrier system, and that entrapment of the cables in the suspension still occurred. Furthermore, due to contact with the cable spacers, sections of the vehicle's sheet metal were torn off and entangled in the spacers. Following this test, the use of spacers was abandoned.

It was determined that an alternative to using cable spacers to prevent cable entrapment was to use a smaller cable spacing. The three-cable system was modified in test no. 7-68 by cutting the cable spacing in half. In addition, the end assemblies were improved such that a breaking load of 32 kips (142.4 kN) was maintained before release. The test vehicle impacted the barrier system at a speed of 44 mph (71 km/h) and 25 degrees. Maximum vehicle penetration was reduced, and the cables did not enter the wheel well of the vehicle during the test. The vehicle came to rest in contact with the barrier system with acceptable ridedown decelerations. No snagging was observed in this test. Photographs from test no. 7-68 are shown in Figure 27.

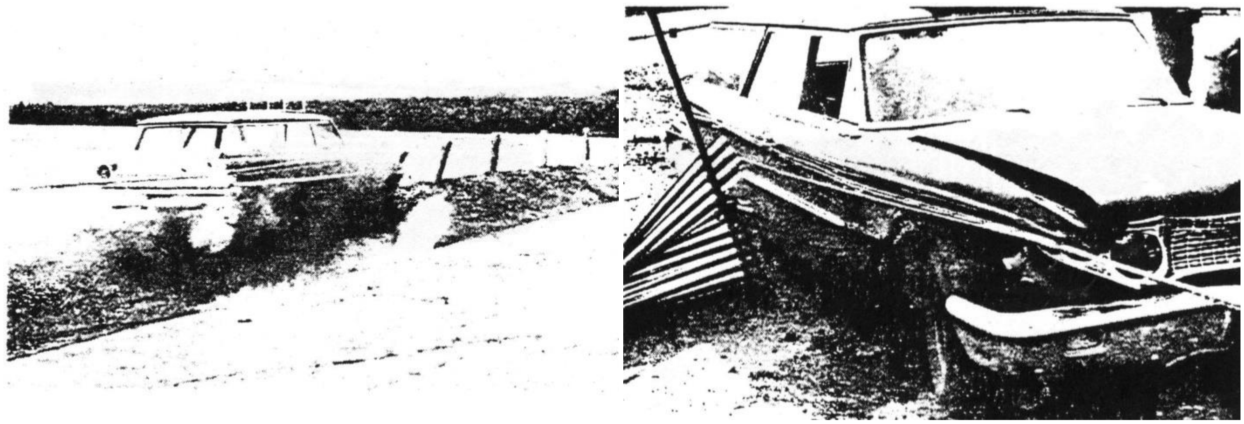


Figure 27. Test No. 7-68, 1968 [19]

Following the successful performance of test no. 7-68, researchers again investigated the contribution of the 6-in. (152-mm) posts. All of the posts between the end anchors were removed in test no. 7A-68, and the system was tested again at 48 mph (77 km/h) and 25 degrees. The vehicle penetrated into the ditch and struck the backslope, where the cables slid over the roof and the vehicle rolled over. Researchers believed that if the ditch was wider or had been a fill slope, the vehicle may have been contained and captured rather than rolling over. Nonetheless, this test confirmed the results of test no. 5A-68 that posts in the impact area were critical to the acceptable performance of the cable barrier system. Additional unnamed tests were conducted on barrier systems implementing 2-in. x 2-in. (51-mm x 51-mm) posts, which led to significant increases in dynamic deflection and in some cases vehicle penetration.

Finally, researchers evaluated the "Expanding Steel" anchor, which may have some use on sloped terrain or in locations not advantageous to "Concrete" block anchorages. Test no. 8-68 consisted of the same barrier system tested in test no. 7-68, except for the different anchorage. The test vehicle impacted the barrier at 50 mph (80.5 km/h) and 25 degrees, and was redirected. The vehicle spun out following redirection, and posts were pulled out of the ground. Researchers believed that this was the result of saturated soil due to rain prior to the test. Thus, the "Expanding Steel" anchor was considered an acceptable alternative to the "Concrete" anchor.

2.2.2.2 Development of Cable Barrier Simulation Model

Based on the results of the cable testing, an additional study was conducted in 1972 that attempted to determine the absolute position and angular velocity of the vehicle based on photogrammetrics, aeronautical surveying, and precision targeting using a single video camera [20]. Researchers used concepts from photogrammetric measurements to determine target locations, camera angles, and field of view for a 16-mm video camera. Then, researchers applied motion-sensitive pinpointing techniques used in aeronautical surveying to determine the absolute position of the vehicle in the video frame. Six targets were placed on the front plane of the vehicle to determine pitch, roll, and yaw angular displacements as well as longitudinal, lateral, and vertical motion. This method was applied to videos of four full-scale crash tests, which were not described, and indicated good correlation with physical measurements.

An extension of the photogrammetric method of analyzing full-scale vehicle crash testing was conducted to validate a model of vehicle impact with cable guardrail systems [21]. Five full-scale crash tests were conducted at the Canadian Department of Highways on a modified version of the slotted-post cable guardrail system first developed by the Road Research Laboratories (**18**). The S3x5.7 (S76x8.5) posts measured 42 in. (1,067 mm) long and were embedded 18 in. (457 mm) in rectangular steel sockets in concrete footings. The flanges and webs of the posts were notched to ensure post strength of 3.9 kips (17.4 kN). The slots in the webs of the posts were 4 in. (102 mm) deep, and tapered slightly to promote cable release from the posts. Both cables were located in the top slot, with mounting heights of approximately 28 and 28 $^{3}/_{4}$ in. (711 and 730 mm).

System lengths for all five tests were 400 ft (122 m), and the cable pretensions were 5.0 kips (22.2 kN). Test nos. 77, 78, and 79 were conducted with post spacings of 8 ft (2.4 m) and consisted of a 1963 Pontiac Strato-Chief 2-door sedan, weighing approximately 5,000 lb (2,268 kg), impacting the system at the midspan between post nos. 11 and 12. Systems evaluated in test nos. 81 and 82 had post spacings of 16 ft (4.9 m). Both test nos. 81 and 82 also used the same 1963 Pontiac Strato-Chief 2-door sedan, weighing approximately 5,000 lb (2,268 kg), impacting at the midspan between post nos. 5 and 6. Furthermore, the test vehicle used in all of the tests used a 6-in. x 6-in. (152-mm x 152-mm) box beam section placed on the impacting side of the vehicle, to increase vehicle rigidity.

Test no. 77 was conducted at 45 mph (72 km/h) and 24.55 degrees. The test vehicle was smoothly redirected and damaged a total of nine posts, with a reported maximum dynamic tension of 16 kip (71.2 kN).

Test no. 78 was conducted at 34.5 mph (55.5 km/h) and 24.35 degrees. Dynamic test data were not recorded for the test, but motion of the vehicle was consistent with smooth redirection and containment. Therefore, it was believed that test no. 78 was successful.

Test no. 79 was conducted at 55.0 mph (88.5 km/h) and 24.75 degrees. The vehicle was smoothly redirected, and eleven posts were damaged during the test. The reported maximum dynamic tension was 22 kip (97.9 kN).

Test no. 81 was conducted at 44.5 mph (71.6 km/h) and 24.71 degrees. The cables disengaged from a total of six posts, and the maximum dynamic tension in the cables was reported to be 18 kips (80.1 kN).

Test no. 82 consisted of the sedan impacting at 54.5 mph (87.7 km/h) and 24.55 degrees. The vehicle was smoothly redirected, but the cable disengaged from seven posts before the vehicle was redirected. The reported maximum dynamic tension was more than 20 kips (89.1 kN).

3 NCHRP REPORT 230 AND INTERNATIONAL TESTING, 1978-1995

The use of testing and evaluation guidelines expanded to most testing agencies after the publication of the Transportation Research Circular 191 in 1978 [1] and the NCHRP Report 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, published in 1981 [4]. Following the publication of formal testing procedures, new testing focused on satisfying performance and safety criteria recommended in these reports. Barrier construction details are shown in Appendix C, and crash test details are shown in Appendix D.

3.1 Texas Transportation Institute (TTI), 1978-1985

TTI conducted two cable tests prior to the 1980, but followed the test procedures presented in NCHRP Report 230 to evaluate a cable guardrail installed on a 6H:1V fill slope [22]. The systems consisted of S3x5.7 by 63-in. long (S76x8.5 by 1,600-mm) steel posts with 24-in. x 8-in. by $^{1}/_{4}$-in. thick (610-mm x 203-mm by 6-mm) soil bearing plate welded to the back of the posts. Spring compensators were installed on the upstream end of the system, and turnbuckles were located downstream of impact. Test no. 3659-5 was conducted with the cable barrier system located 6 ft (1.8 m) down the slope from the slope break point (SBP) of a 6:1 slope, and test 3659-5 was conducted 12 ft (3.7 m) down the slope from the SBP of a 6:1 slope. Both installations were anchored on both ends with concrete anchors, and the systems measured 200 ft (61.0 m) long.

Test no. 3659-6 was conducted with a 1974 Chevrolet Vega, weighing 2,250 lb (1,021 kg). The test vehicle impacted the system at the midspan between post nos. 2 and 3 with a test speed and angle of 58.4 mph (94.0 km/h) and 17.25 degrees, respectively, and the vehicle was captured. The vehicle impacted and snagged on the downstream end anchor prior to exiting the system; nonetheless, this test was determined to be acceptable.

Test no. 3659-5 was conducted with a Plymouth Sedan, weighing 4,500 lb (2,041 kg). The test vehicle impacted the cable barrier system at a test speed and angle of 59.6 mph (95.9 km/h) and 24.75 degrees, respectively, and the test vehicle was also captured by the system. Ridedown decelerations and vehicle damage were minimal during the impact event; however, the vehicle impacted the downstream end anchor assembly, as also occurred in test no. 3659-6.

As a result of these tests, it was concluded that the performance of the G1 guardrail system placed at 6 ft (1.8 m) and 12 ft (3.7 m) from the SBP of a 6:1 slope safely redirected small and large-size passenger cars. The cables remained at essentially the same height relative to the ground throughout impact, resulting in acceptable vehicle redirection. Because of this, cable guardrail performed better than the G4(1S) system and the G9 system when installed on or near sloped terrain, since the rail does not deflect backward and downward during impact.

Following the acceptance of NCHRP Report 230, TTI also evaluated the performance of cable guardrail placed in a V-ditch [23]. System details are shown in Figure 28. The cable barrier tested was a modified version of a Minnesota cable guardrail system, incorporating 5 $^{1}/_{2}$-in. diameter by 72-in. long (140-mm by 1,829-mm) round wood posts, spaced 12 $^{1}/_{2}$ ft (3.81 m) on center, with $^{5}/_{16}$-in. (7.9-mm) diameter J-bolts, and cable mounting heights of 28, 24, and 20 in. (711, 610, and 508 mm). The cables were terminated using threaded rods, which extended through transverse holes in the post and were fastened with nuts. A bent threaded rod was attached to the top of the post and angled into a concrete block, embedded in the soil.

The first test on the modified Minnesota cable barrier system was conducted in 1983. Test no. 4798-11 consisted of a 1978 Plymouth sedan impacting the cable barrier system at 61.2 mph (98.5 km/h) and 25.5 degrees. The vehicle was captured, even though the system sustained extensive damage.

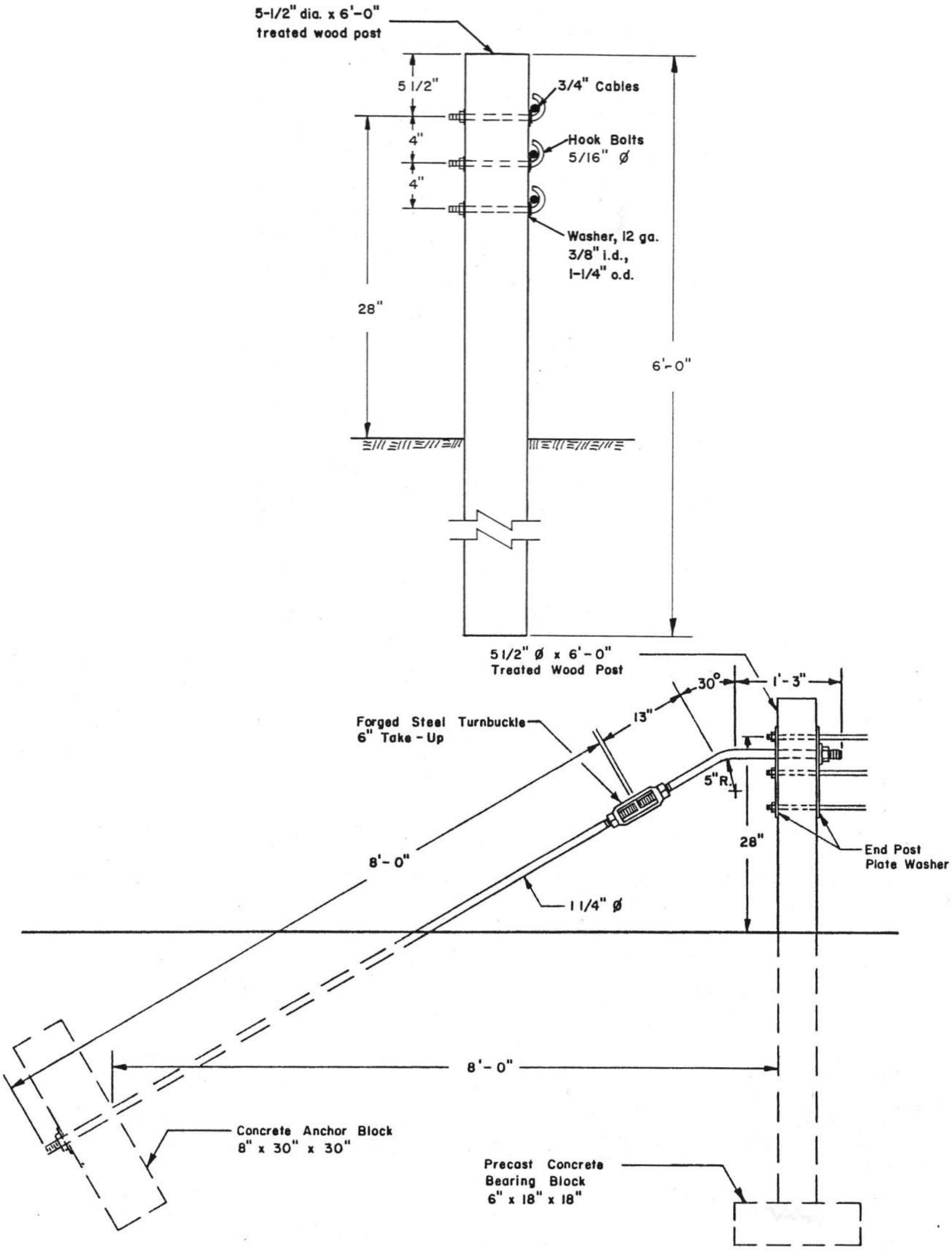


Figure 28. System Details, TTI, 1983-1985 [23]

The second test conducted on the modified Minnesota design, test no. 4798-2, consisted of a 2,220-lb (1,007-kg) Honda small car impacting the barrier at 59.3 mph (95.4 km/h) and 14.5 degrees. The vehicle was redirected with a maximum deflection of 36 in. (914 mm), but rolled after exiting the barrier system due to wheel snag on a post. Since the barrier system did not safely contain and redirect the small car, the system was determined to be unacceptable according to the guidelines provided in NCHRP Report 230.

3.2 ENSCO, Inc., 1986-1989

ENSCO, Inc. conducted a series of five tests on the Minnesota cable barrier system in order to develop a crashworthy end terminal [24]. The barrier utilized the end terminal tested by TTI in 1983 and 1984 [23]. The system was constructed with 5 $^{1}/_{2}$-in. diameter by 72-in. long (140-mm x 1,829-mm) wood posts with a 1 $^{1}/_{2}$-in. (38-mm) diameter longitudinal hole drilled in the posts 33 $^{1}/_{2}$ in. (851 mm) from the bottom of the post. The posts had an embedment depth of 38 $^{1}/_{2}$ in. (978 mm), and supported three $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables with $^{5}/_{16}$-in. (8-mm) diameter J-bolts at mounting heights of 28, 24, and 20 in. (711, 610, and 508 mm). System details are shown in Figure 29.

The first test on the Minnesota system, test no. C-1, consisted of a 2,000-lb (907-kg) small car impacting the system at 60.6 mph (97.5 km/h) and 21 degrees. The vehicle was smoothly redirected and was decelerated, but the anchor post fractured due to cable loads. The vehicle contacted some of the fractured posts downstream of impact and yawed. The compensator assemblies at the end of the guardrail slid over the vehicle's hood and contacted the windshield, causing the vehicle to yaw out of the system and rollover.

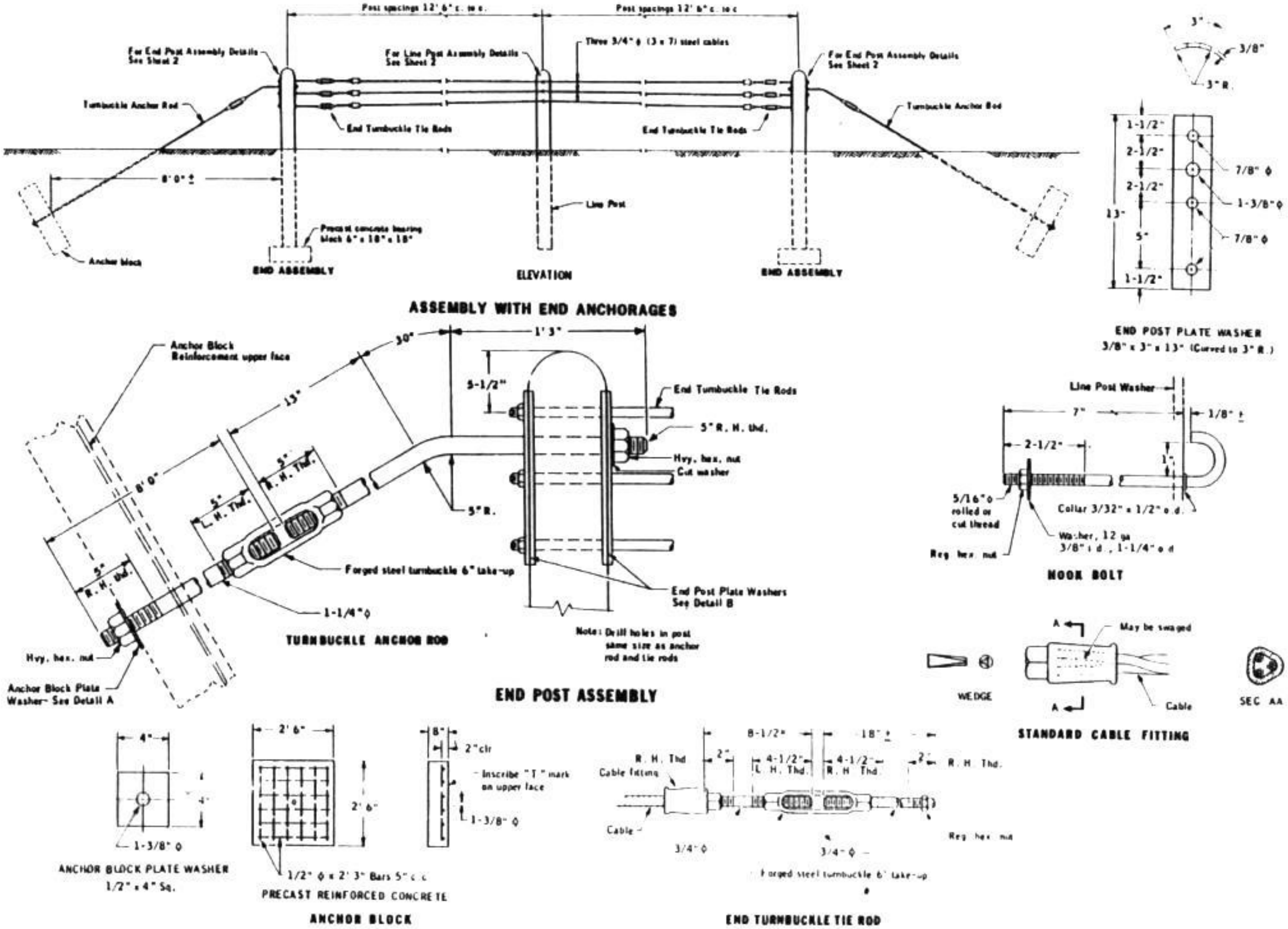


Figure 29. Design Details, Test Nos. GR-1, GR-16, and GR-17, 1987 [24]

The system was modified by increasing the end anchor rod length by 4 ft (1.2 m) to secure the concrete anchor block deeper in the soil. The anchor posts were also strengthened by adding an additional adjacent post at the same location and were fastened to each other with a bracket to facilitate load transfer from the cables to the anchor rod. Test no. C-2 was conducted with a 1981 Honda Civic impacting the system at 62.1 mph (99.9 km/h) and 20 degrees. The vehicle penetrated through the cable system due to the attachment bracket pulling through the dual end posts, causing a U-shaped fracture.

To reduce the cable pull-through, the cable termination bracket was modified by strengthening the cable attachment and increasing the plate bearing area on the double wood posts. The anchor rod connecting to the anchor block was shortened by 2 ft (0.6 m) and a BCT cable anchor was added at the turnbuckle to facilitate some flexibility in the anchor design. The modified system was tested in test no. C-3, which consisted of a 1981 Honda Civic, weighing 1,960-lb (889-kg), impacting the barrier at 61.0 mph (98.2 km/h) and 20 degrees. The vehicle was smoothly redirected, and the anchor performed satisfactorily.

The system was tested again in test no. C-4, consisting of a 1979 Ford LTD II, weighing 4,680-lb (2,123-kg), impacting the cable barrier at 62.7 mph (100.9 km/h) and 26 degrees. The test vehicle was captured by the barrier system and came to a controlled stop after fracturing all of the posts downstream from impact. The vehicle continued out of the system after fracturing the dual end post and came to rest 160 ft (48.8 m) downstream and 25 ft (7.6 m) behind the rail. The test results were determined to be acceptable.

The final test on the modified cable guardrail system consisted of a reverse-direction impact on the cable barrier system at the dual end post. Test no. C-5 consisted of a 1,940-lb (880-kg) small car impacting the dual post at 60.6 mph (97.5 km/h) and 21 degrees. The dual post fractured on impact, but the off-axis hit with the posts near the side of the bumper caused the vehicle to yaw rapidly and rollover.

Based on the results of the crash testing, four recommendations were made regarding the cable barrier system: (1) the end terminal design tested in this study was not crashworthy but demonstrated improvement over the design in use; (2) use of the terminal tested by the New York State Department of Transportation [25] may be more advantageous; (3) all existing line posts should have a longitudinal hole drilled in the post at ground level; and (4) the existing anchor block should be deepened and enlarged to prevent anchor pull-out.

3.3 New York State Department of Transportation (NYSDOT), 1980-1994

3.3.1 Barriers Installed on Curves, 1980

Researchers in New York also desired to test the behavior of cable guardrail in sharply-curved configurations [26]. Two 57 and 114 degree curves with 100 and 50 ft radii (30.4 and 15.2 m) were selected for testing. Concrete anchors were used to provide tension for the guardrail system at both ends of the system. Spring compensators were also used to retain tension in the cables. To test the barrier systems on sharply-curved radii, the impact speeds were reduced from 60 mph (96.6 km/h) to 40 mph (64.4 km/h), but the impact angles were increased from 25 degrees to 90 degrees relative to the barrier system. This represented nearly a 150% increase in impact severity from typical testing conditions and represented the worst practical impact scenario.

Test no. 5 was conducted on the cable barrier system installed on a 100-ft (30.4-m) radius with posts spaced 4 ft - 2 in. (1,270-mm) on center, and consisted of a 1969 Ford Fairline sedan weighing 3,060 lb (1,388 kg) and impacting at 47.9 mph (77.0 km/h). The cable barrier contained the vehicle and brought it to a controlled stop. The cables released from 23 posts, with a dynamic deflection of 29.0 ft (8.84 m). The maximum 50-ms average longitudinal deceleration was 0.98 g's. The test was considered acceptable.

The second test on the cable system, test no. 6, was conducted on a G1 guardrail system installed on a 50-ft (15.2 m) radius with a 3-ft 1 $^{1}/_{2}$-in. (953-mm) post spacing. The test vehicle, a 1974 AMC Matador sedan, with a weight of 3,540 lb (1,606 kg), impacted the barrier system at 32.8 mph (52.8 km/h). The cable barrier system captured the test vehicle with a dynamic deflection of 17.5 ft (5.33 m) and a maximum longitudinal acceleration of 9.70 g's. It should be noted that the impact speed was considerably less than anticipated; nonetheless, accelerations were well within the recommended limits and vehicle damage was minimal.

3.3.2 End Terminal Development, 1990-1994

The NYSDOT conducted a total of 12 tests on cable guardrail end terminals between 1990 and 1994 [25]. Though the cable guardrail originally developed by NYSDOT was capable of redirecting or capturing large sedans, mid-sized cars, and small cars, no crashworthy terminal meeting safety performance evaluation criteria presented in NCHRP Report 230 had been tested.

The original terminal design consisted of a cable anchor bracket with three slots for threaded anchor rods. The anchor bracket was modified by chamfering the slots at 45 degree angles, and the anchor rods were swaged onto the cable ends. The rods were 1-in. (25-mm) diameter and were double-nutted. Three $^{13}/_{16}$-in. inner diameter x 2 $^{7}/_{8}$-in. outer diameter by 0.165-in. thick (21-mm x 73-mm by 4.19-mm) washers were placed between the nuts and the anchor bracket to facilitate the threaded rod release from the bracket. The terminal was flared behind the tangent length of guardrail.

Test no. 96 consisted of a reverse-direction impact with a small car weighing 1,800-lb (816-kg) and impacting the guardrail 34 ft (10.4 m) upstream of the terminal. The vehicle impacted the system at 58.6 mph (94.3 km/h) and 14 degrees relative to the tangent section. The vehicle engaged the cables prior to impact with the terminal, but the proximity of the test vehicle to the anchor at the time of the threaded rod release caused the vehicle to trip and roll over several times.

The system was modified by placing a heavy washer with a 45 degree notch against the bracket, the steel keeper rod was replaced with a brass keeper rod, and a Teflon washer was placed next to the heavy washer. An additional post was also added in the terminal section to facilitate threaded rod release. Test no. 97 consisted of an 1,800-lb (816-kg) small car impacting the guardrail system 33 ft (10 m) upstream of the terminal. The vehicle impacted the system at 57.1 mph (91.9 km/h) and 13 degrees relative to the tangent section. The vehicle began to redirect, but contacted the terminal section of the guardrail. Upon impact with the terminal, the vehicle snagged and yawed away from the barrier system, subsequently rolling over.

To investigate alternative methods for cable anchor release, the cable anchor bracket and tensioned rod assembly was component tested by placing a ram on the front of a bucket-loader and laterally loading the short cable assembly until the anchor released. Three designs were tested and consisted of: (1) a solid rod placed under the anchor rods to act as a fulcrum; (2) anchor rod slots increased to 90 degrees; and (3) variations of steel and Teflon washers. The component tests were largely unsuccessful in generating a release of the cable anchor rods from the terminal. Researchers noted that the cable transmits axial loads, but is weak in bending. The large axial loads in turn generate frictional resistance to motion.

The system was modified to include an end post near the terminal to create a 45-degree turndown into the anchor bracket. The swaged cable anchor rods were replaced with solid steel rods extending from the turnbuckles on the router post into the anchor bracket, and the bracket was modified to provide a better bearing surface against the anchor rods. During test no. 98, the test vehicle impacted the barrier 39.4 ft (12.0 m) upstream of the anchor at 55.8 mph (89.8 km/h) and 11 degrees. The vehicle penetrated through the cables near the terminal and came to a controlled stop. Therefore, test no. 98 was determined to be acceptable.

Test no. 99 was conducted on the same system and consisted of a 4,780-lb (2,168-kg) sedan impacting the guardrail 76 ft (23.2 m) downstream of the upstream anchor at 57.4 mph (92.4 km/h) and 24 degrees. The test vehicle became entangled in the barrier system as all three cables slid over the hood and roof. The cables captured the vehicle and crushed the roof into the occupant compartment. The occupant risk criteria were satisfied in this test, but the intrusion into the occupant compartment was unacceptable. Thus, the system performance was unsatisfactory.

The propensity for underride beneath the cables was believed to be the result of a 30-in. (762-mm) top cable mounting height. To reduce the risk of underride, the cables were lowered 3 in. (76 mm) to a top mounting height of 27 in. (686 mm). In addition, to prevent the bolted cable hanger bracket from being dislodged and thrown from the system, the bracket was welded onto the router post.

Test no. 100 was conducted as a retest of test no. 99 at a test speed and angle of 57.7 mph (92.9 km/h) and 23 degrees, respectively. The vehicle was smoothly redirected.

Test no. 101 consisted of a small car weighing 1,800 lb (816 kg), which impacted the anchor bracket of the cable barrier at the quarter point of the vehicle bumper. Test speed and angle were 58.1 mph (93.5 km/h) and 2 degrees relative to the tangent, respectively. The vehicle rode up the anchor rods, vaulted over the system, impacted four posts, and rolled over.

The 45-degree turndown post was modified by incorporating a slip base in the design. The modified system was retested in test no. 102 at a test speed and angle of 72.4 mph (116.5

km/h) and 0 degrees relative to the tangent, respectively. It was intended that the vehicle would hit the cable barrier system at 1 $^{1}/_{4}$-ft (0.38 m) from the vehicle centerline. However, it impacted nearly head-on with the anchor at the centerline location. The vehicle rode up and vaulted off of the anchor rods and rolled several times.

The system performance was evaluated after test no. 102. It was observed that the anchor rods caused the vehicle to ride up and strike the second post at a higher elevation than desired. In addition, the anchor was very close to the tangent line posts, which acted to trip the impacting vehicles.

Test no. 103 was conducted on the modified system as a retest of test no. 102. The spacing between the routing post and the second post was increased to 16 ft (4.9 m) while retaining the flare. Swaged anchor rods were used instead of the solid rods extending from the turnbuckles. The vehicle impacted the system at 68.0 mph (109.4 km/h) and 5 degrees and end-on with the barrier at a 1.25-ft (0.38-m) offset. The end post released and the vehicle overrode the terminal.

Test no. 104 consisted of a 1,800-lb (816-kg) small car impacting the cable barrier 43.5 ft downstream of the upstream anchor. Test speed and angle were 61.3 mph (98.7 km/h) and 15 degrees relative to the tangent section, respectively. The vehicle was smoothly redirected and exited the barrier system at an angle of 5 degrees.

Test no. 105 consisted of an 1,800-lb (816-kg) small car impacting midway between the length-of-need (LON) and the terminal to evaluate whether or not the barrier would contain and redirect or capture the vehicle. The vehicle impacted the barrier system with a test speed and angle of 54.8 mph (88 km/h) and 10 degrees relative to the tangent section, respectively. The vehicle was smoothly redirected and exited the barrier, but made secondary contact 129.5 ft

(39.5 m) downstream of impact. The second impact resulted in vehicle snag and spin-out, but the accelerations and yaw rate were not severe. Thus, the test was determined to be acceptable.

Test no. 106 was similar to test no. 105, except that a sedan was used in lieu of a small car according to NCHRP Report 230 Test Designation No. 42. A 4,500-lb (2,041-kg) sedan impacted the barrier 38 ft (11.6 m) downstream of the upstream terminal at 25 degrees. The anchor rods released from the terminal and the sedan penetrated through the cables. Because this test was intended to evaluate the structural adequacy of the barrier when subjected to impact of a heavy 4,500-lb (2,041-kg) sedan, the test was determined to be unacceptable.

Test no. 107 consisted of a retest of test no. 106 with improved anchor rod connection to the end anchor. The 4,850-lb (2,200-kg) sedan impacted the barrier 38 ft (11.6 m) from the upstream terminal at a test speed and angle of 56.6 mph (91.1 km/h) and 25 degrees, respectively. The vehicle was contained and redirected, and the barrier system was determined to successfully meet the criteria provided in NCHRP Report 230.

3.4 Southwest Research Institute, 1980-1989

The Southwest Research Institute (SwRI) conducted a series of tests prior to 1987 on barriers listed in the AASHTO design guide [27, 28]. Three tests were conducted on the G1 guardrail system with end anchors designed by NYSDOT [25]. Due to recommendations from NYSDOT, the top cable height was lowered to 27 in. (686 mm) for all three tests. Design details for the three tests are shown in Figures 30 and 31.

The first test on the cable guardrail system was conducted according to the service level 2 performance criteria presented in NCHRP Report 230 [4]. Test no. GR-5 was conducted on the G1 cable guardrail system, with a 1976 Honda Civic, weighing 1,973 lb (895 kg), impacting at 60.5 mph (97.4 km/h) and 15.8 degrees, respectively. The test vehicle was smoothly redirected

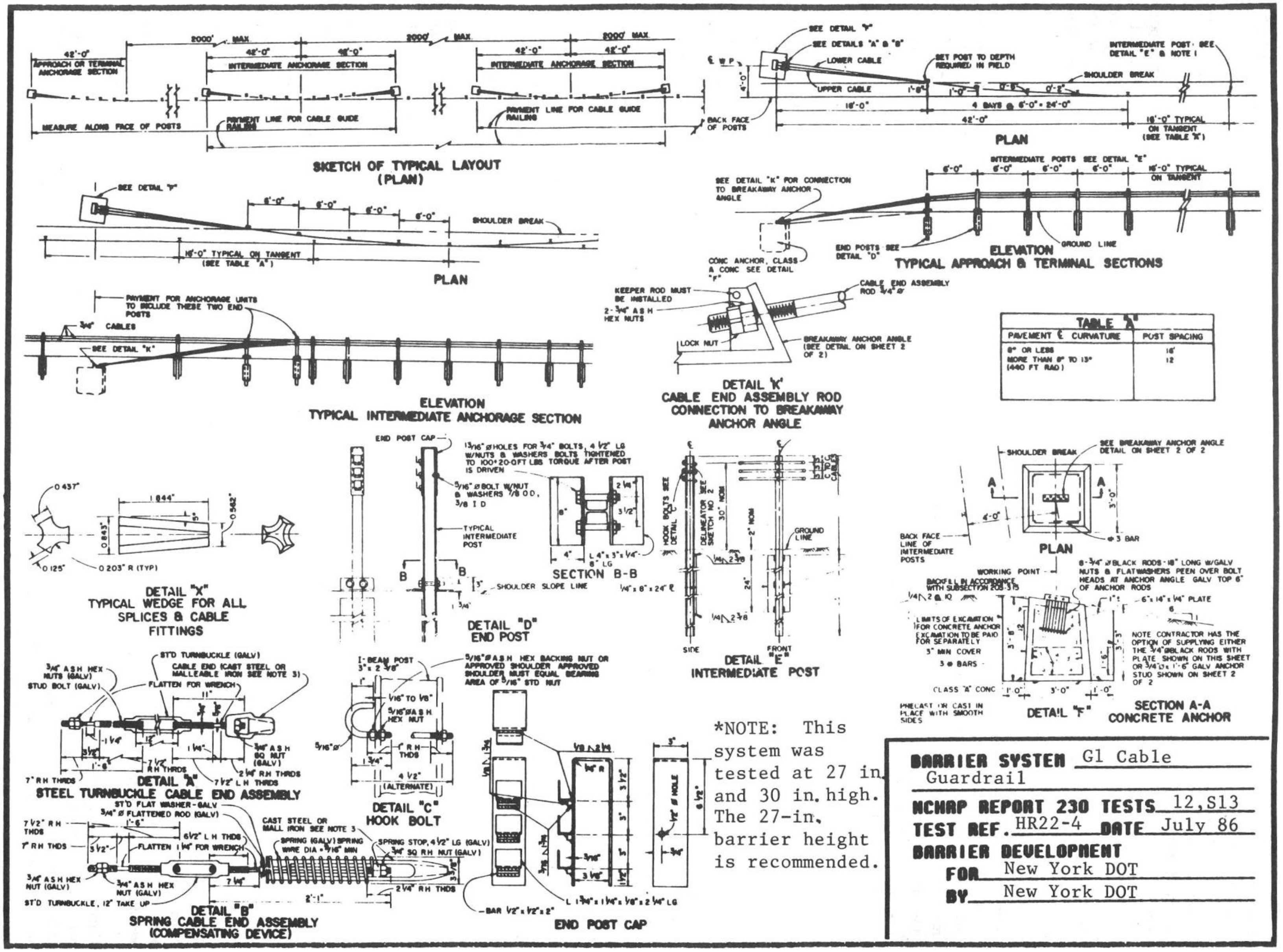


Figure 30. G1 Cable Barrier System Design Details, 1987 [27]

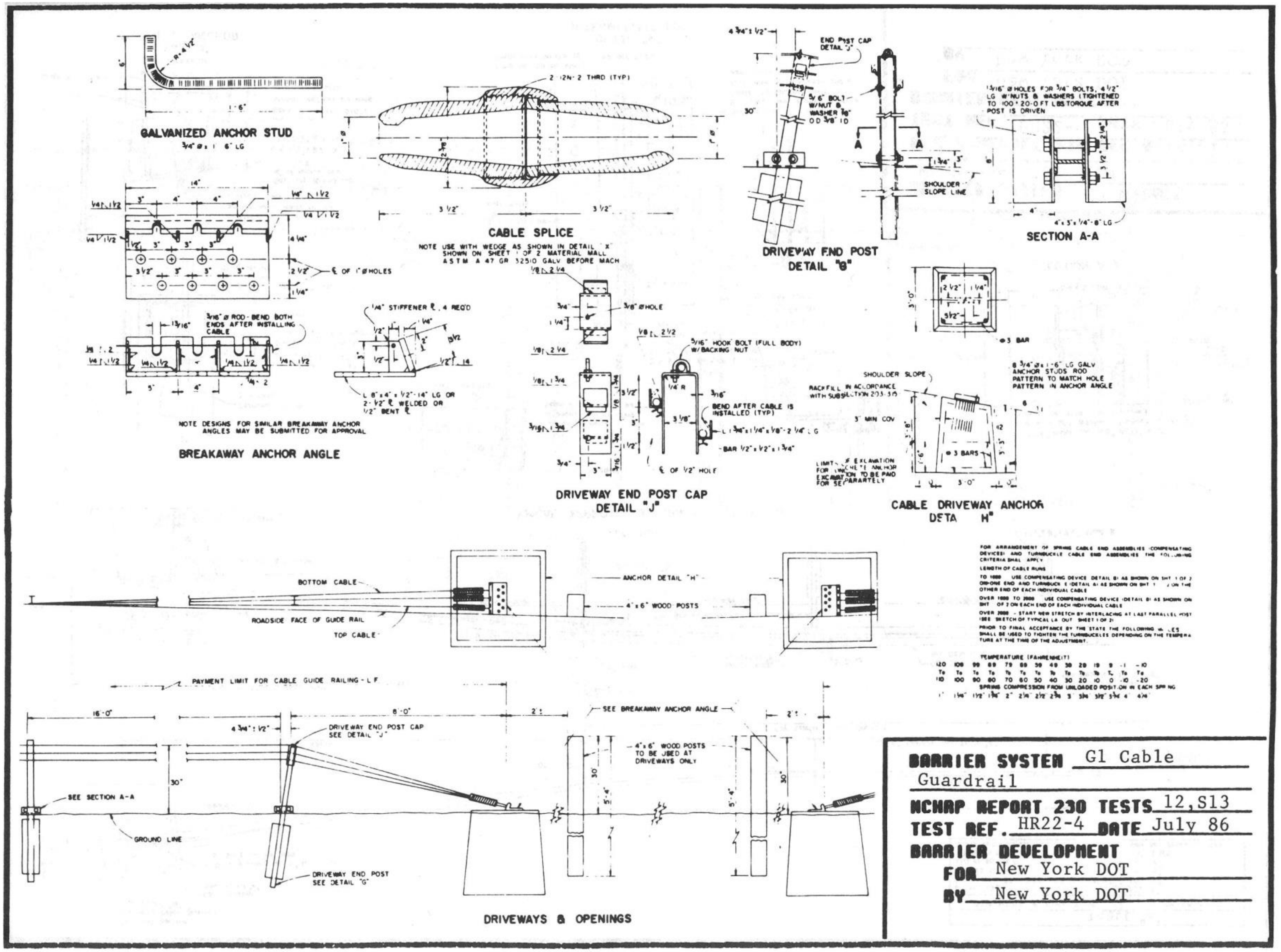


Figure 31. G1 Cable Barrier Design Details, 1987 [27]

and exited the system at 43.8 mph (70.5 km/h) and 1.7 degrees. After exiting the barrier, the vehicle yawed toward the system and made secondary contact with the end anchorage. The front tires snagged on the posts and the vehicle subsequently rolled over. The test was considered a pass, though the secondary impact with the anchorage did result in rollover. This was believed to be more closely related to the anchor design than the performance of the system.

The second test, test no. GR-16, consisted of a 1980 Honda small car, weighing 1,995 lb (905 kg), impacting the cable guardrail system with a test speed and angle of 59.2 mph (95.3 km/h) and 19.5 degrees, respectively. The vehicle was captured by the barrier system and came to a controlled stop. The vehicle remained engaged with the cables throughout the impact event. Though the change in velocity for the impact was considered unacceptable by the criteria presented in NCHRP Report 230, the vehicle was decelerated throughout the impact event and the maximum deceleration in the longitudinal and lateral directions was 4.5 g's and 5.6 g's, respectively. Since the vehicle momentum criterion was not intended for use with cable guardrail systems, the test was judged to be a pass.

The final test of the G1 cable guardrail system, test GR-17, was conducted with a 1979 Dodge van weighing 4,160 lb (1,887 kg). The vehicle impacted the system at 58.1 mph (93.5 km/h) and 24.2 degrees, and was smoothly captured with no snagging. During impact, the test vehicle overran most of the guardrail posts and came to a stop in contact with the system, at 80 ft (24.4 m) downstream of impact. Damage to the cable guardrail system was extensive. However, the vehicle remained stable throughout the impact event, and the impact performance of the G1 guardrail system was determined to be acceptable.

3.4.1 Cable to W-Beam Transition

SwRI then conducted a series of tests on cable barrier transitions to W-beam barriers in 1987-1989 [29-32]. The cable system was a modified G1 guardrail system, consisting of S3x5.7 (S76x8.5) steel posts measuring 60 in. (1,524 mm) long. The $^{3}/_{4}$-in. (19-mm) diameter cables were mounted at 27, 24, and 21 in. (686, 610, and 533 mm) from the ground, and were supported by $^{5}/_{16}$-in. (8-mm) diameter J-bolts. The W-beam end terminal consisted of a BCT terminal on a parabolic flare. Cable post spacing was 6 ft (1.8 m) near the approach from the anchor, 16 ft (4.9 m) in the standard configuration, and 4 ft (1.2 m) in the transition region to the W-beam.

Test no. MSD-2 consisted of a 1978 Plymouth sedan impacting the cable guardrail to W-beam transition with a test speed and angle of 58.9 mph (94.8 km/h) and 27.3 degrees, respectively. The right-side of the vehicle was aligned with the centerline of the end post in the BCT terminal. The vehicle was redirected, but system performance was determined to be unsatisfactory because occupant risk criteria were not satisfied.

The unsatisfactory performance of the transition was believed to be related to the post strength, despite the fact that the S3x5.7 (S76x8.5) posts had low bending strength. An alternative post type consisting of 4 lb/ft (6 kg/m) flanged-channel sections was proposed as a replacement. The cables were attached to the channel posts by $^{5}/_{16}$-in. (8-mm) diameter cable hooks bolted directly into the holes in the back of the post.

To evaluate the use of flanged-channel posts in cable guardrail systems, researchers at SwRI conducted a separate length-of-need test on the flanged-channel post system. Cable heights for the flanged-channel LON test were 30, 27, and 24 in. (762, 686, and 610 mm). Test MSD-3 consisted of a 1981 Volkswagen Rabbit weighing 1,975 lb (896 kg) and impacting the barrier at

59.8 mph (96.2 km/h) and 18.6 degrees, respectively. The vehicle was redirected and remained stable throughout the impact.

Flanged-channel posts were substituted for the standard S3x5.7 (S76x8.5) posts, and the modified system was evaluated in test no. MSD-2A with a 1978 Plymouth sedan. The 4,360-lb (1,978-kg) vehicle impacted the cable guardrail system upstream of the transition at 58.3 mph (93.8 km/h) and 24.4 degrees. The test vehicle was smoothly redirected.

The final crash test on the cable-to-W-beam guardrail transition design with a BCT flared end terminal consisted of a 1978 Dodge sedan weighing 4,740 lb (2,150 kg) and impacting at 58.6 mph (94.3 km/h) and 25 degrees. The vehicle was captured and brought to a controlled stop.

3.4.2 Cable Guardrail System with Franklin Posts

In 1989, following the success of the cable transition to W-beam guardrail with a flared BCT termination, researchers investigated the crashworthiness of cable guardrail located on a 6:1 slope [33-35]. In addition, the use of 4 lb/ft (6.0 kg/m) Franklin flanged-channel posts instead of the standard S3x5.7 (S76x8.5) shape was evaluated. System details are shown in Figures 32 through 36. The posts were 60 in. (1,524 mm) long, and embedded 30 in. (711 mm) in soil. Each post was welded to a 12-in. x 6-in. by 1/8-in. thick (305-mm x 152-mm x 3.1-mm) trapezoidal soil plate, with 3 in. (76 mm) cut from the two top corners to make the trapezoidal shape. The cables were secured to the posts with $^{5}/_{16}$-in. (8-mm) diameter hook bolts. The entire system was installed 6 ft (1.8 m) from the break point of a 6:1 slope. Cable mounting heights were 27, 24, and 21 in. (686, 610, and 533 mm).

Test no. SD-1 consisted of a 4,615-lb (2,093-kg) Oldsmobile sedan impacting the cable barrier system at 60 mph (97 km/h) and 25.7 degrees. The vehicle overrode the cables and traversed down into the center of the ditch.

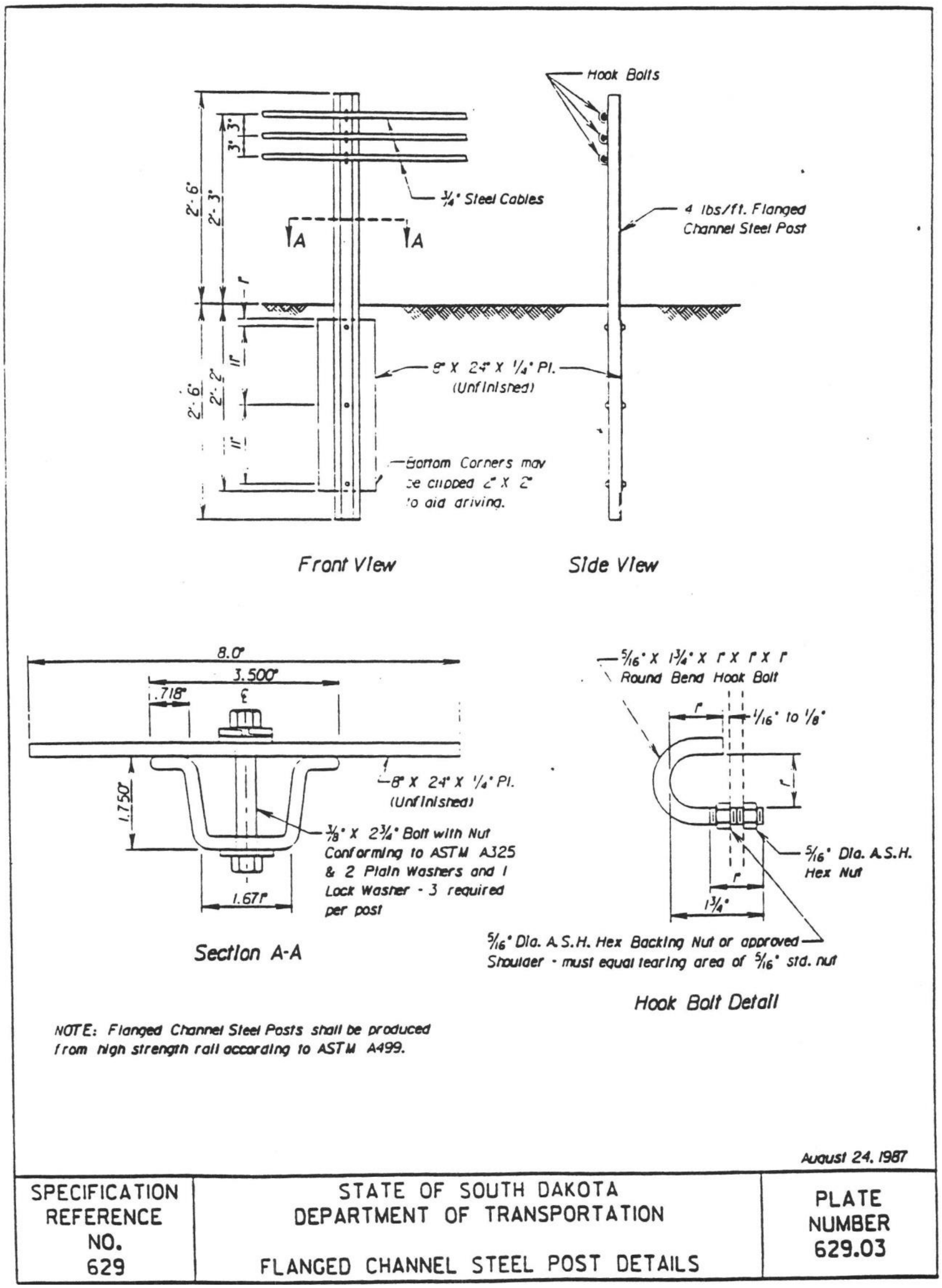


Figure 32. System Details, SwRI Test Nos. SD-1 through SD-3

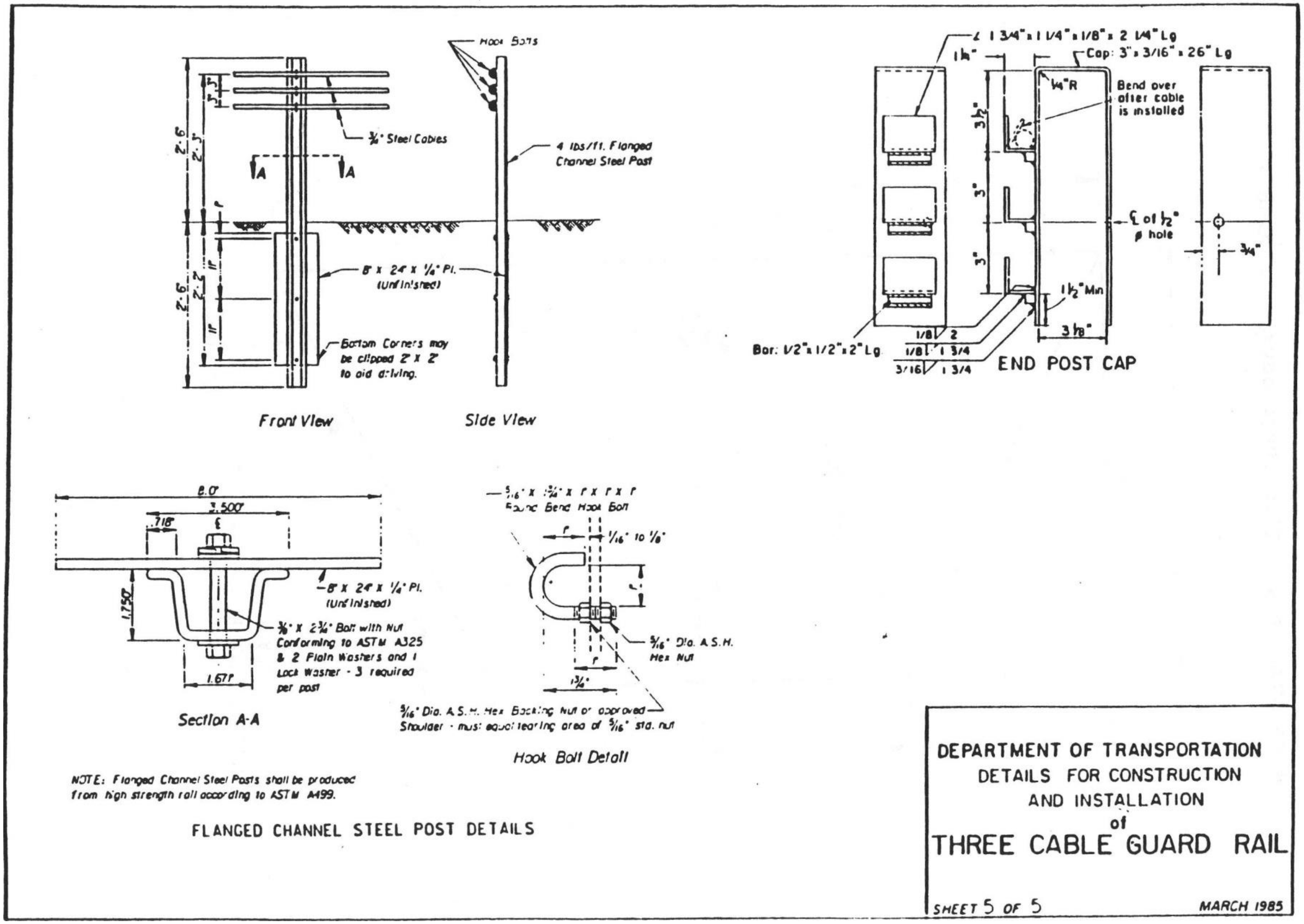


Figure 33. System Details, SwRI Test Nos. SD-1 through SD-3

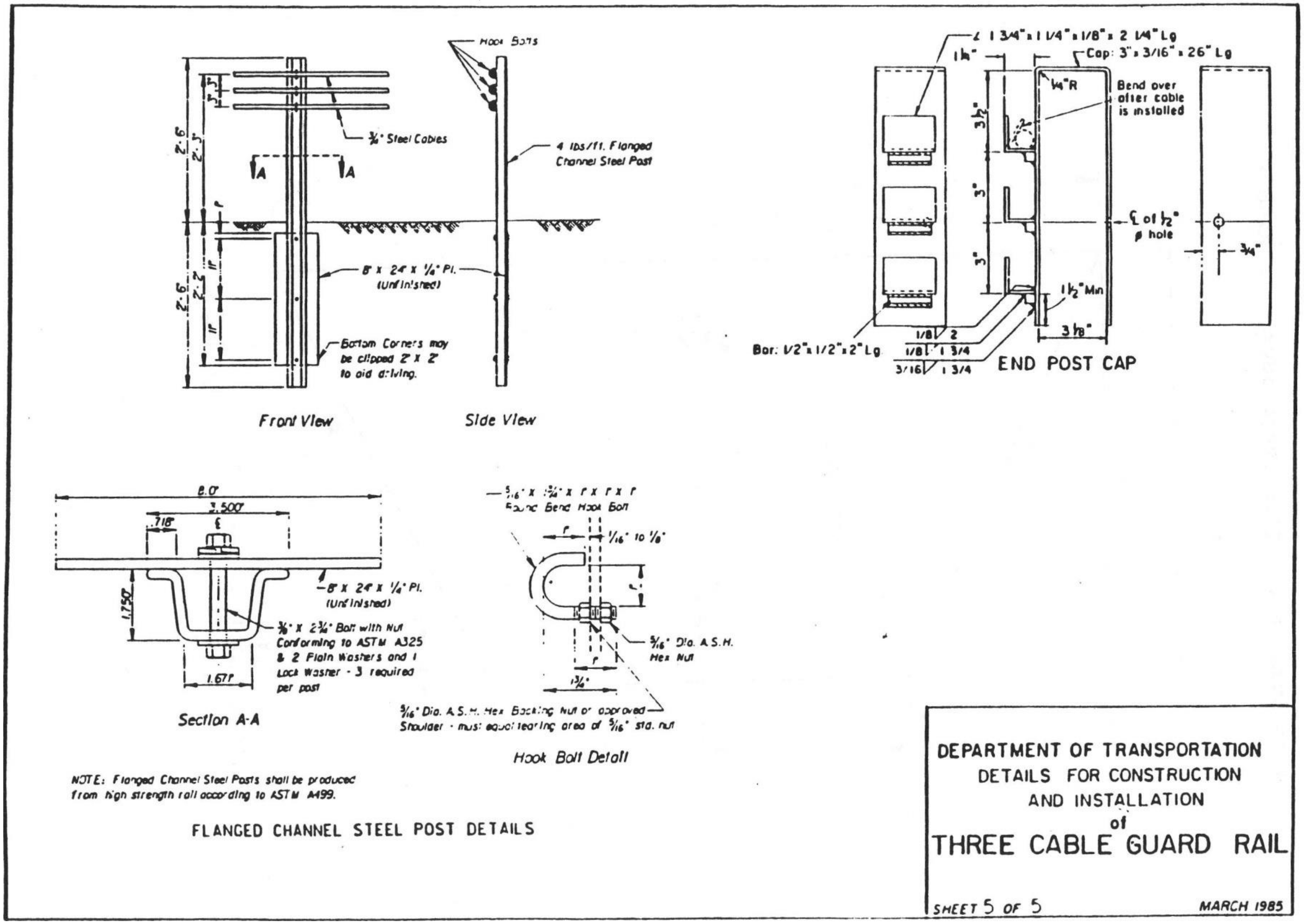


Figure 34. System Details, SwRI Test Nos. SD-1 through SD-3

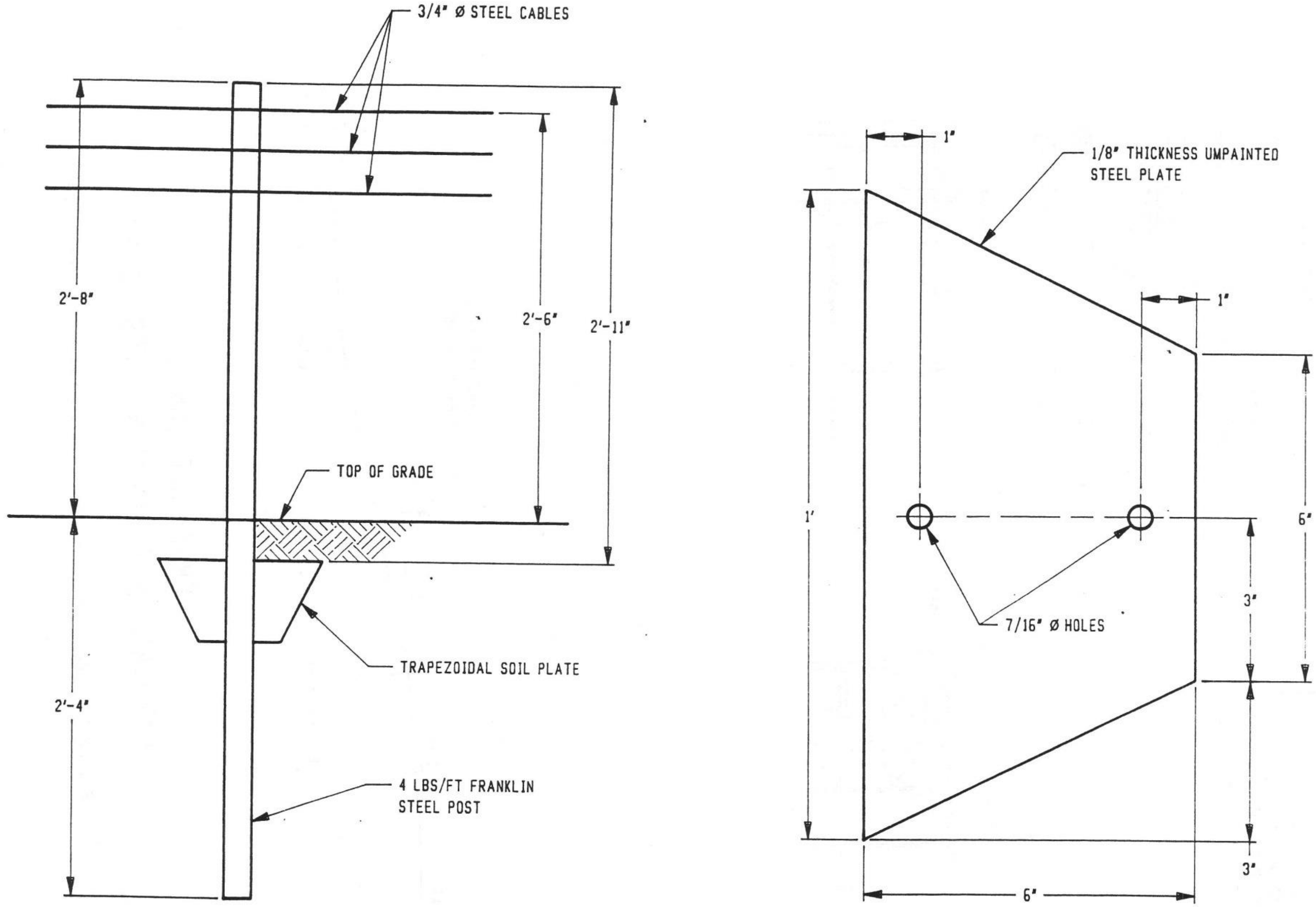


Figure 35. System Details, SwRI Test Nos. SD-1 through SD-3

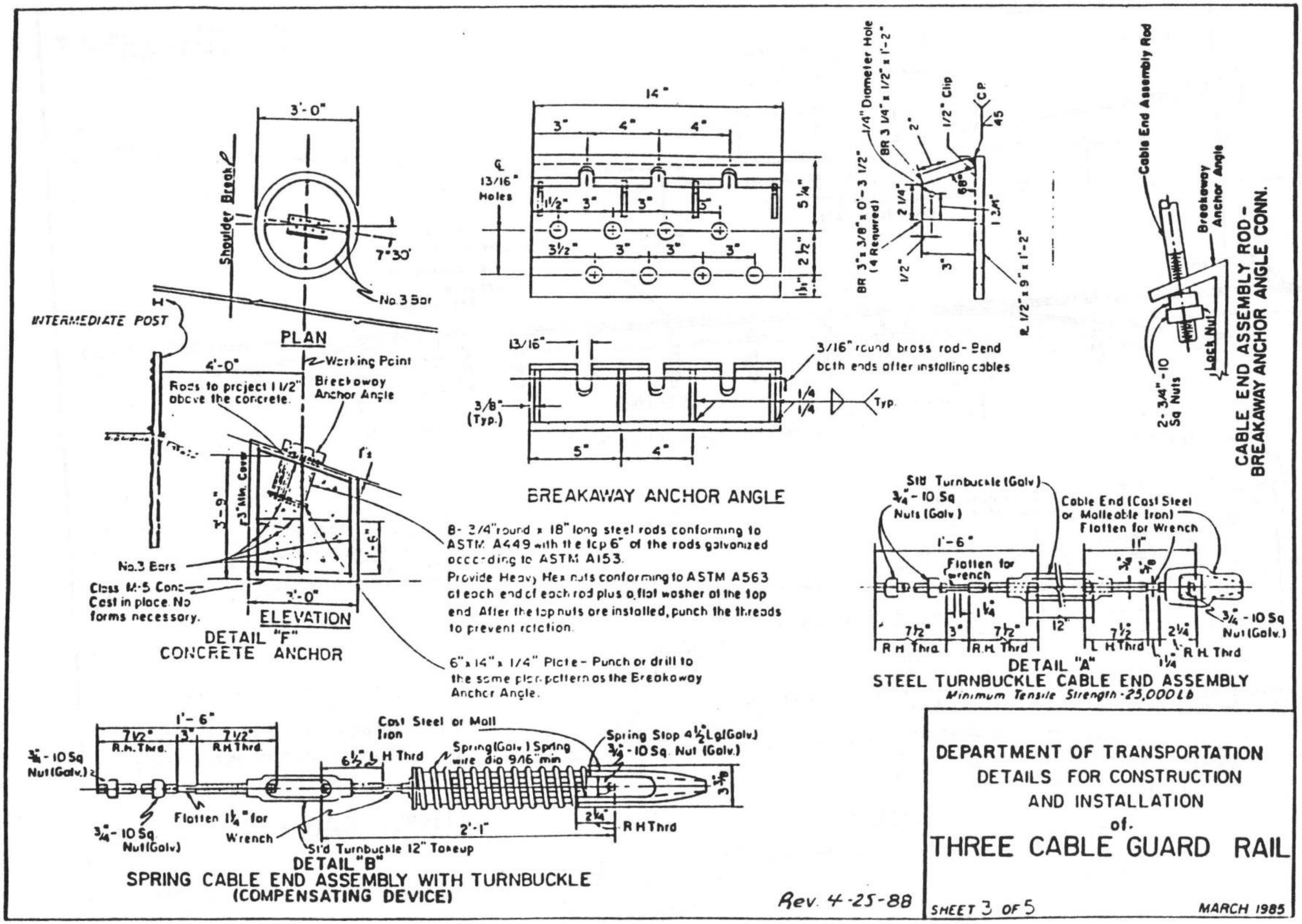


Figure 36. System Details, SwRI Test Nsos. SD-1 through SD-3

The system was modified by shifting the cable guardrail system 2 ft (0.6 m) further back on the slope. Test no. SD-2 consisted of a 4,650-lb (2,109-kg) sedan impacting the guardrail system at a test speed and angle of 60 mph (97 km/h) and 25 degrees, respectively. The vehicle was captured and came to rest engaged with the cables.

The final test on the SwRI design consisted of a 1984 Volkswagen Rabbit impacting the system at 61.4 mph (98.8 km/h) and 21.2 degrees. The small car was captured and brought to a controlled stop. Therefore, based on the results of the final two tests, the cable guardrail system was determined to be acceptable according to the criteria presented in NCHRP Report 230.

3.5 Bridon Ropes, 1987-1993

Bridon Ropes conducted many tests on a high-tension slotted-post cable median barrier [36, 1]. The tests were conducted at the United Kingdom Transportation Road Research Laboratory, which later became the Motor Industry Research Association (MIRA). Previous designs for cable guardrail required that posts be placed in a hardened running surface (i.e., concrete tarmac) to ensure adequate post strength and smooth redirection terrain. This resulted in a high installation cost and fewer installations of the cable barrier system.

Bridon Ropes conducted a seven-test series in 1988 and 1989 and six tests in 1991 through 1995 to evaluate an alternative to the single-cable height design previously crash-tested by the Road Research Laboratory researchers in the 1960s [17-18]. The design was required to have a maximum dynamic deflection less than 6.6 ft (2.0 m) and was to be crash tested at 70 mph (113 km/h) and 20 degrees. System details for the four-cable guardrail system are shown in Figure 37.

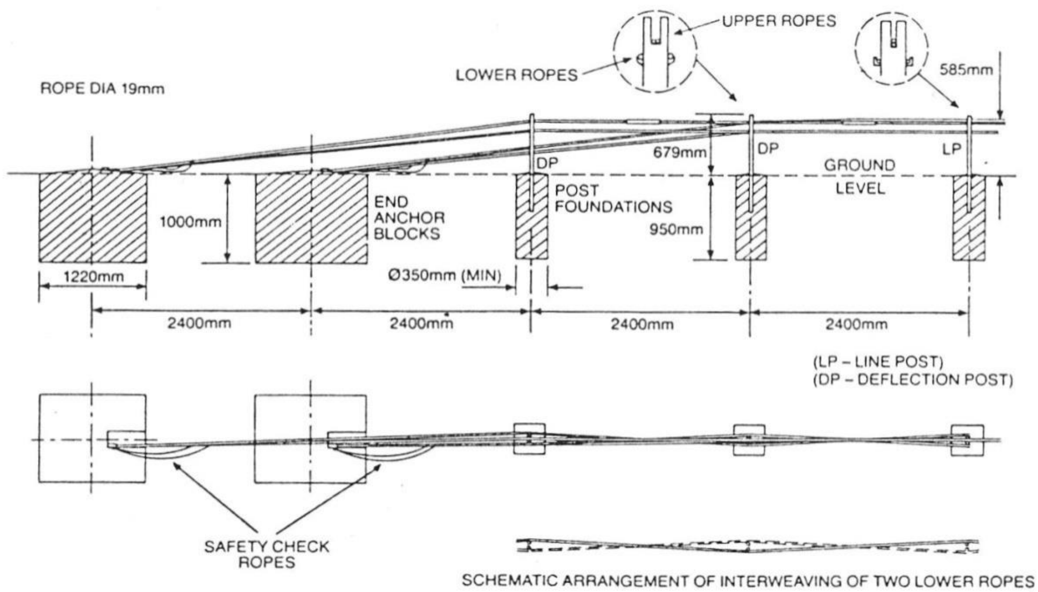


Figure 37. Four-Rope System Details, Bridon Ropes, 1988-1989 [36]

The first series of tests was conducted with two pairs of ropes placed in slots in the webs of the posts with the lower set of ropes set just above the bumper height of a Vanguard small car. To accommodate the lower ropes, the vertical slot in the post was deepened and spacers separated the lower and upper ropes. Rope tensions were adjusted to 3.0 kips (13 kN). When impacted, the flanges of the posts fractured and the cables were run over by the test vehicle. The vehicle was contained but the test was considered to be unacceptable.

In the second test, the rope tensions were increased from 3.0 to 6.0 kips (13 to 27 kN). Cable heights were maintained at 25 in. (635 mm) for the top two ropes and 15 $^{3}/_{4}$ in. (400 mm) for the bottom two ropes. These ropes were also spaced inside of the slot cut in the web of the post. The second test was run at the standard impact conditions of approximately 70 mph (113 km/h) and 20 degrees with a 3,306-lb (1,500-kg) test vehicle. Though the pretension in the cables was increased for the second test, the test results were contradictory to what was expected. The dynamic deflection increased from 10.2 ft to 16.1 ft (3.1 m to 4.9 m).

The system was modified prior to the third test by shifting the lower ropes from deep within the post slot to the outside of the post. The cables were supported by welded brackets. The slot in the web was shortened, and the two upper ropes were placed in the upper slot. The upper and lower pairs of ropes had tensions of 7.0 and 3.0 kips (31 and 13 kN), respectively. The lower ropes were woven between every other post. Cable heights in the third test were 25 in. (635 mm) for the top two ropes and 15 $^{3}/_{4}$ in. (400 mm) for the bottom two ropes. The vehicle impacted the modified system and was successfully redirected, but the maximum deflection was 7.9 ft (2.4 m).

The system was modified again prior to the fourth test by increasing post thickness from 5-gauge (5 mm) to 0.24 in. (6 mm). The cable pretension in the test was 7.0 kip (31 kN) for the upper cables and 6,000 lb (27 kN) for the lower cables. The cable mounting heights were 25.0 in. (635 mm) for the upper cables and 19.1 in. (485 mm) for the lower cables. During the fourth test, the vehicle was redirected and the maximum deflection was 5.9 ft (1.8 m).

Prior to the fifth test, the upper ropes were raised 2.0 in. (50 mm), for upper and lower cable mounting heights of 27.0 and 19.1 in. (685 and 485 mm), respectively. Cable tensions were 7.0 kips (31 kN) for the upper cables and 6.0 kips (27 kN) for the lower cables. The fifth test consisted of a small car impacting the barrier system. The vehicle redirected but made secondary contact with the system, which caused the vehicle to rollover.

The sixth test consisted of a retest of the fifth test, after lowering the upper cables 2.0 in. (50 mm) to 25 in. (685 mm). Cable pretension was reduced to 5.0 kip (22 kN) for each cable. The system was impacted by a vehicle weighing approximately 1,640 lb (750 kg) with a speed and angle of nominally 70 mph (113 km/h) and 20 degrees, respectively, and was redirected.

Prior to the seventh test, the system was modified such that the lower ropes were woven between every post to increase cable interaction with the posts. Upper cable heights were reduced by 2.0 in. (50 mm) such that the upper and lower cable mounting heights were 23.0 and 19.1 in. (585 and 485 mm), respectively. The static tension in the cables was 5.0 kips (22 kN). A sedan impacted the system and was redirected. It was determined that the configuration in the seventh test was optimal for impact performance.

Based on the results of the previous tests, Bridon Ropes designed a guardrail system which consisted of four $^{3}/_{4}$-in. (19-mm) diameter cables on 42.5-in. long by 0.24-in. thick (1,080-mm by 6-mm) Z-section posts with embedment depths of 15.75 in. (400 mm) [1]. Two ropes were placed in a shallow slot in the top of the posts, and two ropes were cross-woven between the posts and supported on angle brackets. Rope mounting heights were 23.0 and 19.1 in. (585 and 490 mm) for the upper and lower pairs of ropes, respectively. Cable pretension was 5.0 kips (22.2 kN) per rope. All tests were conducted in accordance with the English Standard BS6579 and DTp Departmental Standard TD32/89.

Two tests were conducted on a system with a 7.75 ft (2.4 m) post spacing [36]. The first consisted of a 3,308-lb (1,500-kg) saloon car impacting the barrier at 70.2 mph (113.0 km/h) and 19 degrees. The vehicle was smoothly redirected, exited the barrier at 7 degrees, and contacted the barrier a second time before coming to rest. The second test consisted of a 1,654-lb (750-kg) small car impacting at 72.0 mph (115.9 km/h) and 19 degrees. The vehicle was redirected at 61.5 mph (99.0 km/h) and 7 degrees.

Two additional tests were conducted according to the English standards on the Wire Rope Safety Fence (WRSF) with a post spacing of 3 ft – 3.4 in. (1.0 m). The first test consisted of a 3,306-lb (1,500 kg) small car impacting at 72.0 mph (115.8 km/h) and 19 degrees. The vehicle was successfully redirected with a maximum dynamic deflection of 3 ft – 8 in. (1.12 m). The second test on the 3 ft – 3.4 in. (1.0 m) post spacing consisted of a 1,653-lb (750 kg) small car impacting at 70.5 mph (113.4 km/h) and 19 degrees. The maximum dynamic deflection was 2 ft – 10 in. (0.84 m). Thus, the modified WRSF was determined to be successful according to English performance evaluation criteria.

4 NCHRP REPORT 350 TESTING, 1993-2006

The safety performance criteria recommended for evaluating roadside hardware was updated with the publication of NCHRP Report 350, *Recommended Procedures for the Safety Performance Evaluation of Roadside Features* [5]. This report updated the recommended vehicles for crash testing to include a 4,409-lb (2,000-kg) pickup. A baseline performance standard was recommended using Test Level 3 (TL-3) impact conditions. System and testing details for systems tested to NCHRP Report 350 are shown in Appendix E and Appendix F, respectively. Proprietary system and crash testing details for some systems accepted by FHWA according to NCHRP Report 350 criteria are shown in Appendix I and Appendix J, respectively.

4.1 Bridon Ropes, 1993-1999

Bridon Ropes conducted many tests between 1989 and 1995 [1, 37-50]. One of these tests was conducted according to NCHRP Report 350 for acceptance in the United States; the remainder of the referenced tests occurred as part of the development of the WRSF. Bridon Ropes sought to reduce installation costs in order to make the system more competitive with other guardrail systems as well as reduce deflections and risk of underride or override. The system that was evaluated according to the criteria in NCHRP Report 350 consisted of 0.24-in. thick by 42.5-in. long (6-mm by 1,080-mm) Z-section posts embedded to a depth of 15.7 in. (400 mm). The top two ropes were mounted in the slotted web of the post at a height of 26.6 in. (675 mm) and the lower ropes, supported by brackets, were mounted at a height of 22.8 in. (580 mm). On each end of the installation, 6.0-in. x 6.0-in. (152-mm x 152-mm) box beam sections were used to anchor the cables.

The system was crash tested in test no. L6016 with a 4,432-lb (2,010-kg) Ford F-250 impacting at 60.7 mph (97.7 km/h) and 26.2 degrees. The pickup was brought to a controlled stop within the system after traveling 232 ft (70.7 m) along the cables and damaging 26 posts. The maximum dynamic tension in the cables was measured to be 18.0 kips (80 kN).

Five additional tests were conducted in 1994 and 1995 by changing the spacing of the cables and the heights to investigate the effects on vehicle redirection and impact performance. System modifications for these tests are unknown. All tests were conducted at approximately 71.6 mph (115 km/h) and 20 degrees. Test results were satisfactory. In one test, the ropes were located at 26.4 in. (670 mm) for the upper pair and 3.6 in. (90 mm) for the lower pair. This test was also successful.

Further tests were conducted in 1999 and 2000 to evaluate a terminal for the four-rope cable barrier, renamed the WRSF. The cable guardrail system was terminated with a WRSF termination, developed by Bridon [48-50]. The system was similar to the final design tested originally in 1994 and 1995, using 0.24-in. (6-mm) thick Z-sections measuring 42.5 in. long (1,080 mm) and placed in sleeves cast in concrete. The top two ropes were located in the slotted web of the post, and the side ropes were supported on brackets.

The first test, test no. 01LB, consisted of a 3,243-lb (2,832-kg) Ford Granada impacting the barrier system at 70.2 mph (113.0 km/h) and 20 degrees. The vehicle was smoothly redirected and exited the system at 58.2 mph (93.7 km/h) and 10 degrees. The tension in the cables at the time of the test was 5,058 lb (22.5 kN).

Test no. 01MB consisted of a 3,197-lb (1,450-kg) Saab 900 impacting the cable guardrail system at 70.8 mph (113.9 km/h) and 20.1 degrees. The test vehicle was smoothly redirected and exited the system at 55.9 mph (90.0 km/h). Tension in the cables at the time of the test was 4,946 lb (22.0 kN).

4.2 Texas Transportation Institute, 1994-2008

4.2.1 Length-of-Need Tests

With the publication of NCHRP Report 350, many of the systems approved under NCHRP Report 230 were evaluated with the new 2000P vehicle. The G1 guardrail system, which was derived from the New York design developed in the 1970s and 1980s, was tested by TTI to NCHRP Report 350 impact conditions in 1994 [51].

The G1 guardrail system consisted of S3x5.7 (S76x8.5) steel posts measuring 63 in. (1,600 mm) long, embedded to a depth of 30 in. (764 mm). Three $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables were supported on the posts with $^{5}/_{16}$-in. (8-mm) diameter hook bolts. The cable mounting heights were 30, 27, and 24 in. (762, 686, and 610 mm) to the center of the cables. Posts were spaced 16 ft (4.9 m) on center. At the cable termination, the posts were spaced 8 ft (2.4 m) on center for 24 ft (7.3 m), and the anchor was located 18 ft (5.5 m) from the end post. The end post supported the cables with shelf angles attached to the post. System details are shown in Figures 38 and 39.

Test no. 471470-28 consisted of a 1989 Chevrolet C2500 weighing 4,570-lb (2,075-kg) and impacting the barrier at the midspan between post nos. 10 and 11 at 59.1 mph (95.1 km/h) and 26.7 degrees. The pickup was redirected and exited the system at 37.5 mph (60.3 km/h) and 2.0 degrees. Therefore, the G1 guardrail system was determined to satisfy the safety performance criteria found in NCHRP Report 350.

TTI conducted another crash test on a low-tension 3-cable guardrail design with field fittings designed to be upgraded to high tension [52]. The test installation consisted of S3x5.7. (S76x8.5) steel posts measuring 63 in. (1,600 mm) long and embedded to a depth of 30 in. (762 mm). Three cables were mounted using $^{5}/_{16}$ in. (8 mm) J-bolts attached to the flanges and

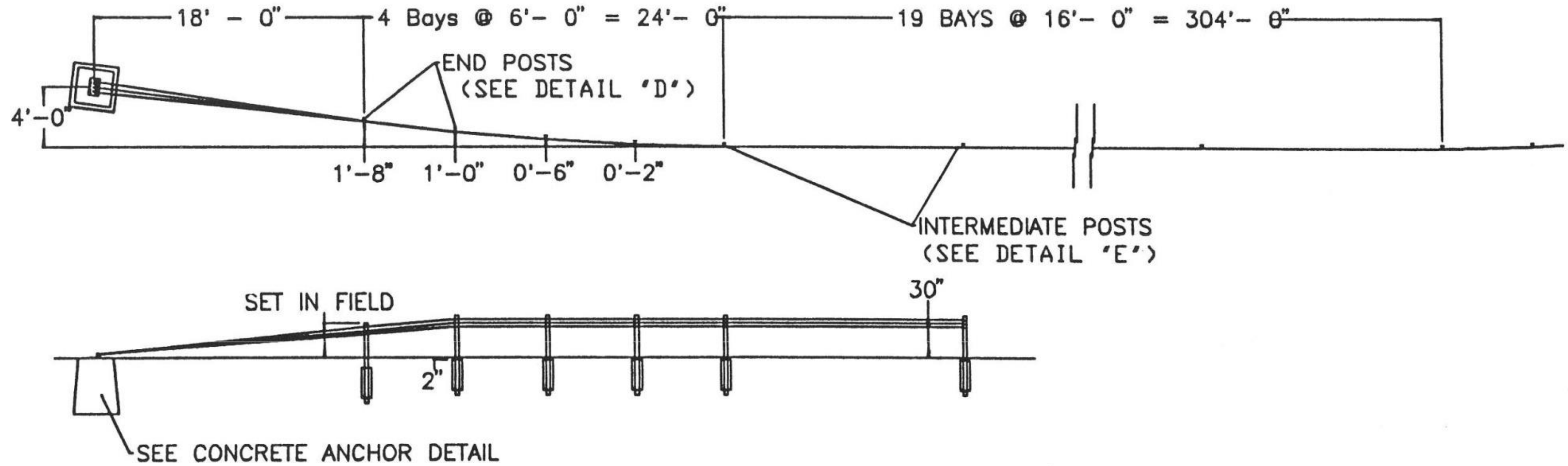


Figure 38. System Details, G1 Guardrail System, 1994 [51]

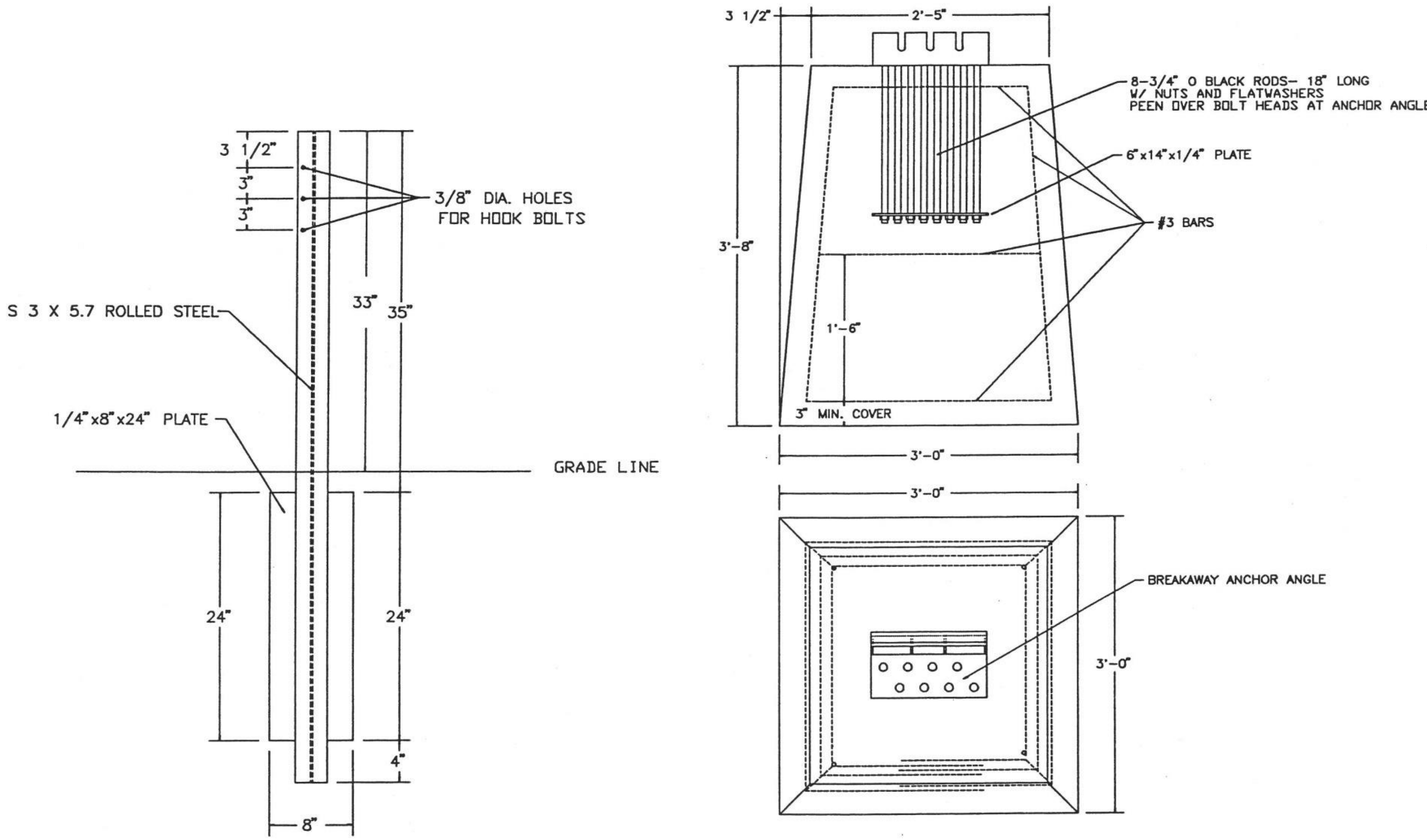


Figure 39. Line Post and Anchor Block Details, G1 Guardrail System, 1994 [51]

supporting the cables at mounting heights of 30, 25 $^{1}/_{2}$, and 21 in. (762, 648, and 533 mm). Cables were anchored with epoxy sockets, using eye sockets for the terminations and splices.

Test no. 405160-11-1 consisted of a 1999 Chevrolet C2500 impacting the system at post no. 13 with a test speed and angle of 62.3 mph (100.3 km/h) and 25.4 degrees, respectively. The test vehicle was redirected and exited the barrier system 460 ft (140.2 m) downstream of impact, after impacting an estimated 20 posts, based on post-testing photographs. Maximum dynamic deflection was 122 in. (3,100 mm).

4.2.2 Median Barrier Tests

In 1996, TTI tested a 3-strand cable median barrier system used by the Washington Department of Transportation [53-55]. System details are shown in Figures 40 through 43. The three-cable median barrier consisted of S3x5.7 (S76x8.5) steel posts, measuring 63 in. long (1,800 mm), with an embedment depth of 30 in. (762 mm). The posts supported three $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables on $^{5}/_{16}$-in. (8-mm) diameter hook bolts at mounting heights of 30 $^{1}/_{4}$ and 20 $^{3}/_{4}$ in. (770 mm and 530 mm) on one side of the post and 25 $^{1}/_{2}$ in. (650 mm) on the other. The terminal developed by NYSDOT was used with the cable guardrail system for the end anchorages.

Test no. 270687 WDT-2 consisted of a 1991 Ford Festiva, weighing 1,975 lb (896 kg), impacting the cable guardrail system at 62.0 mph (99.8 km/h) and 20.4 degrees. Impact location was at post no. 12 on the single-cable side of the system, and the tension in the cables prior to the test was 950 lb (4.2 kN). The small car was captured as it overrode the impact-side cable and became wedged between the cables. Though the wedging action of the cable barrier system was undesirable, occupant risk criteria were satisfied and no occupant compartment deformation

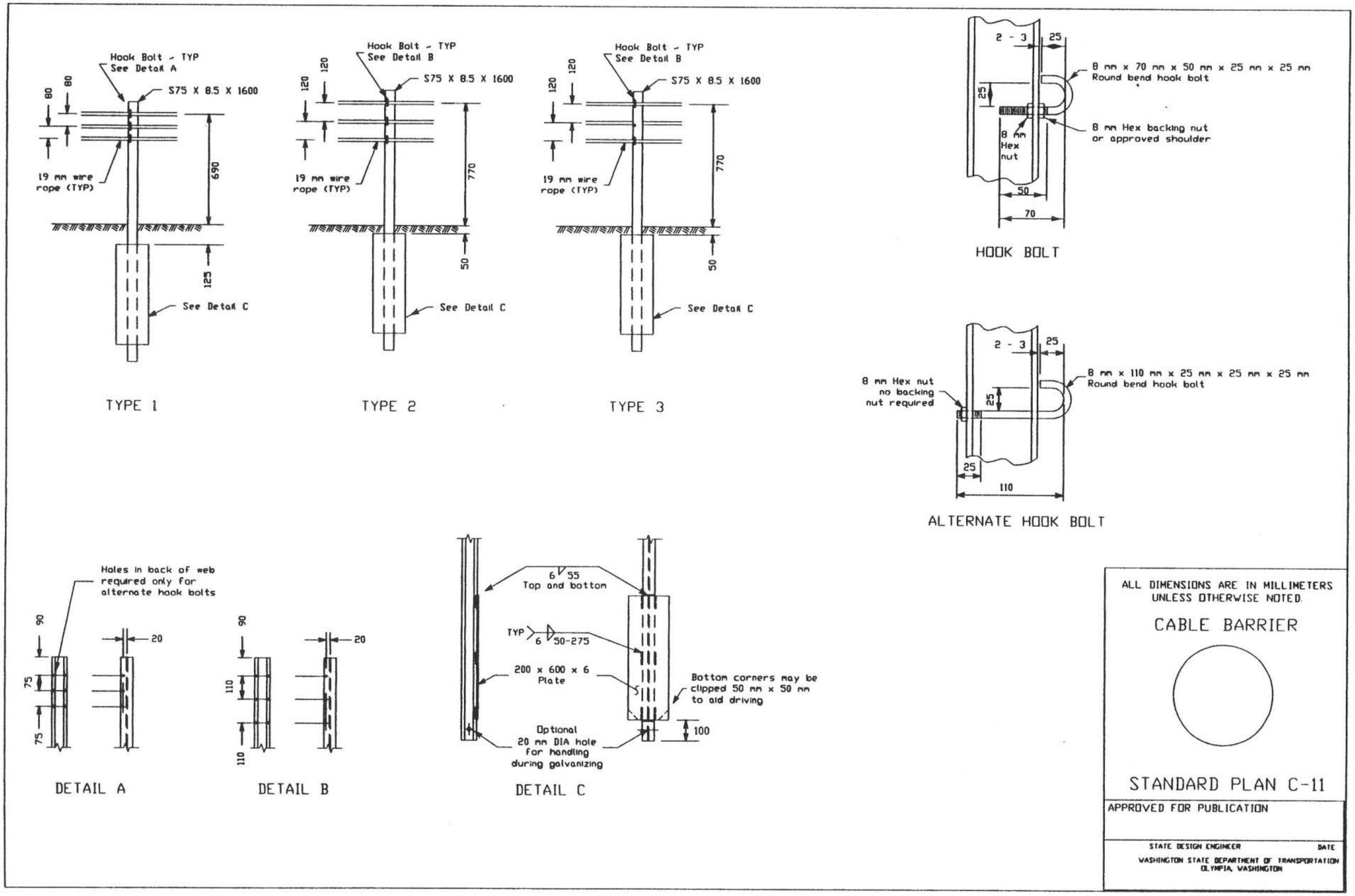


Figure 40. System Details, WSDOT Tested Design, 1996 [53-55]

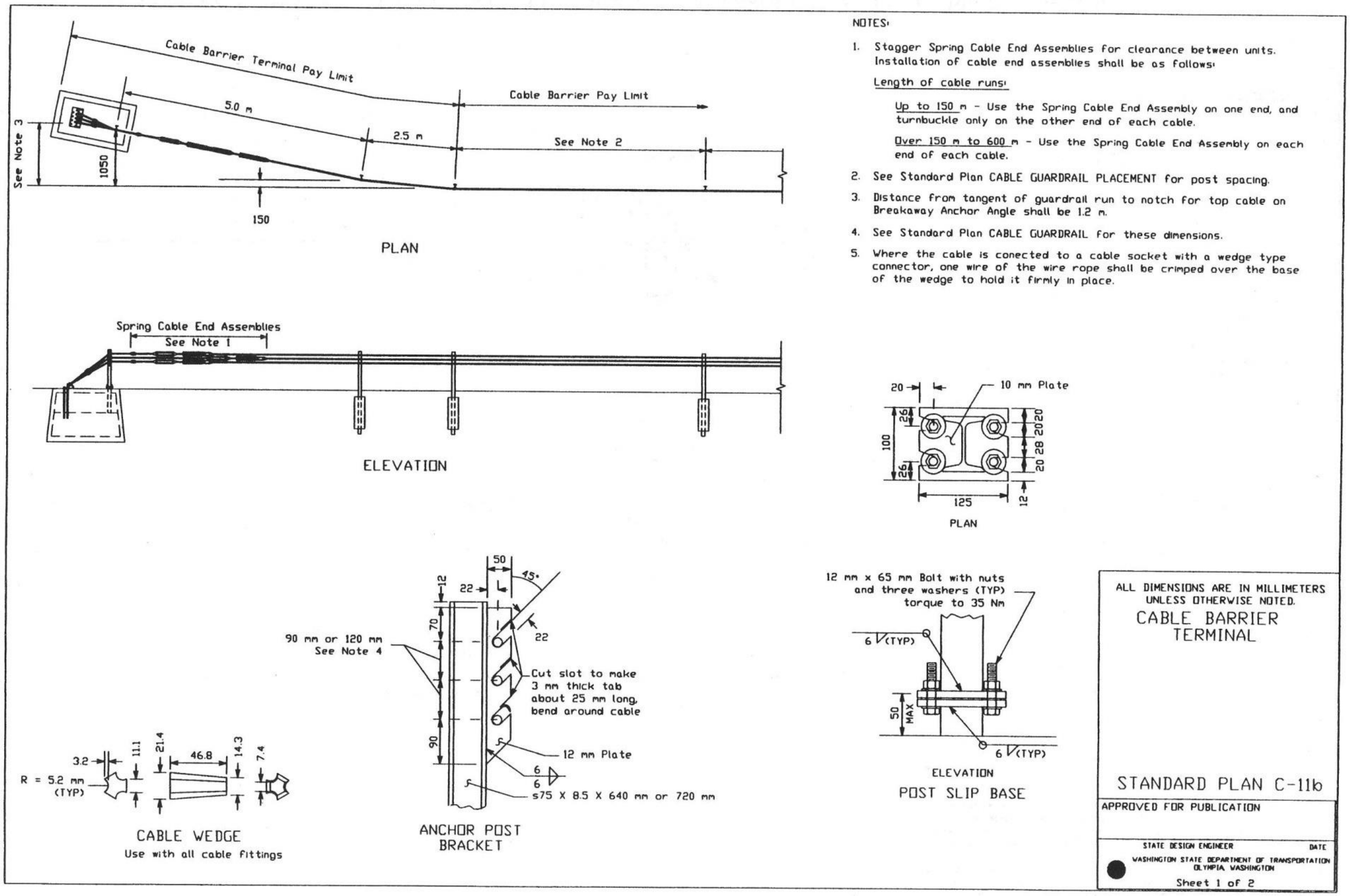


Figure 41. System Details, WSDOT Tested Design, 1996 [53-55]

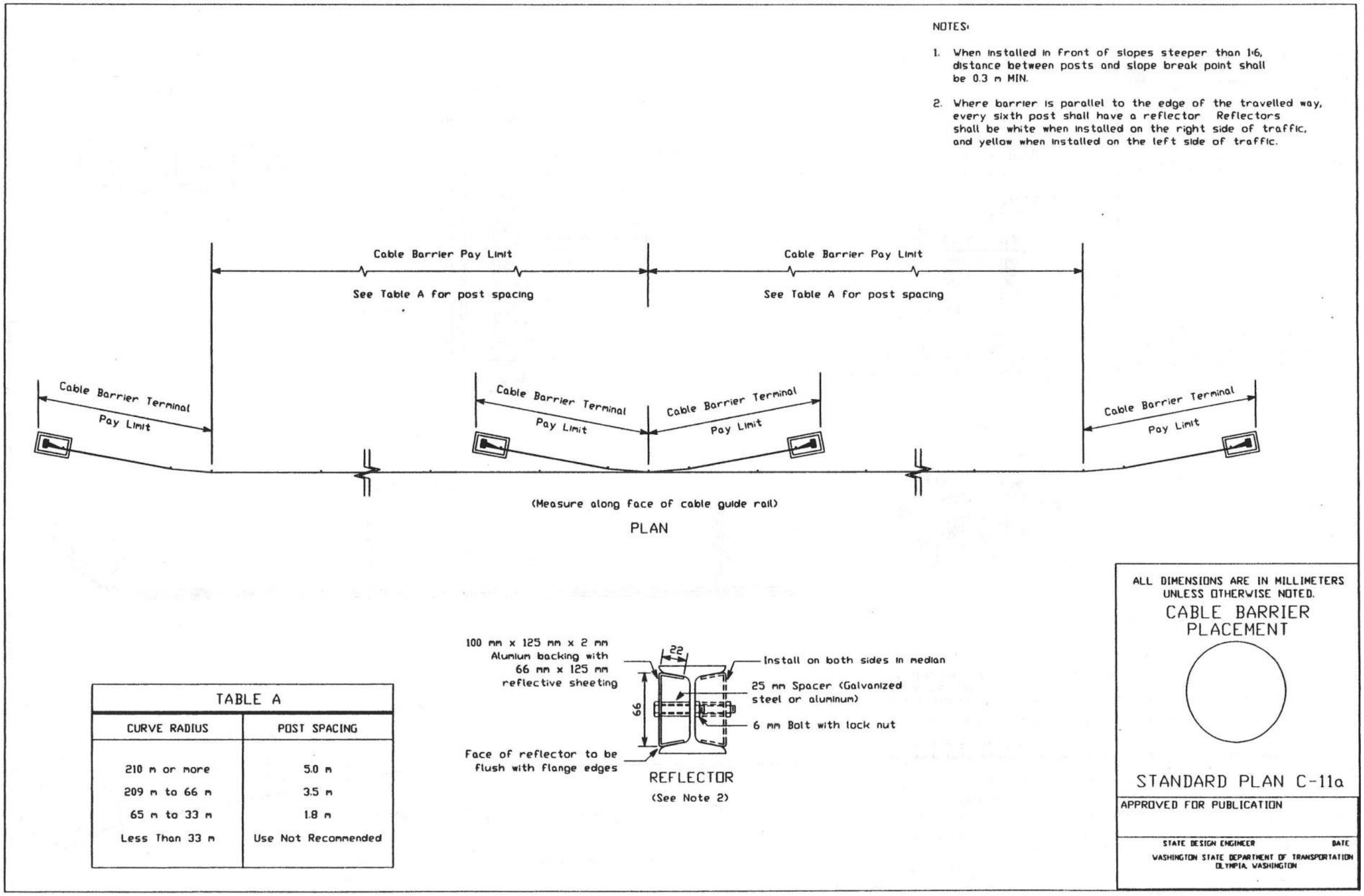


Figure 42. System Details, WSDOT Tested Design, 1996 [53-55]

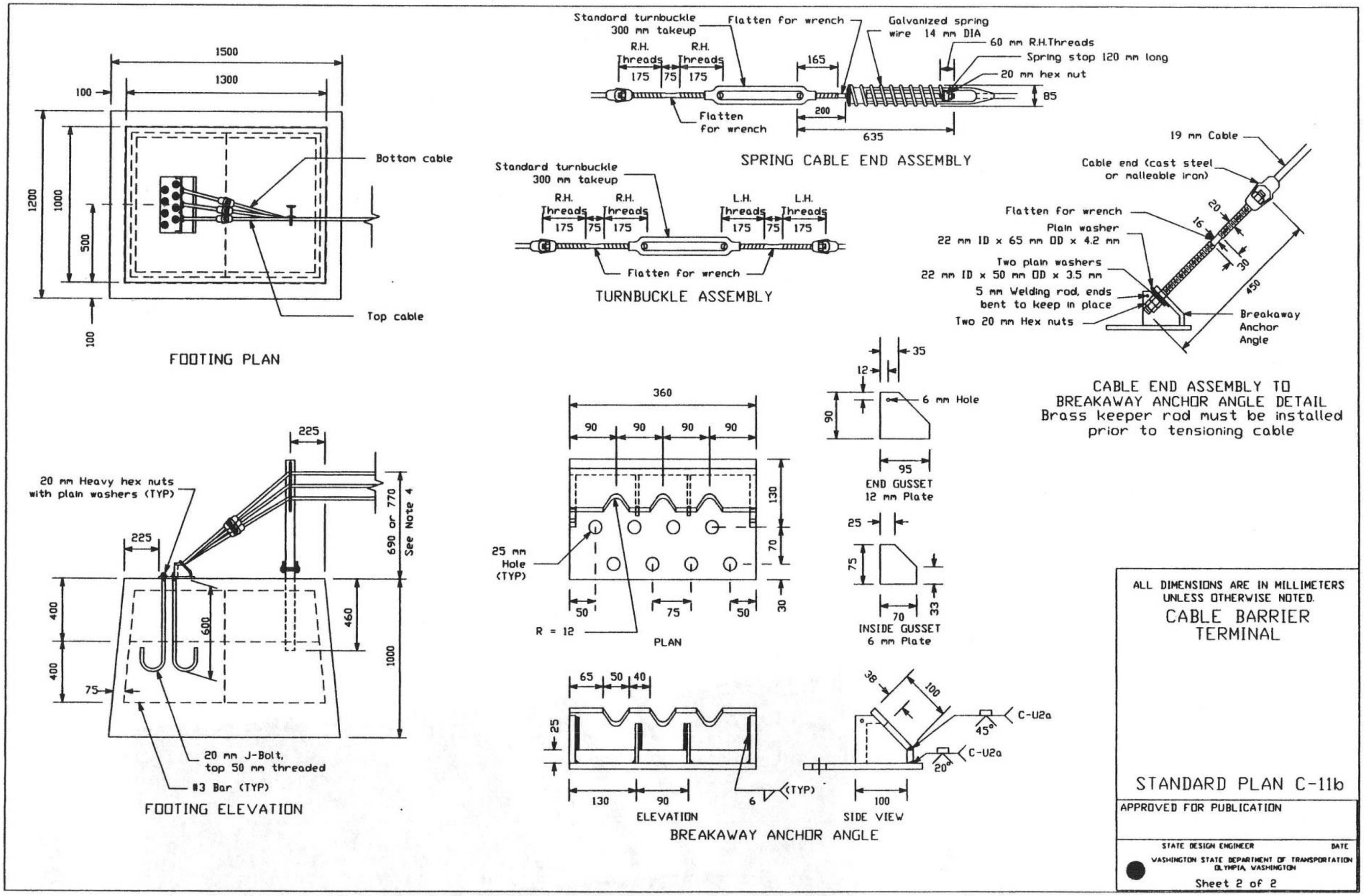


Figure 43. System Details, WSDOT Tested Design, 1996 [53-55]

occurred. Therefore, the test was determined to be successful according to the criteria presented in NCHRP Report 350.

Test no. 404211-8 consisted of a 1994 Chevrolet C2500 weighing 4,410 lb (2,000 kg) impacting the cable guardrail system at 63.0 mph (101.4 km/h) and 24.8 degrees. Impact was to occur on the single-cable side of the system. The vehicle penetrated to 11.2 ft (3.4 m) dynamic deflection before it was captured and brought to a controlled stop.

TTI also conducted a crash test of a pickup with a cable median system installed on Marion Steel flanged U-channel section posts [56]. The posts consisted of 4 lb/ft (6 kg/m) flanged-channels measuring 63 in. (1,600 mm) long. The cable mounting heights were approximately 30 $^{1}/_{4}$ and 20 $^{1}/_{2}$ in. (770 and 520 mm) on one side and 25 $^{3}/_{8}$ in. (645 mm) on the other. Trapezoidal soil bearing plates were welded to the U-channel posts. The New York cable end terminal design was used for the end anchorages.

The cable guardrail system with Marion Steel flanged U-channel posts was crash tested in test no. 400001-MSC1 with a 1996 Chevrolet C2500 impacting at post no. 11 at a speed and angle of 62.9 mph (101.2 km/h) and 25.5 degrees, respectively. The test vehicle overrode the cables and came to rest straddling the system. Since the test vehicle was captured by the system, it was determined that the cable guardrail system with Marion Steel flanged U-channel posts was acceptable under TL-3 impact conditions.

4.2.3 Terminal Tests

The New York cable terminal design was tested to NCHRP Report 230 and determined to be acceptable. Upon evaluation of the tests conducted in support of the development of the New York cable guardrail end terminal, it was determined that the terminal could be accepted according to criteria presented in NCHRP Report 350 if the system was evaluated for the critical impact point (CIP) for small car impacts. TTI conducted test no. 3-34 on the New York cable terminal system in 1998 [57].

The New York terminal was tested in test no. 404211-6 with a 1992 Ford Festiva, weighing 1,975 lb (896 kg), impacting the barrier system at 61.7 mph (99.3 km/h) and 14.7 degrees. Impact location was at the anchor post. The small car rode over the anchor, released the cables and came to a controlled stop. Therefore, the New York design of the low-tension cable end terminal was determined to successfully meet the criteria presented in NCHRP Report 350.

4.3 Midwest Roadside Safety Facility, 1998-2006

4.3.1 South Dakota Cable to W-Beam Transition

The Midwest Roadside Safety Facility (MwRSF) conducted 12 full-scale tests and many cable component tests in accordance with NCHRP Report 350. In 1996 through 1998, MwRSF evaluated the South Dakota 3-cable guardrail transition to W-beam guardrail according to TL-3 impact conditions [58]. The system consisted of S3x5.7 (S76x8.5) steel posts with soil bearing plates spaced 6 ft (1.8 m) on center near the transition. Cable mounting heights were 27, 24, and 21 in. (686, 610, and 533 mm). The cables were supported with $^{5}/_{16}$-in. (8-mm) diameter hook bolts bolted to the flange of the post and were tensioned to 900 lb (4.0 kN). This system was similar to the one tested by SwRI [29-32]

The first performance evaluation test, test no. SDC-1, was conducted with a 1993 GMC 2500 impacting the barrier 17 $^{1}/_{4}$ in. (438 mm) upstream of post no. 14C at a test speed and angle of 63.3 mph (101.9 km/h) and 27.6 degrees, respectively, according to NCHRP Report 350 test designation 3-21. The vehicle was captured by the barrier and came to rest in contact with both the W-beam guardrail and the cables. The test was determined to satisfactorily meet the criteria in NCHRP Report 350.

The second test, test no. SDC-2, consisted of a 1993 GMC 2500 impacting the barrier at post no. 4C with a test speed and angle of 63.3 mph (101.9 km/h) and 25.2 degrees, respectively. Test conditions for test no. SDC-2 were also consistent with test designation 3-21 of NCHRP Report 350. The vehicle contacted the cable and the BCT end anchorage and was redirected laterally out of the barrier system. The vehicle came to a stop 36.0 ft (10.97 m) from impact. Test no. SDC-2 was also considered acceptable according to the criteria in NCHRP Report 350.

Test no. SDC-3 was conducted according to NCHRP Report 350 test designation 3-20. Test no. SDC-3 consisted of a 1991 Geo Metro, weighing 1,935 lb (878 kg), impacting the cable transition 12 in. (305 mm) downstream of post no. 1C at a test speed and angle of 61.9 mph (99.6 km/h) and 20.2 degrees, respectively. Upon impact, the cables deflected, and the small car contacted the flared W-beam end terminal and was redirected smoothly out of the system with no snagging. The vehicle exited the system at 49.0 mph (78.9 km/h) and 7.4 degrees. Therefore, the South Dakota cable guardrail transition to W-beam system was determined to be acceptable according to the criteria in NCHRP Report 350.

In 2003, this system was later tested with a Flared Energy Absorbing Terminal (FLEAT) on the W-beam guardrail [59]. Instead of a parabolic transition, a straight flare was utilized. System details are shown in Figures 44 through 46. Test no. FCT-1 consisted of a 1998 Chevrolet C2500 impacting the barrier system at a test speed and angle of 63.8 mph (102.6 km/h) and 25.6 degrees, respectively. The pickup was slowed by the cables until impact with the FLEAT system and then was safely decelerated to a stop. The vehicle came to rest 3.6 ft (1.09 m) laterally from the system. Therefore, test no. FCT-1 was determined to be acceptable according to the criteria in NCHRP Report 350.

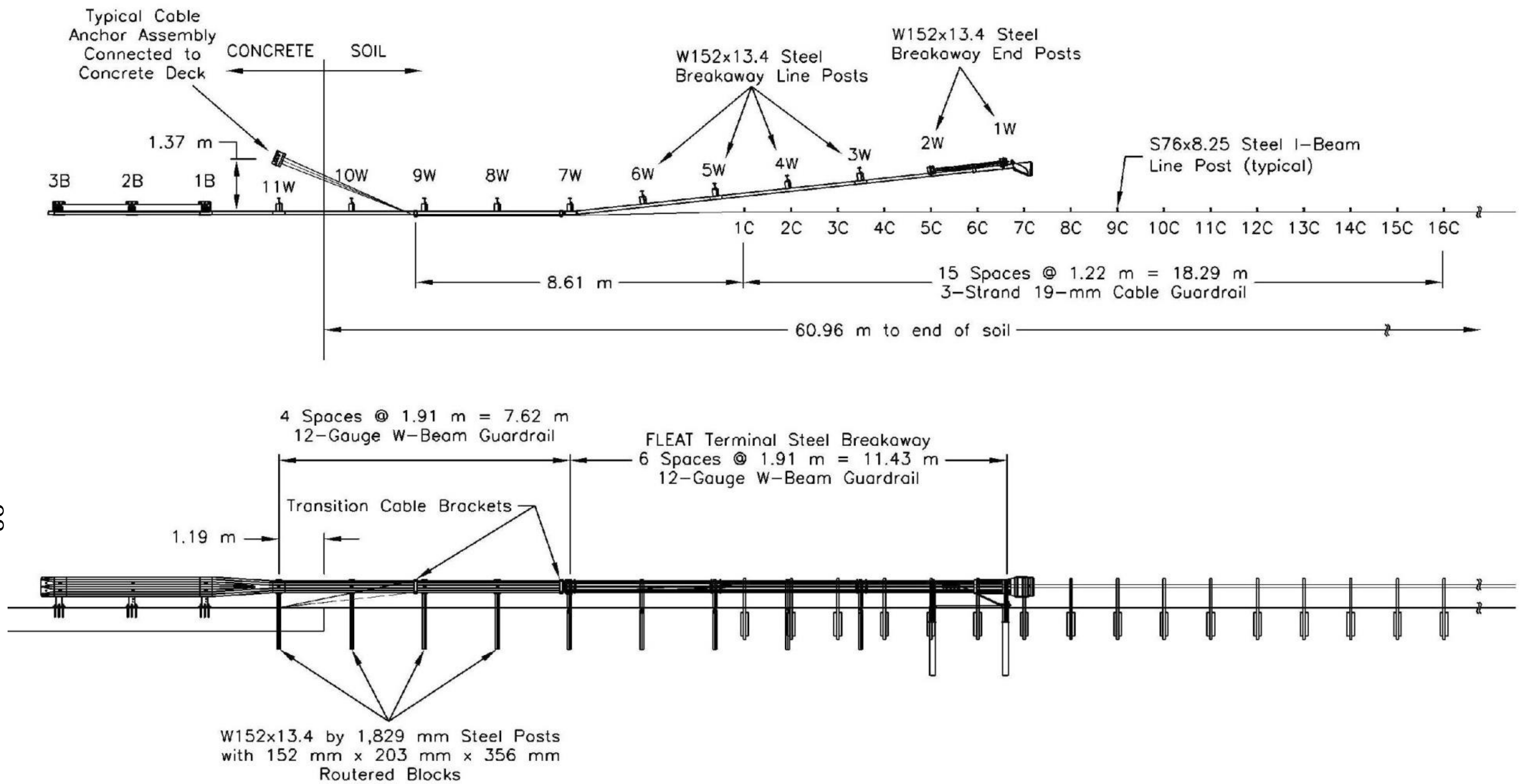


Figure 44. Cable Transition to FLEAT End Terminal Details, Test FCT-1, 2003 [59]

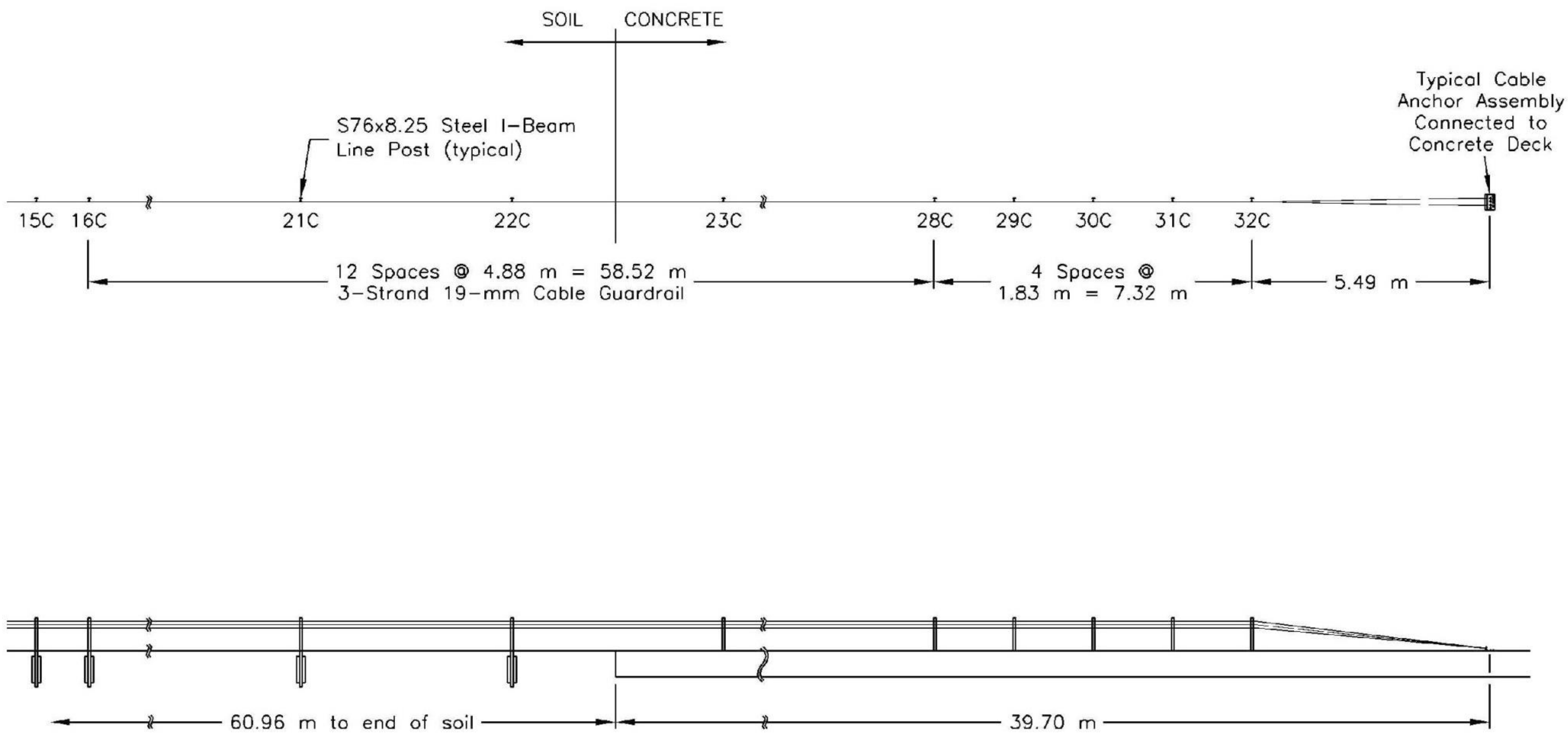
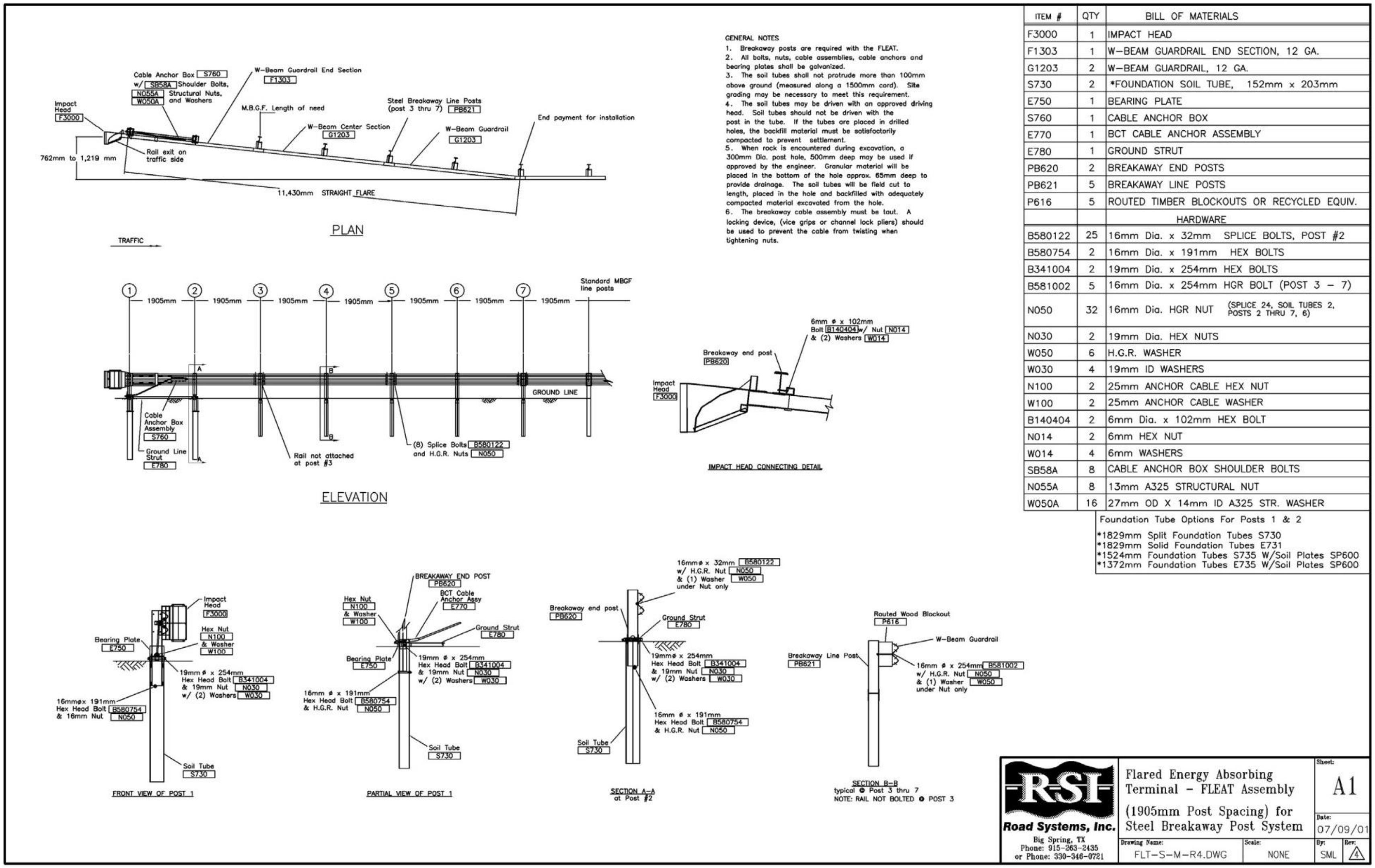


Figure 45. Cable Transition to FLEAT End Terminal Details, Test FCT-1, 2003 [59]



ITEM #	QTY	BILL OF MATERIALS
F3000	1	IMPACT HEAD
F1303	1	W-BEAM GUARDRAIL END SECTION, 12 GA.
G1203	2	W-BEAM GUARDRAIL, 12 GA.
S730	2	*FOUNDATION SOIL TUBE, 152mm x 203mm
E750	1	BEARING PLATE
S760	1	CABLE ANCHOR BOX
E770	1	BCT CABLE ANCHOR ASSEMBLY
E780	1	GROUND STRUT
PB620	2	BREAKAWAY END POSTS
PB621	5	BREAKAWAY LINE POSTS
P616	5	ROUTED TIMBER BLOCKOUTS OR RECYCLED EQUIV.
		HARDWARE
B580122	25	16mm Dia. x 32mm SPLICE BOLTS, POST #2
B580754	2	16mm Dia. x 191mm HEX BOLTS
B341004	2	19mm Dia. x 254mm HEX BOLTS
B581002	5	16mm Dia. x 254mm HGR BOLT (POST 3 - 7)
N050	32	16mm Dia. HGR NUT (SPLICE 24, SOIL TUBES 2, POSTS 2 THRU 7, 6)
N030	2	19mm Dia. HEX NUTS
W050	6	H.G.R. WASHER
W030	4	19mm ID WASHERS
N100	2	25mm ANCHOR CABLE HEX NUT
W100	2	25mm ANCHOR CABLE WASHER
B140404	2	6mm Dia. x 102mm HEX BOLT
N014	2	6mm HEX NUT
W014	4	6mm WASHERS
SB58A	8	CABLE ANCHOR BOX SHOULDER BOLTS
N055A	8	13mm A325 STRUCTURAL NUT
W050A	16	27mm OD X 14mm ID A325 STR. WASHER

Figure 46. Cable Transition to FLEAT End Terminal Details, Test FCT-1, 2003 [59]

4.3.1 Cable Adjacent to Slope

MwRSF also conducted a full-scale crash test on cable guardrail installed adjacent to steep slope [60]. The South Dakota 3-cable guardrail design consisted of S3x5.7 (S76x8.5) steel posts measuring 63 in. (1600 mm) long and located 12 in. (305 mm) from the break point of a 1.5:1 slope. The tension in the cables prior to the test was approximately 900 lb (4.0 kN), and the cable mounting heights were 30, 27, and 24 in. (762, 686, and 610 mm). Post embedment depth was 30 in. (762 mm). Standard 24-in. x 8-in. x $^{1}/_{4}$-in. thick (610-mm x 203-mm x 6-mm) soil plates were welded to the posts, 3 in. (51 mm) from the bottom of the post. Post spacing was 16 ft (4.9 m) throughout the system.

Test no. CS-1 conducted on the cable barrier adjacent to steep slope consisted of a 1995 GMC 2500 pickup impacting the barrier 108 in. (2,743 mm) downstream of post no. 12 at 61.0 mph (98.2 km/h) and 26.2 degrees. The vehicle deflected the cables and extended out over the slope before rolling counterclockwise. The cables rebounded, causing the vehicle to roll and pitch into the ditch. The maximum dynamic tension in the system was 11.1 kips (49.3 kN) in the lowest cable. Because the truck rolled, the system was determined to be unacceptable according to the criteria in NCHRP Report No. 350.

The South Dakota system was retested in 2006 with system modifications: (1) post spacing was reduced adjacent to the slope to 48 in. (1,219 mm), or set at $^{1}/_{4}$-post spacing, and(2) posts were installed 4 ft (1.2 m) from the break point of the 1.5:1 slope [61]. Post length, post embedment depth, cable mounting heights, and cable tension were unchanged from test no. CS-1.

Test no. CS-2 was conducted as a retest of test no. CS-1 with a 1999 Chevrolet 2500 pickup impacting the barrier system at post no. 32 with a test speed and angle of 61.6 mph (99.1

km/h) and 23.6 degrees, respectively. The vehicle was smoothly redirected and the maximum dynamic deflection of the barrier system was 124.5 in. (3,163 mm). The maximum dynamic tension in the guardrail system was 8.9 kips (39.4 kN) in the bottom cable. Therefore, the cable guardrail system installed adjacent to a steep slope was determined to be acceptable according to the TL-3 criteria in NCHRP Report 350.

4.3.2 Low-Tension Cable Median Barrier

A non-proprietary low-tension cable median barrier meeting TL-4 impact conditions was desired. During 2000 and 2003, prior to designing and full-scale testing a cable barrier design, MwRSF conducted a series of component tests on post designs to determine optimized post size and strength for cable applications [62-63]. It was determined that an M8x6.5 (M203x9.7) post had acceptable post section properties and that the M-shape posts were more resistant to strong-axis bending than the S3x5.7 (S76x8.5) posts commonly used in cable systems.

Between 2000 and 2008, MwRSF tested designs for a low-tension cable median barrier incorporating four cables instead of three [64]. It was believed that four cables may perform better in the redirection and capture of both small and large vehicles when placed in a median and reduce the risk of underride and/or override. The first design consisted of M8x6.5 (M203x9.7) steel posts measuring 78 in. (1,981 mm) long and embedded to a depth of 42 in. (1,067 mm). The four $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables were supported with $^{5}/_{16}$-in. (8-mm) diameter J-bolts at mounting heights of 34, 27, 20, and 13 in. (864, 686, 508, and 330 mm). The cables were woven between every post.

Test no. CMB-1 was conducted on the four-cable low-tension median barrier system. The 1997 Chevrolet Metro impacted the system at 60.6 mph (97.5 km/h) and 19.7 degrees, and the car was redirected by the cables with a maximum dynamic deflection of 44 in. (1,128 mm).

During the test, the small car overrode the bottom two cables. Following redirection by the barrier, the small car began to exit the system with a very small roll angle and trapped the cables which were overridden. The vehicle subsequently rolled over. Safety performance was determined to be unacceptable due to rollover.

It was observed that the bottom two cables were overridden by the test vehicle and wrapped around the left-front and left-rear tires as the vehicle redirected. Due to the tight weave of the cables around the posts and the small post spacing, the cables were pulled taut, and generated a clockwise roll in the vehicle. Additionally, as the vehicle exited the barrier, the left-front tire contacted and rode over consecutive line posts. Due to the large web surface of the M-posts, the post shapes formed ramps which contributed to the vehicle instability.

In addition, the weave of the cables with the posts caused a pinching effect between the cables on the impact side of vehicle and the cable which was overridden on the opposite side. The pinching effect contributed to the roll moment of the vehicle, rather than aiding in vehicle capture, because the cables were constrained on opposite flanges of the posts at every other post. Cable tension was also more localized, due to the weave of the cables between the posts.

The system was modified by removing the cable weave between the posts and exchanging the M-posts for S3x5.7 (S76x8.5) steel posts commonly used in cable guardrail systems. The embedment depth was decreased to 31 in. (787 mm), and post spacing was increased from 6 ft (1.8 m) to 8 ft (2.4 m). In addition, hook plates were utilized in lieu of the $^{5}/_{16}$-in. (8-mm) diameter J-bolts to provide better support for the cables and retain the cables on the posts for a longer duration during impact.

Test no. CMB-2 was conducted on the modified system and consisted of a 1996 Chevrolet Metro impacting the system at 62.8 mph (101.1 km/h) and 19.7 degrees. The small car was captured with a maximum dynamic deflection of 75 $^{1}/_{2}$ in. (1,917 mm) and came to a stop after yawing out of the system. During the test, the top cable released from the posts and extended over the vehicle's hood and roof, trapping the vehicle between the cables. Subsequent impact with the posts caused the yaw motion out of the barrier. Nonetheless, the test was considered a success.

To alleviate the early cable release from the barrier, the system was modified to incorporate retainer bolts on the flanges of the posts above the hook plates to hold the cables on the posts for a greater duration during impact. System details of the successful test are shown in Figures 47 through 51. Since the change was minor and believed to not increase the instability of the impacting vehicle nor detract from system performance, the system was not retested with the smaller vehicle. Test no. CMB-3 consisted of a 1998 GMC pickup impacting the barrier at 60.8 mph (97.8 km/h) and 25.4 degrees. The pickup was smoothly redirected and exited the barrier system at a speed and angle of 42.0 mph (67.6 km/h) and 7 degrees. The tires were not deflated and vehicle damage was limited to grooves and minor tearing of the vehicle's sheet metal near the front wheel well on the impact side. Therefore, the four-cable low-tension median barrier was considered acceptable according to the criteria in NCHRP Report 350.

4.3.3 Terminal Testing

It was observed that even though the New York design for a low-tension cable end terminal was successful and significantly improved cable end treatment safety, it was not always possible to construct the cable end terminal at a flare or on a 6:1 back slope. Therefore, between 2000 and 2007, MwRSF designed and tested a low-tension cable guardrail end terminal [65].

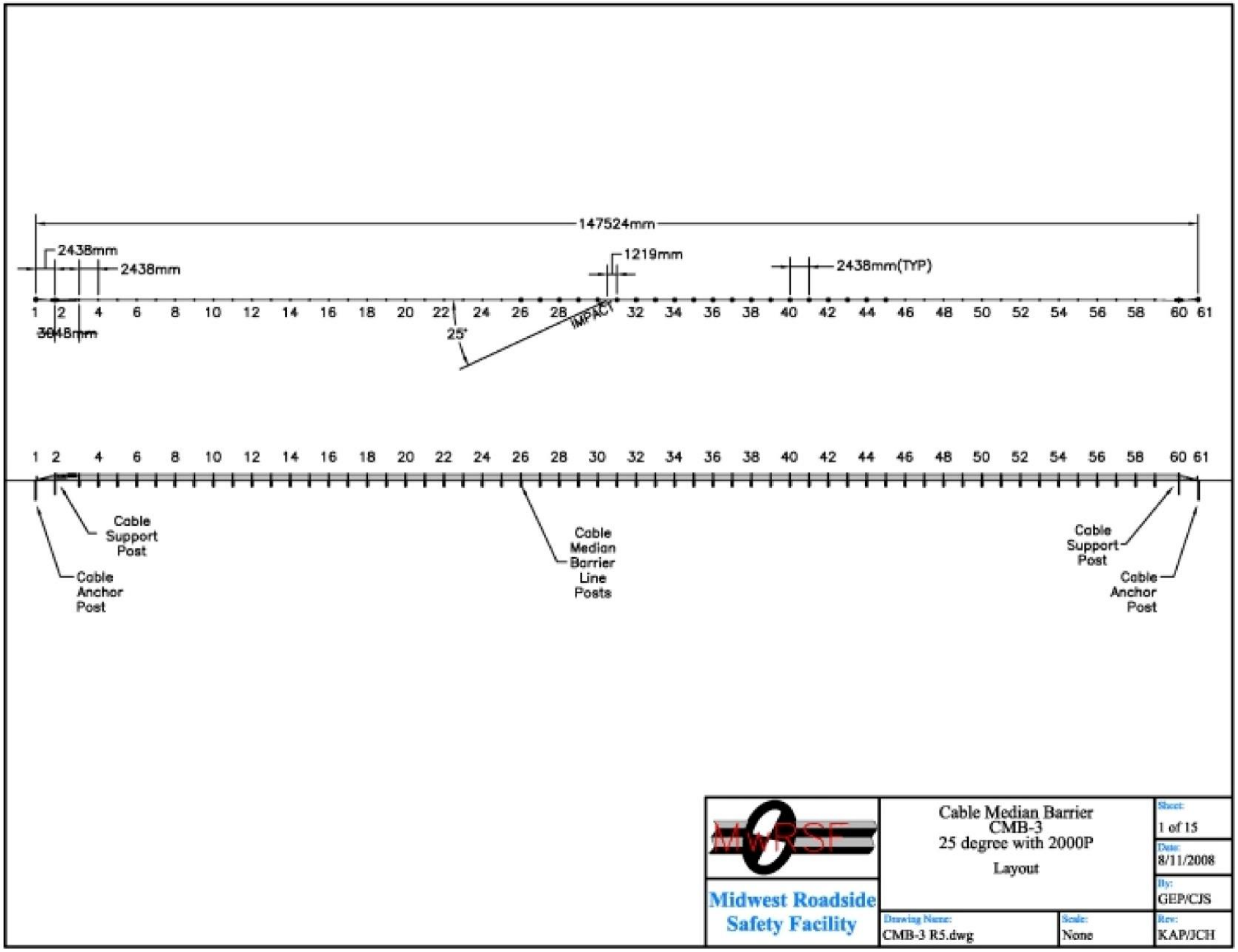


Figure 47. Low Tension Cable Median Barrier System Details, 2000-2008 [64]

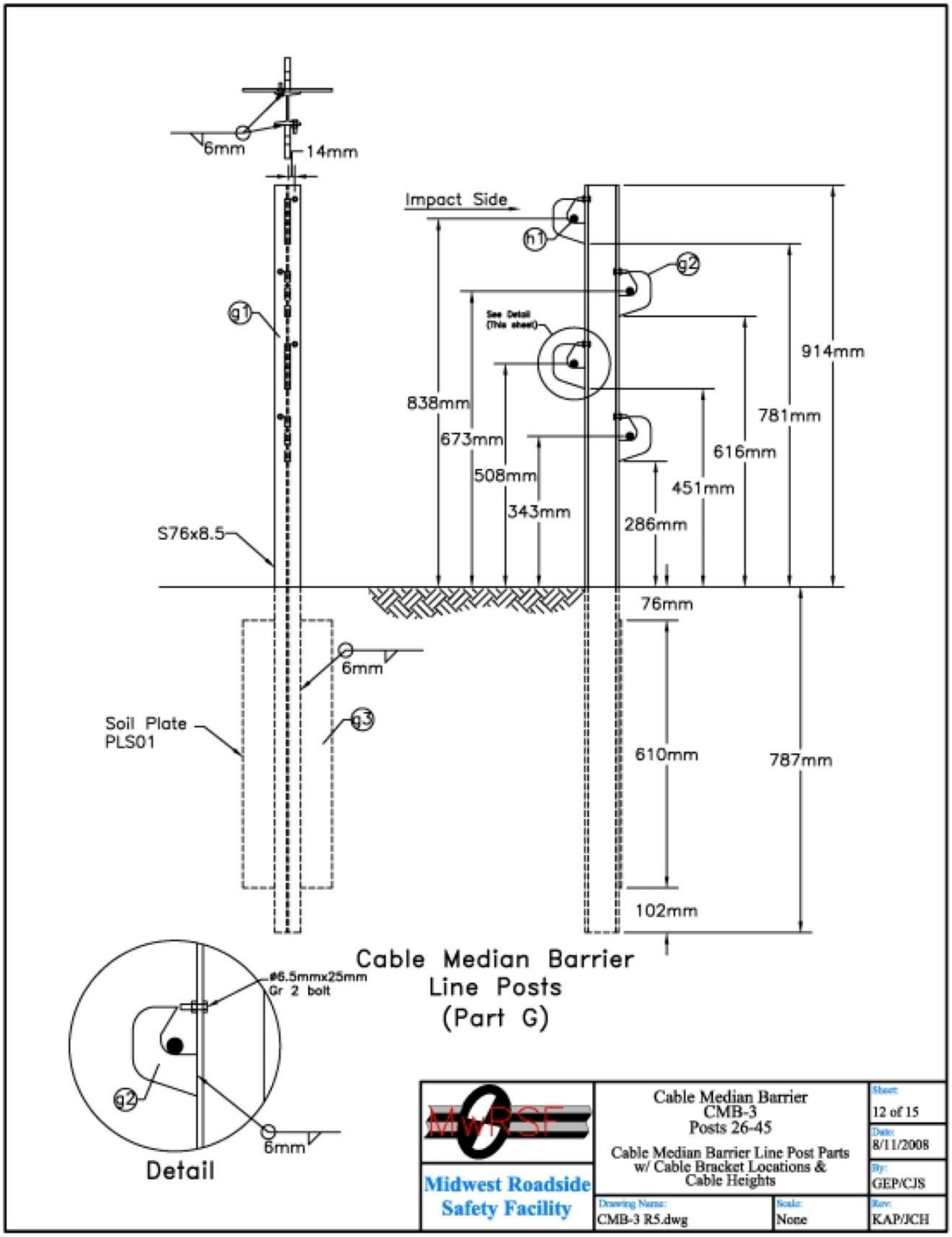


Figure 48. Low Tension Cable Median Barrier System Details, 2000-2008 [64]

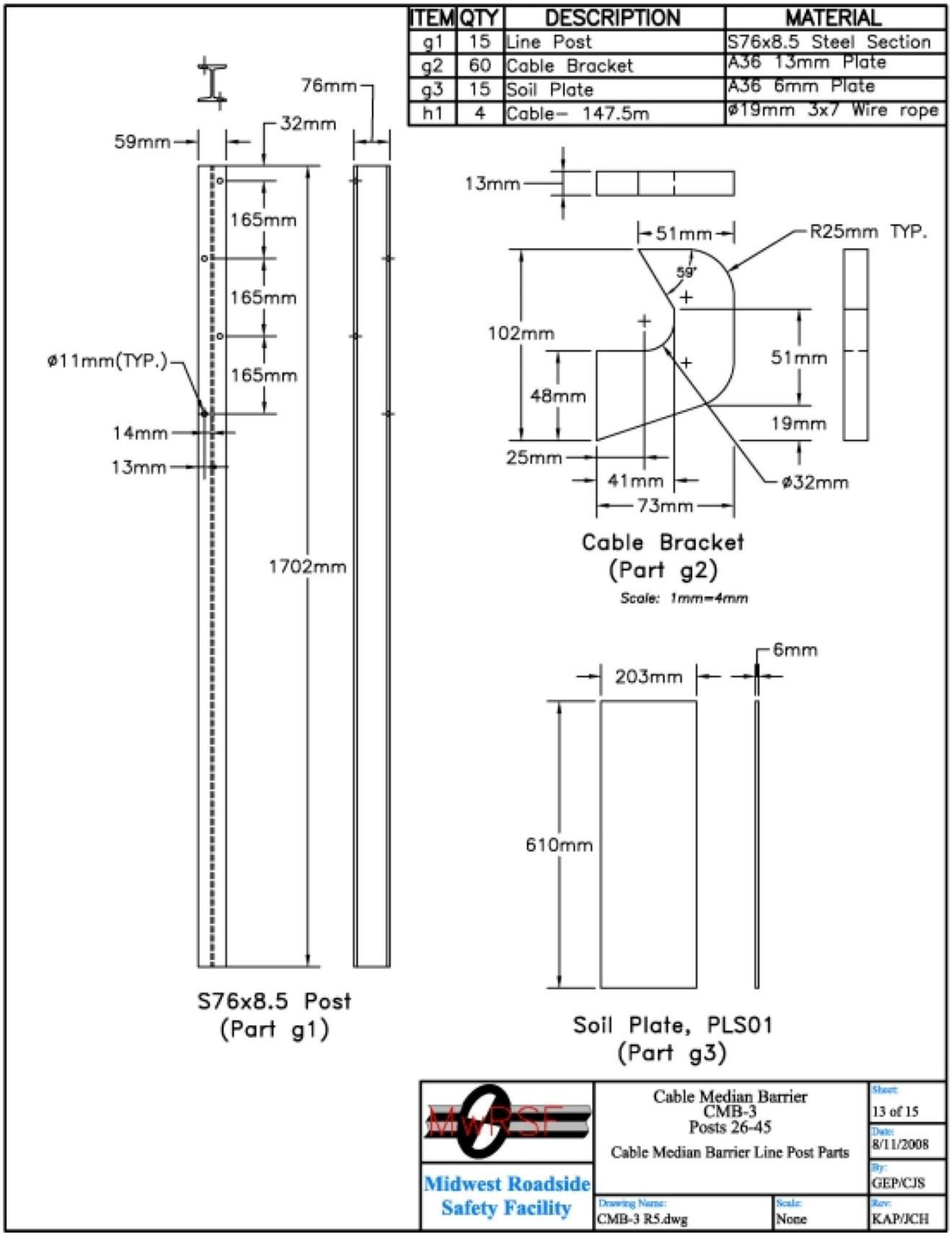


Figure 49. Low Tension Cable Median Barrier System Details, 2000-2008 [64]

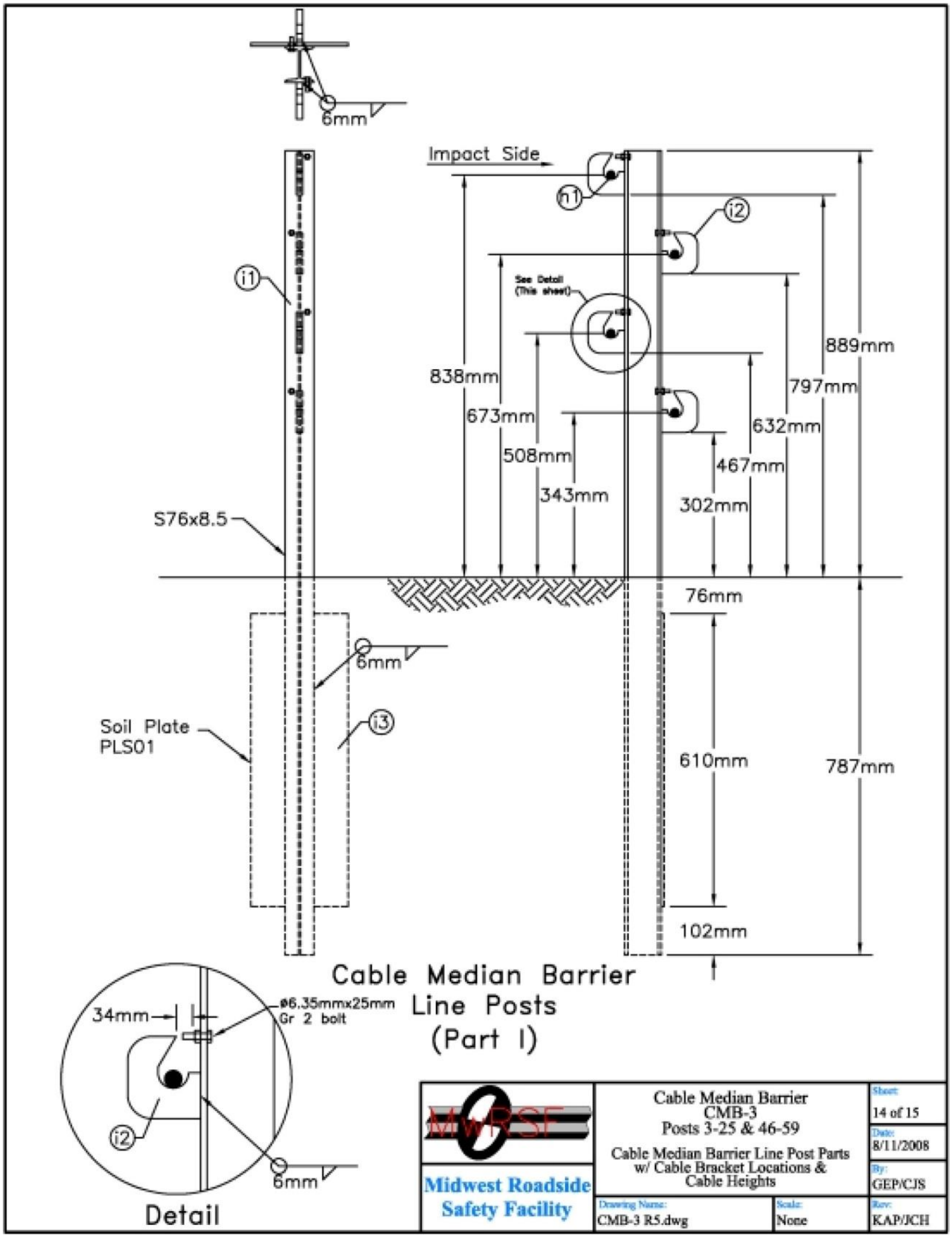


Figure 50. Low Tension Cable Median Barrier System Details, 2000-2008 [64]

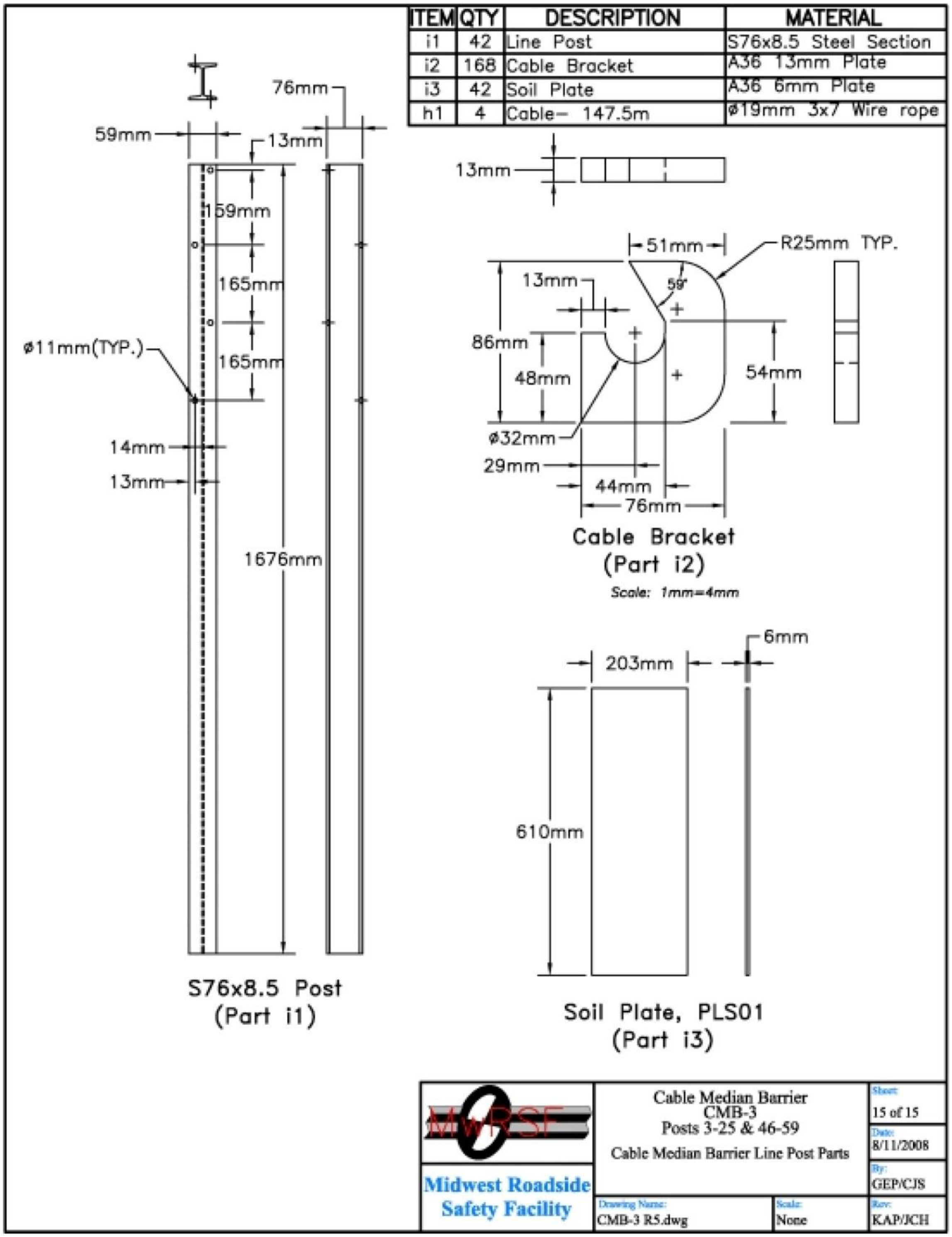


Figure 51. Low Tension Cable Median Barrier System Details, 2000-2008 [64]

The terminal system contained hardware which was similar to that used in the New York flared cable terminal design and incorporated the anchor bracket and second post with a slip base. Researchers at MwRSF replaced the large concrete anchor block with a steel anchor post and cable support post design. The anchor post was a W6x25 (W152x37.2) post with an anchor plate welded to the top, four studs mounted on the plate, and four holes for threaded rod anchor bolts and nuts. Soil plates were welded to the posts such that the soil plates faced the center of the system. The steel anchor post was identical to the one used in the cable guardrail adjacent to steep slope design (test nos. CS-1 and CS-2).

The cable support post was a slip-base post with a soil bearing plate, and was installed 60 in. (1,524 mm) from the anchor bracket. Since the barrier was installed tangent to the roadway, a cable release lever was created to trigger the slip-out of cables from the cable anchor bracket. All of the posts in the length of need section were S3x5.7 (S76x8.5) steel posts measuring 63 in. (1,600 mm) long and embedded 30 in. (762 mm) in the soil. Three cables were supported on $^{5}/_{16}$-in. (8-mm) diameter hook bolts at mounting heights of 30, 27, and 24 in. (762, 686, and 610 mm).

Test no. CT-1 was conducted with a 1996 GMC 2500 pickup impacting the terminal at post no. 3 with a test speed and angle of 63.3 mph (101.9 km/h) and 20.7 degrees, respectively. The vehicle was smoothly redirected and the system encountered a maximum dynamic deflection of 84.1 in. (2,136 mm) before the vehicle exited the barrier at 59.7 mph (96.1 km/h) and 4 degrees. The vehicle came to rest with minimal damage, mostly consisting of grooves in the lower left-front quarter panel and tearing of the sheet metal around the wheel well.

The system was tested again according to test designation 3-30 of NCHRP Report 350 in test no. CT-2. The 1,965-lb (891-kg) small car impacted the barrier system with a $^{1}/_{4}$-width offset to post no. 1 at 62.1 mph (100.0 km/h) and 1.5 degrees. Vehicle contact with the cable release lever allowed the cables to release from the terminal and relax in front of the vehicle. The cable release lever was then run over by the small car, and caused gouging and floorboard penetration. Furthermore, the small car impact with the posts, combined by the vaulting effect of impact with the cable release lever, caused the vehicle to rollover in the system.

The system was modified by including a retainer cable to the cable release lever. The system was retested in test no. CT-3 with a $^{1}/_{4}$-offset to post no. 1 at 61.4 mph (98.8 km/h) and 0.1 degrees. Again the cables were released upon impact with the cable release lever, but the vehicle yawed due to contact with the posts. As the vehicle yawed and redirected out of the system, successive impacts with the line posts increased the vehicle roll displacement and the vehicle subsequently tripped and rolled over.

The system was modified again by changing the first six posts after the terminal to slip-base posts, based on the number of posts that were impacted by the vehicle in test no. CT-3. The final cable terminal design is shown in Figures 52 through 56. Test no. CT-4 was a retest of test CT-2 and CT-3 and consisted of a 1998 Chevrolet Metro impacting the system at a $^{1}/_{4}$-offset to post no. 1 at 61.1 mph (98.3 km/h) and 0.1 degrees. Impact with the cable release lever released the cables and the vehicle engaged post nos. 2 through 7, causing post nos. 2 through 6 to release from the slip bases and post no. 7 to fracture at the slip-plate weld line. The vehicle yawed due to contact with the posts and experienced roll displacement of nearly 90 degrees, but exited the system at 46.4 mph (74.7 km/h) and 13 degrees. The vehicle came to rest on all four tires 145 ft - 3 in. (44.3 m) downstream and 28 ft - 5 in. (8.66 m) laterally from the system. The low-tension cable guardrail end terminal system was determined to satisfactorily meet the criteria presented in NCHRP Report 350, but acceptance of the system was not pursued.

MwRSF has not applied for FHWA acceptance of this system due to several reasons: (1) state Departments of Transportation have not requested it; (2) it is not clear what the performance of the 1100C would be under MASH requirements; and (3) the system was redesigned for use in a high-tension cable median barrier system. Therefore, further research is ongoing in development of a crashworthy, non-proprietary, four-cable high-tension cable barrier end terminal.

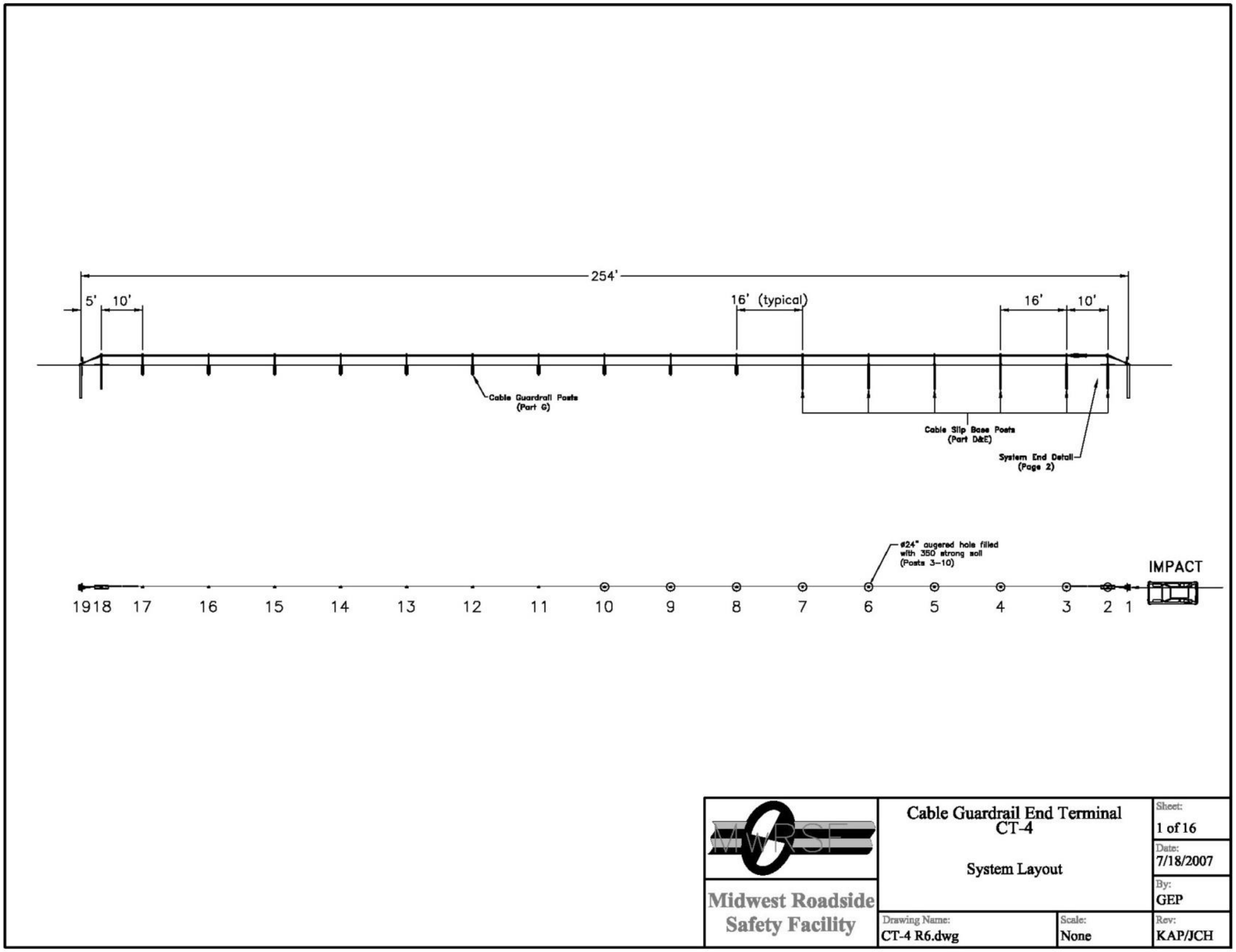


Figure 52. Final System Details, Cable Terminal Testing, 2000-2007 [65]

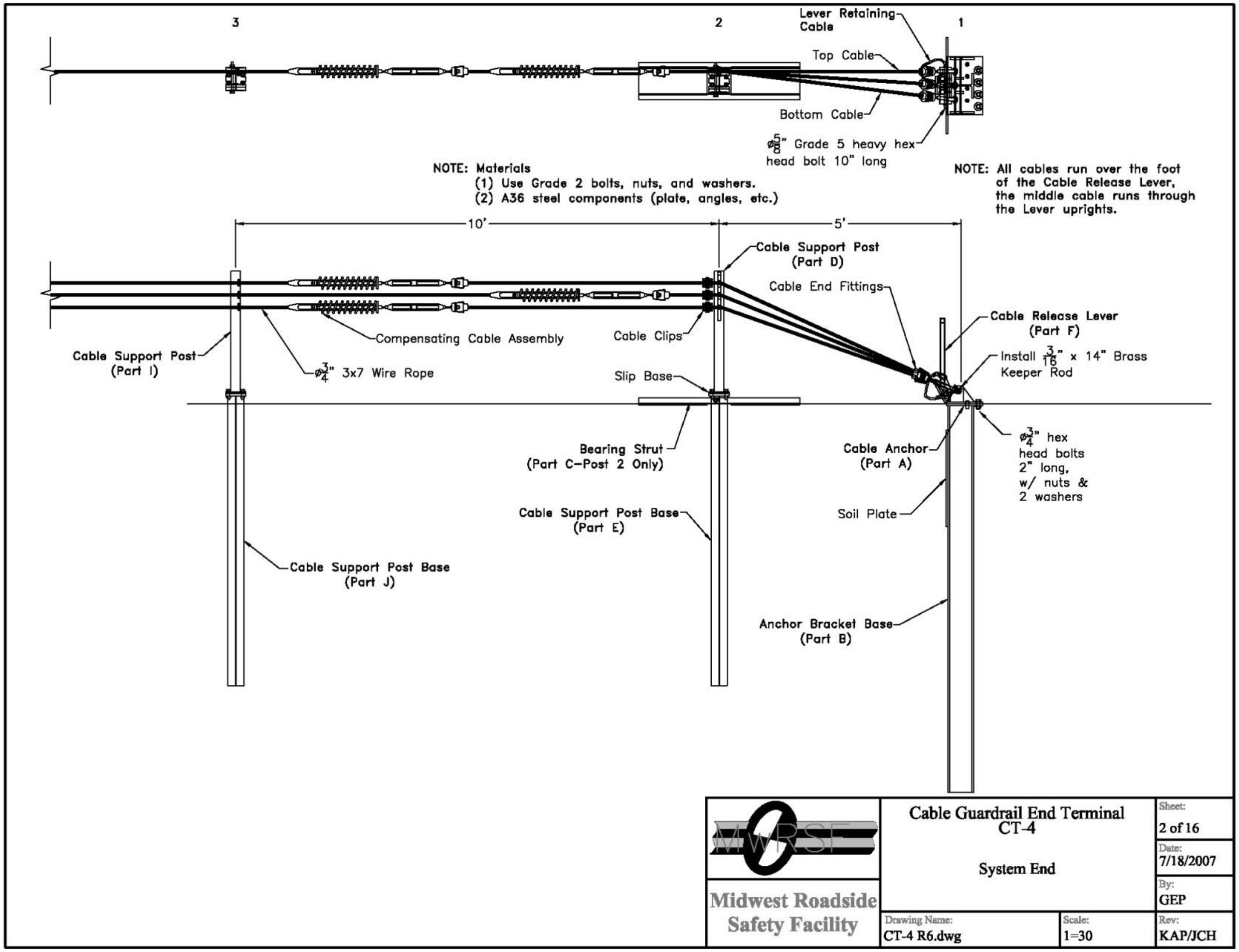


Figure 53. End Terminal Details, Cable Terminal Testing, 2000-2007 [65]

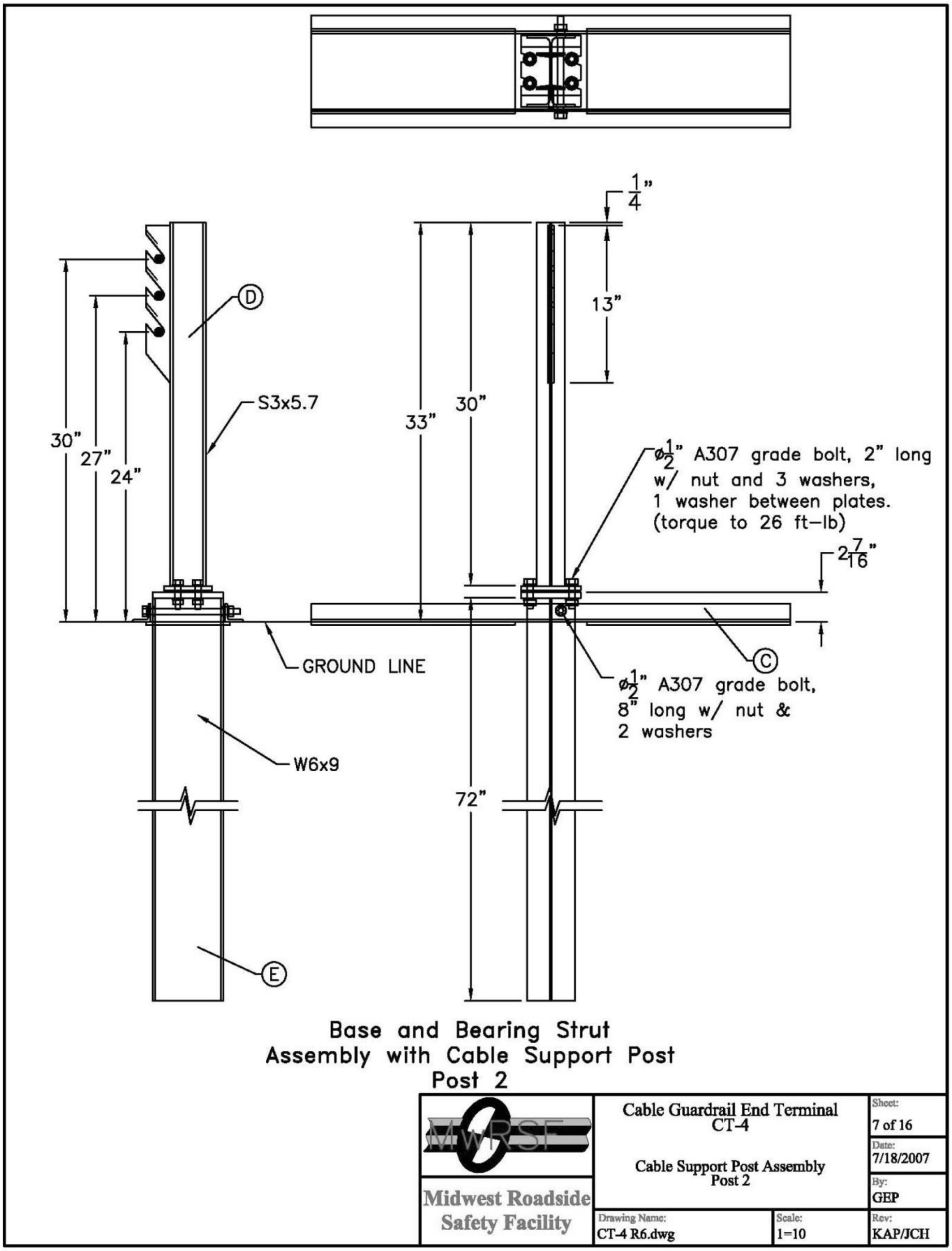


Figure 54. Cable Support Post Details, Cable Terminal Testing, 2000-2007 [65]

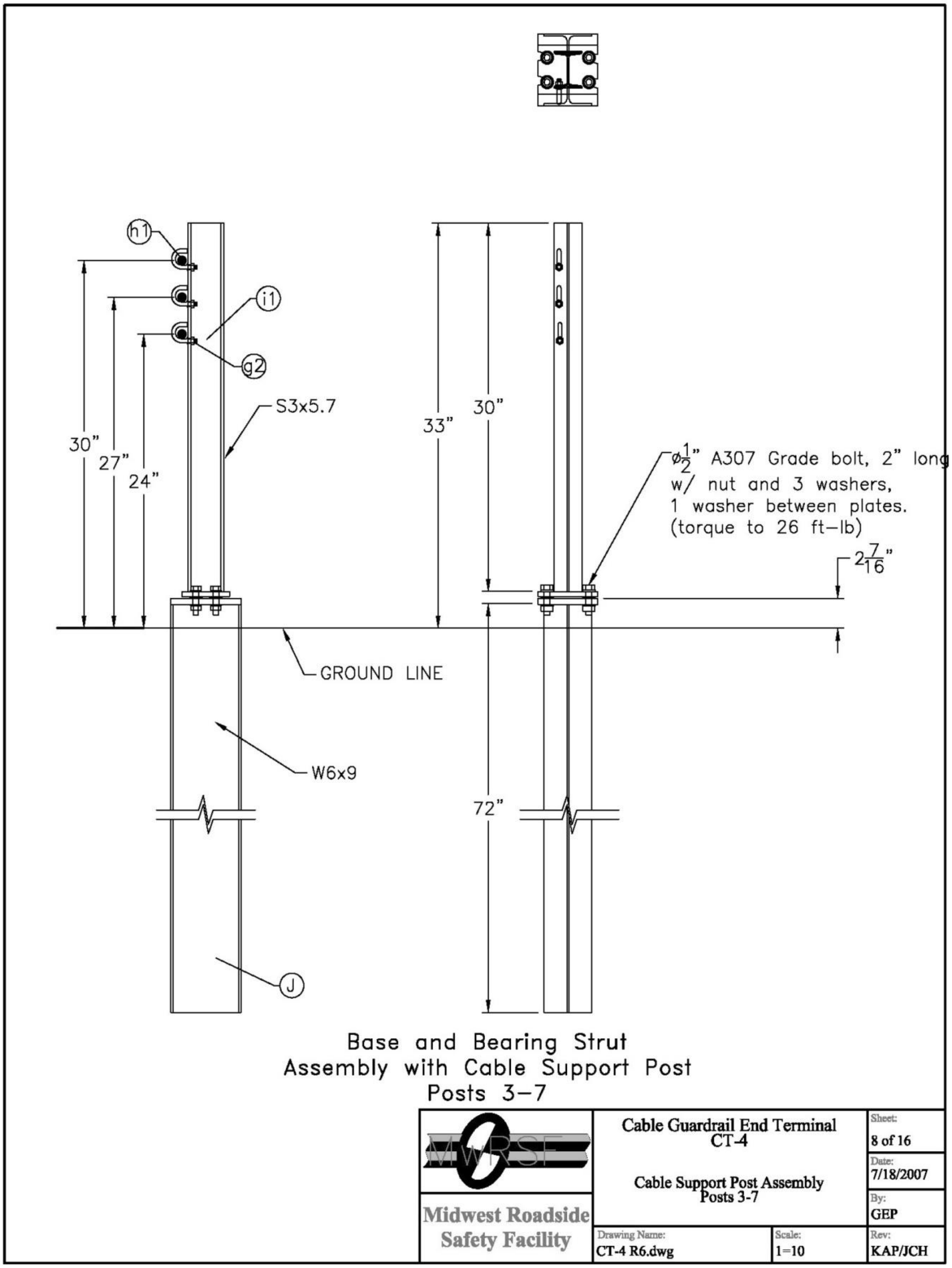


Figure 55. Slip Post Details, Cable Terminal Testing, 2000-2007 [65]

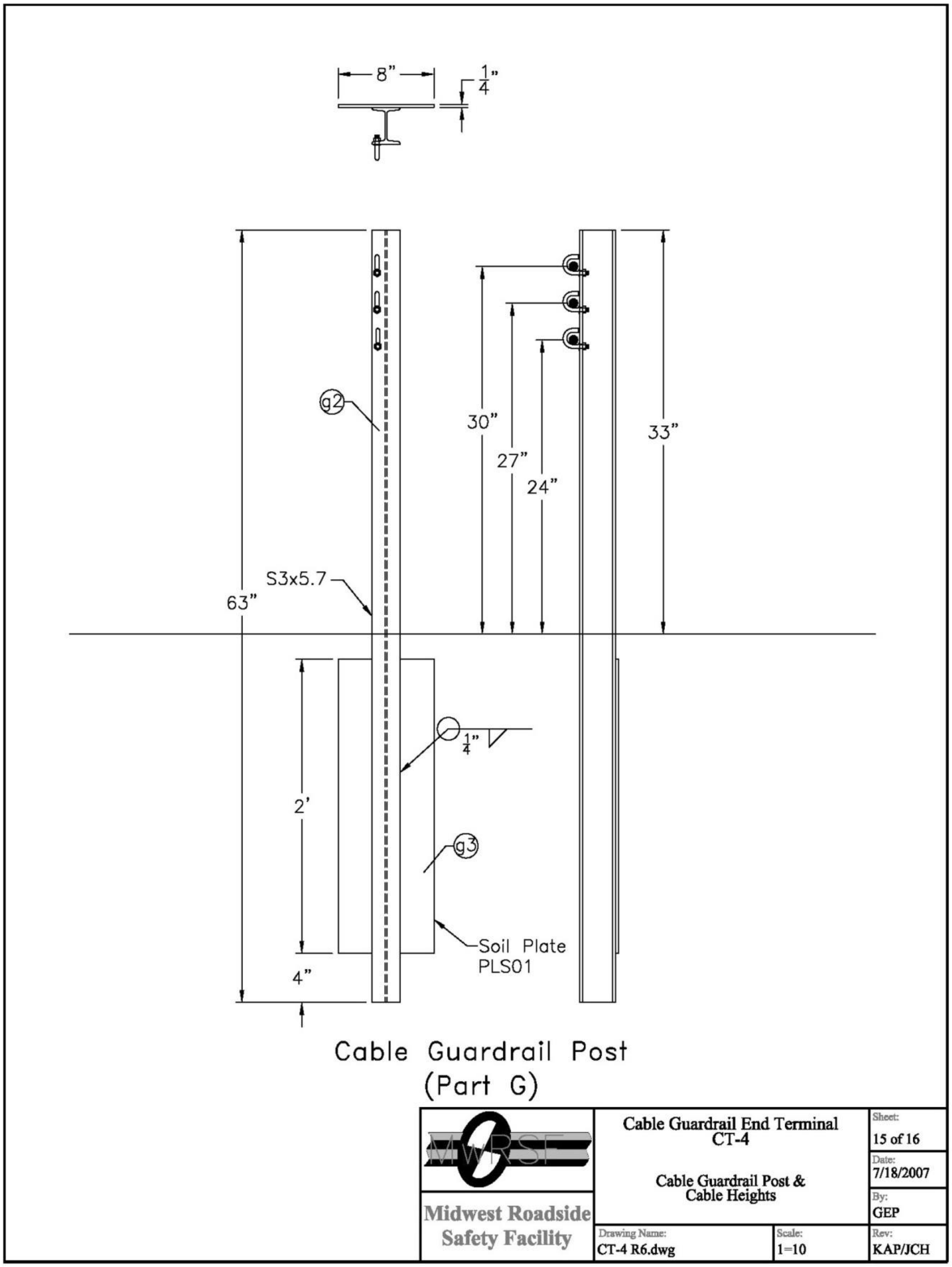


Figure 56. Line Post Details, Cable Terminal Testing, 2000-2007 [65]

5 MASH AND DEMONSTRATIVE TESTING

Following the acceptance of the Manual for Assessing Safety Hardware (MASH, 6), some testing organizations have full-scale tested experimental cable barrier designs to the new criteria. The new testing criteria for safety performance evaluation for roadside hardware consists of impact testing with a heavier 5,000-lb (2,268-kg) pickup impacting length-of-need installations at 62 mph (100 km/h) and 25 degrees. Small car testing was also updated to consist of a 2,425-lb (1,100-kg) small car impacting at 62 mph (100 km/h) and 25 degrees as well. Other organizations used testing to demonstrate a purpose, without following formally-established evaluation criteria. System and testing details of systems tested to MASH are shown in Appendix G and Appendix H, respectively.

5.1 Midwest Roadside Safety Facility, 2005-2009

State DOTs in the Midwest States' Regional Pooled Fund Program desired a high-tension cable median barrier. Research has shown that high-tension cable guardrail systems are resistant to sag in warm weather and retain tension under most impact events. Furthermore, it was desired that the high-tension cable barrier meet MASH testing criteria when placed in a 4:1 V-ditch. The low-tension 4-cable median barrier developed previously was modified and crash tested in two positions on the 4:1 slopes [66].

System details are shown in Figures 57 through 62. The high-tension cable guardrail system consisted of S3x5.7 (S76x8.5) steel posts measuring 87 in. (2,210 mm) long and embedded 39 in. (991 mm) in soil. Based on results from a dynamic cable post impact testing study, no soil plates were attached to the posts [67]. Four $^{3}/_{4}$-in. (19-mm) diameter 3x7 cables were tensioned to 4,100 lb (18.2 kN) and had mounting heights of 45, 35, 25, and 15 in. (1,154, 889, 635, and 381 mm). The cables were mounted on the posts with keyed

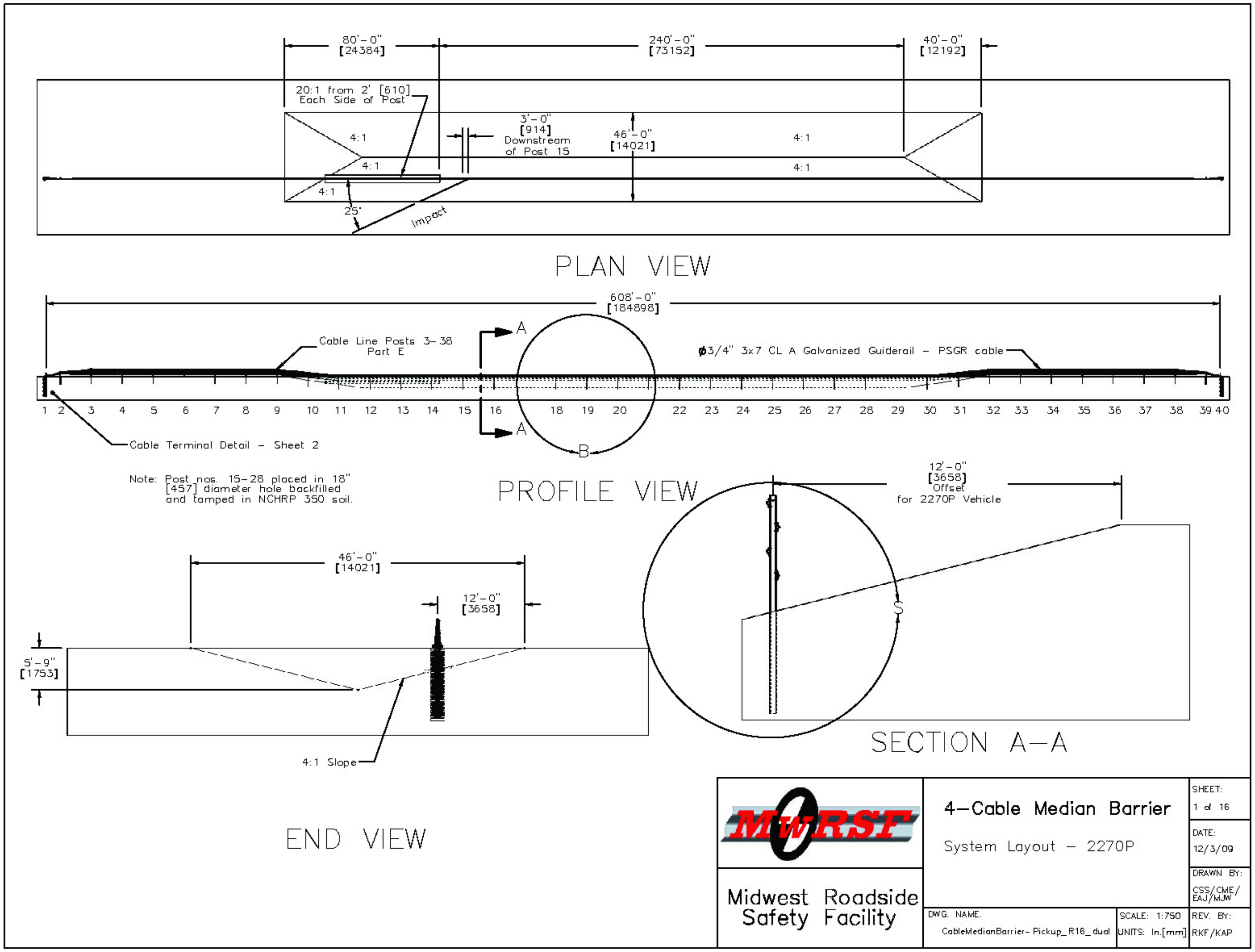


Figure 57. System Details, Test No. 4CMB-1, 2007 [66]

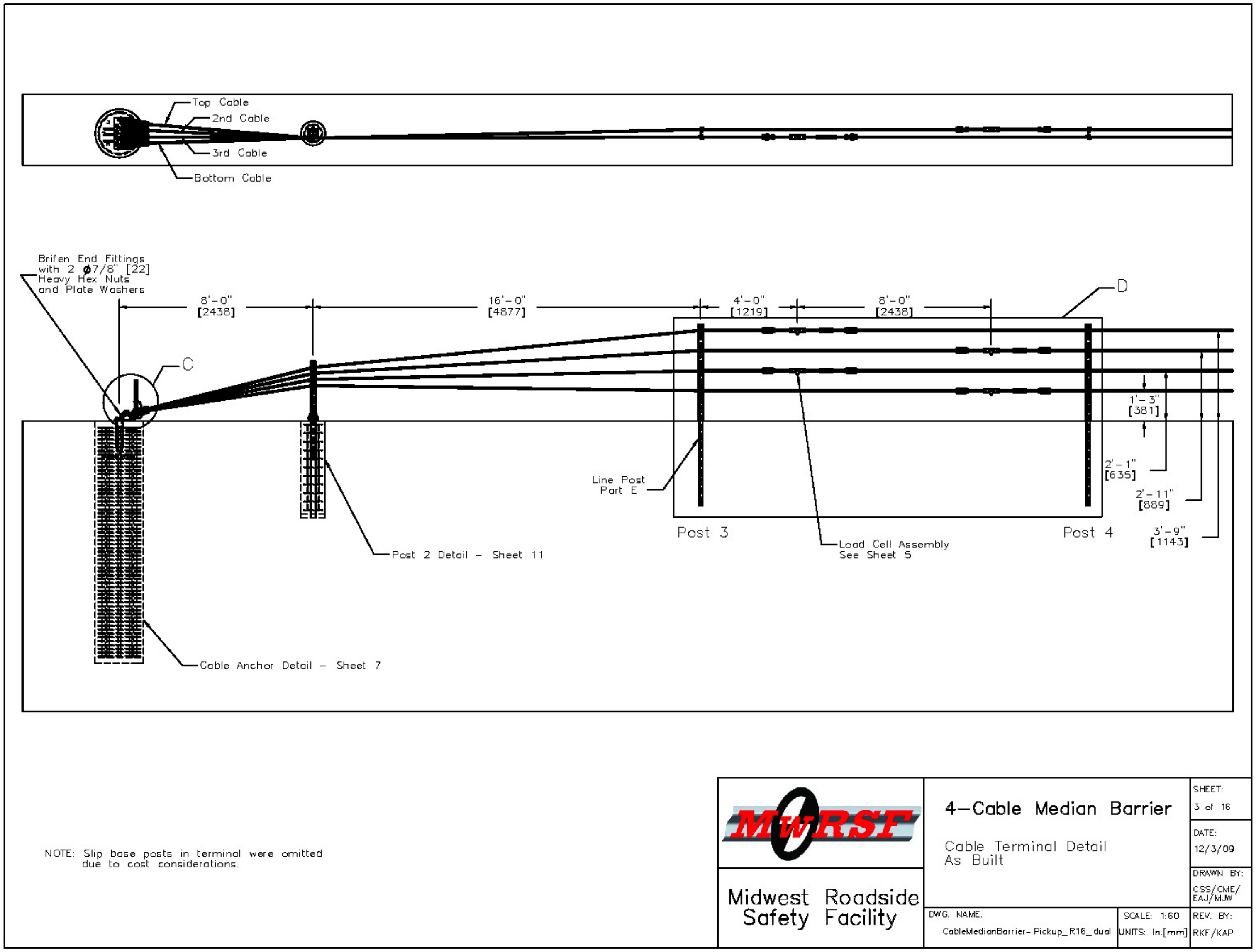


Figure 58. Cable Anchorage Details, Test No. 4CMB-1, 2007 [66]

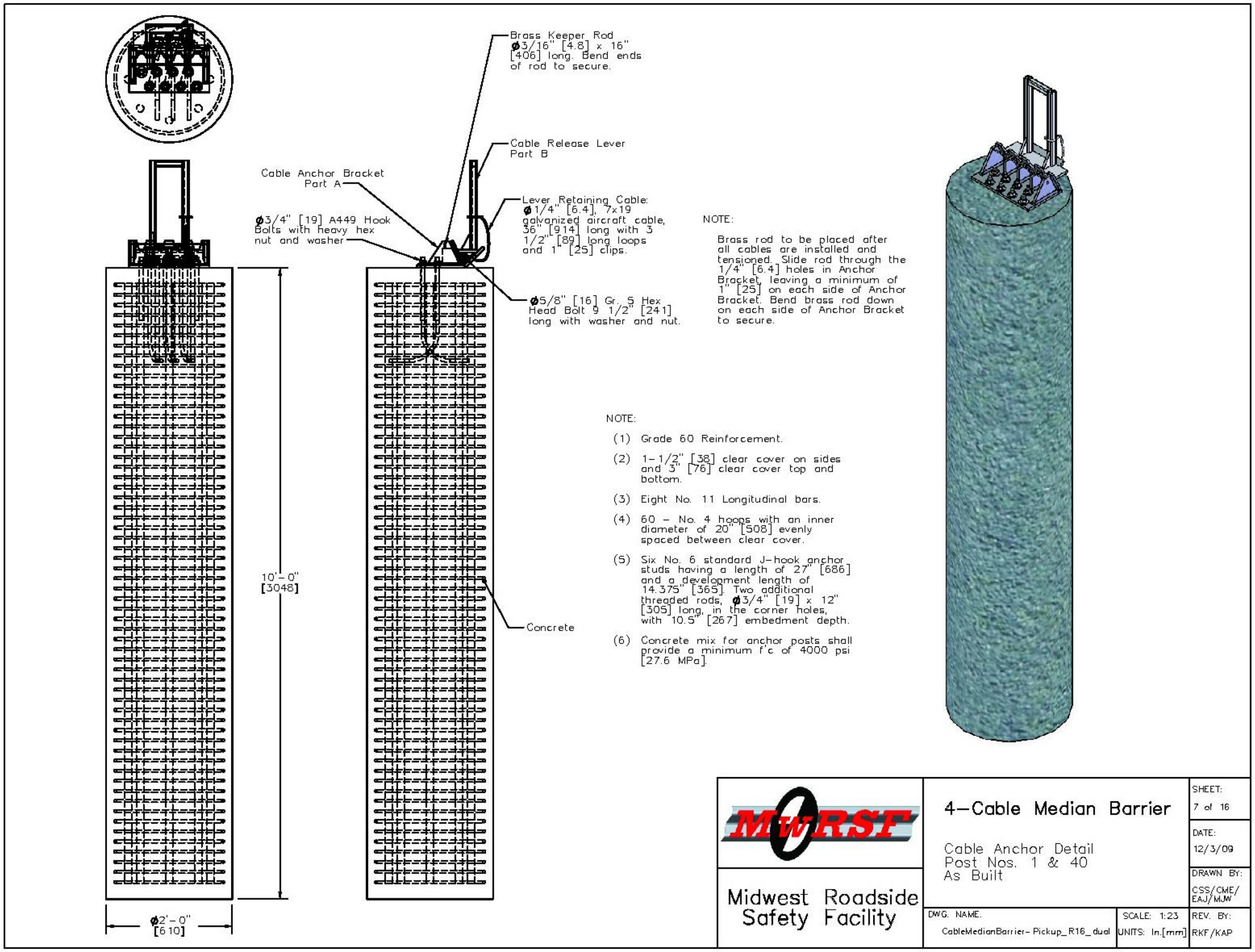


Figure 59. Cable Anchor Construction Details, Test No. 4CMB-1, 2007 [66]

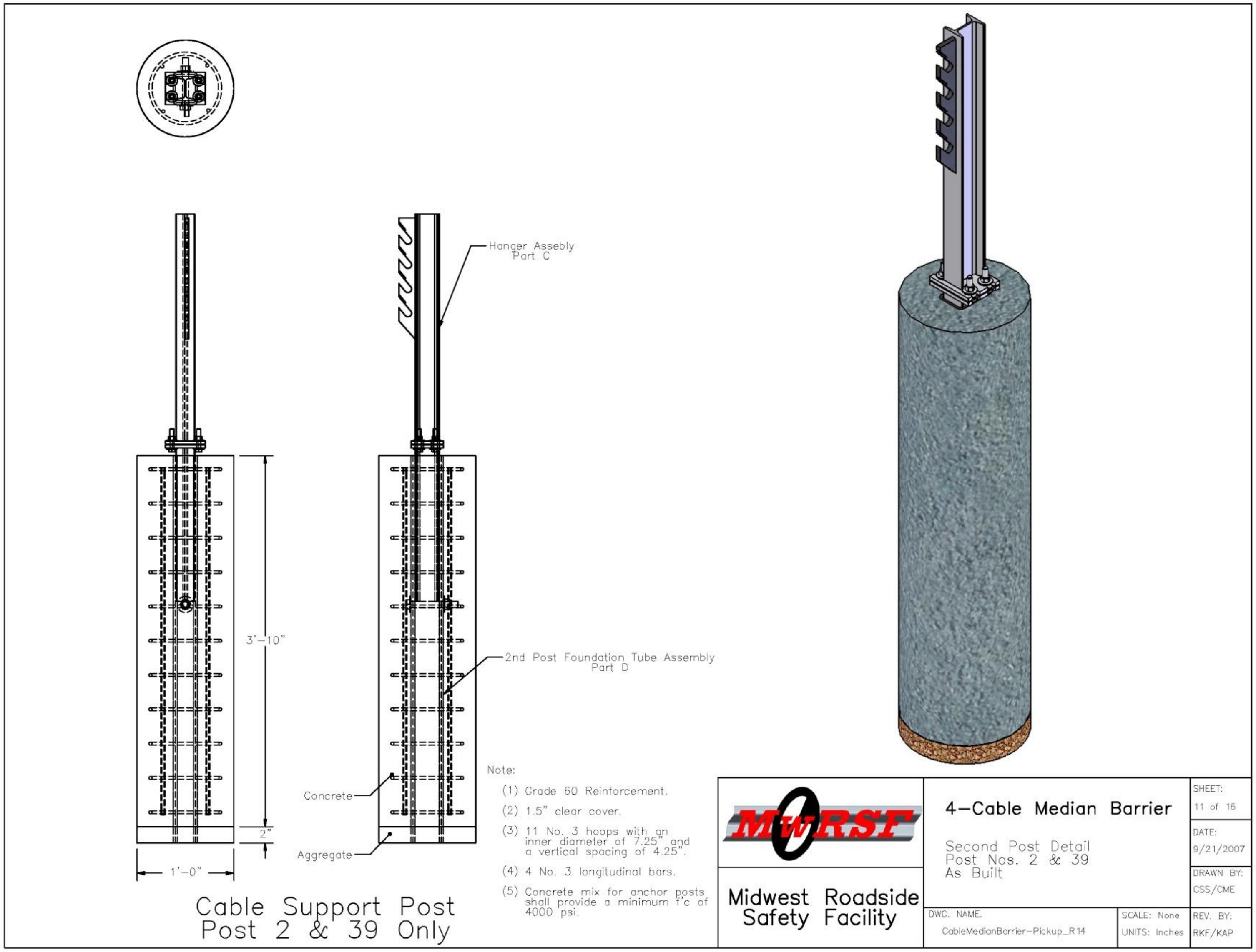


Figure 60. Cable Support Post Details, Test No. 4CMB-1, 2007 [66]

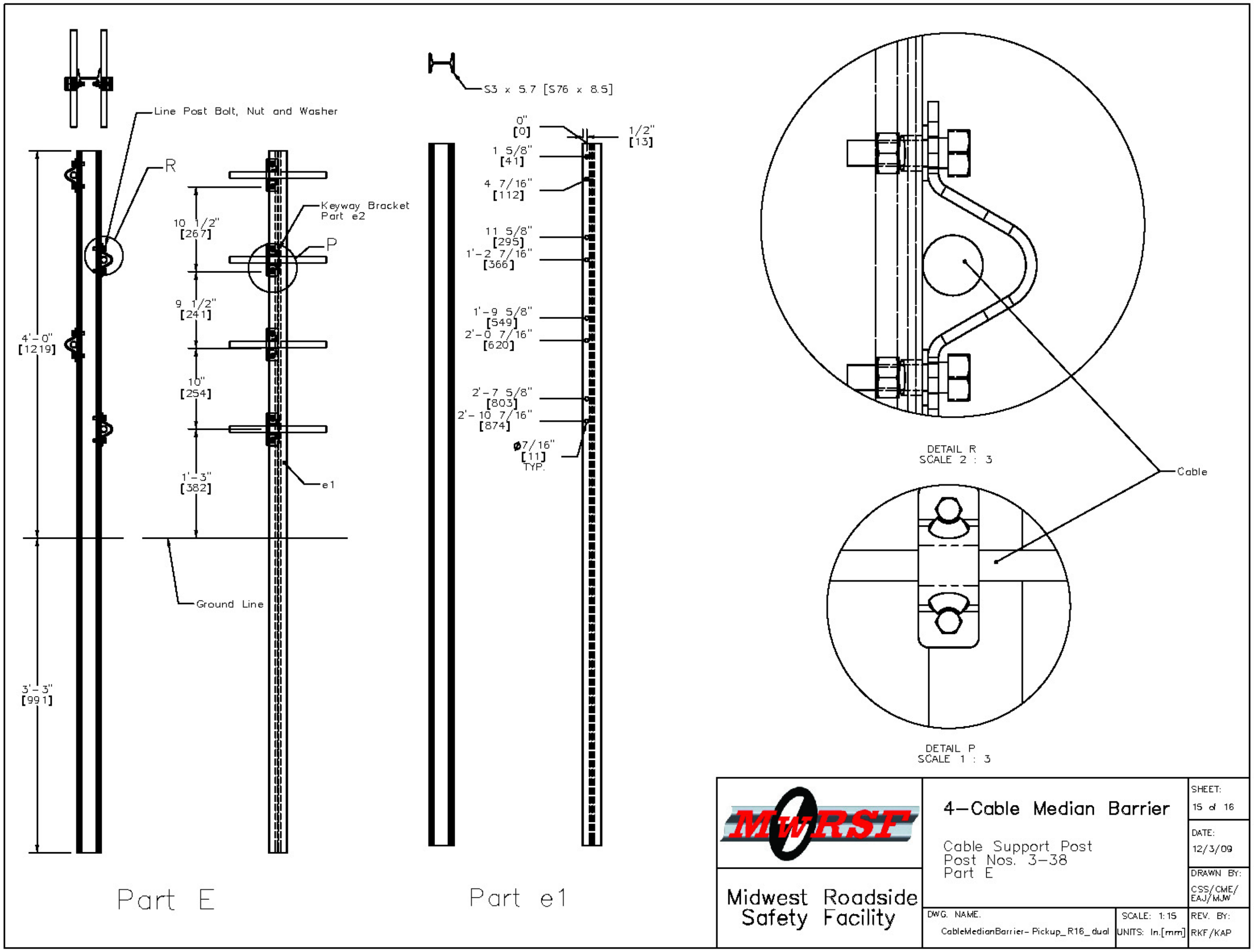


Figure 61. Post Details, Test No. 4CMB-1, 2007 [66]

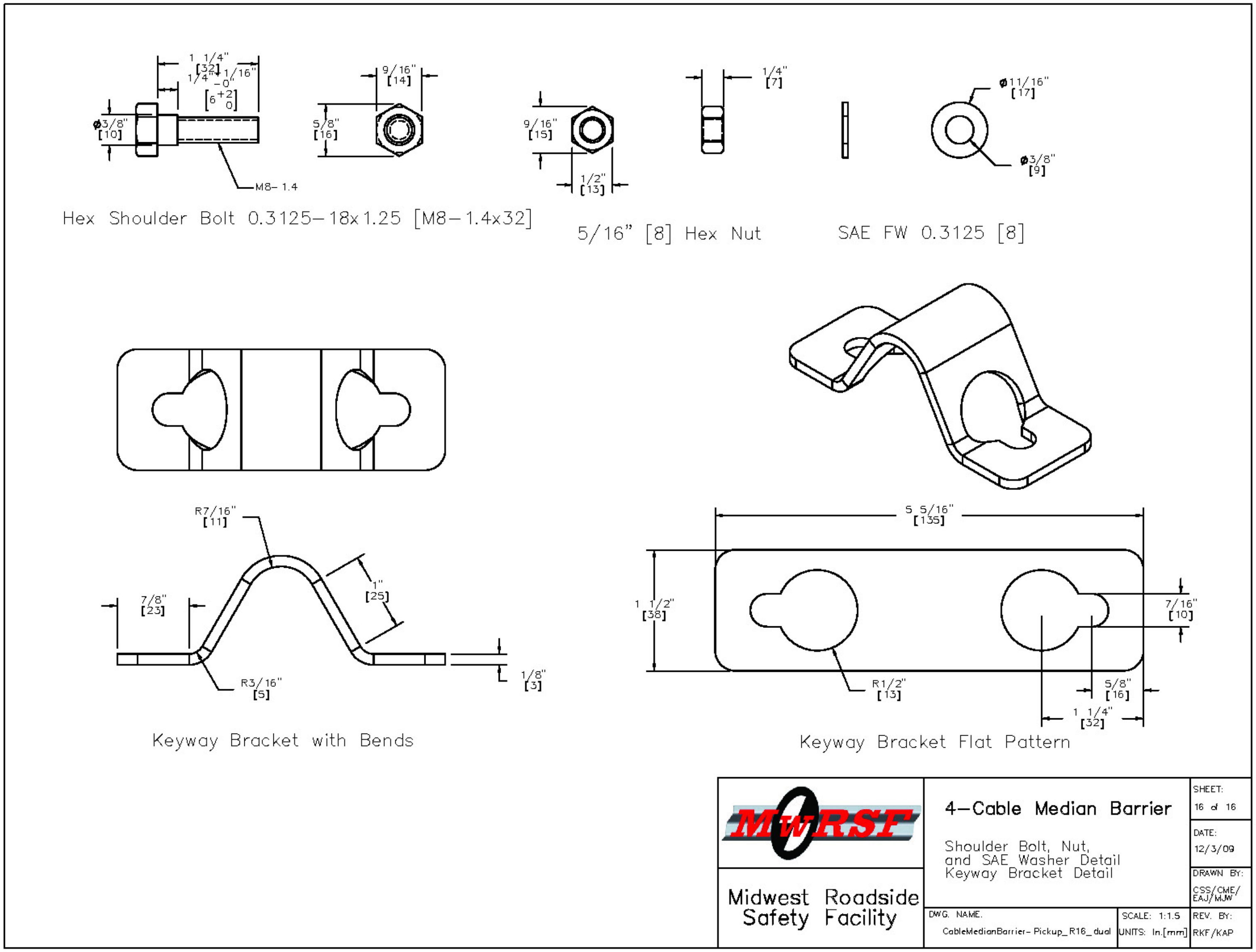


Figure 62. Cable Bracket Details, Test No. 4CMB-1, 2007 [66]

brackets, which were fastened to the flanges of the posts with two $^{5}/_{16}$-in. (8-mm) diameter hex bolts with nuts.

In test no. 4CMB-1, the system was installed 12 ft (3.7 m) from the SBP of a 4:1 slope in a 46-ft (14-m) wide V-ditch. A 2002 Dodge Ram, weighing 4,988 lb (2,263 kg), impacted the system at 61.8 mph (99.5 km/h) and 27.9 degrees. The pickup was captured and came to a stop in contact with the cable barrier system. During the test, the lower three cables were overridden and the top cable captured the vehicle.

The system was modified prior to test no. 4CMB-2 by increasing the embedment depth of the posts to 42 in. (1,067 mm) and shifting the cable guardrail system 4 ft (1.2 m) from the center of the V-ditch on the opposite side of the ditch from the vehicle (upslope). In test no. 4CMB-2, a 2002 Kia Rio, weighing 2,557 lb (1,160 kg), impacted at 62.8 mph (101.1 km/h) and 26.4 degrees. The vehicle became airborne as it entered the ditch, and impacted the ground in front of the barrier system. The vehicle was decelerated rapidly due to the front end plowing through the soil after the vehicle landed. All four cables extended over the vehicle's hood and contacted the windshield. The vehicle came to rest with all four cables resting on the vehicle's windshield and left-front A-pillar. The windshield was not damaged, and the vehicle was captured by the system, but occupant decelerations were high and a propensity for underride was observed.

The system was retested in test no. 4CMB-3 with highly-compacted soil in the impact region. In addition, cable spacing was increased to 10 $^{1}/_{2}$ in. (267 mm) and the top cable height was set to 45 in. (1,143 mm). The 2002 Kia Rio, weighing 2,586 lb (1,173 kg), became airborne as it entered the ditch at 62.0 mph (99.7 km/h) and 26.8 degrees and impacted the ground with the left-front corner of the vehicle. The vehicle made initial contact with the upslope of the V-ditch and decelerated rapidly, the front end of the vehicle pitched rapidly, and the bumper underrode the cables. The vehicle was captured by the cables, but resulted from grooves formed in the left-front A-pillar of the vehicle and windshield deformation beneath the cables. Thus, test no. 4CMB-3 was determined to be unacceptable according to the criteria presented in MASH.

5.2 National Crash Analysis Center, 2006-2008

The National Crash Analysis Center (NCAC) conducted full-scale crash tests in support of computer simulation efforts and to determine acceptable locations of cable guardrails installed on sloped terrains [68-69]. The crash tests were conducted with Ford Crown Victoria sedans impacting in sloped ditch configurations.

The guardrail system tested was a 3-cable median barrier design consisting of S3x5.7 (S76x8.5) steel posts spaced 16 ft (4.9 m) on center. The cables had mounting heights of 30 $^{1}/_{2}$, 25 $^{3}/_{4}$, and 21 in. (775, 654, and 533 mm). The design was consistent with the system crash-tested by TTI in test no. 404211-8. The system was installed on a 6:1 slope.

Test no. 04010 consisted of a Ford Crown Victoria impacting the guardrail system located 4 ft (1.2 m) from the center of the 6:1 V-ditch at 62 mph (100 km/h) and 25 degrees. The test vehicle underrode the cable guardrail system as the lower cable rose over the bumper and hood, allowing the test vehicle to penetrate the system.

Test no. 04011 consisted of a Ford Crown Victoria impacting the guardrail system located 1 ft (0.3 m) from the center of the 6:1 V-ditch at 62 mph (100 km/h) and 25 degrees. The test vehicle was redirected by the system and smoothly decelerated. It should be noted that the tests conducted in this study were not consistent with the evaluation criteria found in MASH, but instead the crash tests were used as demonstration tools to indicate the effects of improper cable barrier placement on slopes. Additionally, the use of the Ford Crown Victoria is not a standard test vehicle, and different vehicles will react differently to changes in barrier geometry, positioning, height, and strength.

6 CABLE GUARDRAIL SIMULATION EFFORTS

Many efforts have been taken to determine the cable guardrail performance under a variety of impact conditions using computer simulation. Early simulation efforts used 2-dimensional analysis to determine cable tension and transfer of motion to posts under impact for differing post strengths and cable mounting heights. More advanced efforts, mainly consisting of LS-DYNA simulations, were later conducted to determine the dynamic response of vehicles to cable guardrail systems using finite element analysis (FEA) software.

6.1 Historical Development, Prior to 1980

6.1.1 John Hopkins University, 1954-1956

Cable barrier impacts were simulated using scale models prior to the development of finite element analysis software and extensive use of the computer to solve analytical models for dynamics equations. Researchers at the John Hopkins University conducted a series of cable barrier simulation tests using rigid scale vehicles and rigid posts [70-72]. The cable barriers were modeled with variations in post spacings, rail tensions, vehicle impact velocities and impact angles, and frictional coefficients between vehicle tires and the ground. Though researchers did not conclude that scale model tests were acceptable for full-scale crash test substitution, scale models were concluded to offer insight into cable tension and vehicle reaction. Furthermore, redirection speeds and exit angles were correlated with post spacing and rail tension.

6.1.2 New York State Department of Public Works, 1967

Some of the earliest efforts using computer simulations of cable barrier reactions were conducted by NYSDPW in 1967 [13]. Researchers desired to quantify behavior of cable barrier systems under impact loading and develop a generalized model for predicting deflection and lateral force exerted by guardrail systems in impact loadings. The cable barrier system was classified as a “tension-only” system, meaning that the bending strength of the cable was assumed to be negligible. Instead, it was assumed that cable acted solely to redirect vehicles due to tension caused by deflections of the wire rope.

Mathematical models were formulated and simulated using five assumptions: (1) impacting vehicles are rigid bodies; (2) vehicle-barrier friction was negligible; (3) cable and post materials were elastic-perfectly plastic; (4) cable length between six posts was sufficient to redirect a vehicle; and (5) unloading from the maximum dynamic deflection to the permanent set followed a linear trend.

It was noted that the vehicle deformation is limited to a small scope relative to the vehicle’s dimensions, and thus the moment-of-inertia and vehicle dimensions are approximately constant, which validates the rigid body assumption. Since length of vehicle contact was important to estimating dynamic deflection and response, the length of cable between six posts was assumed sufficient to capture a vehicle. Thus when solving the numerical equations, the deflection of the barrier after the sixth post was assumed to be zero.

Results of the simulation were acceptable and closely resembled experimental data for the first 0.5 sec of test data. Researchers concluded that despite a lack of correlation of the deceleration data, the decelerations were likely less accurate since they were derived from a finite set of relatively few points tracked during impact and thus do not accurately represent the true vehicle decelerations. The model was believed to be generally representative of cable barrier impacts.

6.1.3 National Aeronautical Establishment (NAE) of Canada, 1967-1977

A generalized model of a cable barrier with definable curvature, post spacing, and cable heights was developed by the NAE of Canada in 1972 [21]. Researchers investigated full-scale crash test videos and analyzed vehicle redirection characteristics. It was concluded that unlike rigid or semi-rigid barriers, cable guardrail impacts generally resulted in very minor vehicle damage. Furthermore, the bending strength of the cable was very small with relation to its size, thus allowing researchers to investigate modeling the cable guardrail as a tensioned-wire system.

Three factors were believed to be critical in the vehicle redirection by cable barriers: cable height, post strength, and post spacing. Thus, the NAE model of vehicle impact into rigid and semi-rigid barriers was modified to accommodate impacts with cable barriers.

The vehicle crush algorithm in the NAE model was modified to reflect full-scale crash testing behavior. Since significant vehicle crush did not occur, calculations of crush and crush energy were removed. Instead, researchers utilized the idea of a three-point contact for cable barriers. It was observed that minor crushing occurred around the front fender of the vehicle, which ceased when the entire front corner was engaged with the cable barrier. The rear of the vehicle often also made contact with the cables, though damage was limited and often negligible. Thus, a 45 degree chamfer on the front corners of the simulated vehicles was used for constrained point contact, in addition to one point on the rear corner of the vehicle.

Tension in the cables was calculated based on a series of constitutive equations. Tension was related to deflection using the effective Young's Modulus of the material, whereby incremental elongations of the cables resulted in tension increases. Iterative equation solving was used to ensure answers were convergent. Wave speed propagation of the cable after releasing from one post was accounted for by ramping up the redirective load on the next post in line. The cable geometry itself was incrementally adjusted at each time step to accommodate the number of vehicle contact points, splitting each cable section into discrete lengths in contact with the vehicle and posts. Finally, Coulomb friction and kinetic sliding friction were used to transition tension in the cables to the surrounding posts and cable segments.

Post rotation through the soil was not investigated. Instead, the weak cable-post connection of a slotted top post was used to determine when cables released from the posts. The lateral resistance load at the cable height was estimated contingent with an input cable release load. If the cable load exceeded the cable release load, the cable was no longer restrained by the post. The lateral cable load was estimated by taking the tension in the cable multiplied by the sine of the angle between the cable near the vehicle and cable in the tangent line.

The model was also updated with features to estimate vehicle roll angle at each time step, so that the vehicle orientation throughout impact would be accurately treated. Terrain was an input function to permit evaluation of the cable guardrail system on sloped or rough terrain or adjacent to curbs. Additionally, a curvature parameter was implemented in the code to evaluate cable guardrail systems installed along curves.

Using the successful full-scale crash tests on wire-rope slotted post crash barriers [18], researchers modified the system details and conducted full-scale crash tests to verify the results of the simulations. In general, simulation results were consistent with the full-scale crash testing data. Roll, pitch, and yaw angles differed slightly in the simulations; this may be related to the impact with posts occurring in the full-scale tests, which did not occur in the simulated model. However, longitudinal and lateral CG locations, post release time, and cable tension were estimated accurately in the simulations, indicating its potential use in evaluating the slotted-post cable guardrail systems.

Additional simulation efforts were conducted in Canada at the NAE in 1977 [73]. Researchers examined factors affecting cable barrier performance, and determined that the interaction between vehicles and cable guardrail was dependent on seven critical parameters: (1) post spacing; (2) post strength and type; (3) cable tension; (4) cable height; (5) cable effective modulus; (6) degree of curvature; and (7) location relative to slopes. The cable effective modulus was defined by the elastic modulus multiplied by the cross-sectional area of the cable.

Computer simulations were conducted by varying the input parameters stated above. Several critical relations were observed as a result of the simulation studies. First, it was observed that cable-related parameters have greater correlation with cable tension, whereas post-related parameters, including cable mounting height, have a stronger correlation with system performance. Cable-related parameters included pretension, cable size, length, and number of cables. Post-related parameters included post spacing, cable mounting height, and post strength.

The cable length had the strongest correlation with cable tension. Changes in cable length due to impacts increased the tension less in long systems than in shorter systems. Temperature had a significant correlation with cable tension, as hot weather may cause cables to sag if the tension is not compensated by spring compensators. This was expected and could be analytically explained by approximating the cable as a rod. Increasing the temperature causes the rod to expand volumetrically, which leads to large extensional strains in the axial direction if the cable is very long. Similarly, contraction will occur if the cable is cooled by a reduction in temperature. Cable effective modulus has an effect on cable tension and strength, but less so due to small differences in stress for small changes in diameter.

The post properties with the greatest influence on cable barrier redirection were the post spacing and strength. Tight post spacing reduced deflections and increased vehicle exit angles, whereas long post spacings resulted in high deflections and small exit angles. Stronger posts reduced deflections at the risk of causing rollover to small cars.

Degrees of curvature and directions of curvature affected both dynamic deflection and vehicle dynamics. Exterior curvature of cable systems resulted in much higher tensile loads in the cable, but lower exit angles and speeds. By contrast, interior curves resulted in high exit angles and speeds and low dynamic tensions, though deflections were higher.

6.2 Parameter Simulation Models

Many organizations conducted cable barrier simulation efforts to determine the effects of cable system parameters on system performance. Most parameter evaluation studies were conducted to predict cable tension loads and cable deflections under varying impact conditions. Some simulation models were related to optimization of cable system components and arrangements, such as pretension, post spacing, and post properties.

6.2.1 University of Sheffield, 1998-2007

The University of Sheffield conducted several cable guardrail impact simulations using a mathematical model [74, 75]. Several key assumptions were made based on full-scale test results prior to modeling the vehicle-cable interaction. It was noted that the vehicle motion remained nearly planar during impact and that posts will deform both elastically and plastically prior to releasing the cables. Once the cables are released, the posts rebound elastically.

Researchers approximated the cable guardrail system as a series of connected bays. Bays were defined as the section of cable guardrail between adjacent posts. For robustness and simplicity, the rope was considered a segmented length of tensioned wire with uniform properties and no bending strength. The rope spanned each bay and was secured to rope in the adjacent bays.

Two frictional interactions were modeled in the study. To approximate the motion of the vehicle's tires, the wheels were assumed to have zero rolling resistance in the longitudinal direction and always point in the direction of the vehicle's longitudinal axis. Thus, only lateral friction was developed in the wheels corresponding to lateral force applied to the vehicle.

The second frictional method considered cables wrapping around posts. The friction between cables and posts was approximated as similar to a rope around a sheave, and followed the mathematical model

$$t_{\Gamma_1} = e^{-\mu\xi} t_{r_1}$$

t_{Γ_1} = frictional resistance at the post
$e^{-\mu\xi}$ = frictional coefficient
t_{r_1} = tension in the bay of the deflected cable

Here, ξ was the angle formed between the straight rope and the deflected rope, and μ was the static friction coefficient. When frictional resistance was overcome, the cables would slip past the posts at constant force in accordance with the stretch of the cable.

Post deflection was considered in cable release algorithms. With a known value of the bending resistance of the post, the normal force on the post was calculated based on the angle formed between deflected and undeflected cables in adjacent bays. When the post formed a plastic hinge, due to normal load exceeding the bending capacity of the post, the cable was released. Upon cable release, the simulation was paused and the rope was adjusted to a new quasi-static tension in pseudo time prior to continuing the simulation. When multiple cables were used, force resultants based on forces from each cable were used to calculate post deformations and cable release.

Rope wave motion phenomena, which caused cables to release from the tops of the posts in impact tests, were modeled as a double-leg system. The vertical wave was transmitted in only the top cables to the adjacent posts in the bays based on the longitudinal wave speed equation:

$$c = \sqrt{\frac{T}{\rho}}$$

c = wave speed
T = tension
ρ = density

for c the wave speed, T the tension, and ρ the effective density of the cable. Each vertical wave was assumed to reflect once off of the adjacent post, then off of the vehicle, prior to causing cable release from the top of the post. The wave then traveled toward the vehicle, was reflected, and the process was re-initiated for the next post.

Two simulation programs were developed as a result of the study, a prototype Brifsim1 and an updated Brifsim2. Each incorporated the ability to vary post properties, cable weaves, and systems lengths. The simulations were effective in predicting vehicle reaction under dynamic loading.

A follow-up study was conducted by the University of Sheffield in 2007 [48]. Nominal friction values for the tire-ground, cable-vehicle, and cable-post interaction were provided. Since tire friction with the ground was relatively insensitive to frictional coefficient, a coefficient of 0.8 was recommended without further investigation. Additionally, frictional coefficient of the cable with respect to the post was also found to have little effect on predicted system performance, so a value of 0.17, derived by Bateman in the study of MIRA impact test no. L1016, was used.

Cable-vehicle frictional interaction with the vehicle did have an effect on the results. During impact, the cables form grooves in the sides of test vehicles and may cut into the sheet metal. This effect is more pronounced in larger vehicles with thin exterior sheet metal. The friction for the gouging and creasing effect is comparable to simple sliding friction with little deformation (i.e., kinetic friction). Thus, for light vehicles, a frictional coefficient of 0.2 was recommended, with coefficients of 0.3 and 0.4 recommended for medium-sized and large vehicles, respectively.

The schematic simulations were compared with test results from 12 impact tests conducted at MIRA and a Swedish testing organization. Correlation of dynamic deflection and results of the simulations indicated that a maximum difference of -18 percent and an average difference of -3.5 percent occurred. Prediction of post collapse indicated that the simulation could accurately predict the number of posts damaged in an impact event. Thus, the Brifsim2 was validated for use in iterative evaluation of the wire rope safety fence on level terrain.

6.2.2 LB International PTY LTD, 2002

The LB International PTY LTD company, based in Australia, conducted a review of past tests on the WRSF systems conducted by Bridon Ropes [76]. The designs consisted of a two-rope in post slot design, similar to that tested in the 1960s, a four-rope in post slot design, and a four-rope design with two ropes in slot and two ropes in side-mounted brackets. Cables were weaved between each post, and were tested in a variety of lengths and rope tensions.

The simulations of the LB International PTY LTD were conducted with the same simulation procedures used by the University of Sheffield. The bay analysis with woven and straight ropes was considered, and a variety of system lengths were simulated for deflection analysis. Additional deflection-sensitivity simulations were conducted to evaluate what dynamic deflections would be expected, based on impact position along a fence.

For four-rope, high-tension systems with lengths between 1,522 ft (464 m) and 6,562 ft (2,000 m), woven systems had a constant deflection of nearly 4.9 ft (1.50 m). Systems with straight ropes had a small linearly increasing deflection of up to 7.4 ft (2.25 m). Similar analyses were conducted with three-rope systems and different post spacings.

Simulations were also conducted to determine the tension distribution throughout the wire ropes. Since linear translational friction was not present in the parameter simulation tests, the tension in the straight-rope systems was constant throughout the system length except in the impact zone. By contrast, the woven-rope system had a location-specific tension that was in excess of 18.4 kips (82 kN) on a 1,640-ft (500-m) long system. Longer system lengths were typical of the tension distribution in the 1,640-ft (500-m) long system. Further, it was determined that the woven fence limited tension differences in the system to 140 bays, equivalent to 1,102 ft (336 m), based on 8-ft (2.4-m) post spacing.

6.2.3 Midwest Roadside Safety Facility, 2006-2009

From 2006 to 2009, a series of benefit-to-cost simulations were conducted on cable barrier placement in medians of a variety of widths to determine cost-effective cable median barrier placement guidelines [77-78]. Accidents from Kansas records were analyzed in a benefit-to-cost analysis program to determine appropriate placement and installation guidelines. The guidelines were observed to be similar to the recommendations found in the AASHTO Roadside Design Guide of 1977 [79]. It should be noted that all simulation efforts in this respect were limited to cost-effectiveness analysis and the behavior of the wire rope was approximated in terms of probability of deflection vs. penetration or underride, as well as safety benefits from usage of cable barriers in wide medians.

6.3 Finite Element Analysis

6.3.1 Midwest Roadside Safety Facility

Cable modeling has been conducted on an as-needed basis to predict vehicle interaction with cable barriers for several full-scale crash tests. Finite element models were also used to simulate smaller-diameter cable use in bullnose median barrier applications [80-81], short-radius guardrail applications [82], as well as cable barrier installations. A new wire rope model for cable barrier system simulations was also created [83].

The first finite element models simulated by MwRSF were focused toward development of finite element models of cable guardrail system components. A detailed study evaluating the finite element model of $^{5}/_{16}$-in. (8-mm) diameter hook bolts was undertaken to determine the optimum post bolt cross-sectional construction for use in cable guardrail applications [84]. A total of 21 component tests were conducted to consider bolt strengths when loaded vertically upward and horizontally in a "pull-out" load condition. Then, finite element (FE) models were created to simulate the behaviors observed.

Six different cross-sections were evaluated, as shown in Figure 63. The cross-sections had 5, 8, 9, 12, 32, and 48 elements. It was observed that with increasing numbers of elements, the strength of the hook bolts increased in the vertical load test. Though increasing the mesh density typically reduces the strength of the components, the cross-sectional areas of the hook bolts were more accurately modeled with a finer discretized mesh. Simulations conducted with the 9- and 12-element cross-sections were similar, as were the 32- and 48-element cross-sections. Based on a timestep analysis and vertical pull-out loading evaluation, it was determined that further analysis was required to determine the adequacy of a post-bolt model.

In support of the cable terminal development project conducted by MwRSF, Reid and Hiser conducted a series of simulations on the effects of friction with relation to solid elements in slippage conditions [85]. It was observed that solid elements have a tendency to "catch" when relative motion between solid elements occurs. Further, since the penalty method requires finite penetrations to calculate surface pressures and forces, nodes in the elements at sharp corners of

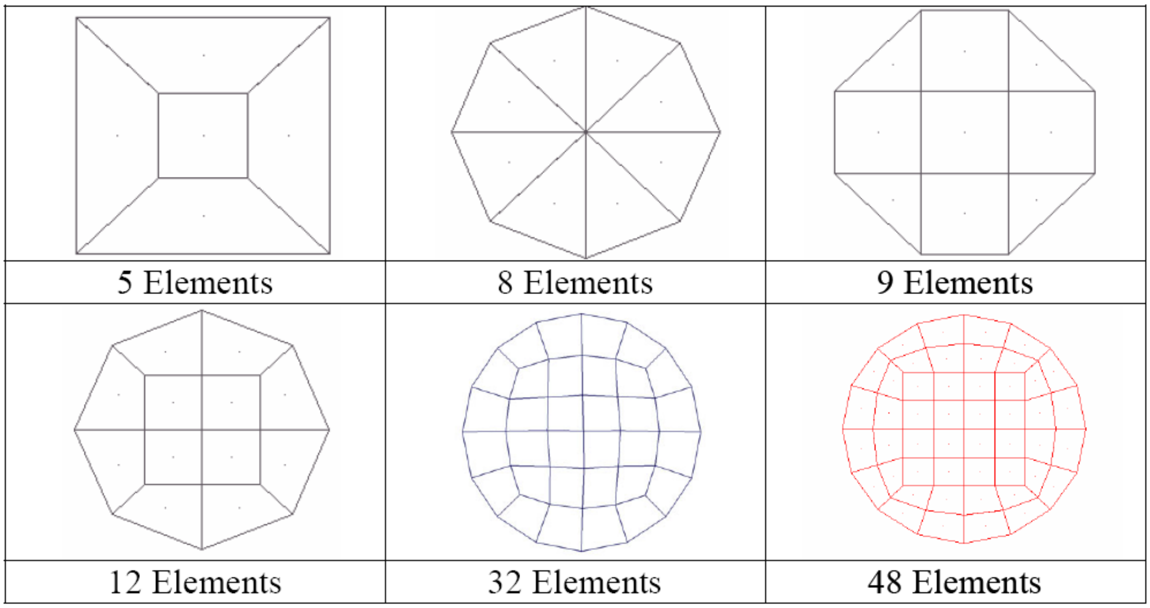


Figure 63. Cross-Sections Modeled for Hook Bolt Simulations, 2002

sliding parts have a tendency to contact element boundaries within a part and become wedged. Smoothing of sharp corners resulted in substantially-improved sliding behavior.

In addition to the frictional tripping mechanism investigated, researchers also investigated the effects of different frictional slip coefficients. LS-DYNA permits the use of a frictional relation given by

$$f = N\mu = N[\mu_d + (\mu_s - \mu_d)]e^{-Cv}$$

f = frictional force
N = normal force
μ = friction coefficient
μ_d = dynamic frictional coefficient
μ_s = static frictional coefficient
C = decay coefficient
v = relative velocity between surfaces

Varying static and dynamic frictional coefficients, as well as decay coefficients, were investigated to determine relation between static and kinematic friction definitions.

The frictional modeling results were used extensively in the development of a slip-base post for cable guardrail terminal using LS-DYNA [86]. Following the failure of test no. CT-2, cable terminal components were modeled to analyze the terminal impact. The first cable terminal component developed was the slip-base cable support post, or post no. 2.

The slip-base post consisted of a 30-in. (762-mm) long S3x5.7 (S76x8.5) post with a welded slip plate mounted on a 72-in. long (W152x13.4) (1,829-mm) W6x9 foundation post. The slip configuration consisted of four $^{1}/_{2}$-in. (13-mm) diameter bolts through the upper and lower slip plates with washers separating the bolt head, upper slip plate, lower slip plate, and nut. The bolts were torqued to 26 ft-lb (35 N-m). Slip post details are shown in Figure 55.

To test the frictional values for the slip plate and the slip mechanism, a test fixture was created with similar dimensions to the slip plate. Two plates were clamped with a $^{1}/_{2}$-in. (13-mm) diameter bolt torqued to 26 ft-lb (35 N-m) with washers separating the bolt head, outer plate, inner plate, and nut. The force required to initiate slip and the displacement of the plates were measured to determine the slip response as a function of displacement and velocity.

The results from the bolt slip testing were simulated using two methods. The first simulation method pre-tensioned the bolt using a discrete spring element, with an initial tension adjusted so that the resultant tension was correct, and the second bolt tension method which utilized a prestressed bolt. While both methods resulted in acceptable accuracy in slip forces generated, neither followed a linear decreasing friction force trend at the bolt release, as observed in physical testing. The linear decreasing trend in frictional response was captured using deformable washers with the stress-based clamping design. However, this resulted in a 91 percent increase in computational time.

The slip-base post was simulated using both the discrete-based clamping (DBC) and stress-based clamping (SBC) bolt preloading methods. Simulation component testing was conducted to determine which method, if any, would accurately capture the slip-base behavior of the post. Lateral impacts of the slip post resulted in acceptable performance of both methods, but a high-moment impact at the bumper height of a car resulted in wedging action of the rigid washers with the DBC method. This caused the slip base to lock up.

Further simulation of an impact at the post flange indicated bolt and washer locking in the DBC method due to bolt deformation and ultimate rupture, but acceptable behavior in the SBC method. The rigid bolt and washer locked due to high normal forces exerted at the edges of the bolt head and washer, preventing clean release of the DBC bolts. However, small deformations of the bolt shaft with the SBC method resulted in acceptable performance. Thus, the SBC method was used for the slip post modeling.

After generating a finite element model of the cable anchor bracket and end fittings for the first post in the cable terminal system, the system was tested in head-on impact conditions [87-91]. The first test conducted on the system consisted of a surrogate test vehicle impacting the cable release lever to disengage the cables. Contact definitions used in the cable release lever impact consisted of a global *CONTACT_AUTOMATIC_SINGLE_SURFACE definition, with frictional coefficients of 0.74 and 0.5 for static and dynamic cases, respectively, and a decay coefficient of 1.0. Due to modeling instabilities and excessive deformations of the terminal components not witnessed in the bogie testing, the friction values were shifted to the *PART cards for individual treatment.

The simulated cable consisted of beam elements with an outer “coating” of solid elements to improve contact definitions and give some stiffness to provide bending strength. The beam elements were assigned properties representative of cable, while the solid elements forming the octagonal ring were defined with the contact definitions. However, the solid ring of the cable snagged on the shell elements used to represent the cable hanger, so the hanger was redefined with rigid, solid elements.

Iterative tests with the welds on the cable anchor bracket were also required to capture the rupture of the welds in the anchor bracket under the cable release lever. It was found that modeling the fillet welds with an ultimate strain of 0.06 resulted in acceptable tear-away and release of the cable release lever. The modified model was retested and the surrogate test vehicle results were acceptable.

To further validate the cable terminal model, test nos. CT-1 and CT-2 were simulated for comparison with the end terminal behavior. The CT-1 simulation resulted in similar bending deformations and accelerations in the first stages of impact compared with the full-scale test results. Furthermore, the cable terminal released the cables and reacted similarly to the full-scale testing in test no. CT-2. Thus, the simulation of impact behavior of the first two posts in the cable terminal was judged to be acceptable.

Additional simulation efforts were undertaken to simulate the unacceptable behavior of test no. CS-1. The model consisted of a Chevrolet C2500 pickup impacting the cable guardrail system at 62.1 mph (100 km/h) and 25 degrees. Posts were modeled with shell elements embedded in a “soil tube” with soil springs to simulate post-soil interaction. The tripping mechanism observed in test no. CS-1 was replicated and accurately modeled.

The model was updated prior to test no. CS-2, which was conducted with an 8-ft (2.4-m) post spacing placed 4 ft (1.2 m) from the break point of the 1.5:1 slope. In the simulation, the pickup impacted the cable guardrail system and was redirected smoothly with little tendency to roll or override the cable. Full-scale test results for test no. CS-2 confirmed the results of the simulation, indicating a good correlation.

6.3.2 National Crash Analysis Center, 2006-2008

NCAC conducted two full-scale tests and several simulations of low-tension three-strand barriers in median configurations [68-69]. A full-scale crash test model, incorporating posts, cable hook bolts, and cables, was simulated under impact conditions in order to represent an impact with a cable median barrier. The cables were modeled using beam and shell elements. Beam elements formed the center of each cable and were defined with type 1 (Hughes-Liu) elements. Cross-sectional bending properties approximated a solid $^3/_4$-in. (19-mm) diameter rod. The cable was modeled with a linear elastic material model, with an elastic modulus of 12.3 Mpsi (85 GPa), a Poisson's ratio of 0.30, and a density of 286.4 lb/ft^3 (4,587 kg/m^3). Cables were surrounded with a hexagonal mesh of shell elements with null material, constrained at each beam node with nodal rigid body definitions. The element lengths were 1.57 in. (40 mm) long. The posts were comprised of shell elements, and a Lagrangian mesh was used to simulate the post-soil interaction using a cylindrical solid soil mesh. Hook bolts were simulated using solid elements with discrete clamping to the post to simulate bolt preload.

Initial impact simulations with the cable guardrail system resulted in core dumps due to contact instabilities using the *CONTACT_AUTOMATIC_SINGLE_SURFACE definition. Researchers determined that the single-surface contact permitted free edges of shell elements to “catch” the null shells around the cable, resulting in snagging and shooting nodes. Contact definitions were redefined with *CONTACT_AUTOMATIC_NODES_TO_SURFACE, which resulted in better cable-vehicle interaction. The *CONTACT_AUTOMATIC_GENERAL definition was also successfully implemented.

Sliding contacts were defined between the cable posts and the soil to model the pull-out of posts during some impacts. All other contact definitions were treated with standard contact algorithms to simplify the simulations.

The test of the Washington 3-strand cable median barrier conducted at TTI was simulated using the cable posts, cables, hook bolts, and soil meshes. The simulations were tuned until the model accurately reflected the full-scale testing, both in vehicle redirection and system reaction. Once the model was validated, researchers examined median barrier placement in medians.

Bumper trajectories of three vehicles were simulated and evaluated for vehicle departures into V-ditch medians with 6:1 side slopes. The three vehicles evaluated were a Ford Crown Victoria sedan, a Mitsubishi Mirage small car, and a Chevrolet C2500 pickup. The trajectories of the vehicles were simulated using Human Vehicle Environment (HVE) software package and evaluated under a variety of impact speeds and angles. Based on the evaluations, it was observed that the vehicle bumpers of most small vehicles and sedans would underride a cable barrier when placed 4 ft (1.2 m) from the center of the V-ditch on the upslope, but vehicle bumpers were within the cable heights when the system was installed 1 ft (0.3 m) from the center of the median on the upslope side.

The finite element model of the cable guardrail system was modified by spacing the cables 6 in. (152 mm) apart, rather than the 4 $^{3}/_{4}$-in. (120-mm) spacing used in the Washington system. Lower cable mounting heights were identical for both systems. The modified system was simulated in an impact event with a Ford Crown Victoria impacting the system 4 ft (1.2 m) from the center of the V-ditch with 6:1 side slopes. The vehicle underrode the barrier and climbed the upslope of the V-ditch with virtually no redirection.

The system was modeled again with the 3-cable median barrier located 1 ft (0.3 m) from the center of the ditch on the upslope, and the test vehicle was satisfactorily contained. The test vehicle was redirected by the system.

Two full-scale tests were conducted to validate the results of the simulations, and it was observed that the full-scale tests reacted similarly to the simulations. The vehicle underrode the barrier when the cable system was installed 4 ft (1.2 m) from the center of the ditch on the upslope, but was contained when installed 1 ft (0.3 m) from the center of the ditch on the upslope. Thus, the finite element model was determined to be successful in predicting the redirection of vehicles based on the V-ditch geometry.

NCAC also conducted simulation efforts to determine the effects of end anchor spacing, cable pretension, and number of cables used in guardrail systems to determine the deflection limits of cable systems [92]. It was desired that a finite element model be constructed to consider the deflection of cables in the Brifen WRSF in straight and weaved system configurations.

The WRSF was modeled to resemble the tested system. Post sleeves, concrete, and soil were modeled to capture the post behavior in the ground. Posts were modeled with shell elements and defined with contacts and friction to the sleeves and the concrete. The cables were modeled with beam elements to form the cross-section, each with properties approximating a $^3/_4$-in. (19-mm) diameter 3x7 cable. Around the cable, shell elements with null properties were used to improve cable contacts and were constrained by the beam element nodes via nodal rigid body definitions. The beams were prestressed according to the evaluated tension in the cables.

The finite element model of the WRSF was simulated in impact conditions with a pickup and small car to validate the model. Post configurations and cable mounting heights were consistent with those used in the full-scale tests. The simulations were validated against the full-scale models, and modeled with additional modifications for further evaluations.

Simulations were conducted to evaluate weaved vs. straight cable configurations of the WRSF. The weaved systems had smaller deflections on average than the straight cable systems. Furthermore, the weaved cable system had a limiting deflection which occurred with system lengths of 984 ft (300 m) or longer, whereas the WRSF with straight ropes did not reach a maximum value until a system length of 3,281 ft (1,000 m).

Cable tensions affected the dynamic deflection of the system. Simulations were conducted with cable tensions at 3,370 lb (15 kN) and 5,400 lb (24 kN) resulted in reductions to the dynamic deflection. The total reduction was between 0.7 and 2.0 percent for an increase in pretension of approximately 1,000 lb (4,448 N). This occurs because the lateral redirective force is related to the sine of the angle formed between the deflected and undeflected cables, which is typically small in impact events. Researchers postulated that low-tension cable guardrail systems typically underwent higher deflections on impact due to the weak cable-post connections, permitting the cables to release from the posts under small dynamic loads. By contrast, the high-tension systems have stronger cable-post connections, thereby reducing the release of the cables from many posts.

The final evaluation was conducted with three-cable and four-cable versions of the WRSF. As expected, the three-cable system underwent larger deflections for the same system lengths than four-cable systems. Researchers observed that in the four-cable system simulations, three cables typically would engage the vehicle. By contrast, in the three-cable simulations, only two cables typically engaged the vehicle. Since the impact loads were distributed between the cables which engaged the test vehicle, a higher resultant force applied from more cables occurred even though the forces in the individual cables were reduced. This led to a reduction in dynamic deflection of approximately 8 percent when a four-cable system was evaluated over a three-cable system.

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

More than 200 cable guardrail crash tests have been conducted since the 1950s worldwide, and efforts to improve modeling accuracy of simulated cable guardrail systems is underway. Researchers throughout the world have sought to develop crashworthy, cost-effective cable guardrail systems that result in low occupant risk, minimal system damage, and low-cost maintenance for transportation agencies.

Many cable barrier systems were successfully tested to meet the performance criteria presented in TRC 191, NCHRP Report 230 and 350, or MASH. Transportation agencies and producers of wire rope have also evaluated cable systems to international guidelines, but several systems have been approved for use in the United States. A list of FHWA acceptance letters provided for cable guardrail systems is shown in Table 5. A list of FHWA acceptance letters provided for cable guardrail end terminal systems is shown in Table 6. The acceptance letters may be viewed on the FHWA website.

While the results of full-scale crash tests are known, a comprehensive evaluation of cable guardrail accident statistics has never been conducted. Vehicles used in full-scale crash testing according to federal safety guidelines are generally specific makes with similar geometries. However, vehicles involved in real-world accidents with cable guardrail systems vary significantly in front-end geometry, weight, CG height, bumper height, hood height, and wheelbase. Some of these vehicles may be more susceptible to underride, override, or penetration through cable guardrail systems than the vehicles used to evaluate systems according to guidelines provided in the reports noted above. Accident statistics will lead to better understanding of an estimated severity index for cable guardrail impacts, which may be utilized in such cost-effectiveness analysis programs as the Roadside Safety Verification and Validation Program (RSVVP).

Lastly, improved models for cable guardrail systems are currently under development at MwRSF. Researchers hope that the research leads to a validated model of $^{3}/_{4}$-in. (19-mm) diameter 3x7 wire rope which may be extended to many impact situations. As the accuracy of the wire rope model increases, simulations may become increasingly more accurate and may better resemble physical phenomena. Furthermore, validation of the new cable model may reduce future time spent validating base models of cable guardrail systems. These advancements may assist in the development of the four-cable high-tension guardrail system which may be installed at any location in a 4:1 V-ditch.

Table 5. FHWA Acceptance Letters for Cable Guardrail Systems

Letter No.	Acceptance For:	Submitted By:	Date Accepted	No. Full-Scale Tests	NOTES:
b64	TL-3 Status SGR01a-b	N/A	2/14/2000	N/A	Acceptance of tested systems proven to be crashworthy
b64sup	TL-3 Status SGR01c (G1c) plus additional 3-cable median	N/A	9/12/2005	N/A	Acceptance of tested systems proven to be crashworthy
b82	Brifen WRSF @ TL-3	Brifen Ltd	4/10/2001	2	
b82b	Brifen WRSF @ TL-4	Hill & Smith Ltd	3/27/2005	2	
b82b1	Brifen WRSF @ TL-3 on 4:1 Slope	Hill & Smith Ltd, SwRI	5/9/2006	3	Placed 4 ft from SBP
b82c	3-cable version of Brifen WRSF @ TL-3	Hill & Smith Ltd, SwRI	5/26/2005	4	
b82c1	Reduced post spacing, short length of 3-cable Brifen WRSF	Hill & Smith Ltd, SwRI	4/13/2006	2	
b88	4-strand Safence @ TL-3	Blue Systems AB	7/13/2001	2	
b88a	4-strand Safence @ TL-3 for roadside applications	Safence, Inc	1/28/2004	2	
b88b	4-strand Safence @ TL-3 with posts set in concrete footings	Blue Systems AB	6/8/2004	0	
b88c	4-strand Safence @ TL-3 with alternative posts (C-channel)	Safence, Inc	5/26/2005	2	
b88d	3-strand Safence @ TL-4	Safence, Inc	12/27/2006	2	
b88e	4-strand Safence @ TL-4 with different cable heights	Safence, Inc	7/31/2007	0	
b96	Marion Steel U-channel posts with cable	Nucor Steel Marion Inc	8/30/2002	1	
b96a	2 variations on 3-strand MS U-channel post systems	Nucor Steel Marion Inc	10/12/2005	2	
b119	CASS 3-strand system	Trinity Highway Safety	5/13/2003	1	
b119a	CASS 3-strand system with 5m post spacing	Trinity Highway Safety	5/13/2003	1	
b119b	CASS 3-strand system with 2m post space with conc footings	Trinity Highway Safety	8/28/2003	1	

Table 5 (cont). FHWA Acceptance Letters for Cable Guardrail Systems

Letter No.	Acceptance For:	Submitted By:	Date Accepted	No. Full-Scale Tests	NOTES:
b137	High-tension 3-cable Gibraltar	Gibraltar	6/13/2005	2	
b137a	High-tension 3-cable Gibraltar @ TL-4	Gibraltar	9/9/2005	1	
b137a1	High-tension 4-cable Gibraltar @ TL-4	Gibraltar	10/27/2006	0	
b137b	High-tension 3-cable Gibraltar @ TL-4 with socketed posts	Gibraltar	4/3/2006	1	Alternative post spacings: 10 ft and 30 ft
b137c	High-tension 4-cable Gibraltar @ TL-4 with lower post terminated	Gibraltar	2/8/2008	0	
b141	Modified CASS @ TL-3 and TL-4 with S4x7.7 posts	Trinity Highway Safety	11/17/2005	2	
b141a	Modified CASS @ TL-3 and TL-4 with S4x7.7 driven posts	Trinity Highway Safety	5/2/2006	1	
b141b	CASS on 32.5' post spacing	Trinity Highway Safety	5/8/2006	1	
b147	Cable guardrail (G1) transition to W-beam guardrail, also CASS	Trinity Highway Safety (MwRSF testing G1)	5/8/2006	3	
b147a	Gibraltar TL-3 and TL-4 transition to W-beam	Gibraltar	6/16/2006	0	
b157	CASS terminal and barrier	Trinity Highway Safety	4/24/2007	0	
b161	4-strand version of generic 3-strand cable guardrail	NYDOT	7/12/2007	0	
b162	Nucor Steel post for use in guardrail systems	Nucor Steel Marion Inc	9/11/2007	3	
b167	TL-4 Nucor Wire Rope Barrier	Nucor Steel Marion Inc	1/24/2008	2	
b183	Nucor Steel Flanged U-Channel Post in Various Socket Types	Nucor Steel Marion Inc	11/26/2008	2	
b184	Revised hanging clip for Nucor Steel posts	Nucor Steel Marion Inc	12/9/2008	0	
b184a	Design deflection distance for Nucor Steel Marion cable guardrail system	Nucor Steel Marion Inc	9/23/2009	1	
b193	Nucor Steel Marion guardrail on 4:1 slope	Nucor Steel Marion Inc	7/27/2009	3	

Table 6. FHWA Acceptance Letters for Cable Guardrail End Terminal Systems

Letter No.	Acceptance For:	Submitted By:	Date Accepted	No. Full-Scale Tests	NOTES:
cc12n	Modified Cable Release Post	TTI	6/15/2005	0	
cc63	New York Standard 3-cable guardaril	NYDOT	2/14/2000	12	
cc76	3-strand guardaril terminal	TTI	8/29/2002	1	
cc86	Brifen gating terminal	Hill & Smith Ltd	1/28/2004	4	
cc86a	Optional End Anchor for Brifen gating terminal	BRIFEN USA, Incorporated	8/10/2005	0	
cc86b	Modified proprietary end terminal for Brifen	Hill & Smith Ltd	1/5/2007	1	
cc92	Gibraltar terminal	Gibraltar	6/23/2005	4	
cc92a	Driven socket anchor terminal posts for Gibraltar	Gibraltar	9/10/2007	0	
cc93	Safence terminal	Safence, Inc	8/16/2005	4	
cc93a	TL-3 vesion of Safence terminal (3-strand)	Safence, Inc	12/28/2006	0	
cc98	Armorwire terminal ends for high-tension cable barrier terminals	Armorflex	4/9/2007	4	
cc105	Armorwire 4-cable end terminal system	Armorflex	7/10/2010	1	
cc105A	Clarification that system in cc105 can be used on 3-cable sysetms	Armorflex	10/23/2010	0	Clarification; no new system or system modification was evaluated

8 REFERENCES

1. Coon, B.A., Faller, R.K., and Reid, J.D., *Cable Barrier Literature Review*, Final Report to the Midwest States' Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-118-02, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, July 12, 2002.

2. Bronstad, M.E., and Michie, J.D., "Recommended Procedures for Vehicle Crash Testing of Highway Appurtances", National Cooperative Highway Research Program (NCHRP) Report No. 153, Transportation Research Board, National Research Council, Washington, D.C., 1974.

3. "Recommended Procedures for Vehicle Crash Testing of Highway Appurtances", Transportation Research Circular No. 191, Transportation Research Board, National Academy of Sciences, Washington, D.C., February 1978.

4. Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program (NCHRP) Report No. 230, Transportation Research Board, Washington, D.C., March 1981.

5. Ross, HE Jr, DL Sicking, RA Zimmer, and JD Michie. "Recommended Procedures for the Safety Performance Evaluation of Highway Features." National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, DC. 1993.

6. Manual for Assessing Safety Hardware (MASH), American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2009.

7. Beaton, J.R., and Field, R.N., *Dynamic Full-Scale Tests of Median Barriers*, Highway Research Record No. 206, California Department of Highways, 1960, pp 78-125.

8. Field, R.N., Nordlin, E.F., Souza, R.M., and Beaton, J.L., *Dynamic Full-Scale Impact Tests of Cable-Type Median Barriers, Test Series VII*, California Department of Highways, Materials and Research Department, March 1964.

9. Nordlin, E.F., Field, R.N., Johnson, M.H., and Souza, R.M., *Dynamic Full-Scale Impact Tests of Cable-Type Median Barriers, Test Series IX*, California Highway Transportation Agency, June 1965.

10. Nordlin, E.F., Juergens, W.R., Tye, E.J., Stoker, J.R., Stoughton, R.L., Parks, D.M., *Dynamic Test Of A Slipformed Concrete Barrier Type 50 Placed Over Lowered Existing Cable Barrier*, Research Report CA-DOT-TL-6696-1-74-36, California Highway Transportation Agency, December 1974.

11. Lundstrom, L.C., and Skeels, P.C., "Full-Scale Appraisal of Guardrail Installations by Car Impact Tests", *Proceedings of the Highway Research Board*, Volume 38, Highway Research Board, 1959.

12. Cichowski, W.G., Skeels, P.C., and Hawkins, W.R., "Appraisal of Guardrail Installations by Car Impact and Laboratory Tests", *Proceedings of the Highway Research Board*, Volume 40, Highway Research Board, 1961, pp. 137-178.

13. Graham, M.D., Burnett, W.C., Gibson, J.L., and Freer, R.H., *New Highway Barriers: The Practical Application of Theoretical Design*, Highway Research Record No. 174, New York State Department of Transportation, 1967, pp 88-167.

14. Whitmore, J.L., Picciocca, R.G., and Snyder, W.A., *Testing of Highway Barriers and Other Safety Accessories*, Research Report No. NYSDOT-ERD-76-RR 38, New York State Department of Transportation, New York, December, 1976.

15. "National Automotive Sampling System", Case Number 102002664, http://www-nass.nhtsa.dot.gov/BIN/NASSCASELIST.EXE/SETFILTER?CASETYPE=PUBLIC.

16. Post, E.R. and Buth, E., *Head-on Test of Cable Guardrail*, Research Report No. RF 3012, Texas Transportation Institute, Texas A&M University, March 1974.

17. Jehu, V.J., and Laker, I.B., *The Cable and Chain-Link Crash Barrier*, Research Report Number LR 105, Road Research Laboratory, Crowthorne, England, 1967.

18. Jehu, V.J., and Laker, I.B., *The Wire-Rope Slotted-Post Crash Barrier*, Research Report Number LR 127, Road Research Laboratory, Crowthorne, England, 1967.

19. Smith, P., *Development of a Three Cable Guide Rail System and Other Guide Rail Tests*, 1967-1968, Research Report No. RR157, Department of Highways, Canada, March 1970.

20. Wijk, M.C., and Pinkney, H.F.L., *A Single Camera Method for the 6-Degree of Freedom Sprung Mass Response of Vehicles Redirected by Cable Barriers*, National Aeronautical Establishment, Canada, November 1972.

21. Pinkney, H.F.L., Basso, G.L., and Fraser, I.J., *The NAE Model of the Highway Cable Barrier for Parametric Studies of Vehicle Redirection using Digital Simulation*, Research Report No. NRC No. 12694, National Aeronautical Establishment of Canada, Ottawa, May 1972.

22. Ross, H.E. Jr., Smith, D.G., Sicking, D.L., and Hall, P.R., *Development of Guidelines for Placement of Longitudinal Barriers on Slopes*, Research Report No. 3659-2, Texas Transportation Institute, Texas A&M University, May 1983.

23. Buth, C.E., Campise, W.L., Griffen III, L.I., Love, M.L., and Sicking, D.L., *Performance Limits of Longitudinal Barrier Systems*, Submitted to the Federal Highway Administration, Research Report No. FHWA/RD-86/153, Texas Transportation Institute, Texas A&M University, May 1986.

24. Stout, D. and Hinch, J., *Test and Evaluation of Traffic Barriers*, Research Report No. FHWA-RD-89-119, ENSCO, Inc, Springfield, Virginia, April 1989.

25. Phillips, R.G., Tyrell, A.B., Bryden, J.E., and Fortuniewicz, J.S., *Cable Guiderail Breakaway Terminal Ends*, Research Report No. 148, New York State Department of Transportation, 1998.

26. Bryden, J.E., and Hahn, K.C., *Crash Tests of Sharply Curved Light-Post Guiderail*, Research Report No. 83, New York State Department of Transportation, July 1980.

27. Bronstad, M.E., Michie, J.D., and Mayer, J.D. Jr., *Performance of Longitudinal Traffic Barriers*, NCHRP Report No. 289, Transportation Research Board, Washington, D.C., June 1987.

28. *Guide for Selecting, Locating, and Designing Traffic Barriers*, American Association of State Highway Transportation Officials (AASHTO), Washington, D.C., 1977.

29. *Test No. MSD-2*, Research Report No. 06-8299-001, Southwest Research Institute, January 1989.

30. *Test No. MSD-2A*, Research Report No. 06-8299-001, Southwest Research Institute, January 1989.

31. *Test No. MSD-3*, Research Report No. 06-8299-001, Southwest Research Institute, January 1989.

32. *Test No. MSD-4*, Research Report No. 06-8299-001, Southwest Research Institute, January 1989.

33. *Crash Test and Evaluation of a Franklin Post and Cable Guardrail System: Test No. SD-1*, Research Report No. 06-2696-001, Southwest Research Institute, August 1989.

34. *Crash Test and Evaluation of a Franklin Post and Cable Guardrail System: Test No. SD-2*, Research Report No. 06-2696-001, Southwest Research Institute, August 1989.

35. *Crash Test and Evaluation of a Franklin Post and Cable Guardrail System: Test No. SD-3*, Research Report No. 06-2696-001, Southwest Research Institute, August 1989.

36. Laker, I.B., and Naylor, A.W., "Development and Proving Tests of a Four-Rope Safety Fence", Transportation Research Record No. 1419, Transportation Research Board, 1993, pp 1-8.

37. *Impact Test Results: MIRA Test No. E166*, MIRA Project No. K436106, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1989.

38. Hedges, R.H., *Vehicle Impact Tests on a Wire Rope Road-Side Safety Fence – Four Rope System: MIRA Test Nos. E167 and F190*, MIRA Report No. 88-K436109, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1989.

39. Hedges, R.H., *Vehicle Impact Tests on a Four Wire Rope – Wire Rope Safety Fence: MIRA Test Nos. J0903 and J0904*, MIRA Report No. 91-430903, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1991.

40. Fenn, M.A., *The Impact of a 1500 kg Car into a Wire Rope Safety Fence: 585.6 m Long, Test 01LB*, Research Report No. PR/SE/114/00, Transportation Research Laboratory Ltd, Nuneaton, Warwickshire, May 2000.

41. Fenn, M.A., *The Impact of a 1500 kg Car into a Wire Rope Safety Fence: 102.8 m Long, Test 01MB*, Research Report No. PR/SE/326/01, Transportation Research Laboratory Ltd, Nuneaton, Warwickshire, June 2001.

42. *Impact Test Results: MIRA Test No. L6016*, MIRA Project No. 436016, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1993.

43. Roddis, C.D., *The Impact of a 1500kg Saloon Car into a 4-rope Wire Rope Safety Fence 0.5m in front of a 2m Wide Ditch: MIRA Test No. M6035*, MIRA Report No. 94-436035, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1994.

44. Hedges, R.H., *The Impact of a 900kg Small Car into a 4 Rope Wire Rope Safety Fence with Post Spacings at 3.2m: MIRA Test No. N6014*, MIRA Report No. 95-436014, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1995.

45. Hedges, R.H., *The Impact of a 1500kg Car into a 4 Rope Wire Rope Safety Fence with Post Spacings at 3.2m: MIRA Test No. N6015*, MIRA Report No. 95-436015, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1995.

46. Hedges, R.H., *The Impact of a 900kg Small Car into a 3 Rope Wire Rope Safety Fence with Post Spacings at 3.2m: MIRA Test No. N6016*, MIRA Report No. 95-436016, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1995.

47. Hedges, R.H., *The Impact of a 1500kg Car into a 4 Rope Wire Rope Safety Fence with Post Spacings at 3.2m: MIRA Test No. N6017*, MIRA Report No. 95-436017, Motor Industry Research Association, Nuneaton, Warwickshire, UK, 1995.

48. Bateman, M. B., Howard, I. C., Johnson, A. R., and Walton, J. M., "Validation of a Computer Simulation of the Impact Performance of a Wire Rope Safety Fence", *IMechE Journal*, Volume 221 Part C, University of Sheffield, 2007, pp. 1557-1570.

49. Fenn, M.A., *The Impact of a 1500 kg Car into a Wire Rope Safety Fence: 102.8 m Long, Test 01MB*, Research Report No. PR/SE/326/01, Transportation Research Laboratory Ltd, Nuneaton, Warwickshire, June 2001.

50. Titmus, M., and Fenn, M., *The Impact of a 1500 kg car into a Tensioned Wire Rope Safety Fence*, Transportation Research Laboratory Summary Report, 2002.

51. Mak, K.K., and Menges, W.C., *Crash Testing and Evaluation of the G1 Wire Rope Guardrail System*, Research Report No. 471470-28, Texas Transportation Institute, Texas A&M University, 1994.

52. Arrington, D.R., Alberson, D.C., and Menges, W.L., *Development of Field Applied Fittings for Cable Barrier and Conversion to High-Tension*, Final Report to the Roadside Safety

Research Program Pooled Fund, Research Report No. 405160-11-1, Texas Transportation Institute, Texas A&M University, December 2008.

53. Bullard, D.L. Jr., and Menges, W.L., *Crash Testing and Evaluation of the WSDOT Three Strand Cable Rail System*, Final Report to the Washington State Department of Transportation, Research Study No. 270687-WDT2, Texas Transportation Institute, Texas A&M University, June 1996.

54. Albin, R.B., Bullard, D.L., and Menges, W.L., "Washington State Cable Median Barrier", Transportation Research Record No. 1743, Washington, D.C., 2001, pp. 71-79.

55. Bullard, D.L. Jr., Menges, W.L., Buth, C.E., and Schoeneman, S.K., *NCHRP Report 350 Test 3-11 of the Washington 3-Strand Cable Barrier with New York Cable Terminal*, Project 404211-8, Texas Transportation Institute, Texas A&M University, 2000.

56. Alberson, D.C.., Bullard, D.L. Jr., Menges, W.L., and Schoeneman, S.K., *NCHRP Report 350 Test 3-11 on the Cable Barrier with Marion Steel Posts*, Project 400001-MSC1, Texas Transportation Institute, Texas A&M University, 2000.

57. Horne, DA, Director, Office of Highway Safety Infrastructure, Federal Highway Administration. "Report 350 Acceptance of New York 3-Strand Cable Terminal." Memorandum to Resource Center Directors, HMHS-CC63. February 14, 2000.

58. Faller, R.K., Sicking, D.L., Rohde, J.R., Holloway, J.C., Keller, E.A., and Reid, J.D., *Crash Testing of South Dakota's Cable Guardrail to W-Beam Transition*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-80-98, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December 4, 1998.

59. Polivka, K.A., Faller, R.K., Holloway, J.C., Rohde, J.R., Reid, J.D., and Sicking, D.L., *Safety Performance Evaluation of South Dakota's Cable Guardrail to W-Beam Transition System with a FLEAT End Terminal*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-138-03, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, September 2003.

60. Nelson, R.M., Sicking, D.L., Faller, R.K., Reid, J.D., Rohde, J.R., Polivka, K.A., and Hascall, J.A., *Evaluation of Alternative Cable Anchor Designs and Three-Cable Guardrail Adjacent to Steep Slope*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-155-05, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, February 2005.

61. Terpsma, R.J., Polivka, K.A., Sicking, D.L., Rohde, J.R., Reid, J.D., and Faller, R.K., *Evaluation of a Modified Three-Cable Guardrail Adjacent to Steep Slope*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-192-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, March 2008.

62. Fating, R.M., and Reid, J.D., *Dynamic Impact Testing of S75x8.5 Steel Posts (Cable Barrier Posts)*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF

Research Report No. TRP-03-117-02, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, November 2002.

63. Kuipers, B.D., and Reid, J.D., *Testing of M203x9.7 (M8x6.5) and S76x8.5 (S3x5.7) Steel Posts - Post Comparison Study for the Cable Median Barrier*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-143-03, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, October 2003.

64. Molacek, K.M., Lechtenberg, K.A., Faller, R.K., Rohde, J.R., Sicking, D.L., Bielenberg, R.W., Reid, J.D., Stolle, C.J., Johnson, E.A., and Stolle, C.S., *Design and Evaluation of a Low-Tension Cable Median Barrier System*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-195-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December 2008.

65. Hitz, R.A., Molacek, K.M., Stolle, C.S., Polivka, K.A., Faller, R.K., Rohde, J.R., Sicking, D.L., and Reid, J.D., *Design and Evaluation of a Low-Tension Cable Guardrail End Terminal System*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-131-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, July 2008.

66. Johnson, E.A., Sicking, D.L., Faller, R.K., Reid, J.D., Lechtenberg, K.A., Rohde, J.R., and Bielenberg, R.W., *Four-Cable High Tension Median Barrier*, Draft Report in Progress to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-213-09, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, In Progress.

67. Stolle, C.S., Faller, R.K., and Polivka, K.A., *Dynamic Impact Testing of S76x8.5 (S3x5.7) Steel Post for Use in Cable Guardrail Systems*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-186-07, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December 2007.

68. Marzougui, D., Mohan, P., Kan, C.D., and Opiela, K.S., “Performance Evaluation of Low-Tension Three-Strand Cable Median Barriers”, *Transportation Research Record No. 2025*, Transportation Research Board, 2007, pp 34-44.

69. Marzougui, D., Mohan, P., Mahadevaiah, U., and Kan, S., *Performance Evaluation of Low-Tension, Three-Strand Cable Median Barriers on Sloped Terrains*, Research Report No. 2007-R-003, National Crash Analysis Center, George Washington University, April 2007.

70. Ayre, R.S., and Abrams, J.I., "Dynamics of Guardrail Systems", *Proceedings of the 33rd Annual Meeting of the Highway Research Board*, Washington, D.C., 1954, pp. 201-209.

71. Ayre, R.S., and Abrams, J.I., "Dynamics of Highway Guardrails: Laboratory Experiments (I)", *Proceedings of the 34th Annual Meeting of the Highway Research Board*, Washington, D.C., 1955, pp 162-172.

72. Ayre, R.S., and Abrams, J.I., "Dynamics of Highway Guardrails: Laboratory Experiments (II)", *Proceedings of the 35th Annual Meeting of the Highway Research Board*, Washington, D.C., 1956, pp. 237-250.

73. Basso, G.L., *A Parametric Study on Highway Cable Barrier Performance and its Effect on Vehicle Redirection Dynamics*, National Aeronautical Establishment of Canada, February 1977.

74. Bateman, M.B., Howard, I.C., Johnson, A.R., and Walton, J.M., “Model of the Performance of a Roadway Safety Fence and its Use for Design”, Transportation Research Record No. 1657, Transportation Research Board, 1998, pp 122-129.

75. Bateman, M.B., Howard, I.C., Johnson, A.R., and Walton, J.M., “Computer Simulation of the Impact Performance of a Wire Rope Safety Fence”, International Journal of Impact Engineering, Volume 25, University of Sheffield, 2001, pp. 67-85.

76. Hansen, P., Zvirbulis, E., Nathan, S., and Rodger, E., *Performance Variability of Wire Rope Safety Barriers*, LB International PTY LTD, Girraween, New Queensland, Australia, November 2002.

77. Sicking, D.L., de Albuquerque, F.D.B., and Lechtenberg, K.A., *Cable Median Barrier Guidelines*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-208-08, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December 2008.

78. Sicking, D.L., de Albuquerque, F.D.B., Lechtenberg, K.A., and Stolle, C.S., "Guidelines for Implementation of Cable Median Barrier", Transportation Research Record No. 2120, Washington, D.C., 2009, pp. 82-90.

79. *Roadside Design Guide*, American Association of State Highway Transportation Officials, Washington, D.C., 1977.

80. Reid, J.D., and Bielenberg, R.W., "Using LS-DYNA Simulation to Solve a Design Problem: Bullnose Guardrail Example", Transportation Research Record No. 1690, Washington, D.C., 1999, pp. 99-102.

81. Bielenberg, R.W., Reid, J.D., and Faller, R.K., “Compliance Testing of a Median Barrier System”, Transportation Research Record No. 1743, Washington, D.C., 2001, pp. 60-70.

82. Stolle, C.S., Polivka, K.A., Bielenberg, R.W., Reid, J.D., Faller, R.K., Rohde, J.R., and Sicking, D.L., *Phase III Development of a Short-Radius Guardrail for Intersecting Roadways*, Final Report to the Midwest States Regional Pooled Fund Program, MwRSF Research Report No. TRP-03-183-07, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December, 2007.

83. Stolle, C.S., *A Concise Model of 3x7 Wire Rope Used in Cable Guardrail Systems*, Thesis, University of Nebraska-Lincoln, April 29, 2010.

84. Reid, J.D., and Coon, B.A., "Finite Element Modeling of Cable Hook Bolts", Conference Proceedings, Presented at the 7th International LS-DYNA Users Conference, Dearborn, Michigan, May 2002, pp. 17-11 through 17-23.

85. Reid, J.D., and Hiser, N.R., "Friction Modeling Between Solid Elements", *IJ Crash 2004*, Vol 9 No. 1, Presented at the International Crashworthiness Conference, San Francisco, 2004, pp 65-72.

86. Reid, J.D., and Hiser, N.R., "Detailed Modeling of Bolted Joints with Slippage", *Finite Elements in Analysis and Design*, Volume 41, December 18, 2004, pp 547-562.

87. Reid, J.D., and Hiser, N.R., "Modeling Slip Base Mechanisms", International Journal of Crashworthiness, Vol 10 No. 5, pp. 463-472.

88. Reid, J.D., Paulsen, T., and Hiser, N.R., "Simulation and Bogie Testing of a New Cable Barrier Terminal", Presented to Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems Conference 2003, Paper No. IMECE2003-55104, ASME, November 2003.

89. Hiser, N.R., Slip Base Modeling for Cable Guardrail Systems, Thesis, University of Nebraska-Lincoln, April 2003.

90. Reid, J.D., and Hiser, N.R., *Cable Guardrail End Terminal Simulation: FHWA Center of Excellence in DYNA3D Analysis*, Final Report to the Federal Highway Administration, MwRSF Research Report No. TRP-03-142-03, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, October 2003.

91. Reid, J.D., "LS-DYNA Simulation Influence on Roadside Hardware", Transportation Research Record No. 1890, Transportation Research Board, Washington, D.C., January 2004, pp. 34-41.

92. Marzougui, D., *Effects of End Anchor Spacing and Initial Tension on Cable Barrier Deflection*, National Crash Analysis Center, George Washington University, 2008.

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9 APPENDICES

Appendix A - Historical Development Testing, System Details

The historical development refers to the time during which testing was conducted to any standard that did not include NCHRP Report 230 or 350 or MASH, or were conducted before 1980. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Performing Organization
- System Length
- Anchor Type
- System Configuration (i.e. on slope, curve, transition etc.)
- Post Properties
  - Section Type
  - Length
  - Embedment Depth
  - Spacing

Page B

- Test Name
- Test Date
- Reference Number
- Cable Properties
  - Diameter and Weave
  - Attachment Hardware to Posts
  - Pretension
- Mounting Heights
  - Top Cable
  - 2nd Cable
  - 3rd Cable
  - Bottom Cable
- Additional Components
- System Design Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 12	11/3/1958	7	California DOT	96	Concrete	N/A	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 14	12/26/1958	7	California DOT	192	Concrete	N/A	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 19	3/5/1959	7	California DOT	400	Concrete	N/A	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 20	3/10/1959	7	California DOT	400	Concrete	10 ft Crossover section with 2 anchors	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 21	3/20/1959	7	California DOT	600	Concrete	1200 ft radius curve	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 23	4/21/1959	7	California DOT	304	Concrete	N/A	2.5" x 4.1 lb/ft H-Section	Unk	Unk	8
Test 1	8/9/1962	8	California DOT	500	3'x2.5' by 1.75' deep concrete block each end	N/A	2.25"x4.1 lb/ft H-section	88	30	8
Test 2	8/16/1962	8	California DOT	500	3'x2.5' by 1.75' deep concrete block each end	N/A	2.25"x4.1 lb/ft H-section	88	30	8
Test 3	8/22/1962	8	California DOT	500	3'x3' by 2' deep concrete block each end	N/A	2.25"x4.1 lb/ft H-section	88	30	8
Test 4	8/30/1962	8	California DOT	500	3'x3' by 2' deep concrete block each end	N/A	2.25"x4.1 lb/ft H-section	69	30	8
Test 91	1/9/1964	9	California DOT	225	Concrete block with anchor rod	Center of 7' wide Raised Median with 6" Class B curbs	2.25"x4.1 lb/ft H-section	88	30	8
Test 92	2/4/1964	9	California DOT	200	Concrete block with anchor rod	Center of 7' wide Raised Median with 6" Class B curbs	2.25"x4.1 lb/ft H-section	88	30	8
Test 93	2/26/1964	9	California DOT	600	Concrete block with anchor rod	N/A	2.25"x4.1 lb/ft H-section	88	30	8
Test 94	3/18/1964	9	California DOT	600	Concrete block with anchor rod	N/A	2.25"x4.1 lb/ft H-section	88	30	8
Test 95	4/22/1964	9	California DOT	175	Concrete block with anchor rod	15" above ground, at peak of 2:1 and 6:1 slopes	2.25"x4.1 lb/ft H-section	88	30	8
Test 96	5/7/1964	9	California DOT	175	Concrete block with anchor rod	15" above ground, at peak of 2:1 and 6:1 slopes	2.25"x4.1 lb/ft H-section	88	30	8
511	4/4/1958	12	General Motors	115	Unk	N/A	6"x4"x 8.5 lb/ft I-section	69	42.25	12.2

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 12	11/3/1958	7	3/4"	U-bolts	Unk	27	9	N/A	N/A	Turnbuckles	Chain-link mesh 36" tall intertwined with wire ropes; posts set in 8" diameter x 30" long concrete footers, rope woven between posts
Test 14	12/26/1958	7	3/4"	U-bolts	Unk	30	30	9	N/A	Turnbuckles	Chain-link mesh ; posts set in 8" diameter x 30" long concrete footers
Test 19	3/5/1959	7	3/4"	U-bolts	Unk	30	30	9	N/A	Turnbuckles	Chain-link mesh intertwined with wire ropes; posts set in 8" diameter x 30" long concrete footers
Test 20	3/10/1959	7	3/4"	U-bolts	Unk	30	30	9	N/A	Turnbuckles, log binders	Chain-link mesh ; posts set in 8" diameter x 30" long concrete footers
Test 21	3/20/1959	7	3/4"	U-bolts	Unk	30	30	9	N/A	Turnbuckles	Chain-link mesh intertwined with wire ropes; posts set in 8" diameter x 30" long concrete footers
Test 23	4/21/1959	7	3/4"	U-bolts	Unk	30	30	9	N/A	Turnbuckles	Chain-link mesh intertwined with wire ropes; posts set in 8" diameter x 30" long concrete footers
Test 1	8/9/1962	8	3/4" 6x19 IWRC	0.75 U-bolts	Unk	30	30	N/A	N/A	Pipe-type turnbuckles, swaged cable end sockets, wire mesh	Posts anchored in 8" diameter asphalt cores; chain link mesh on opposite side from impact
Test 2	8/16/1962	8	3/4" 6x19 IWRC	0.75 U-bolts	Unk	30	30	N/A	N/A	Pipe-type turnbuckles, swaged cable end sockets, wire mesh, wire splices	Posts anchored in 8" diameter asphalt cores
Test 3	8/22/1962	8	3/4" 6x19 IWRC	0.75 U-bolts	Unk	30	30	N/A	N/A	Pipe-type turnbuckles, swaged cable end sockets, wire mesh, wire splices, 2 wire patch kits	Posts anchored in 8" diameter asphalt cores
Test 4	8/30/1962	8	3/4" 6x19 IWRC	0.75 U-bolts	Unk	30	30	N/A	N/A	Pipe-type turnbuckles, wire splices, wire patch kits	Posts anchored in 8" diameter asphalt cores
Test 91	1/9/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts	Unk	26	26	N/A	N/A	Pipe-Type Turnbuckles	Pretension noted as "standard", comparative to other CAL tests; 48" tall chain link fence mounted 9" above ground
Test 92	2/4/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts	Unk	26	26	N/A	N/A	Pipe-Type Turnbuckles	48" tall chain link fence mounted 9" above ground
Test 93	2/26/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts	Unk	26	26	18	N/A	Pipe-Type Turnbuckles	Top cables at either side of post; breakaway cable on opposite side from impact; 48" tall chain link fence mounted 8" above ground
Test 94	3/18/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts, 9 and 12 gauge steel wire, 3/8" button head rivets	Unk	27	27	18	N/A	Pipe-Type Turnbuckles	Top cables at either side of post; breakaway cable on opposite side from impact; 48" tall chain link fence mounted 9" above ground
Test 95	4/22/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts, 9 and 12 gauge steel wire, 3/8" button head rivets	Unk	27	27	18	N/A	Pipe-Type Turnbuckles	Top cables at either side of post; breakaway cable on impact side; 48" tall chain link fence mounted 9" above ground
Test 96	5/7/1964	9	3/4" 6x19 IWRC	0.445" diameter U-bolts, 9 and 12 gauge steel wire, 3/8" button head rivets	Unk	27	27	18	N/A	Pipe-Type Turnbuckles	Top cables at either side of post; breakaway cable on impact side; 48" tall chain link fence mounted 9" above ground
511	4/4/1958	12	3/4" with 25 kip breaking load	Oblong sleeve with cut grooves, 0.625" bolt	Unk	26	22	18	14	Turnbuckles, anchor rods	Embedment, attachment piece, and cable heights are approximate; test run in glacial till soil

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
542	12/26/1958	12	General Motors	Unk	Unk	N/A	6"x4"x 8.5 lb/ft I-section	69	42.25	12.5
591	5/24/1960	12	General Motors	288	Concrete block	N/A	2.25" x 4.1 lb/ft H-section	76	30	8
593	6/3/1960	12	General Motors	288	Concrete block	N/A	2.25" x 4.1 lb/ft H-section	75	30	8
596	6/23/1960	12	General Motors	144	Concrete block	N/A	2.25" x 4.1 lb/ft H-section	75	30	8
Test 1	1960	13	NYDOT	100	Unk	N/A	6B8.5 (W6x9)	Unk	Unk	10
Test 12	1960-1963	13	NYDOT	200	2.25"x2.25" by 6 ft long H-section posts at 6' centers	Bridge Rail	2.25"x2.25" H-section post	~36	0	6
Test 18	1963	13	NYDOT	200	7 ft x 4 ft x 1.5 ft Concrete Anchor	18" from SBP of 2:1 slope	2.25"x2" 4.1 lb/ft	66	30	8
Test 20	1965	13	NYDOT	1000	7 ft x 4 ft x 1.5 ft Concrete Anchor	18" from SBP of 2:1 slope	3I5.7 (S3x5.7)	81	39	8
Test 28	1965	13	NYDOT	500	7 ft x 4 ft x 1.5 ft Concrete Anchor	8 degree inside radius curve	3I5.7 (S3x5.7)	81	39	8
Test 33	1965	13	NYDOT	1000	7 ft x 4 ft x 1.5 ft Concrete Anchor	18" from SBP of 2:1 slope	3I5.7 (S3x5.7)	75	39	12
Test 36	1965	13	NYDOT	1000	7 ft x 4 ft x 1.5 ft Concrete Anchor	18" from SBP of 2:1 slope	3I5.7 (S3x5.7)	72	39	12
Test 37	1965	13	NYDOT	1000	7 ft x 4 ft x 1.5 ft Concrete Anchor	18" from SBP of 2:1 slope	3I5.7 (S3x5.7)	75	39	12
Test 46	1965	13	NYDOT	1000	3 ft x 3 ft x 3 ft concrete anchor with wide-flanged anchor post	18" from SBP of 2:1 slope	3I5.7 (S3x5.7)	69	39	16
Test 1	1976	14	NYDOT	300	Concrete block	N/A	S3x5.7	Unk	Unk	16
Test 9	1976	14	NYDOT	1000	3 ft x 3 ft x 3 ft concrete anchor with wide-flanged anchor post	2:1 ditch 18" behind barrier	S3x5.7	69	39	16
Test 10	1976	14	NYDOT	1000	3 ft x 3 ft x 3 ft concrete anchor with wide-flanged anchor post	2:1 ditch 18" behind barrier	S3x5.7	~75	~39	12
Test 11	1976	14	NYDOT	1000	3 ft x 3 ft x 3 ft concrete anchor with wide-flanged anchor post	2:1 ditch 18" behind barrier	S3x5.7	81	39	8

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
542	12/26/1958	12	3/4" with 25 kip breaking load	Oblong sleeve with cut grooves, 0.625" bolt	Unk	26	22	18	14	Turnbuckles, anchor rods	System details are approximate; test run in glacial till soil, frozen to 18" deep
591	5/24/1960	12	3/4"	0.5" U-bolts, 9-gauge galvanized wire ties	Unk	30	30	9	N/A	36" chain link mesh, 8" diameter concrete footings at post locations	
593	6/3/1960	12	3/4"	0.5" U-bolts, 7- and 9-gauge galvanized wire ties	Unk	26	26	9	N/A	36" chain link mesh, 8" diameter concrete footings at post locations	
596	6/23/1960	12	3/4"	0.5" U-bolts, 7- and 9-gauge galvanized wire ties	Unk	34	34	12	N/A	36" chain link mesh, 8" diameter concrete footings at post locations	
Test 1	1960	13	3/4"	Spring Blockout	Unk	26	22	18	14		Blockouts used in GM tests also used here
Test 12	1960-1963	13	3/4"	1/4" J-bolts	Unk	~32	~24	~16	N/A	Turnbuckles on each cable	Diagonal crossing cables
Test 18	1963	13	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	Two 48" angled drive anchors attached to post at ground level	
Test 20	1965	13	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	
Test 28	1965	13	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	
Test 33	1965	13	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles, 3 in. x 3 in. x 24 in. fastened to cables between posts using J-bolts	
Test 36	1965	13	3/4"	1/4" J-bolts	Unk	27	21	15	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles, 3 in. x 3 in. x 24 in. fastened to cables between posts using J-bolts	
Test 37	1965	13	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles, 3 in. x 3 in. x 24 in. fastened to cables between posts using J-bolts	
Test 46	1965	13	3/4"	1/4" J-bolts	Unk	27	24	21	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	
Test 1	1976	14	3/4"	1/4" J-bolts	Unk	27	24	21	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	
Test 9	1976	14	3/4"	1/4" J-bolts	Unk	27	24	21	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	Retest of test no. 46 (above)
Test 10	1976	14	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	Retest of test no. 33 (above)
Test 11	1976	14	3/4"	1/4" J-bolts	Unk	30	24	18	N/A	8"x24"x0.25" soil plates at ground level, turnbuckles	Retest of test no. 20 (above)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 12 and 35	1976	14	NYDOT	470	Concrete Block	Transition to box beam	S3x5.7	Unk	Unk	4
Test 13	1976	14	NYDOT	300	2 50' radius curves on ends of installation (18 posts on 3' centers)	Tangent section adjacent to curves	S3x5.7	Unk	Unk	16
Test 17	1976	14	NYDOT	500	Concrete block with anchor rod	N/A	S3x5.7	Unk	Unk	16
Test 21	1976	14	NYDOT	500	Concrete block	N/A	S3x5.7	Unk	Unk	16
Test 22	1976	14	NYDOT	150	Anchor bracket mounted on concrete block anchor	Terminal test	S3x5.7	Unk	Unk	6
Test 23	1976	14	NYDOT	340	Anchor bracket mounted on concrete block anchor	Terminal test	S3x5.7	Unk	Unk	6
Test 30	1976	14	NYDOT	200	Concrete block on parabolic flare	Transition to box beam (also on parabolic flare)	S3x5.7	Unk	Unk	16
Test 31	1976	14	NYDOT	200	Concrete block	Transition to box beam	S3x5.7	Unk	Unk	16
Test 32	1976	14	NYDOT	200	Concrete block	Transition to box beam	S3x5.7	Unk	Unk	6
Test 33	1976	14	NYDOT	200	Concrete block	Transition to box beam	S3x5.7	Unk	Unk	6
Test 34	1976	14	NYDOT	200	Concrete block	Transition to box beam	S3x5.7	Unk	Unk	6
Test 36	1976	14	NYDOT	200	Concrete block	Transition to W-beam	S3x5.7	Unk	Unk	16
Test 52	1976	14	NYDOT	Unk	Unk	N/A	6"x8" wood post	Unk	Unk	10
Test 53	1976	14	NYDOT	Unk	Unk	N/A	6"x8" wood post	Unk	Unk	10
Test 8330B	1974	16	TTI	100	Concrete Block 6"x18"x18"	Terminal test	5.5" nominal round wood with 18"x18"x6" concrete footers	72	38	12.5
Test 11	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	63	~18	8
Test 12	1967	17	Road Research Laboratories	200	Concrete Block	N/A	2 1/4"x1" I-section	~57	~18	8

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 12 and 35	1976	14	3/4"	1/4" J-bolts	Unk	30	24	18	N/A		Transition tested, but used for post spacing analysis
Test 13	1976	14	3/4"	5/16" J-bolts	Unk	30	24	18	N/A		Impacted in the tangent area, not in the curved section
Test 17	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		Ground was saturated at time of test, due to rain
Test 21	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		
Test 22	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Routing post with ground anchor angles and cable routing brackets	
Test 23	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Routing post with ground anchor angles and cable routing brackets	Terminal flared 4' back and 18' longitudinally from system to upstream front corner of anchor
Test 30	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket	
Test 31	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		Box beam flared with reversed open C-channel section leading to specially-made tapered open box beam, transitioned to normal beam
Test 32	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Curved steel section (similar to ELT head) placed at end of box beam near the cable intake hole	Box beam at cable inlet tapered from 6"x2" to 6"x8"
Test 33	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Welded taper of 6x8, 6x4, and 6x2 beams with slots	Cable entered box beam through slot, exited out back to concrete block
Test 34	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		Last section of box beam with hole cut for cable passeage; flared away from road with small section
Test 36	1976	14	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		Curved W-beam at attachment to cable, standard post spacing maintained throughout
Test 52	1976	14	3/4"	Thin V-clips made from sheet stock	Unk	28	22	18	14	Elliptical spacer blockouts with slots cut for cables, small retainer clips placed over slots to keep cables in elliptical spacers	These systems were similar to systems tested by GM
Test 53	1976	14	3/4"	Thin V-clips made from sheet stock	Unk	28	22	18	14	Elliptical spacer blockouts with slots cut for cables, small retainer clips placed over slots to keep cables in elliptical spacers	Posts sawed 5 in. at ground line to promote cleaner fracture and release
Test 8330B	1974	16	3/4"	Plate with hooks attached at top of post	Unk	28.5	24.5	20.5	N/A	Tension springs (compensators) and anchor rods, cable terminal plates	Cables terminate at end posts through swaged ends bearing on plate; anchor cable run into concrete block
Test 11	1967	17	3/4"	1/2" Tespa clips	1000	27	27	19	19	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 44" tall, chain link 8" off ground, posts anchored in concrete; assumed 18" post embedment depth; Deflector system
Test 12	1967	17	3/4"	1/2" Tespa clips	1000	27	27	19	19	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 44" tall, chain link 2-3" off ground, posts anchored in concrete; assumed 18" post embedment depth; Deflector system

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 13	1967	17	Road Research Laboratories	200	Concrete Block	N/A	2 1/4"x1" I-section	~55 1/2	~18	8
Test 14	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	~63	~18	8
Test 15	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	~63	~18	8
Test 16	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	~48	~18	8
Test 17	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	~63	~18	8
Test 19	1967	17	Road Research Laboratories	200	Concrete Block	N/A	3"x1 1/2" I-section	~63	18	8
Test 20	1967	17	Road Research Laboratories	200	Concrete Block	N/A	1.875" OD x 1.5" ID tubes	~61	~18	8
Test 21	1967	17	Road Research Laboratories	200	Concrete Block	N/A	2.25"x1" I-section	61	18	8
Test 22	1967	18	Road Research Laboratories	200	Concrete Block	N/A	2.25"x1" I-section	47	18	8
Test 23	1967	18	Road Research Laboratories	200	Concrete Block	N/A	2.5"x1" I-section	47	18	16
Test 24	1967	18	Road Research Laboratories	200	Concrete Block	N/A	2.5"x1" I-section	47	18	16
Test 25	1967	18	Road Research Laboratories	200	Concrete Block	N/A	2.5"x1" I-section	47	18	8
Test 26	1967	18	Road Research Laboratories	200	Concrete Block	N/A	2.5"x1" I-section	47	18	8
Test 27	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.5"x1" I-section	50	18	8
Test 28	1967	18	Road Research Laboratories	100	Concrete Block	N/A	2.5"x1" I-section	50	18	8
Test 29	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48.5	18	8
Test 30	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48.5	18	8

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 13	1967	17	3/4"	1/2" Tespa clips	1000	27	27	N/A	N/A	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 43" tall, chain linkn 7" above ground, posts anchored in concrete; assumed 18" post embedment depth; Arrestor system
Test 14	1967	17	3/4"	1/2" Tespa clips	1000	27	27	N/A	N/A	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 44" tall, chain link 8" off ground, posts anchored in concrete; assumed 18" post embedment depth; Arrestor system
Test 15	1967	17	3/4"	1/2" Tespa clips	1000	24.5	24.5	N/A	N/A	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 44" tall, chain link 8" off ground, posts anchored in concrete; assumed 18" post embedment depth
Test 16	1967	17	3/4"	1/2" Tespa clips	1000	24.5	24.5	N/A	N/A	Turnbuckles	Posts anchored in concrete (no chain link fence); assumed 18" pos embedment depth
Test 17	1967	17	3/4"	1/2" Tespa clips	1000	24.5	24.5	N/A	N/A	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 43" tall, chain link 7" above ground, posts anchored in concrete; assumed 18" post embedment depth
Test 19	1967	17	3/4"	1/2" Tespa clips	1000	24.5	24.5	N/A	N/A	2"x2" plastic coated chain link fence, turnbuckles	System 44" tall, chain link 8" off ground, posts anchored in concrete; assumed 18" post embedment depth
Test 20	1967	17	3/4"	0.5" U-bolts	1000	24.5	24.5	N/A	N/A	2"x2" chain link mesh, plastic coated, with welded horns, turnbuckles	System 44.5" tall, chain link 6.5" off ground, posts anchored in concrete; assumed 18" post embedment depth
Test 21	1967	17	3/4"	0.625" Tespa Clips	800	24.5	24.5	N/A	N/A	2"x2" plastic coated chain link fence, turnbuckles	System 44" tall, chain link 8" off ground, posts anchored in concrete; assumed 18" post embedment depth
Test 22	1967	18	3/4"	2" Slot top of post	1000	27.375	N/A	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 23	1967	18	3/4"	2" Slot top of post	860	27.375	N/A	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 24	1967	18	3/4"	2" Slot top of post	900	27.375	N/A	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 25	1967	18	3/4"	3" Slot top of post	1000	27.125	26.375	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 26	1967	18	3/4"	3" Slot top of post	1000	27.125	26.375	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 27	1967	18	3/4"	6" Slot top of post	1000	26.375	N/A	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 28	1967	18	3/4"	6" Slot top of post	1000	26.375	N/A	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 29	1967	18	3/4"	4.5" Slot top of post	1000	26.375	27.125	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 30	1967	18	3/4"	4.5" Slot top of post	1000	26.375	27.125	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 31	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48.5	18	8
Test 32	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 33	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 34	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 35	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 36	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 37	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 38	1967	18	Road Research Laboratories	790	Concrete Block	N/A	2.25"x1" I-section	48	18	8
Test 39	1967	18	Road Research Laboratories	790	Concrete Block	Emergency access gate located 23' from impact	2.5"x1" I-section	49	18	8
Test 40	1967	18	Road Research Laboratories	2000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 41	1967	18	Road Research Laboratories	1000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 42	1967	18	Road Research Laboratories	500	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 43	1967	18	Road Research Laboratories	5000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 44	1967	18	Road Research Laboratories	2000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 45	1967	18	Road Research Laboratories	2000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 46	1967	18	Road Research Laboratories	4000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	8
Test 47	1967	18	Road Research Laboratories	2000	Concrete Block	Center of ~16' wide median	2.5"x1" I-section	49	18	16

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 31	1967	18	3/4"	4.5" Slot top of post	1000	26.375	27.125	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 32	1967	18	3/4"	4.5" Slot top of post, side bracket	1000	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 33	1967	18	3/4"	4.5" Slot top of post, side bracket	1000	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 34	1967	18	3/4"	4.5" Slot top of post, side bracket	1000	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 35	1967	18	3/4"	4.5" Slot top of post, side bracket	3850 upper, 5000 lower	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 36	1967	18	3/4"	4.5" Slot top of post, side bracket	3000	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 37	1967	18	3/4"	4.5" Slot top of post, side bracket	2500	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 38	1967	18	3/4"	4.5" Slot top of post, side bracket	2500	30	25	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
Test 39	1967	18	3/4"	4.5" Slot top of post	2500	27.625	26.875	N/A	N/A	Emergency access gate, 2 additional cable anchors, steel sockets anchored in concrete	Top rope anchored into tarmac to form discontinuous top cable on US and DS sides; formed "gate" or cable maintenance length
Test 40	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables not prestretched, posts placed in sockets
Test 41	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables not prestretched, posts placed in sockets
Test 42	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables not prestretched, posts placed in sockets
Test 43	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables not prestretched, posts placed in sockets
Test 44	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables prestretched prior to use, posts placed in sockets
Test 45	1967	18	3/4"	4.5" Slot top of post	6000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables prestretched prior to use, posts placed in sockets
Test 46	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables prestretched prior to use, posts placed in sockets
Test 47	1967	18	3/4"	4.5" Slot top of post	3000	27.625	26.875	N/A	N/A	Steel sockets anchored in concrete	Cables prestretched prior to use, posts placed in sockets

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 70	1967	18	Road Research Laboratories	790	Concrete Block	N/A	3"x1.5" I-section	32.5	0	10.5
Test 73	1967	18	Road Research Laboratories	790	Concrete Block	N/A	3"x1.5" I-section	47	18	8
1-67	8/23/1967	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, dual soil paddles	N/A	6" square cedar	77	42	12
2-67	8/29/1967	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, steel bearing pad and secondary buried soil anchor	N/A	6" square cedar	77	42	12
8-67	9/22/1967	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, steel bearing pad and secondary buried soil anchor	N/A	6" square cedar	77	42	12
3-68	6/27/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	6" square cedar	77	42	12
1A-68	7/9/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	6" square cedar	77	42	12
1-68	8/1/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	6" diameter cedar	77	42	12
5-68	8/27/1968	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, steel bearing pad and secondary buried soil anchor	Ditch	6" square cedar	77	42	12
9-68	8/28/1968	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, steel bearing pad and secondary buried soil anchor	Ditch	6" square cedar	77	42	12
5A-68	8/29/1968	19	Canada Dept of Highways	500	Two 6" diameter posts, 81" long, with tension wire and compression strut, steel bearing pad and secondary buried soil anchor	Ditch	N/A	N/A	N/A	N/A
6-68	9/4/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	6" square cedar	77	42	12
7-68	9/11/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	6" square cedar	77	42	12
7A-68	9/12/1968	19	Canada Dept of Highways	350	Two angle-drilled router posts and 3'x3'x3', 3000 psi strength concrete anchor block with anchor rod termination	Ditch	N/A	N/A	N/A	N/A
8-68	9/23/1968	19	Canada Dept of Highways	350	6" diameter routing post with 3 10' long independent expanding anchors fastened to 10" diameter x 4 ft deadman logs at 45° angles	Ditch	6" diameter cedar	77	42	12
Test 77	1972	22	Canada Dept of Highways	400	Concrete Block	N/A	S3x5.7	42	18	8
Test 78	1972	22	Canada Dept of Highways	400	Concrete Block	N/A	S3x5.7	42	18	8

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 70	1967	18	3/4"	6" Slot top of post	3000	27.625	26.875	N/A	N/A		Posts bolted to concrete footings
Test 73	1967	18	3/4"	4.5" Slot top of post	3000	25.625	24.875	N/A	N/A	Steel sockets anchored in concrete	Posts placed in sockets
1-67	8/23/1967	19	1/2"	Staples/Hooks	Unk	25	N/A	N/A	N/A		Grade 50 cable; see report for anchorage details
2-67	8/29/1967	19	3/4"	Staples/Hooks	Unk	27	N/A	N/A	N/A		Grade 50 cable
8-67	9/22/1967	19	1/2"	Staples/Hooks	Unk	27	24	21	N/A		Grade 50 cable
3-68	8/1/1968	19	1/2"	Staples/Hooks	785	27	24	21	N/A		Grade 110 cables; assemblies torqued to 30 ft-lb
1A-68	7/9/1968	19	1/2"	Staples/Hooks	1180	27	24	21	N/A		Grade 110 cables; assemblies torqued to 45 ft-lb
1-68	8/1/1968	19	1/2"	Staples/Hooks	Unk	27	24	21	N/A		Top cable Grade 50, bottom and middle cable Grade 110
5-68	8/27/1968	19	3/4"	Staples/Hooks	Unk	27	N/A	N/A	N/A		Single cable Grade 50
9-68	8/28/1968	19	3/4"	Staples/Hooks	Unk	27	N/A	N/A	N/A		Single cable Grade 50
5A-68	8/29/1968	19	3/4"	Staples/Hooks	Unk	27	N/A	N/A	N/A		No posts used in impact area; Grade 50 cable
6-68	9/4/1968	19	1/2"	Staples/Hooks	Unk	27	24	21	N/A	Swaged spacers attached to cables	Grade 110 cables
7-68	9/11/1968	19	1/2"	Staples/Hooks	Unk	27	25.5	24	N/A		Stronger end assembly, Grade 110 cables
7A-68	9/12/1968	19	1/2"	Staples/Hooks	Unk	27	25.5	24	N/A		Grade 110 cables; no posts used between anchors
8-68	9/23/1968	19	1/2"	Staples/Hooks	Unk	27	25.5	24	N/A		Grade 110 cables
Test 77	1972	22	3/4"	4" tapered slot in top of post	5000	28.75	28	N/A	N/A	Turnbuckles for pretensioning, threaded rods into concrete anchor block	Systems in test nos. 77 through 82 were modifications of systems tested by RRL in "Wire Rope Slotted-Post Barrier"; all posts notched in web, flange for strength of 3900 lb
Test 78	1972	22	3/4"	4" tapered slot in top of post	5000	28.75	28	N/A	N/A	Turnbuckles for pretensioning, threaded rods into concrete anchor block	Posts notched in web and flanges for strength of 3900 lb

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
Test 79	1972	22	Canada Dept of Highways	400	Concrete Block	N/A	S3x5.7	42	18	8
Test 81	1972	22	Canada Dept of Highways	400	Concrete Block	N/A	S3x5.7	42	18	16
Test 82	1972	22	Canada Dept of Highways	400	Concrete Block	N/A	S3x5.7	42	18	16

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 79	1972	22	3/4"	4" tapered slot in top of post	5000	28.75	28	N/A	N/A	Turnbuckles for pretensioning, threaded rods into concrete anchor block	Posts notched in web and flanges for strength of 3900 lb
Test 81	1972	22	3/4"	4" tapered slot in top of post	5000	28.75	28	N/A	N/A	Turnbuckles for pretensioning, threaded rods into concrete anchor block	Posts notched in web and flanges for strength of 3900 lb
Test 82	1972	22	3/4"	4" tapered slot in top of post	5000	28.75	28	N/A	N/A	Turnbuckles for pretensioning, threaded rods into concrete anchor block	Posts notched in web and flanges for strength of 3900 lb

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Appendix B - Historical Development Testing, Crash Test Details

The historical development refers to the time during which testing was conducted to any standard that did not include NCHRP Reports 230 or 350 or MASH, and were generally conducted before 1980. These tables incorporate the following testing details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Speed
- Angle
- Impact Severity
- Impact Location
- Vehicle Description
    - Year
    - Make
    - Model
    - Weight
- Results
- Test Designation
- Vehicle Damage
- Exit Speed
- Exit Angle
- Test Criteria Analysis

Page B

- Test Name
- Test Date
- Reference Number
- Maximum Tension
- No. Posts Requiring Maintenance
- Length of Contact
- Max Deflection
- Maximum Decelerations
    - 50-ms Average
    - Longitudinal
    - Lateral (positive is to passenger side)
- OIV
- ORD
- Testing Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 12	11/3/1958	7	56.0	27	117.2	Between post nos. 6 and 7	1952	Ford	Sedan	4002	Redirected, snagged	N/A	Unk	Unk	Unk	Pass
Test 14	12/26/1958	7	61.0	31	178.9	Post centerline (unk post number)	1953	Chevrolet	Sedan	4000	Captured, snagged	N/A	Unk	Unk	Unk	Pass
Test 19	3/5/1959	7	41.0	15	18.9	Midspan between posts (unk post numbers)	1953	Chevrolet	Sedan	3700	Captured	N/A	Unk	Unk	Unk	Pass
Test 20	3/10/1959	7	52.0	32	127.3	At center of cable gate transition	1954	Chevrolet	Sedan	3700	Snagged, pitched, yawed	N/A	Unk	Unk	Unk	Fail
Test 21	3/20/1959	7	60.0	31	166.6	Midspan between posts (unk post numbers)	1953	Chevrolet	Sedan	3850	Captured, snagged	N/A	Unk	Unk	Unk	Pass
Test 23	4/21/1959	7	42.0	34	437.5	At post centerline (unk post number)	1937	N/A	40 Passenger Bus	17500	Captured	N/A	Unk	Unk	Unk	Pass
Test 1	8/9/1962	8	90.0	25	282.0	Unk	1960	Dodge	Sedan	4300	Captured, snagged	N/A	Unk	N/A	N/A	Pass
Test 2	8/16/1962	8	83.0	25	239.8	Unk	1960	Dodge	Sedan	4300	Rollover	N/A	Unk	N/A	N/A	Fail
Test 3	8/22/1962	8	84.0	25	245.6	Unk	1960	Dodge	Sedan	4300	Captured, spun out	N/A	Unk	Unk	Unk	Pass
Test 4	8/30/1962	8	87.0	25	263.5	Unk	1960	Dodge	Sedan	4300	Captured, spun out	N/A	Unk	Unk	Unk	Pass
Test 91	1/9/1964	9	67.0	7	12.5	Post centerline	1960	Ford	Sedan	4138	Snagged and spun out	N/A	Unk	Unk	Unk	Marginal
Test 92	2/4/1964	9	67.0	25	92.3	Midspan between posts	1958	N/A	Triumph	2540	Captured, snagged	N/A	Unk	N/A	N/A	Pass
Test 93	2/26/1964	9	65.0	7	11.8	Midspan between posts	1960	Ford	Sedan	4138	Snagged, rolled onto side	N/A	Unk	Unk	Unk	Fail
Test 94	3/18/1964	9	60.0	7	10.0	Post centerline	1960	Ford	Sedan	4138	Snagged and spun out	N/A	Unk	Unk	Unk	Pass
Test 95	4/22/1964	9	65.0	25	86.9	Post centerline	1958	N/A	Triumph	2540	Penetrated	N/A	Unk	Unk	Unk	Fail
Test 96	5/7/1964	9	63.0	25	81.6	Midspan between posts	1960	N/A	Triumph	2540	Penetrated	N/A	Unk	Unk	Unk	Fail
511	4/4/1958	12	41.0	20	36.9	At post no. 4	1956	Pontiac	4-door	4137	Captured	N/A	Unk	N/A	N/A	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 12	11/3/1958	7	Unk	7	50	7	2	86	N/A	N/A	6.9	15.4	Unk	Unk	Unk	Unk	Some snag occurred; yaw angle nearly 90 degrees
Test 14	12/26/1958	7	Unk	11	80	8	6	102	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle came to rest with cable engaged in suspension behind impacting front wheel
Test 19	3/5/1959	7	Unk	4	35	3	4	40	N/A	N/A	5.5	2.2	Unk	Unk	Unk	Unk	Impacting wheel snagged on chain link mesh at vehicle final rest
Test 20	3/10/1959	7	Unk	4	24	9	0	108	N/A	N/A	53	34	Unk	Unk	Unk	Unk	Vehicle snagged and pitched, yawed around front impacting corner; vehicle nearly rolled over
Test 21	3/20/1959	7	Unk	12	56	8	0	96	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle came to rest with cable engaged in suspension behind impacting front wheel
Test 23	4/21/1959	7	Unk	23	90	12	0	144	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 1	8/9/1962	8	Unk	39	320	17	0	204	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
Test 2	8/16/1962	8	N/A	37	N/A	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Anchor block failed, releasing cable; vehicle peentrated and rolled over
Test 3	8/22/1962	8	Unk	29	225	17	0	204	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Cables were frayed after impact; vehicle snagged on post following redirection
Test 4	8/30/1962	8	Unk	27	216	17	0	204	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Splices were destoryed in impact
Test 91	1/9/1964	9	Unk	12	96	3	7	43	N/A	N/A	3.7	3.5	Unk	Unk	Unk	Unk	Cable height referenced from raised median; yaw displacement 130 deg; dummy decelerations noted
Test 92	2/4/1964	9	Unk	10	31	7	6	90	N/A	N/A	7.5	7	Unk	Unk	Unk	Unk	Cable height referenced from raised median; vehicle came to rest with cables snagged on impacting front wheel; dummy decelerations noted
Test 93	2/26/1964	9	Unk	9	80	4	6	54	N/A	N/A	4.5	3	Unk	Unk	Unk	Unk	Roll angle near 90 degrees; lower cable breakaway mechanism did not function as it was designed to; dummy decelerations noted
Test 94	3/18/1964	9	Unk	16	80	3	0	36	N/A	N/A	3.5	3.7	Unk	Unk	Unk	Unk	Vehicle snagged and yawed away from barrier; dummy decelerations noted
Test 95	4/22/1964	9	Unk	5	35	N/A	N/A	N/A	N/A	N/A	38	16.5	Unk	Unk	Unk	Unk	Cable splice failed; dummy was struck causing rubbing damage on shoulder; dummy decelerations noted
Test 96	5/7/1964	9	Unk	4	16	N/A	N/A	N/A	N/A	N/A	58	29.5	Unk	Unk	Unk	Unk	Could have resulted in decapitation; dummy decelerations noted
511	4/4/1958	12	Unk	4	Unk	2	0.75	24.75	N/A	N/A	N/A	5.8	Unk	Unk	Unk	Unk	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
542	12/26/1958	12	61.5	20	-	Post centerline	1958	Oldsmobile	4-door	Unk	Penetrated, fractured cables	N/A	Unk	N/A	N/A	Fail
591	5/24/1960	12	65.0	16.7	66.3	146 ft downstream of post no. 3	1960	Pontiac	2-door sedan	4190	Captured	N/A	Unk	N/A	N/A	Pass
593	6/3/1960	12	65.0	8	18.3	56 ft downstram of post no. 3	1957	Cadillac	4-door	4922	Captured, spun out	N/A	Unk	N/A	N/A	Pass
596	6/23/1960	12	35.0	8.5	4.7	24 ft downstream of post no. 3	1960	Pontiac	2-door sedan	3870	Captured	N/A	Unk	N/A	N/A	Pass
Test 1	1960	13	41.0	34	90.5	Unk	1957	Ford	Sedan	3800	Snagged, spun out	N/A	Unk	N/A	N/A	Fail
Test 12	1960-1963	13	52.0	21	-	Unk	Unk	Unk	Sedan	Unk	Captured	N/A	Unk	N/A	N/A	Fail
Test 18	1963	13	62.0	32	190.8	Unk	1960	Plymouth	Sedan	3900	Redirected	N/A	Unk	37	10	Pass
Test 20	1965	13	55.0	25	85.7	Unk	1961	Plymouth	2-door sedan	3500	Rolled over	N/A	Unk	42	23	Fail
Test 28	1965	13	53.0	25	79.6	Unk	1961	Plymouth	2-door sedan	3500	Redirected	N/A	Unk	45+	Large (unk)	Pass
Test 33	1965	13	54.0	25	82.6	Midspan between posts (unk post numbers)	1961	Plymouth	2-door sedan	3500	Redirected	N/A	Unk	33	12	Marginal
Test 36	1965	13	43.0	35	96.5	Midspan between posts	1961	Plymouth	2-door sedan	3500	Snagged, yawed	N/A	Unk	N/A	N/A	Marginal
Test 37	1965	13	53.0	5	3.4	At post centerline (unk post number)	1961	Plymouth	2-door sedan	3500	Captured	N/A	Unk	N/A	N/A	Pass
Test 46	1965	13	44.0	25	54.9	At post centerline (unk post number)	1961	Plymouth	2-door sedan	3500	Redirected	N/A	Unk	32	15	Pass
Test 1	1976	14	28.0	90	110.3	Center of system	1965	Plymouth	4-door sedan	3105	Captured, rebounded	N/A	Unk	~0	90	Pass
Test 9	1976	14	53.0	25	75.0	At post centerline (unk post number)	1961	Plymouth	4-door sedan	3300	Redirected	N/A	Unk	32	15	Pass
Test 10	1976	14	58.0	25	89.9	Unk	1961	Plymouth	2-door sedan	3300	Redirected	N/A	Unk	33	12	Pass
Test 11	1976	14	58.0	25	89.9	Unk	1961	Plymouth	2-door sedan	3300	Redirected, snagged	N/A	Unk	42	23	Marginal

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
542	12/26/1958	12	Unk	9	112.5	N/A	N/A	N/A	N/A	N/A	7	6	Unk	Unk	Unk	Unk	3 cables fractured, all posts DS of impact knocked down
591	5/24/1960	12	Unk	16	99	8	0	96	1.6	1.6	4.5	5.5	Unk	Unk	Unk	Unk	Vehicle had yawed prior to impact; yaw angle 26 degrees with respect to barrier
593	6/3/1960	12	Unk	13	90	3	8	44	1.5	2.0	34	4.5	Unk	Unk	Unk	Unk	Threw upstream concrete anchor 27'-6" downstream; vehicle yawed 53 degrees
596	6/23/1960	12	Unk	7	41	3	2	38	1.0	0.6	3.8	2.6	Unk	Unk	Unk	Unk	
Test 1	1960	13	Unk	6	20	12	0	144	4.4	Unk	N/A	N/A	Unk	Unk	Unk	Unk	One cable fractured, one cable separated at splice; vehicle came to rest on top of barrier
Test 12	1960-1963	13	Unk	12	42	4	0	48	12.2	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Many posts fractured; cables crushed windwhield due to underride
Test 18	1963	13	Unk	>25	95	11	0	132	5.2	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 20	1965	13	Unk	9	56	11	0	132	3.9	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Following redirection, vehicle snagged and rolled
Test 28	1965	13	Unk	7	56	8	6	102	3.5	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 33	1965	13	Unk	6	60	8	8	104	2.4	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Large roll displacements noted following redirection; windshield cracked by cables sliding over hood and contacting A-pillar
Test 36	1965	13	Unk	6	72	9	4	112	5.2	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Angles were thrown from cables in tests 33 and 36
Test 37	1965	13	Unk	20	200	1	0	12	0.8	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle overrode lowest cable, came to rest with cable beneath vehicle and 2 cables engaged with body panels
Test 46	1965	13	Unk	6	96	11	0	132	6.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 1	1976	14	Unk	~6	N/A	7	8	92	3.7	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Test used to validate computer model
Test 9	1976	14	Unk	~7	Unk	8	0	96	6.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 10	1976	14	Unk	Unk	Unk	7	0	84	2.4	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 11	1976	14	Unk	Unk	Unk	7	0	84	3.9	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle pitched and yawed very violently during impact

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 12 and 35	1976	14	55.0	25	73.5	Unk	1963	Plymouth	4-door sedan	3000	Captured, spun out	N/A	Unk	Unk	Unk	Pass
Test 13	1976	14	35.0	90	172.4	Center of system	1965	Plymouth	4-door sedan	3105	Captured	N/A	Unk	~0	90	Pass
Test 17	1976	14	39.0	25	184.7	Unk	1956	International	Dump truck	15000	Redirected	N/A	Unk	24	13	Pass
Test 21	1976	14	57.0	25	42.7	Unk	1956	Anglia	2-door sedan	1623	Redirected	N/A	Unk	29	0	Pass
Test 22	1976	14	44.0	0	0.0	Centerline of system	1965	Plymouth	2-door sedan	3105	Terminal gated	N/A	Unk	Unk	Unk	Pass
Test 23	1976	14	55.0	25	88.2	Aligned with first upright post (routing post)	1964	Ford	4-door sedan	3600	Terminal gated	N/A	Unk	Unk	Unk	Fail
Test 30	1976	14	62.0	25	114.5	~24' upstream of cable/box beam overlap	1964	Ford	4-door sedan	3680	Rapid deceleration	N/A	Unk	27	20	Fail
Test 31	1976	14	54.0	25	62.8	Unk	1962	Valiant	4-door Station Wagon	2660	Snagged	N/A	Unk	34	24	Fail
Test 32	1976	14	40.0	20	25.4	Unk	1962	Plymouth	4-door sedan	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 33	1976	14	55.0	22	76.7	Unk	1962	Ford	Station Wagon	3985	Redirected	N/A	Unk	8	0	Pass
Test 34	1976	14	61.0	25	93.5	Unk	1965	Plymouth	2-door sedan	3105	Captured, snagged	N/A	Unk	N/A	N/A	Marginal
Test 36	1976	14	59.0	25	103.7	Unk	1964	Ford	4-door sedan	3680	Penetrated	N/A	Unk	N/A	N/A	Fail
Test 52	1976	14	40.0	25	51.6	Unk	1962	Ford	4-door Station Wagon	3985	Captured	N/A	Unk	N/A	N/A	Pass
Test 53	1976	14	40.0	25	51.6	Unk	1962	Ford	4-door Station Wagon	3985	Captured	N/A	Unk	N/A	N/A	Pass
Test 8330B	1974	16	58.0	5	5.2	Post no. 1 head on at 5 degree offset from tangent	1965	Oldsmobile	98 4-door sedan	4490	Terminal gated	N/A	Unk	40	Unk	Pass
Test 11	1967	17	44.0	20	30.8	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	34	12	Pass
Test 12	1967	17	42.0	19	25.4	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	35	18	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 12 and 35	1976	14	Unk	Unk	Unk	4	10	58	0.9	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle did not impact box beam
Test 13	1976	14	Unk	~9	N/A	Unk	Unk	Unk	2.0	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 17	1976	14	Unk	Unk	Unk	14	0	168	1.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Concrete anchor block pulled out of ground; had rained before test and ground was saturated
Test 21	1976	14	Unk	Unk	Unk	5	10	70	2.2	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Very smooth redirection
Test 22	1976	14	Unk	~6	N/A	N/A	N/A	N/A	1.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 23	1976	14	Unk	~4	N/A	N/A	N/A	N/A	8.4	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Relatively high G-force exerted on vehicle due to FR tire sliding between lower and upper cables, fractured fittings
Test 30	1976	14	Unk	Unk	~24	7	0	84	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Hard hit on box beam caused beam to hinge and collapse at one location, fall off of all upstream posts
Test 31	1976	14	Unk	~2	Unk	6	6	78	2.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Snagging occurred due to tapered section hinging close to the start of the taper
Test 32	1976	14	Unk	~4	Unk	5	0	60	3.0	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Speed was considerably lower than desired for this test
Test 33	1976	14	Unk	~6	Unk	5	0	60	1.6	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
Test 34	1976	14	Unk	~4	Unk	7	7	91	8.1	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle snagged after impacting protruding section of box beam
Test 36	1976	14	Unk	Unk	Unk	N/A	N/A	N/A	4.5	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Penetrated and continued behind system
Test 52	1976	14	Unk	Unk	Unk	5	6	66	1.0	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Previously had thought this system would undergo significant snagging
Test 53	1976	14	Unk	Unk	Unk	7	0	84	1.8	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Did not result in lower accelerations; instead, caused more posts to break; this option was not recommended
Test 8330B	1974	16	N/A	4	Unk	N/A	N/A	N/A	~7.8	Unk	19.7	6	Unk	Unk	Unk	Unk	
Test 11	1967	17	6000	6	~44	2	0	24	1.7	3.7	N/A	N/A	Unk	Unk	Unk	Unk	
Test 12	1967	17	8560	9	~42	3	2	38	1.4	1.9	N/A	N/A	Unk	Unk	Unk	Unk	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 13	1967	17	46.0	20	33.7	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	32	13	Pass
Test 14	1967	17	41.0	20	26.7	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	26.9	17	Pass
Test 15	1967	17	52.0	20	22.4	Midspan between posts (unk post numbers)	N/A	Austin	Minivan	1560	Redirected	N/A	Unk	30	15	Pass
Test 16	1967	17	62.0	19	36.0	At post (unk post number)	N/A	Volkswagon	Small Car	1950	Redirected, spun out	N/A	Unk	48	<5	Pass
Test 17	1967	17	48.0	8	6.1	Unk	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	41	10	Pass
Test 19	1967	17	58.0	10.5	15.2	Unk	N/A	Standard	Vanguard	3000	Rolled over	N/A	Unk	N/A	N/A	Fail
Test 20	1967	17	57.0	6	4.8	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	49	5	Pass
Test 21	1967	17	60.0	10	14.8	Post centerline	N/A	Standard	Vanguard	3000	Rolled over	N/A	Unk	N/A	Unk	Fail
Test 22	1967	18	29.0	9	2.8	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	17.7	7	Pass
Test 23	1967	18	31.7	9	3.3	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	27.9	5	Pass
Test 24	1967	18	43.0	12	10.9	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	37.5	5	Pass
Test 25	1967	18	60.0	10	14.8	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	53	4	Pass
Test 26	1967	18	59.0	20	55.4	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	44.3	3	Pass
Test 27	1967	18	32.0	8	2.7	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	28	6	Pass
Test 28	1967	18	31.0	9	3.2	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	30	4	Pass
Test 29	1967	18	57.0	20	51.7	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	50	9	Pass
Test 30	1967	18	67.0	22	44.5	Midspan between posts (unk post numbers)	N/A	Austin	Minivan	1560	Redirected	N/A	Unk	38	8	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 13	1967	17	11000	7	48	4	0	48	1.7	2.3	N/A	N/A	Unk	Unk	Unk	Unk	
Test 14	1967	17	11000	5	32	2	6	30	1.9	2.0	N/A	N/A	Unk	Unk	Unk	Unk	
Test 15	1967	17	8600	3	36	2	10	34	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Extensive deformation on right side of vehicle
Test 16	1967	17	10400	5	~50	3	3	39	1.8	4.9	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle had an engine in the rear, which affected vehicle dynamics
Test 17	1967	17	6800 front rope, 4300 rear	4	36	1	4	16	1.9	1.2	N/A	N/A	Unk	Unk	Unk	Unk	
Test 19	1967	17	5000	13	98	2	0	24	1.4	1.6	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle ran over bottom cable and was trapped; Test 18 had no data
Test 20	1967	17	7300 front rope, 5100 rear	5	40	1	9	21	1.2	1.3	N/A	N/A	Unk	Unk	Unk	Unk	
Test 21	1967	17	6400 front rope, 5600 rear	15	112	2	2	26	1.5	1.2	N/A	N/A	Unk	Unk	Unk	Unk	
Test 22	1967	18	4500	6	~78	1	7	19	0.6	0.9	N/A	N/A	Unk	Unk	Unk	Unk	
Test 23	1967	18	4250	3	50	2	0	24	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 24	1967	18	10000	5	~72	2	8	32	0.4	1.1	N/A	N/A	Unk	Unk	Unk	Unk	
Test 25	1967	18	5900	11	~77	2	10	34	0.8	1.3	N/A	N/A	Unk	Unk	Unk	Unk	
Test 26	1967	18	12400	15	~108	7	6	90	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 27	1967	18	3440	6	~44	1	8	20	0.6	0.5	N/A	N/A	Unk	Unk	Unk	Unk	
Test 28	1967	18	6400	5	~43	1	10	22	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 29	1967	18	7600	14	~96	7	3	87	0.8	2.0	N/A	N/A	Unk	Unk	Unk	Unk	
Test 30	1967	18	8300	17	~110	8	6	102	0.7	3.8	N/A	N/A	Unk	Unk	Unk	Unk	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 31	1967	18	47.0	17.5	64.5	Midspan between posts (unk post numbers)	N/A	Bedord	Pantechnicon (large truck)	7120	Redirected	N/A	Unk	31	15	Pass
Test 32	1967	18	28.0	20	6.5	Midspan between posts (unk post numbers)	N/A	Austin	Minivan	1560	Redirected	N/A	Unk	Unk	15	Pass
Test 33	1967	18	37.0	20	21.8	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	Unk	10	Pass
Test 34	1967	18	17.5	20	11.6	At post (unk post number)	N/A	Bedord	Pantechnicon (large truck)	7120	Captured	N/A	Unk	N/A	0	Pass
Test 35	1967	18	34.0	20	18.4	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	Unk	9	Pass
Test 36	1967	18	25.2	20	27.6	At post centerline (unk post number)	N/A	Bedord	Truck	8200	Redirected	N/A	Unk	17	7	Pass
Test 37	1967	18	42.3	18	63.5	Midspan between posts (unk post numbers)	N/A	Bedord	Truck	8200	Redirected	N/A	Unk	23.5	1	Pass
Test 38	1967	18	64.0	24	86.0	Midspan between posts	N/A	Austin	Healey 3000	2800	Penetrated	N/A	Unk	N/A	N/A	Fail
Test 39	1967	18	55.2	18	39.6	~24 ft upstream of gate	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	34.1	11	Pass
Test 40	1967	18	55.0	24	68.0	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 41	1967	18	60.0	20	57.3	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 42	1967	18	55.0	20	48.1	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	Unk	Unk	Pass
Test 43	1967	18	50.0	21.5	45.7	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Redirected	N/A	Unk	Unk	Unk	Pass
Test 44	1967	18	62.0	20	61.1	At post centerline (unk post number)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 45	1967	18	58.5	22	65.3	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 46	1967	18	62.5	19	56.3	Midspan between posts (unk post numbers)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass
Test 47	1967	18	65.0	17.5	51.9	At post (unk post number)	N/A	Standard	Vanguard	3000	Captured	N/A	Unk	N/A	N/A	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 31	1967	18	7600	19	~160	13	0	156	0.6	0.6	N/A	N/A	Unk	Unk	Unk	Unk	Truck overran traffic-side cable
Test 32	1967	18	3900	7	~45	3	3	39	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 33	1967	18	5600	7	~50	3	3	39	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 34	1967	18	8200	14	100+	5	6	66	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 35	1967	18	6500 upper rope, 7200 lower	7	~44	2	9	33	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	High-tension system
Test 36	1967	18	7300	10	~70	4	8	56	0.2	0.6	N/A	N/A	Unk	Unk	Unk	Unk	
Test 37	1967	18	10500 upper rope, 13000 lower	23	140+	8	6	102	0.9	0.8	N/A	N/A	Unk	Unk	Unk	Unk	
Test 38	1967	18	5000 upper rope, 13600 lower	11	N/A	N/A	N/A	N/A	2.4	2.1	N/A	N/A	Unk	Unk	Unk	Unk	Top rope slid up hood and struct A-pillar; could have decapitated driver; vehicle impacted rigid object behind barrier
Test 39	1967	18	8500 upper rope, 13500 lower	16	~120	9	0	108	1.7	1.4	N/A	N/A	Unk	Unk	Unk	Unk	Anchor released allowing vehicle to pass through joint area
Test 40	1967	18	8200	25	~150	12	0	144	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 41	1967	18	9200	35	~215	12	6	150	1.8	1.3	N/A	N/A	Unk	Unk	Unk	Unk	Two post footings moved during test
Test 42	1967	18	12550	13	~65	6	4	76	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	One post footing pulled out during test
Test 43	1967	18	5800	15	~95	9	0	108	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	One post footing pulled out during test
Test 44	1967	18	6650	23	~160	8	10	106	2.1	1.5	N/A	N/A	Unk	Unk	Unk	Unk	
Test 45	1967	18	11100	23	~178	9	6	114	1.4	1.6	N/A	N/A	Unk	Unk	Unk	Unk	
Test 46	1967	18	6600	29	~187	13	3	159	3.7	1.3	N/A	N/A	Unk	Unk	Unk	Unk	Two post footings loosened
Test 47	1967	18	8300	19	~225	14	0	168	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	One post footing dislodged

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 70	1967	18	64.5	20	34.4	Post centerline	N/A	Austin	Minivan	1560	Rolled over	N/A	Unk	N/A	N/A	Fail
Test 73	1967	18	62.6	12	12.0	At post centerline (unk post number)	N/A	Austin	Minivan	1560	Redirected	N/A	Unk	50	7	Pass
1-67	8/23/1967	19	51.0	25	84.2	Unk	N/A	N/A	Station Wagon	4000	Penetrated	N/A	Unk	N/A	N/A	Fail
2-67	8/29/1967	19	47.0	25	71.5	Unk	N/A	N/A	Station Wagon	4000	Redirected	N/A	Unk	31	13	Pass
8-67	9/22/1967	19	56.7	25	104.1	Unk	N/A	N/A	Station Wagon	4000	Redirected	N/A	Unk	37	8	Pass
3-68	8/1/1968	19	50.0	25	81.0	Unk	N/A	N/A	Station Wagon	4000	Captured, spun out	N/A	Unk	Unk	Unk	Pass
1A-68	7/9/1968	19	48.0	25	74.6	Unk	N/A	N/A	Station Wagon	4000	Redirected	N/A	Unk	Unk	Unk	Pass
1-68	8/1/1968	19	52.0	25	87.6	Unk	N/A	N/A	Station Wagon	4000	Spun-out	N/A	Unk	N/A	N/A	Marginal
5-68	8/27/1968	19	50.0	25	81.0	Unk	N/A	N/A	Station Wagon	4000	Redirected	N/A	Unk	Unk	5	Pass
9-68	8/28/1968	19	52.0	25	-	Unk	N/A	N/A	VW Beetle	N/A	See Notes	N/A	Unk	N/A	N/A	Likely Pass
5A-68	8/29/1968	19	50.0	25	81.0	Unk	N/A	N/A	Station Wagon	4000	Penetrated	N/A	Unk	N/A	N/A	Fail
6-68	9/4/1968	19	46.0	25	68.5	Unk	N/A	N/A	Station Wagon	4000	Captured, spun out	N/A	Unk	N/A	N/A	Marginal
7-68	9/11/1968	19	44.0	25	62.7	Unk	N/A	N/A	Station Wagon	4000	Captured	N/A	Unk	N/A	N/A	Pass
7A-68	9/12/1968	19	48.0	25	74.6	Unk	N/A	N/A	Station Wagon	4000	Penetrated, overturned	N/A	Unk	N/A	N/A	Fail
8-68	9/23/1968	19	50.0	25	81.0	Unk	N/A	N/A	Station Wagon	4000	Captured, spun out	N/A	Unk	N/A	N/A	Fail
Test 77	1972	22	45.0	24.55	79.2	Between post nos. 11 and 12	1963	Pontiac	Strato-Chief 2-door	5000	Redirected	N/A	Unk	Unk	Unk	Pass
Test 78	1972	22	34.5	24.53	46.5	Between post nos. 11 and 12	1963	Pontiac	Strato-Chief 2-door	5000	Redirected	N/A	Unk	Unk	Unk	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 70	1967	18	9500	6	120+	9	0	108	1.8	2.2	N/A	N/A	Unk	Unk	Unk	Unk	Rope slipped up hood and engaged A-pillar
Test 73	1967	18	6000	7	~52	2	7	31	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Anchor failed, releasing cable
1-67	8/23/1967	19	N/A	8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Anchor failed, releasing cable; 4 g's maximum deceleration
2-67	8/29/1967	19	Unk	10	Unk	6	0	72	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	1.6 g's (average) sustained over 220 ms
8-67	9/22/1967	19	Unk	14	42	5	2.4	62.4	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	2.1 g's (average) sustained over 150 ms
3-68	6/27/1968	19	Unk	12	Unk	7	9	93	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Yaw motion related to vehicle traversing over ditch; cable engaged suspension behind wheel
1A-68	7/9/1968	19	Unk	10	Unk	5	6	66	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle made secondary contact with the system
1-68	8/1/1968	19	Unk	9	Unk	5	9.6	69.6	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Top cable rode up hood and shattered rear windshield; vehicle yawed away from system; vehicle came to rest wit cables engaged in suspension behind impacting wheel
5-68	8/27/1968	19	Unk	8	Unk	7	6	90	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
9-68	8/28/1968	19	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Car chassis not well connected to body; separated after impact, but groove above headlight indicated likelihood of acceptable performance
5A-68	8/29/1968	19	Unk	0	N/A	N/A	N/A	Unk	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	No posts except at anchorages; end anchorages fractured, releasing cables; vehicle rolled over in ditch
6-68	9/4/1968	19	Unk	9	Unk	6	0	72	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Cables were trapped in wheel well after impact
7-68	9/11/1968	19	Unk	9	80	5	6	66	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	
7A-68	9/12/1968	19	Unk	0	N/A	N/A	N/A	N/A	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	No posts except at anchorages
8-68	9/23/1968	19	Unk	9	Unk	5	6	66	Unk	Unk	N/A	N/A	Unk	Unk	Unk	Unk	Posts were pulled out of soil; wet soil conditions at the time of the test
Test 77	1972	22	~16000	~9	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Box beam placed in lieu of bumper on front of vehicle in test nos. 77-82 to reinforce front; box chamfered 45 degrees at edge
Test 78	1972	22	Unk	~6	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 79	1972	22	55.0	24.75	120.2	Between post nos. 11 and 12	1963	Pontiac	Strato-Chief 2-door	5000	Redirected	N/A	Unk	Unk	Unk	Pass
Test 81	1972	22	44.5	24.71	78.4	Between post nos. 5 and 6	1963	Pontiac	Strato-Chief 2-door	5000	Redirected	N/A	Unk	Unk	Unk	Pass
Test 82	1972	22	54.5	24.55	116.2	Between post nos. 5 and 6	1963	Pontiac	Strato-Chief 2-door	5000	Redirected	N/A	Unk	Unk	Unk	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 79	1972	22	~22000	~11	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
Test 81	1972	22	~18000	~6	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
Test 82	1972	22	~20000	~7	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	

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Appendix C - NCHRP Report 230 Testing, System Details

This section details testing that occurred according to performance criteria presented in NCHRP Report 230, and international testing that was conducted prior to the publication of NCHRP Report 350. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Performing Organization
- System Length
- Anchor Type
- System Configuration (i.e. on slope, curve, transition etc.)
- Post Properties
  - Section Type
  - Length
  - Embedment Depth
  - Spacing

Page B

- Test Name
- Test Date
- Reference Number
- Cable Properties
  - Diameter and Weave
  - Attachment Hardware to Posts
  - Pretension
- Mounting Heights
  - Top Cable
  - 2nd Cable
  - 3rd Cable
  - Bottom Cable
- Additional Components
- System Design Note

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
3659-6	10/12/1978	21	TTI	200	Steel Frame and Concrete Block	12' from 6:1 SBP in ditch (located on slope)	S3x5.7	63	29.5	16
3659-5	10/23/1978	21	TTI	200	Steel Frame and Concrete Block	6' from 6:1 SBP in ditch (located on slope)	S3x5.7	63	29.5	16
4798-11	7/19/1983	23	TTI	250	Bent threaded rod with turnbuckle and rod through concrete block	N/A	5.5" diameter wood	72	38.5	12.5
4798-2	1/31/1984	23	TTI	250	Bent threaded rod with turnbuckle and rod through concrete block	N/A	5.5" diameter wood	72	38.5	12.5
1769-C-1-87 (C-1)	6/11/1987	24	Ensco, Inc	200	30"x30"x8" Concrete block	N/A	5.5" nominal round wood	72	38.5	12.5
1769-C-2-87 (C-2)	8/27/1987	24	Ensco, Inc	200	30"x30"x8" Concrete block	N/A	5.5" nominal round wood	72	38.5	12.5
1769-C-3-87 (C-3)	10/16/1987	24	Ensco, Inc	200	30"x30"x8" Concrete block	N/A	5.5" nominal round wood	72	38.5	12.5
1769-C-4-87 (C-4)	11/3/1987	24	Ensco, Inc	200	30"x30"x8" Concrete block	N/A	5.5" nominal round wood	72	38.5	12.5
1769-C-5-87 (C-5)	9/9/1988	24	Ensco, Inc	200	30"x30"x8" Concrete block	Downstream Terminal Impact	5.5" nominal round wood	72	38.5	12.5
Test 5	1980	47	NYDOT	145	Concrete Block	100' radius (inside curve)	S3x5.7	63	29.5	4.2
Test 8	1980	47	NYDOT	138	Concrete Block	50' radius (inside curve)	S3x5.7	63	29.5	3.125
Test 96	1990	25	NYDOT	180	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	Approach Transition	S3x5.7	Unk	Unk	16
Test 97	1990	25	NYDOT	180	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	Approach Transition	S3x5.7	Unk	Unk	16
Test 98	1990	25	NYDOT	180	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	Approach Transition	S3x5.7	Unk	Unk	16
Test 99	1990	25	NYDOT	180	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	Beginning of Length of Need	S3x5.7	Unk	Unk	16
Test 100	1990	25	NYDOT	180	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	Beginning of Length of Need	S3x5.7	Unk	Unk	16
Test 101	1990	25	NYDOT	106.5	3'x3'x3'-3" trapezoidal concrete block with anchor bracket flared 4' behind system and 18" US of post 1	1/4 offset head-on	S3x5.7	Unk	Unk	16

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
3659-6	10/12/1978	21	3/4"	J-bolts	1000	30	27	24	N/A	24"x8"x0.25" soil bearing plate, spring compensators	Standard G1 guardrail
3659-5	10/23/1978	21	3/4"	J-bolts	1000	30	27	24	N/A	24"x8"x0.25" soil bearing plate, spring compensators	Standard G1 guardrail
4798-11	7/19/1983	23	3/4"	5/16" J-bolts with 12-gauge, 0.375" washers	Unk	28	24	20	N/A		Modified GR-1
4798-2	1/31/1984	23	3/4"	5/16" J-bolts with 12-gauge, 0.375" washers	Unk	28	24	20	N/A		Modified GR-1
1769-C-1-87 (C-1)	6/11/1987	24	3/4"	5/16" J-bolts	Unk	28	24	20	N/A	Bent anchor rods, turnbuckles, cable termination bracket	1.5" transverse round hole 5 in. below ground
1769-C-2-87 (C-2)	8/27/1987	24	3/4"	5/16" J-bolts	Unk	28	24	20	N/A	Bent anchor rods, turnbuckles, cable termination bracket	4' rod offset deepened anchor, anchor post strengthened by makin it a dual post, 1.5" transverse hole 5 in. below ground
1769-C-3-87 (C-3)	10/16/1987	24	3/4"	5/16" J-bolts	Unk	28	24	20	N/A	Bent anchor rods, turnbuckles, cable termination bracket	Anchor rod shortened by 2', BCT cable used to connect to anchor rod; 1.5" transverse round hole 5 in. below ground
1769-C-4-87 (C-4)	11/3/1987	24	3/4"	5/16" J-bolts	Unk	28	24	20	N/A	Bent anchor rods, turnbuckles, cable termination bracket	Same installation as C-3; 1.5" transverse round hole 5 in. below ground
1769-C-5-87 (C-5)	9/9/1988	24	3/4"	5/16" J-bolts	Unk	28	24	20	N/A	Bent anchor rods, turnbuckles, cable termination bracket	1.5" transverse hole 5 in. below ground
Test 5	1960	47	3/4"	5/16" J-bolts	Unk	30	27	24	N/A		G1 guardrail; post length and embedment are approximate
Test 8	1960	47	3/4"	5/16" J-bolts	Unk	30	27	24	N/A		G1 guardrail; post length and embedment are approximate
Test 96	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	30	27	24	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Widened slot in anchor bracket
Test 97	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	30	27	24	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Teflon washer set in anchor bracket, brass keeper rod instead of steel, and additional post near anchor
Test 98	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	30	27	24	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	45 degree turndown into anchor, solid anchor rods used to span from anchor over shelf brackets on post no. 1
Test 99	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	30	27	24	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	
Test 100	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Lowered cable height
Test 101	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 102	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Incorporated slip base at cable routing post
Test 103	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Removed 2nd and 3rd posts from terminal, 45 degree cable turndown into anchor with swaged end anchor at bracket
Test 104	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	
Test 105	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	
Test 106	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Extra washer added
Test 107	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Changes to system were cumulative through test 107
GR-5	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
GR-16	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
GR-17	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
MSD-2	1/23/1987	28	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Standard G1 guardrail transitioned to BCT end terminal on flare
MSD-3	2/4/1987	30	3/4"	5/16" J-bolts	Unk	30	27	24	N/A		
MSD-2A	3/12/1987	29	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		
MSD-4	3/12/1987	31	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		
SD-1	3/3/1989	32	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates	
SD-2	6/28/1989	33	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates, 12"/6" x 6" x 0.125"	
SD-3	7/6/1989	34	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates, 12"/6" x 6" x 0.125"	
Test 1	1988-1989	35	3/4"	Slot in top of post	~3000	25	25	15.75	15.75		Lower ropes spaced from upper ropes by spacers; both pairs of ropes located in same slot

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 102	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Incorporated slip base at cable routing post
Test 103	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Removed 2nd and 3rd posts from terminal, 45 degree cable turndown into anchor with swaged end anchor at bracket
Test 104	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	
Test 105	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	
Test 106	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Extra washer added
Test 107	1990	25	3/4"	Angles with welded lip bolted to post, 5/16" J-bolts	Unk	27	24	21	N/A	Threaded rods, turnbuckles, compensators, washers and nuts	Changes to system were cumulative through test 107
GR-5	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
GR-16	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
GR-17	7/1986	26	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Anchor bracket, turnbuckles, 24"x8"x0.25" soil bearing plates, spring compensators	GR-1 guardrail system with New York terminal
MSD-2	1/23/1987	28	3/4"	5/16" J-bolts	Unk	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Standard G1 guardrail transitioned to BCT end terminal on flare
MSD-3	2/4/1987	30	3/4"	5/16" J-bolts	Unk	30	27	24	N/A		
MSD-2A	3/12/1987	29	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		
MSD-4	3/12/1987	31	3/4"	5/16" J-bolts	Unk	27	24	21	N/A		
SD-1	3/3/1989	32	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates	
SD-2	6/28/1989	33	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates, 12"/6" x 6" x 0.125"	
SD-3	7/6/1989	34	3/4"	5/16" J-bolts	900 at 70° F	27	24	21	N/A	Trapezoidal soil plates, 12"/6" x 6" x 0.125"	
Test 1	1988-1989	35	3/4"	Slot in top of post	~3000	25	25	15.75	15.75		Lower ropes spaced from upper ropes by spacers; both pairs of ropes located in same slot

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 2	1988-1989	35	3/4"	Slot in top of post	~6000	25	25	15.75	15.75		Lower ropes spaced from upper ropes by spacers; both pairs of ropes located in same slot
Test 3	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~3000 lower	25	25	15.75	15.75		Lower ropes were woven between every other post
Test 4	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~6000 lower	25	25	19.25	19.25		Lower ropes were woven between every other post
Test 5	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~6000 lower	27	27	19.25	19.25		Lower ropes were woven between every other post
Test 6	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~5000	25	25	19.25	19.25		Lower ropes were woven between every other post
Test 7	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~5000	23	23	19.25	19.25		Lower ropes were woven between every post
E166	1989	36	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
E167	1989	37	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
F190	1989	37	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
J0903	1991	38	3/4"	Unk	Unk	23	23	19.25	19.25		
J0904	1991	38	3/4"	Unk	Unk	23	23	19.25	19.25		
1500-kg Car at 2.4 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	5000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
750-kg Car at 2.4 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	5000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
1500-kg Car at 1.2 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	~6000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
750-kg Car at 1.2 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	~6000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
Test 2	1988-1989	35	3/4"	Slot in top of post	~6000	25	25	15.75	15.75		Lower ropes spaced from upper ropes by spacers; both pairs of ropes located in same slot
Test 3	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~3000 lower	25	25	15.75	15.75		Lower ropes were woven between every other post
Test 4	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~6000 lower	25	25	19.25	19.25		Lower ropes were woven between every other post
Test 5	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~7000 upper, ~6000 lower	27	27	19.25	19.25		Lower ropes were woven between every other post
Test 6	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~5000	25	25	19.25	19.25		Lower ropes were woven between every other post
Test 7	1988-1989	35	3/4"	Slot in top of post, brackets on sides	~5000	23	23	19.25	19.25		Lower ropes were woven between every post
E166	1989	36	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
E167	1989	37	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
F190	1989	37	3/4"	Slot in top of post, brackets on sides	Unk	Unk	Unk	Unk	Unk		
J0903	1991	38	3/4"	Unk	Unk	23	23	19.25	19.25		
J0904	1991	38	3/4"	Unk	Unk	23	23	19.25	19.25		
1500-kg Car at 2.4 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	5000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
750-kg Car at 2.4 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	5000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
1500-kg Car at 1.2 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	~6000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post
750-kg Car at 1.2 m Post Spacing	1991-1993	35	3/4"	Slot in top of post, brackets on sides	~6000	23	23	19.25	19.25	Turnbuckles	Lower ropes were woven between every post

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Appendix D - NCHRP Report 230 Testing, Crash Test Details

This section describes cable testing performed according to the criteria presented in NCHRP Report 230 and international testing conducted between 1980 and 1993. These tables incorporate the following testing details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Speed
- Angle
- Impact Severity
- Impact Location
- Vehicle Description
  - Year
  - Make
  - Model
  - Weight
- Results
- Test Designation
- Vehicle Damage
- Exit Speed
- Exit Angle
- Test Criteria Analysis

Page B

- Test Name
- Test Date
- Reference Number
- Maximum Tension
- No. Posts Requiring Maintenance
- Length of Contact
- Max Deflection
- Maximum Decelerations
  - 50-ms Average Longitudinal
  - 50-ms Average Lateral
  - Longitudinal
  - Lateral (positive numbers indicate acceleration to right side)
- OIV
- ORD
- Testing Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
3659-6	10/12/1978	21	58.4	17.25	30.6	Midspan between post nos. 2 and 3	1974	Chevrolet	Vega	2250	Captured	11	Unk	N/A	N/A	Pass
3659-5	10/23/1978	21	59.6	24.75	127.0	Midspan between post nos. 2 and 3	N/A	Plymouth	Sedan	4500	Captured	10	Unk	N/A	N/A	Pass
4798-11	7/19/1983	23	61.2	25.5	133.7	Between post nos. 10 and 11	1978	Plymouth	Unk	4249	Captured	10	Unk	N/A	N/A	Marginal
4798-2	1/31/1984	23	59.3	14.5	22.2	Between post nos. 10 and 11	1978	Honda	Unk	2220	Rollover	11	Unk	N/A	N/A	Fail
1769-C-1-87 (C-1)	6/11/1987	24	60.6	21	42.8	Midspan bewteen post nos. 7 and 8	1981	Honda	Civic	2000	Captured, rolled over	"S13"	10LFEW1	N/A	N/A	Fail
1769-C-2-87 (C-2)	8/27/1987	24	62.1	20	40.0	Midspan between post nos. 9 and 10	1981	Honda	Civic	1957	Penetrated, rolled over	"S13"	02RYAO2	N/A	N/A	Fail
1769-C-3-87 (C-3)	10/16/1987	24	61.0	20	38.7	Midspan between post nos. 9 and 10	1981	Honda	Civic	1960	Redirected	S13	02RYEW1	47.8	10	Pass
1769-C-4-87 (C-4)	11/3/1987	24	62.7	26	160.2	Midspan between post nos. 9 and 10	1979	Ford	LTD II	4680	Captured	10	02RDEW2	N/A	N/A	Pass
1769-C-5-87 (C-5)	9/9/1988	24	60.6	21	41.5	Post no. 17	1981	Honda	Civic	1940	Rolled over	Special	01FDEO,	N/A	N/A	Fail
Test 5	1960	47	47.9	90	318.2	Center of Radius	1969	Ford	Fairlane	3060	Captured	N/A	12FDMW5	N/A	N/A	Pass
Test 8	1960	47	32.8	90	172.6	Center of Radius	1974	AMC	Matador	3540	Captured	N/A	12FDMW3	N/A	N/A	Pass
Test 96	1990	25	58.6	14	16.4	34.3 ft upstream from downstream anchor	N/A	N/A	Sedan	1800	Snagged, rolled over	N/A	Unk	N/A	N/A	Fail
Test 97	1990	25	57.1	13	13.5	33 ft upstream of downstream anchor	N/A	N/A	Sedan	1800	Snagged, rolled over	N/A	Unk	N/A	N/A	Fail
Test 98	1990	25	55.8	11	9.2	39.4 ft upstream of downstream anchor	N/A	N/A	Sedan	1800	Penetrated	N/A	Unk	N/A	N/A	Pass
Test 99	1990	25	57.4	24	103.8	76 ft downstream of upstream anchor	N/A	N/A	Sedan	4200	Captured	40	Unk	N/A	N/A	Fail
Test 100	1990	25	57.7	23	110.1	81 ft downstream of upstream anchor	N/A	N/A	Sedan	4780	Redirected	40	Unk	40.5	15	Pass
Test 101	1990	25	58.1	2	N/A	End-on impact; post no. 1	N/A	N/A	Sedan	1800	Rollover	45	Unk	N/A	N/A	Fail

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
3659-6	10/12/1978	21	Unk	11	~150	4	2	50	2.04	0.72	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle impacted concrete and steel anchor at end of test
3659-5	10/23/1978	21	Unk	11	~150	9	6	114	2.26	3.19	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle impacted concrete and steel anchor at end of test
4798-11	7/19/1983	23	Unk	16	~100	11	5	137	3.4	2.5	7.3	-3.5	Unk	Unk	Unk	Unk	Anchor block uprooted and damaged during redirection; cables fractured
4798-2	1/31/1984	23	Unk	5	50	3	0	36	6.2	4.5	12.8	7.2	Unk	Unk	Unk	Unk	Snagged on post after redirecting
1769-C-1-87 (C-1)	6/11/1987	24	Unk	~10	~110	5	6	66	1.7	4.3	4.9	-7.3	-10.4	-12.9	-4.9	-9.3	Vehicle rolled over after impacting post debris and downstream compensator assemblies
1769-C-2-87 (C-2)	8/27/1987	24	Unk	~4	Unk	N/A	N/A	N/A	2.0	3.3	4.2	7	-10.6	-12.6	-4.2	-7.2	Vehicle rolled over after penetrating through barrier
1769-C-3-87 (C-3)	10/16/1987	24	Unk	10	Unk	4	6	54	2.3	5.9	6	10.2	-12.7	-14.3	-6	-10.2	
1769-C-4-87 (C-4)	11/3/1987	24	Unk	10	Unk	8	0	96	2.0	3.8	3	6.1	-13	-12.3	-3	-6.1	
1769-C-5-87 (C-5)	9/9/1988	24	Unk	1	Unk	N/A	N/A	N/A	-16.2	5.1	3.6	4.1	-34.3	-8.6	-3.6	-4.1	Dummy struck windshield; windshield released from vehicle
Test 5	1980	26	Unk	15	N/A	29	0	348	N/A	N/A	0.98	N/A	Unk	Unk	Unk	Unk	
Test 8	1980	26	Unk	9	N/A	17	6	210	2.7	1.1	11.4	7.7	Unk	Unk	Unk	Unk	
Test 96	1990	25	Unk	5	34.3	N/A	N/A	N/A	3.8	2.1	N/A	N/A	12.2	4.1	15.1	6.2	Cables did not release from terminal during reverse-direction impact; cables sliding over bumper contributed t rollover
Test 97	1990	25	Unk	5	33	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Test 98	1990	25	Unk	5	39.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Test 99	1990	25	Unk	Unk	104	9	6	114	1.4	3.2	N/A	N/A	9.9	10.9	4.5	6.2	Vehicle underrode cables, which crushed vehicle roof - tes results unacceptable
Test 100	1990	25	Unk	11	86	8	0	96	0.1	0.1	N/A	N/A	N/A	N/A	N/A	N/A	
Test 101	1990	25	Unk	4	22	N/A	N/A	N/A	6.3	0.6	N/A	N/A	N/A	N/A	N/A	N/A	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 102	1990	25	72.4	0	N/A	End-on impact; post no. 1	N/A	N/A	Sedan	1800	Rollover	45	Unk	N/A	N/A	Fail
Test 103	1990	25	68.0	5	N/A	End-on impact; post no. 1	N/A	N/A	Sedan	1800	Terminal gated	45	Unk	56.3	-1	Pass
Test 104	1990	25	61.3	15	20.5	43.5 ft upstream of downstream anchor	N/A	N/A	Sedan	1800	Redirected	N/A	Unk	Unk	5	Pass
Test 105	1990	25	54.8	10	7.4	23.5 ft downstream from upstream anchor	N/A	N/A	Sedan	1800	Captured	44	Unk	N/A	N/A	Pass
Test 106	1990	25	-	25	-	38 ft downstream from upstream anchor	N/A	N/A	Sedan	4500	Penetrated	42	Unk	Unk	24	Fail
Test 107	1990	25	56.6	25	125.8	38 ft downstream from upstream anchor	N/A	N/A	Sedan	4850	Contained	42	Unk	32	16	Pass
GR-5	7/1986	26	60.5	15.8	24.3	Unk	1976	Honda	Civic	1973	Redirected	SL-2 12	Unk	43.8	1.7	Pass
GR-16	7/1986	26	59.2	19.5	35.3	Unk	1980	Honda	Unk	1995	Captured	SL-2 11	Unk	N/A	N/A	Pass
GR-17	7/1986	26	58.1	24.2	106.9	Unk	1979	Dodge	Van	4160	Redirected	SL-2 10	Unk	Unk	Unk	Pass
MSD-2	1/23/1987	28	58.9	27.3	155.1	Right side of vehicle aligned with centerline of post no. 1	1978	Plymouth	Sedan	4690	Redirected, snagged	30	01FREE5	Unk	Unk	Fail
MSD-3	2/4/1987	30	59.8	18.6	32.6	8 ft downstream of Post 11	1981	Volkswagon	Rabbit	1975	Redirected	12	11FLEE2	Unk	Unk	Pass
MSD-2A	3/12/1987	29	58.3	24.4	114.6	Right side of vehicle aligned with centerline of post no. 1 (W-beam)	1978	Plymouth	Sedan	4360	Redirected	30	01FREE5	Unk	Unk	Pass
MSD-4	3/12/1987	31	58.6	25	131.8	Left side of vehicle aligned with centerline of post no. 1 (W-beam)	1978	Dodge	Sedan	4740	Captured	Special 30	12FREE4	N/A	N/A	Pass
SD-1	3/3/1989	32	60.0	25.7	141.6	2 ft downstream of post 11	1982	Oldsmobile	N/A	4615	Overrode System	12	11FLEE2	N/A	N/A	Fail
SD-2	6/28/1989	33	60.0	25	135.5	2 ft downstream of post 11	1984	Oldsmobile	N/A	4650	Captured	30	11FLEE2	N/A	N/A	Pass
SD-3	7/6/1989	34	61.4	21.2	44.1	2 ft downstream of post 11	1984	Volkswagon	Rabbit	1974	Captured	30	11FLEE2	N/A	N/A	Pass
Test 1	1988-1989	35	70	20	86	Unk	Unk	Unk	Unk	3306	Captured	N/A	Unk	Unk	Unk	Fail

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 102	1990	25	Unk	Unk	20.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Test 103	1990	25	Unk	1	12' first contact	N/A	N/A	N/A	3.7	1.0	N/A	N/A	11.5	Unk	1.6	Unk	
Test 104	1990	25	Unk	3	40	N/A	N/A	N/A	3.7	2.9	N/A	N/A	12.7	9	8.5	9.9	
Test 105	1990	25	Unk	Unk	64.5' first contact	1	0	12	2.6	2.5	N/A	N/A	10.8	5.5	6	9.7	
Test 106	1990	25	Unk	Unk	N/A	Unk	Unk	Unk	3.0	3.7	N/A	N/A	15.8	8	5.1	9.8	Anchor released during the test permitting vehicle to pass through barrier
Test 107	1990	25	Unk	Unk	122	12	0	144	3.0	3.4	N/A	N/A	14.3	9.6	2	7.1	Vehicle remained in contact with the barrier, passed over end terminal and came to rest behind system
GR-5	7/1986	27	Unk	Unk	Unk	3	7.4	43.4	2.1	2.2	1.7	8.7	Unk	Unk	Unk	Unk	Vehicle rolled over after recontacting the terminal section
GR-16	7/1986	27	Unk	Unk	Unk	5	10	70	3.6	3.5	4.5	5.6	Unk	Unk	Unk	Unk	
GR-17	7/1986	27	Unk	Unk	80	8	11	107	6.9	3.1	Unk	Unk	Unk	Unk	Unk	Unk	
MSD-2	1/23/1987	29	Unk	~7	33.2	6	0	72	6.9	7.5	N/A	N/A	20.2	-16.9	-4	11.4	
MSD-3	2/4/1987	31	Unk	Unk	64	6	4	76	2.6	3.8	N/A	N/A	12.2	9.5	-9.7	-11.6	
MSD-2A	3/12/1987	30	Unk	~4	Unk	5	10	70	5.7	6.8	N/A	N/A	19.5	-16	-9.5	8.4	
MSD-4	3/12/1987	32	Unk	8	54	6	6	78	8	5.9	N/A	N/A	23	12.8	-5.1	8.5	
SD-1	3/3/1989	33	Unk	>8	N/A	N/A	N/A	N/A	1.3	1.1	N/A	N/A	7.6	5.7	-1.4	Unk	Vehicle overrode cables, came to rest in ditch
SD-2	6/28/1989	34	Unk	~13	201	9	10	118	1.5	2.3	N/A	N/A	1.5	10	N/A	-3.5	
SD-3	7/6/1989	35	Unk	17	250	6	2.4	74.4	1.7	3.7	N/A	N/A	10.6	12	-1.5	-5.1	
Test 1	1988-1989	36	Unk	Unk	Unk	10	2	122	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Flanges fractured, releasing cables prematurely; this design was abandoned

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
Test 2	1988-1989	35	70	20	86	Unk	Unk	Unk	Unk	3306	Redirected	N/A	Unk	Unk	Unk	Pass
Test 3	1988-1989	35	70	20	86	Unk	Unk	Unk	Unk	3306	Redirected	N/A	Unk	Unk	Unk	Pass
Test 4	1988-1989	35	70	20	86	Unk	Unk	Unk	Unk	3306	Redirected	N/A	Unk	Unk	Unk	Pass
Test 5	1988-1989	35	70	20	43	Unk	Unk	Unk	Unk	1640	Rolled over	N/A	Unk	Unk	Unk	Fail
Test 6	1988-1989	35	70	20	43	Unk	Unk	Unk	Unk	1640	Redirected	N/A	Unk	Unk	Unk	Pass
Test 7	1988-1989	35	70	20	-	Unk	Unk	Unk	Unk	Unk	Redirected	N/A	Unk	Unk	Unk	Pass
E166	1989	36	Unk	20	-	Unk	Unk	Unk	Unk	Unk	Captured	N/A	Unk	Unk	Unk	Pass
E167	1989	37	Unk	20	-	Unk	Unk	Unk	Unk	Unk	Unk	N/A	Unk	Unk	Unk	Unk
F190	1989	37	Unk	20	-	Unk	Unk	Unk	Unk	Unk	Unk	N/A	Unk	Unk	Unk	Unk
J0903	1991	38	71.6	19	82.0	200 ft downstream of terminal	N/A	Rover	SD1	3329	Redirected	N/A	Unk	Unk	8	Pass
J0904	1991	38	71.6	19	40.4	200 ft downstream of terminal	N/A	Rover	Mini	1640	Redirected	N/A	Unk	Unk	1	Pass
1500-kg Car at 2.4 m Post Spacing	1991-1993	35	70.2	19	78.3	Unk	Unk	Unk	Unk	3306	Redirected	N/A	Unk	Unk	7	Pass
750-kg Car at 2.4 m Post Spacing	1991-1993	35	72.1	19	41.3	Unk	Unk	Unk	Unk	1653	Redirected	N/A	Unk	61.5	7	Pass
1500-kg Car at 1.2 m Post Spacing	1991-1993	35	72.0	19	82.3	Unk	Unk	Unk	Unk	3306	Redirected	N/A	Unk	55.9	8	Pass
750-kg Car at 1.2 m Post Spacing	1991-1993	35	70.5	19	39.5	Unk	Unk	Unk	Unk	1653	Redirected	N/A	Unk	55.9	1	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
Test 2	1988-1989	36	Unk	Unk	Unk	16	1	193	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Two cables overridden; not much known about tests 1 through 7
Test 3	1988-1989	36	Unk	Unk	Unk	7	10	94	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	One cable overridden
Test 4	1988-1989	36	Unk	Unk	Unk	5	11	71	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	One cable contacted windshield
Test 5	1988-1989	36	Unk	Unk	Unk	3	7	43	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Rolled due to secondary contact with system
Test 6	1988-1989	36	Unk	Unk	Unk	Unk	Unk	Unk	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
Test 7	1988-1989	36	Unk	Unk	Unk	Unk	Unk	Unk	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Impact speeds and angles are nominal (target numbers)
E166	1989	36	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	It is possible that due to test naming ambiguity, the tests E166 through F190 represent three of the seven tests noted above (Test 1 through Test 7 at the MIRA labs, years 1988-1989). Tests J0903 and J0904 were likely conducted after the completion of the seven tests noted above.
E167	1989	37	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
F190	1989	37	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
J0903	1991	38	Unk	18	Unk	3	8	44	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
J0904	1991	38	Unk	13	Unk	2	7	31	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
1500-kg Car at 2.4 m Post Spacing	1991-1993	36	Unk	9	62	5	7	67	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Vehicle made secondary contact with barrier, impacted 9 additional posts
750-kg Car at 2.4 m Post Spacing	1991-1993	36	Unk	7	49	3	11	47	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Many tests were run by Bridon Ropes, LTD, but not all were named; some ambiguity exists in test naming
1500-kg Car at 1.2 m Post Spacing	1991-1993	36	Unk	17	~52	3	8	44	N/A	N/A	-3.3	-5.9	Unk	Unk	Unk	Unk	Vehicle made secondary contact with barrier, impacted 10 additional posts
750-kg Car at 1.2 m Post Spacing	1991-1993	36	Unk	13	39	2	10	34	N/A	N/A	-5.8	-4.7	Unk	Unk	Unk	Unk	

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Appendix E - NCHRP Report 350 Testing, System Details

This section contains the system details for tests that were conducted according to criteria presented in NCHRP Report 350 as well as international tests conducted between 1993 and 2009. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Performing Organization
- System Length
- Anchor Type
- System Configuration (i.e. on slope, curve, transition etc.)
- Post Properties
  - Section Type
  - Length
  - Embedment Depth
  - Spacing

Page B

- Test Name
- Test Date
- Reference Number
- Cable Properties
  - Diameter and Weave
  - Attachment Hardware to Posts
  - Pretension
- Mounting Heights
  - Top Cable
  - 2nd Cable
  - 3rd Cable
  - Bottom Cable
- Additional Components
- System Design Note

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
L6016	9/28/1993	39	UK MIRA	630	6"x6" box beam anchors	N/A	0.25" thick Z-section in sockets	42.5	15.75	7.9
M6035	1994	41	UK MIRA	630	Unk	N/A	0.25" thick Z-section in sockets	Unk	Unk	7.9
N6014	1995	42	UK MIRA	348	Unk	N/A	0.25" thick Z-section in sockets	Unk	Unk	10.5
N6015	1995	43	UK MIRA	348	Unk	N/A	0.25" thick Z-section in sockets	Unk	Unk	10.5
N6016	1995	44	UK MIRA	348	Unk	N/A	0.25" thick Z-section in sockets	Unk	Unk	10.5
N6017	1995	45	UK MIRA	348	Unk	N/A	0.25" thick Z-section in sockets	Unk	Unk	10.5
01LB	2000	48	UK MIRA	1921	WRSF Terminal	N/A	0.25" thick Z-section in sockets	42.5	15.75	7.75
01MB	2002	49	UK MIRA	337.3	WRSF Terminal	N/A	0.25" thick Z-section in sockets	42.5	15.75	7.75
471470-28	11/15/1994	51	TTI	388	3'x3'x3'-8" tall trapezoidal concrete block with anchor bracket	N/A	S3x5.7	63	30	16
405160-11-1	7/11/2008	52	TTI	476	Steel Post anchor developed by TTI	N/A	S3x5.7	63	30	16
270687 WDT-2	3/6/1996	53	TTI	500	New York Terminal Anchor	N/A	S3x5.7	63	~29.25	16
404211-8	2/16/2000	55	TTI	475	New York Terminal Anchor	Transition	S3x5.7	63	~29.25	16
400001-MSC1	6/1/2000	56	TTI	475	New York Terminal Anchor	N/A	4 lb/ft Marion U-channel	63	33.25	16
404211-6	10/1/1998	57	TTI	393	New York Terminal Anchor	Terminal Located on 6:1 Slope	S3x5.7	63	33	16
SDC-1	8/11/1998	58	MwRSF	289.75	Concrete block and anchor bracket	Transition	S3x5.7	63	33	4' (terminal) 16' (standard) 6' (transition)
SDC-2	8/18/1998	58	MwRSF	289.75	Concrete block and anchor bracket	Transition	S3x5.7	63	33	4' (terminal) 16' (standard) 6' (transition)
SDC-3	8/31/1998	58	MwRSF	289.75	Concrete block and anchor bracket	Transition	S3x5.7	63	33	4' (terminal) 16' (standard) 6' (transition)

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
L6016	9/28/1993	39	3/4"	Slot in top of post, brackets on sides	Unk	26.6	26.6	22.8	22.8		
M6035	1994	41	3/4"	Slot in top of post, brackets on sides	Unk	22.8	22.8	19.3	19.3		
N6014	1995	42	3/4"	Slot in top of post, brackets on sides	Unk	22.8	22.8	19.3	19.3		
N6015	1995	43	3/4"	Slot in top of post, brackets on sides	Unk	22.8	22.8	19.3	19.3		
N6016	1995	44	3/4"	Slot in top of post, brackets on sides	Unk	26.4	26.4	3.6	3.6		
N6017	1995	45	3/4"	Slot in top of post, brackets on sides	Unk	22.8	22.8	19.3	19.3		
01LB	2000	48	3/4"	Slot in top of post, brackets on sides	5058	24.5	23.75	20	20	Anchor bolts M24 threaded in large concrete blocks	
01MB	2002	49	3/4"	Slot in top of post, brackets on sides	4946	24.5	23.75	20	20	Anchor bolts M24 threaded in large concrete blocks	
471470-28	11/15/1994	51	3/4"	5/16" J-bolts	Unk	30	27	24	N/A		Two 42' terminal sections included
405160-11-1	7/11/2008	52	3/4"	5/16" J-bolts	Unk	30	25.5	21	N/A	Epoxy eye-sockets were used to fasten the cables to the terminal posts, pin-and-loop sockets for splices	
270687 WDT-2	3/6/1996	53	3/4"	5/16" J-bolts	950	30.25	25.5	20.75	N/A		Cable locations are approximate
404211-8	2/16/2000	55	3/4"	5/16" J-bolts	970	30.25	25.5	20.75	N/A	Additional anchorage	Anchorage transition from one part to the next tested for adequacy cable locations are approximate
400001-MSC1	6/1/2000	56	3/4"	5/16" J-bolts	970	30.25	25.25	20.75	N/A	Trapezoidal soil plates	Cable locations are approximate
404211-6	10/1/1998	57	3/4"	5/16" J-bolts	970	27	24	21	N/A	Cable anchors	
SDC-1	8/11/1998	58	3/4"	5/16" J-bolts	~900	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Transitioned to Flared W-beam at BCT
SDC-2	8/17/1998	58	3/4"	5/16" J-bolts	~900	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Transitioned to Flared W-beam at BCT
SDC-3	8/31/1998	58	3/4"	5/16" J-bolts	~900	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Transitioned to Flared W-beam at BCT

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
FCT-1	12/3/2002	59	MwRSF	334	Concrete block and anchor bracket	Transition	S3x5.7	63	33	4' (terminal) 16' (standard) 6' (transition)
CS-1	11/1/2001	60	MwRSF	485	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	At 1.5:1 slope break point	S3x5.7	63	30	16
CS-2	11/1/2006	61	MwRSF	494	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	4' from SBP of 1.5:1 slope	S3x5.7	63	30	4
CMB-1	7/2/2003	64	MwRSF	486	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	N/A	M8x6.5	78	42	6
CMB-2	11/10/2004	64	MwRSF	484	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	N/A	S3x5.7	66	31	8
CMB-3	3/14/2005	64	MwRSF	484	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	N/A	S3x5.7	67	31	8
CT-1	7/3/2002	65	MwRSF	254	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	CIP	S3x5.7	63	30	16
CT-2	7/16/2002	65	MwRSF	254	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	1/4 offset head-on	S3x5.7	63	30	16
CT-3	10/10/2003	65	MwRSF	254	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	1/4 offset head-on	S3x5.7	63	30	16
CT-4	6/8/2005	65	MwRSF	254	W6x25 8' long with 24"x24"x1/2" soil bearing plate and cable anchor	1/4 offset head-on	S3x5.7	63	30	16

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
FCT-1	12/3/2002	59	3/4"	5/16" J-bolts	~900	27	24	21	N/A	Cable routing bracket, BCT end terminal, W-beam installation	Transitioned to FLEAT terminal
CS-1	11/1/2001	60	3/4"	5/16" J-bolts	~900	30	27	24	N/A		
CS-2	11/1/2006	61	3/4"	5/16" J-bolts	~900	30	27	24	N/A		
CMB-1	7/2/2003	64	3/4"	5/16" J-bolts	900	34	27	20	13		Cables woven between every post; middle 2 cables located on opposite side of posts from top and bottom cables
CMB-2	11/10/2004	64	3/4"	3 3/8"x3"x1/2" welded cable hook plate	900	33	26.5	20	13.5		
CMB-3	3/14/2005	64	3/4"	4"x2 7/8"x1/2" welded cable hook plate with 1/4" bolts	900	33	26.5	20	13.5	Retainer bolts fastened to flanges of posts	
CT-1	7/3/2002	65	3/4"	5/16" J-bolts	~900	30	27	24	N/A	Cable release lever	Turnbuckles and compensators were standard at this point
CT-2	7/16/2002	65	3/4"	5/16" J-bolts	~900	30	27	24	N/A	Cable release lever	
CT-3	10/10/2003	65	3/4"	5/16" J-bolts	~900	30	27	24	N/A	Cable release lever secured with 0.25" diameter cable	Cable added to prevent the cable release lever from wedging unde the vehicle
CT-4	6/8/2005	65	3/4"	5/16" J-bolts	~900	30	27	24	N/A	Cable release lever secured with 0.25" diameter cable	Post nos. 3 through 7 added slip base

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Appendix F - NCHRP Report 350 Testing, Crash Test Details

This section describes tests that were conducted according to the criteria presented in NCHRP Report 350 and international testing conducted between 1993 and 2009. These tables incorporate the following testing details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Speed
- Angle
- Impact Severity
- Impact Location
- Vehicle Description
  - Year
  - Make
  - Model
  - Weight
- Results
- Test Designation
- Vehicle Damage
- Exit Speed
- Exit Angle
- Test Criteria Analysis

Page B

- Test Name
- Test Date
- Reference Number
- Maximum Tension
- No. Posts Requiring Maintenance
- Length of Contact
- Max Deflection
- Maximum Decelerations
  - 50-ms Average Longitudinal
  - 50-ms Average Lateral
  - Longitudinal
  - Lateral (positive numbers indicate acceleration to right side)
- OIV
- ORD
- Testing Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
L6016	9/28/1993	39	60.7	26.2	144.3	243 ft downstream of terminal	1986	Ford	F250	4432	Captured	3-11	Unk	N/A	N/A	Pass
M6035	1994	41	71.6	20	90.2	213 ft downstream of impact	N/A	Rover	SDI	3317	Redirected	N/A	Unk	Unk	4	Pass
N6014	1995	42	73.8	20	57.9	89 ft downstream of impact	N/A	Ford	Fiesta	2004	Redirected	N/A	Unk	Unk	13	Pass
N6015	1995	43	71.6	20	89.8	85 ft downstream of impact	N/A	Ford	Scorpio	3305	Redirected	N/A	Unk	Unk	11	Pass
N6016	1995	44	71.6	20	54.1	89 ft downstream of impact	N/A	Ford	Festiva	1991	Redirected	N/A	Unk	Unk	11	Pass
N6017	1995	45	71.6	20	90.2	85 ft downstream of impact	N/A	Ford	Scorpio	3318	Redirected	N/A	Unk	Unk	8	Pass
01LB	2000	48	70.2	20	84.7	Centerline of vehicle with midspan between post nos. 50 and 51	Unk	Ford	Granada	3243	Redirected	N/A	Unk	58.2	10	Pass
01MB	2002	49	70.8	20.1	85.8	At post no. 18	Unk	Saab	900	3197	Redirected	N/A	Unk	55.9	Unk	Pass
471470-28	11/15/1994	51	59.1	26.7	146.1	Midspan between post nos. 10 and 11	1989	Chevrolet	2500	4570	Redirected	3-11	11FYEK1 11LDEW2	37.5	2	Pass
405160-11-1	7/11/2008	52	62.3	25.4	146.4	At post 13	1999	Chevrolet	C2500	4522	Captured	3-11	11LDEW2	Unk	Unk	Pass
270687 WDT-2	3/6/1996	53	62.0	20.4	41.8	At post no. 12	1991	Ford	Festiva	1975	Captured	3-10	N/A	N/A	N/A	Pass
404211-8	2/16/2000	55	63.0	24.8	139.6	At post no. 11	1994	Chevrolet	2500	4410	Captured	3-11	11FLEK2 11LDEW2	N/A	N/A	Pass
400001-MSC1	6/1/2000	56	62.9	25.5	152.1	At post 11	1996	Chevrolet	C2500	4577	Captured	3-11	11FLEK2 11LDEW2	N/A	N/A	Pass
404211-6	10/1/1998	57	61.7	14.7	21.9	At post 1	1992	Ford	Festiva	1975	Terminal gated	3-34	12FRLN1	58.7	15.7	Pass
SDC-1	8/11/1998	58	63.3	27.6	173.0	17.25 in. upstream of post no. 14C	1993	GMC	2500	4438	Captured	3-21	01FFEW2 12FCLN1	N/A	N/A	Pass
SDC-2	8/17/1998	58	63.3	25.2	146.8	At post no. 4C	1994	GMC	2500	4460	Captured	3-21	01RFEW3	N/A	N/A	Pass
SDC-3	8/31/1998	58	61.9	20.2	40.1	12 in. downstream of post no. 1C	1991	Geo	Metro	1935	Redirected	3-20	01RDAW2	49	7.4	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
L6016	9/28/1993	48	18000	13	232	6	7	79	N/A	N/A	1.7	4.5	Unk	Unk	Unk	Unk	
M6035	1994	41	Unk	12	Unk	4	11	59	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
N6014	1995	44	Unk	5	Unk	4	4	52	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
N6015	1995	45	Unk	8	Unk	5	10	70	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
N6016	1995	46	Unk	6	Unk	4	4	52	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
N6017	1995	47	Unk	8	Unk	5	8	68	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	
01LB	2000	40	Unk	10	86.1	6	7	79	N/A	N/A	-2.27	3.45	Unk	Unk	Unk	Unk	
01MB	2002	41	Unk	11	75.8	5	7	67	N/A	N/A	2.2	4.5	Unk	Unk	Unk	Unk	
471470-28	11/15/1994	51	Unk	~7	~90	7	10	94	1.9	2.9	N/A	N/A	14.2	11.6	-4	5.6	
405160-11-1	7/11/2008	52	Unk	~20	~288	10	2	122	3.8	5.5	N/A	N/A	6.9	10.5	-16.4	15.2	
270687 WDT-2	3/6/1996	53	Unk	10	112	8	5.6	101.6	2.5	2.8	N/A	N/A	13.5	9.5	-3.6	3.9	Vehicle remained between cables following test
404211-8	2/16/2000	55	Unk	11	180	11	2	134	1.6	2.1	N/A	N/A	7.2	9.5	-2.7	4.9	
400001-MSC1	6/1/2000	56	Unk	~14	230	15	9	189	1.6	2.8	N/A	N/A	5.2	8.9	-2.3	4.7	Pickup overrode cables
404211-6	10/1/1998	57	N/A	1	N/A	N/A	N/A	N/A	2.3	1.4	N/A	N/A	5.9	3.0	-3.1	-3	Small car rolled after test; this was believed to be related to the ditch profile behind the barrier rather than the performance of the barrier itself
SDC-1	8/11/1998	58	Unk	~15	73	7	10.5	94.5	N/A	N/A	N/A	N/A	15.2	9.8	12.21	7.36	
SDC-2	8/18/1998	58	Unk	~5	36	Unk	Unk	N/A	N/A	N/A	N/A	N/A	22.4	12.4	9.52	5.97 / -7.44	Vehicle rebounded laterally after impacting W-beam
SDC-3	8/31/1998	58	Unk	1	~20	1	7.6	19.6	N/A	N/A	N/A	N/A	18.77	19.49	2.83 / -3.24	16.64	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
FCT-1	12/3/2002	59	63.8	25.4	151.7	17.2 in. upstream of post no. 14C	1998	Chevrolet	C2500	4469	Captured	3-21	01RFEW3	N/A	N/A	Pass
CS-1	11/1/2001	60	61.0	26.2	147.4	108 in. downstream of post no. 12	1995	GMC	2500	4484	Rollover	3-11	N/A	N/A	N/A	Fail
CS-2	11/1/2006	61	61.6	23.6	123.7	At post 32	1999	Chevrolet	C2500	4487	Redirected	3-11	12FYES3	32.8	16.3	Pass
CMB-1	7/2/2003	64	60.6	19.7	37.2	33.3 in. upstream of post no. 31	1997	Chevrolet	Metro	1969	Rollover	3-10	11LFMN3	N/A	N/A	Fail
CMB-2	11/10/2004	64	62.8	19.7	39.8	4 ft upstream from centerline of post no. 31	1996	Chevrolet	Metro	1960	Captured	3-10	11FEDW3	N/A	N/A	Pass
CMB-3	3/14/2005	64	60.8	25.4	137.5	4 ft upstream from centerline of post no. 31	1998	GMC	Pickup	4459	Redirected	3-11	11LFMN3	42	7	Pass
CT-1	7/3/2002	65	63.3	20.7	100.9	At post no. 3	1996	GMC	2500	4448	Redirected	3-35	11LDES3	59.7	4	Pass
CT-2	7/16/2002	65	62.1	1.5	N/A	1/4 offset from centerline of post no. 1 (release lever)	1995	Geo	Metro	1965	Rollover	3-30	12TDDO8	N/A	N/A	Fail
CT-3	10/10/2003	65	61.4	0.1	N/A	1/4 offset from centerline of post no. 1 (release lever)	1998	Geo	Metro	1952	Rollover	3-30	12TDDO8	N/A	N/A	Fail
CT-4	6/8/2005	65	61.1	0.1	N/A	1/4 offset from centerline of post no. 1 (release lever)	1998	Geo	Metro	1961	Terminal gated	3-30	12FDEW9	46.4	13	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
FCT-1	12/3/2002	59	Unk	12	64	6	2.8	74.8	N/A	N/A	N/A	N/A	11.5	11.5	8.73	7.9	
CS-1	11/1/2001	60	11090	8	~20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.27	8.82	4.9	15.19	Vehicle overrode cables; posts rotated through cut slope with little resistance
CS-2	11/1/2006	61	8860 bottom cable	~20	~60	10	4.5	124.5	N/A	N/A	N/A	N/A	-13.65	11.22	-5.73	6.96	
CMB-1	7/2/2003	64	3230 bottom middle cable	13	~42	3	8.4	44.4	N/A	N/A	N/A	N/A	-16.63	12.83	-8.11	6.32	Vehicle overrode bottom cable barrier, became trapped in weave
CMB-2	11/10/2004	64	Unk	4	~50	6	3.5	75.5	N/A	N/A	N/A	N/A	-20.08	6.3	-8.78	5.3	One post was pulled out of ground, remained attached to vehicle
CMB-3	3/14/2005	64	Unk	15	~76	9	5.3	113.3	N/A	N/A	N/A	N/A	-10.89	10.23	-3.93	6.26	One cable released from end anchor
CT-1	7/3/2002	65	11930 top cable	10	~96'	7	0.1	84.1	N/A	N/A	N/A	N/A	6.04	9.45	4.55	7	
CT-2	7/16/2002	65	Unk	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9.81	0.39	5.37	3.99	Router post tore through floorboard, caused vehicle trip initiation
CT-3	10/10/2003	65	Unk	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	11.02	0.72	9.56	-13.72	Cable release lever separated from anchor, fractured retainer cable
CT-4	6/8/2005	65	Unk	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	11.42	2.53	7.85	-3.48	Vehicle experienced roll displacement very large

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Appendix G - MASH and Additional Testing, System Details

This section contains the system details for tests that were conducted according to criteria presented in MASH as well as non-compliant tests conducted during and after acceptance of the MASH recommendations. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Performing Organization
- System Length
- Anchor Type
- System Configuration (i.e. on slope, curve, transition etc.)
- Post Properties
  - Section Type
  - Length
  - Embedment Depth
  - Spacing

Page B

- Test Name
- Test Date
- Reference Number
- Cable Properties
  - Diameter and Weave
  - Attachment Hardware to Posts
  - Pretension
- Mounting Heights
  - Top Cable
  - 2nd Cable
  - 3rd Cable
  - Bottom Cable
- Additional Components
- System Design Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
4CMB-1	10/30/2007	66	MwRSF	608	2' diameter x 10' concrete anchor with cable anchor bracket and cable release lever	12' from SBP of 4:1 V-ditch, 46' wide, located on downhill side	S3x5.7	87	39	16
4CMB-2	11/16/2007	66	MwRSF	608	2' diameter x 10' concrete anchor with cable anchor bracket and cable release lever	4' from center of 4:1 V-ditch, 46' wide, on uphill side	S3x5.7	90	42	16
4CMB-3	8/25/2008	66	MwRSF	608	2' diameter x 10' concrete anchor with cable anchor bracket and cable release lever	4' from center of 4:1 V-ditch, 46' wide, on uphill side	S3x5.7	90	42	16
04010	2007	89	NCAC	Unk	New York Terminal Anchor	4' from center of 4:1 V-ditch, 16' wide, on uphill side	S3x5.7	63	30	16
04011	2007	89	NCAC	Unk	New York Terminal Anchor	1' from center of 4:1 V-ditch, 16' wide, on uphill side	S3x5.7	63	30	16

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
4CMB-1	10/30/2007	66	3/4"	Slotted cable brackets	~4100	45	35	25	15	Modified low-tension 3-cable anchor bracket and kicker lever for 4-cable system	
4CMB-2	11/16/2007	66	3/4"	Slotted cable brackets	~4100	45	35	25	15	Modified low-tension 3-cable anchor bracket and kicker lever for 4-cable system	
4CMB-3	8/25/2008	66	3/4"	Slotted cable brackets	~4100	45	34.5	24	13.5	Modified low-tension 3-cable anchor bracket and kicker lever for 4-cable system	Compacted soil in impact region
04010	2007	89	3/4"	5/16" J-bolts	970	~30.5	~25.75	~21	N/A		System details are uncertain; due to comment in report stating similarity to Washington design tested by TTI, Washington 3-strand cable median barrier details used
04011	2007	89	3/4"	5/16" J-bolts	970	~30.5	~25.75	~21	N/A		

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Appendix H - MASH and Additional Testing, Crash Test Details

This section describes tests that were conducted according to the criteria presented in MASH and non-compliant tests conducted during and after the acceptance of the MASH recommendations. These tables incorporate the following testing details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Speed
- Angle
- Impact Severity
- Impact Location
- Vehicle Description
    - Year
    - Make
    - Model
    - Weight
- Results
- Test Designation
- Vehicle Damage
- Exit Speed
- Exit Angle
- Test Criteria Analysis

Page B

- Test Name
- Test Date
- Reference Number
- Maximum Tension
- No. Posts Requiring Maintenance
- Length of Contact
- Max Deflection
- Maximum Decelerations
    - 50-ms Average Longitudinal
    - 50-ms Average Lateral
    - Longitudinal
    - Lateral (positive numbers indicate acceleration to right side)
- OIV
- ORD
- Testing Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
4CMB-1	10/30/2007	66	61.8	27.9	189.1	36" downstream of post no. 15	2002	Dodge	Ram	4988	Captured	3-10	11LYEN5	N/A	N/A	Pass
4CMB-2	11/16/2007	66	62.8	26.4	90.4	61" downstream of post no. 17	2002	Kia	Rio	2557	Captured, underrode	3-10	11LYAN6	N/A	N/A	Fail
4CMB-3	8/25/2008	66	62.0	26.8	91.6	64" downstream of post no. 16	2002	Kia	Rio	2586	Captured, underrode	3-11	11LYAW8	N/A	N/A	Fail
04010	2007	89	62.1	25	-	Unk	N/A	Ford	Crown Victoria	N/A	Underrode system	N/A	Unk	N/A	N/A	Fail
04011	2007	89	62.1	25	-	Unk	N/A	Ford	Crown Victoria	N/A	Redirected	N/A	Unk	Unk	Unk	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
4CMB-1	10/30/2007	66	23280	23	142.9	13	10.5	166.5	N/A	N/A	N/A	N/A	-5.19	9.06	-5.19	3.97	Only top cable redirected vehicle; other three cables overridden
4CMB-2	11/16/2007	66	8410	3	N/A	4	1	49	N/A	N/A	N/A	N/A	-41.32	4.48	-7.94	-6.25	Vehicle underrode cables; significant vehicle deceleration caused by plowing through ditch rather than guardrail system
4CMB-3	8/25/2008	66	13731	3	N/A	5	4.5	64.5	N/A	N/A	N/A	N/A	-31.17	-6.5	-6.51	-6.86	Cables damaged, cut into A-pillar; vehicle underrode cables
04010	2007	68	Unk	Unk	Unk	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	Nose of vehicle went under all cables
04011	2007	68	Unk	Unk	Unk	Unk	Unk	Unk	N/A	N/A	N/A	N/A	Unk	Unk	Unk	Unk	

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Appendix I - FHWA Accepted Proprietary Testing, System Details

This section contains the system details for tests that were accepted by FHWA according to criteria presented in NCHRP Report 350. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Performing Organization
- System Length
- Anchor Type
- System Configuration (i.e. on slope, curve, transition etc.)
- Post Properties
    - Section Type
    - Length
    - Embedment Depth
    - Spacing

Page B

- Test Name
- Test Date
- Reference Number
- Cable Properties
    - Diameter and Weave
    - Attachment Hardware to Posts
    - Pretension
- Mounting Heights
    - Top Cable
    - 2nd Cable
    - 3rd Cable
    - Bottom Cable
- Additional Components
- System Design Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
3-10	5/26/2005	-	Karco Engineering	200	Gibraltar End Terminal	N/A	3.25"x1.25"x0.15" C-channel	48	15	10
3-11	5/26/2005	-	Karco Engineering and Gibraltar	200	Gibraltar End Terminal	N/A	3.25"x1.25"x0.15" C-channel	48	15	10
4-12	8/5/2005	-	Exponent Failure Analysis Labs and Gibraltar	350	Gibraltar End Terminal	N/A	3.25"x1.25"x0.15" C-channel	84	42	14
26021-01-A	1/6/2006	-	Karco Engineering and Gibraltar	305	Gibraltar End Terminal	N/A	3.25"x1.25"x0.15" C-channel	59	15	10
26028-01-A	1/6/2006	-	Karco Engineering and Gibraltar	305	Gibraltar End Terminal	N/A	3.25"x1.25"x0.15" C-channel	59	15	30
400001-TCR1	1/8/2003	-	TTI and Trinity	334	TTI End Terminal	N/A	4"x2"x0.15" C-channel	63	32.3125	10
400001-TCR2	1/31/2003	-	TTI and Trinity	334	TTI End Terminal	N/A	4"x2"x0.15" C-channel	63	32.3125	16.4
400001-TCR3	Unk	-	TTI and Trinity	334	TTI End Terminal	N/A	4"x2"x0.15" C-channel	47.25	23.6	7
MIRA-99-436008	Unk	-	MIRA and Hill and Smith, LTD	358	Concrete block	N/A	0.25"-thick S-post	60	Unk	10.5
MIRA-99-436009	Unk	-	MIRA and Hill and Smith, LTD	358	Concrete block	N/A	0.25"-thick S-post	60	Unk	10.5
MIRA-05-1008159	1/10/2005	-	MIRA and Hill and Smith, LTD	902	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	56	15.75	10.5
MIRA-05-1007578	11/29/2004	-	MIRA and Hill and Smith, LTD	902	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	56	15.75	10.5
BCR-2	2/28/2006	-	SwRI and Hill and Smith, LTD	365	Concrete block	12' up backslope of 4H:1V V-ditch	4"x2.125" by 7-gauge Z-section	56	15.75	10.5
BCR-5	3/1/2006	-	SwRI and Hill and Smith, LTD	365	Concrete block	4' from SBP of 4H:1V V-ditch	4"x2.125" by 7-gauge Z-section	56	15.75	10.5
BCR-4	3/1/2006	-	SwRI and Hill and Smith, LTD	365	Concrete block	4' from SBP of 4H:1V V-ditch	4"x2.125" by 7-gauge Z-section	56	15.75	10.5
B-USA-1	4/11/2005	-	SwRI and Hill and Smith, LTD	912	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	46	30	10.5
B-USA-2	4/11/2005	-	SwRI and Hill and Smith, LTD	912	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	46	30	10.5

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
3-10	5/26/2005	-	3/4"	7/16" hairpin and lock plate	4800	30	25	20	N/A	Turnbuckles	Adjacent posts were installed on opposite sides of the cables; the cables remained essentially straight
3-11	5/26/2005	-	3/4"	7/16" hairpin and lock plate	4800	30	25	20	N/A	Turnbuckles	Adjacent posts were installed on opposite sides of the cables; the cables remained essentially straight
4-12	8/5/2005	-	3/4"	7/16" hairpin and lock plate	4800	39	30	20	N/A	Turnbuckles	Adjacent posts were installed on opposite sides of the cables; the cables remained essentially straight
26021-01-A	1/6/2006	-	3/4"	7/16" hairpin and lock plate	5700	39	30	20	N/A	Turnbuckles	Adjacent posts were installed on opposite sides of the cables; the cables remained essentially straight
26028-01-A	1/6/2006	-	3/4"	7/16" hairpin and lock plate	5700	39	30	20	N/A	Turnbuckles	Adjacent posts were installed on opposite sides of the cables; the cables remained essentially straight
400001-TCR1	1/8/2003	-	3/4"	Plastic cable spacers in post slot	5400	29.5	25.2	20.9	N/A		
400001-TCR2	1/31/2003	-	3/4"	Plastic cable spacers in post slot	5400	29.5	25.2	20.9	N/A		
400001-TCR3	Unk	-	3/4"	Plastic cable spacers in post slot	5400	29.5	25.2	20.9	N/A		Posts placed in socketed concrete foundations
MIRA-99-436008	Unk	-	3/4"	Slot in web of post, brackets on sides	5840 nominal	28.3	26.6	26.6	20.1		Bottom cable weaved every post
MIRA-99-436009	Unk	-	3/4"	Slot in web of post, brackets on sides	5840 nominal	28.3	26.6	26.6	20.1		Bottom cable weaved every post
MIRA-05-1008159	1/10/2005	-	3/4"	Slot in web of post, brackets on sides	5840 nominal	36.6	30.7	24.8	18.9		Top cable transitioned from slot to outside of post between TL-3 and TL-4 systems; posts placed in socketed concrete foundations
MIRA-05-1007578	11/29/2004	-	3/4"	Slot in web of post, brackets on sides	5840 nominal	36.6	30.7	24.8	18.9		Top cable transitioned from slot to outside of post between TL-3 and TL-4 systems; posts placed in socketed concrete foundations
BCR-2	2/28/2006	-	3/4"	Slot in web of post, brackets on sides	4500	36.6	30.7	24.8	18.9		Through-ditch impact
BCR-5	3/1/2006	-	3/4"	Slot in web of post, brackets on sides	4200	36.6	30.7	24.8	18.9		On foreslope
BCR-4	3/1/2006	-	3/4"	Slot in web of post, brackets on sides	5550	36.6	30.7	24.8	18.9		On foreslope
B-USA-1	4/11/2005	-	3/4"	Slot in web of post, brackets on sides	5500 nominal	28.4	23.5	18	N/A		Bottom cable weaved every post
B-USA-2	4/11/2005	-	3/4"	Slot in web of post, brackets on sides	5500 nominal	28.4	23.5	18	N/A		Bottom cable weaved every post

Test Name	Test Date	Reference Number	Performing Organization	System Length (ft)	Anchor Type	Configuration Tested	Post Properties			
							Type	Length (in.)	Embedment (in.)	Spacing (ft)
B-USA-3	4/12/2005	-	SwRI and Hill and Smith, LTD	912	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	46	30	7.9
B-USA-4	4/12/2005	-	SwRI and Hill and Smith, LTD	912	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	46	30	10.5
BCR-1	Unk	-	MIRA and Hill and Smith, LTD	364	Concrete block	N/A	4"x2.125" by 7-gauge Z-section	46	30	10.5
50724121	8/23/2007	-	Holmes Solutions and Nucor Marion Steel	360	26 ft Armorwire terminal	N/A	4 lb/ft flanged U-channel	Unk	Unk	20
0570723102	8/22/2007	-	Holmes Solutions and Nucor Marion Steel	360	26 ft Armorwire terminal	N/A	4 lb/ft flanged U-channel	Unk	Unk	20
CASS-1	8/16/2005	-	SwRI and Trinity	Unk	Unk	N/A	S4x7.7 posts with 9/16" diameter holes drilled in flange at ground line	47.25	15	16.7
CASS-2	8/17/2005	-	SwRI and Trinity	Unk	Unk	N/A	S4x7.7 posts with 9/16" diameter holes drilled in flange at ground line	47.25	15	16.7
400001-TCR8	10/7/2005	-	TTI and Trinity	334	Unk	N/A	S4x7.7 posts with 11/16" diameter holes drilled in flange at ground line	47.25	15	20
400001-TCR9	10/26/2005	-	TTI and Trinity	334	Unk	N/A	S4x7.7 posts with 11/16" diameter holes drilled in flange at ground line	56	15	20
Test 3-11 of CASS with Driven Posts	Unk	-	TTI and Trinity	334	Unk	N/A	S4x7.7 posts with 11/16" diameter holes drilled in flange at ground line	72	39	20
400001-TCR12	3/10/2006	-	TTI and Trinity	330	Unk	N/A	S4x7.7 posts with 11/16" diameter holes drilled in flange at ground line	47.25	15	32.5

Test Name	Test Date	Reference Number	Cable Properties			Nominal Cable Mounting Heights (in.)				Additional Non-Standard Components	Notes
			Cable Diameter (in.)	Cable Attachment Hardware	Pretension, Per Rope (lb)	Top Cable	2nd Cable	3rd Cable	4th Cable		
B-USA-3	4/12/2005	-	3/4"	Slot in web of post, brackets on sides	5500 nominal	28.4	23.5	18	N/A		Bottom cable weaved every post
B-USA-4	4/12/2005	-	3/4"	Slot in web of post, brackets on sides	5500 nominal	28.4	23.5	18	N/A		Terminal length-of-need test; bottom cable weaved every post
BCR-1	Unk	-	3/4"	Slot in web of post, brackets on sides	5000	28.4	23.5	18	N/A		Bottom cable weaved every post
50724121	8/23/2007	-	3/4"	Locking clip for upper cables, hook bolts lower cables	5600	35	25	15	N/A		
0570723102	8/22/2007	-	3/4"	Locking clip for upper cables, hook bolts lower cables	5600	35	25	15	N/A		
CASS-1	8/16/2005	-	3/4"	Plastic cable spacers in post slot	5600	29.5	25.2	21	N/A		
CASS-2	8/17/2005	-	3/4"	Plastic cable spacers in post slot	5600	29.5	25.2	21	N/A		
400001-TCR8	10/7/2005	-	3/4"	Plastic cable spacers in post slot	5600	29.5	25.25	21	N/A		Holes in flange of post at ground level increased to 11/16", and post spacing increased to 20 ft
400001-TCR9	10/26/2005	-	3/4"	Plastic cable spacers in post slot	5600	38	29.5	21	N/A		
Test 3-11 of CASS with Driven Posts	Unk	-	3/4"	Plastic cable spacers in post slot	5600	29.5	25.25	21	N/A		Driven post alternative to socketed post system
400001-TCR12	3/10/2006	-	3/4"	Plastic cable spacers in post slot	5600	29.5	25.25	21	N/A		

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Appendix J - FHWA Accepted Proprietary Testing, Crash Test Details

This section contains the testing details for tests that were conducted for acceptance by FHWA according to criteria presented in NCHRP Report 350. These tables incorporate the following system details, when available:

Page A

- Test Name
- Test Date
- Reference Number
- Speed
- Angle
- Impact Severity
- Impact Location
- Vehicle Description
    - Year
    - Make
    - Model
    - Weight
- Results
- Test Designation
- Vehicle Damage
- Exit Speed
- Exit Angle
- Test Criteria Analysis

Page B

- Test Name
- Test Date
- Reference Number
- Maximum Tension
- No. Posts Requiring Maintenance
- Length of Contact
- Max Deflection
- Maximum Decelerations
    - 50-ms Average Longitudinal
    - 50-ms Average Lateral
    - Longitudinal
    - Lateral (positive numbers indicate acceleration to right side)
- OIV
- ORD
- Testing Notes

Due to the size of the tables, system details were split into two pages. Adjacent pages contain the same test numbers and the complete system details record.

N/A – Not Applicable

Unk – Unknown (not available to researchers)

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
3-10	5/26/2005	-	62.9	20	41.4	~75 ft upstream of terminal	Unk	Chevrolet	Metro 2-door	1974	Redirected	3-10	01RDEN2	49.2	0	Pass
3-11	5/26/2005	-	63.7	25	149.5	~80 ft upstream of terminal	Unk	GMC	Sierra	4552	Redirected	3-11	01RDEN2	29.8	Unk	Pass
4-12	8/5/2005	-	49.7	15	132.0	Unk	Unk	Unk	International/4700	17600	Redirected	4-12	Unk	34.7	<4	Pass
26021-01-A	1/6/2006	-	62.1	25	138.8	Unk	Unk	Chevrolet	C2500	4452	Redirected	3-11	01RDEN2	51.8	<10	Pass
26028-01-A	1/6/2006	-	62.8	25	142.1	Unk	Unk	Chevrolet	C2500	4452	Redirected	3-11	01RDEN2	34.1	<10	Pass
400001-TCR1	1/8/2003	-	62.5	24.2	134.1	4'-10" downstream of post no. 14	1998	Chevrolet	C2500	4508	Redirected	3-11	11FLEW1	8.6	9.4	Pass
400001-TCR2	1/31/2003	-	61.8	25.7	147.1	1'-11" downstream of post no. 11	1998	Chevrolet	C2500	4519	Redirected	3-11	11FLEW1	48.1	9.5	Pass
400001-TCR3	Unk	-	62.5	25.6	Unk	Unk	Unk	Unk	Unk	Unk	Redirected	Unk	Unk	Unk	Unk	Pass
MIRA-99-436008	Unk	-	62.6	20	Unk	Unk	Unk	Unk	Unk	Unk	Redirected	Unk	Unk	Unk	Unk	Pass
MIRA-99-436009	Unk	-	61.8	26	Unk	Unk	Unk	Unk	Unk	Unk	Redirected	Unk	Unk	Unk	Unk	Pass
MIRA-05-1008159	1/10/2005	-	62.6	21.3	46.2	Unk	Unk	Ford	Fiesta	1971	Captured	4-10	Unk	N/A	N/A	Pass
MIRA-05-1007578	11/29/2004	-	49.5	15.8	146.1	Unk	Unk	International	Harvester	17747	Captured	4-12	Unk	N/A	N/A	Pass
BCR-2	2/28/2006	-	60.0	26.5	125.3	Unk	1998	Ford	Crown Victoria	3858	Redirected	3-11	11LFEW5	50.5	11	Pass
BCR-5	3/1/2006	-	62.9	21.1	50.3	Unk	1998	Suzuki	Swift	2165	Redirected	3-10	11LFEW5	44.1	11	Pass
BCR-4	3/1/2006	-	63.0	24.1	141.5	Unk	1998	Chevrolet	C2500	4716	Redirected	3-11	11LFEW4	44.1	8	Pass
B-USA-1	4/11/2005	-	62.3	20.2	45.4	Unk	1998	Suzuki	Swift	2165	Redirected	3-10	11FLLS5	46	10	Pass
B-USA-2	4/11/2005	-	60.9	25.3	141.4	Unk	2000	Chevrolet	C2500	4605	Redirected	3-11	11FLLS5	39	15	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
3-10	5/26/2005	-	Unk	Unk	Unk	2	6	30	Unk	Unk	-6.2	-7.1	7.87	12.14	-6.2	-7.1	
3-11	5/26/2005	-	Unk	Unk	Unk	8	7	103	Unk	Unk	3.7	2.9	11.81	10.83	3.7	2.9	
4-12	8/5/2005	-	Unk	Unk	Unk	7	0	84	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Small car and pickup tests not conducted; however, had signficantly higher cable heights; SUT impacted concrete barrier after test
26021-01-A	1/6/2006	-	Unk	Unk	Unk	6	10	82	Unk	Unk	-2.3	-5.3	13.12	22.3	-2.3	-5.3	
26028-01-A	1/6/2006	-	Unk	Unk	Unk	9	4	112	Unk	Unk	-2.3	-5.3	13.12	22.3	-2.3	-5.3	Exactly the same occupant risk numbers as test 26021-01-A; this is unlikely, and appears that the summary sheet was not updated
400001-TCR1	1/8/2003	-	Unk	18	Unk	7	10	94	2.2	3.2	-3.9	-5.1	8.86	11.48	-3.9	-5.1	
400001-TCR2	1/31/2003	-	Unk	Unk	Unk	9	2	110	2.3	3.0	-4.4	5.2	8.2	10.83	-4.4	5.2	
400001-TCR3	Unk	-	Unk	Unk	Unk	6	8	80	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
MIRA-99-436008	Unk	-	Unk	Unk	Unk	3	5	41	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
MIRA-99-436009	Unk	-	Unk	Unk	Unk	7	10	94	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
MIRA-05-1008159	1/10/2005	-	Unk	Unk	Unk	4	5	53	Unk	Unk	3.53	0.91	12.24	-13.42	3.53	0.91	
MIRA-05-1007578	11/29/2004	-	Unk	Unk	Unk	7	3	87	Unk	Unk	0.49	1.44	2.53	6.07	0.49	1.44	
BCR-2	2/28/2006	-	Unk	Unk	Unk	7	8	92	Unk	Unk	-5.8	6.7	11.81	2.3	-5.8	6.7	Intended to replicate NCAC test with Ford Crown Victoria ducking under cables on V-ditch
BCR-5	3/1/2006	-	Unk	Unk	Unk	4	0	48	Unk	Unk	-9	10.3	11.5	-12.14	-9	10.3	
BCR-4	3/1/2006	-	Unk	Unk	Unk	9	0	108	Unk	Unk	-5.9	8.2	8.86	-9.19	-5.9	8.2	
B-USA-1	4/11/2005	-	Unk	Unk	Unk	2	9	33	Unk	Unk	-8.6	5.4	12.8	-9.84	-8.6	5.4	
B-USA-2	4/11/2005	-	Unk	Unk	Unk	8	7	103	Unk	Unk	-6	6	12.14	-7.22	-6	6	

Test Name	Test Date	Reference Number	Speed (mph)	Angle (degrees)	Impact Severity (kJ)	Impact Location	Vehicle Description				Results	Test Designation	Vehicle Damage (CDC)	Exit Speed (mph)	Exit Angle (degrees)	Pass Test Criteria?
							Year	Make	Model	Weight (lb)						
B-USA-3	4/12/2005	-	61.7	25.1	143.0	Unk	1998	Chevrolet	C2500	4605	Redirected	3-11	11LFLS5	42	17	Pass
B-USA-4	4/12/2005	-	61.4	20.6	97.4	Unk	1998	Chevrolet	C2500	4605	Redirected	3-35	11LFLS5	50	<5	Pass
BCR-1	Unk	-	60.4	24.5	134.1	Unk	Unk	Unk	Unk	4716	Redirected	Unk	Unk	Unk	Unk	Pass
50724121	8/23/2007	-	52.5	15	148.5	Unk	1998	Mitsubishi	Fuso Fighter	17747	Redirected	4-12	11FYSL4	33	4.6	Pass
0570723102	8/22/2007	-	62.4	20.1	41.5	Unk	1997	Toyota	Starlet	1993	Redirected	4-10	11FLAS6	17	10	Pass
CASS-1	8/16/2005	-	62.1	25	137.6	Unk	Unk	Chevrolet	Unk	4409	Redirected	3-10	Unk	Unk	Unk	Pass
CASS-2	8/17/2005	-	62.1	20	40.9	Unk	2000	Suzuki	Swift	2000	Redirected	3-11	Unk	Unk	Unk	Pass
400001-TCR8	10/7/2005	-	60.0	24.7	132.3	At post no. 12	1999	Chevrolet	C2500	4643	Redirected	3-11	11FLEW1	Unk	Unk	Pass
400001-TCR9	10/26/2005	-	51.3	14.1	127.1	At post no. 12	1991	Ford	F-700	17959	Redirected	4-12	11FLEW1	N/A	N/A	Pass
Test 3-11 of CASS with Driven Posts	Unk	-	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Redirected	Unk	Unk	Unk	Unk	Pass
400001-TCR12	3/10/2006	-	63.8	24.9	151.6	At post no. 11	2000	Chevrolet	C2500	4634	Redirected	3-11	11LFEW2	Unk	Unk	Pass

Test Name	Test Date	Reference Number	Maximum Dynamic Tension (lb)	Minimum Num. Posts Requiring Maintenance	Length of Contact (ft)	Max Deflection			Maximum Decelerations (g's)				OIV (ft/s)		ORD (g's)		NOTES
						ft	in.	Total in.	50-ms Avg (Longitudinal)	50ms Avg (Lateral)	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	
B-USA-3	4/12/2005	-	Unk	Unk	Unk	9	0	108	Unk	Unk	-6.3	5.8	9.84	-8.53	-6.3	5.8	
B-USA-4	4/12/2005	-	Unk	Unk	Unk	5	0	60	Unk	Unk	-2.2	4.4	6.23	-8.86	-2.2	4.4	
BCR-1	Unk	-	Unk	Unk	Unk	7	0	84	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	
50724121	8/23/2007	-	Unk	Unk	Unk	7	6	90	0.6	1.3	-0.8	1.4	1.31	-4.92	-0.8	1.4	
0570723102	8/22/2007	-	Unk	Unk	Unk	4	7	55	3.8	3.9	-6	6	11.48	-13.45	-6	6	
CASS-1	8/16/2005	-	Unk	Unk	Unk	Unk	Unk	Unk	1.9	4.4	-3.3	-7.6	11.15	-14.76	-6.2	6.8	Significant vehicle damage
CASS-2	8/17/2005	-	Unk	Unk	Unk	Unk	Unk	Unk	3.9	5.3	-6.2	6.8	7.22	11.48	-3.3	-7.6	Significant vehicle damage
400001-TCR8	10/7/2005	-	Unk	10	Unk	7	9	93	1.6	4.1	-3.5	7.6	6.89	11.15	-3.5	7.6	
400001-TCR9	10/26/2005	-	Unk	>22	185.6	7	3	87	0.7	1.3	-1.1	1.8	4.27	6.56	-1.1	1.8	
Test 3-11 of CASS with Driven Posts	Unk	-	Unk	Unk	Unk	6	2	74	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Unk	Tested to 3-11 impact conditions; test results not provided
400001-TCR12	3/10/2006	-	Unk	Unk	Unk	11	2	134	1.4	3.6	3.9	6.7	6.56	10.5	3.9	6.2	

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