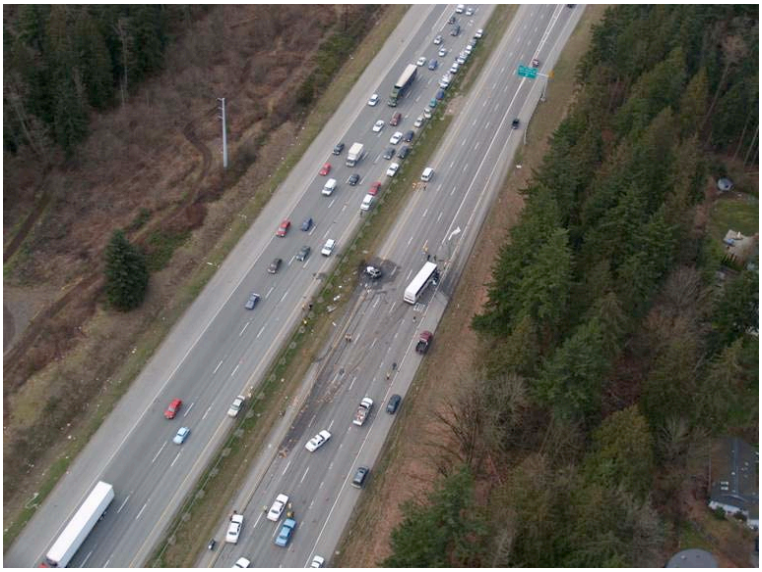
MAJOR ACCIDENT INVESTIGATION TEAM

CASE SUMMARY

CASE NUMBER:	07-001727
LOCATION:	I-5 J/S of 88th St NE (Snohomish County)
DATE:	February 13, 2007 @ 3:08 p.m.

Detective Sergeant Jerry Cooper	Washington State Patrol – Team Leader
Detective Gregory A. Wilcoxson	Washington State Patrol – Reconstructionist
Detective Curt Ladines	Washington State Patrol – Reconstructionist
Detective Robert Schroeder	Washington State Patrol – Reconstructionist
Investigator David J. Temple	W.S.D.O.T – Vehicle Systems Analyst
Transportation Engineers	W.S.D.O.T.



SYNOPSIS

On February 13, 2007 at 3:08 p.m., a two vehicle fatality collision occurred on Interstate 5 approximately 0.36 miles south of 88th St NE in Marysville. The collision events began when a 2001 Infiniti QX4 driven by Clifford Warren of Everett entered the southbound lanes of the freeway from the 88th onramp and suddenly veered left. The Infiniti crossed all three southbound lanes and entered the median where it overrode a three strand high tension cable barrier, continued through the northbound low tension cable, left the median and struck a Prevost charter bus in the northbound left lane. The bus was driven by Sigrid Wosnack of Sechelt, British Columbia (BC). She had driven a group of students to Sea-Tac Airport for a trip and was returning to BC. As a result of the crash, Clifford Warren sustained blunt force trauma and was killed instantly; Sigrid Wosnack suffered a broken femur and shattered knee. She was airlifted from the scene to Harborview Medical Center in Seattle. Investigation by the Washington State Patrol (WSP) Major Accident Investigation Team (MAIT) showed that Warren had been drinking, likely at the nearby Tulalip Casino, and had a blood alcohol content of 0.07g/100mL.

SUPERVISOR:_____ **DATE:**_____

(DETECTIVE SERGEANT JERRY COOPER)

DETAILS

On February 13, 2007, Clifford Warren had spent at least part of his afternoon in the Tulalip Casino[1]. At around 3:07 p.m., he was observed by Tiffany Hempeck driving a 2001 Infiniti QX4 pulling up to the red traffic light southbound on 34th Avenue N.E. at the intersection with 88th St NE. The casino is located approximately 0.80 miles due north of this intersection. Hempeck stated she was directly behind Warren and observed him make a left onto 88th following other traffic, stop at the red light eastbound on 88th and then turning right onto the southbound I-5 ramp. She told a State Patrol detective that the Infiniti accelerated down the ramp to freeway speed and then cut across the end of the gore point veering across all southbound lanes. Hempeck stated she thought he (Warren) made the aggressive maneuver across all lanes to get in the fast lane. Joyce Jones, Kandi Haffe-Nielson, and Jack Paden were all southbound and watched Warren drive across all southbound lanes and enter the median. At the same time, Sigrid Wosnack was driving a 1998 Prevost bus northbound I-5 in lane three. Wosnack had just transported a group of students to Sea-Tac Airport and was returning to her base in British Columbia, Canada.

I-5 in this area consists of three lanes each for both south and northbound traffic with a northbound exit lane for 88th St NE on the right. The two directions of travel are separated by a grassy depressed median with the presence of two sets of cable barriers that parallel the lanes of travel. The roadway is straight with a slight positive grade from south to north. It is constructed of asphalt with both the painted lane edge lines and lane dividers in good condition. The southbound lanes are slightly elevated above the northbound lanes; the posted speed limit is 60 mph for both directions. At the time of the crash, the weather was partly cloudy and the roadway was dry. The temperature was in the upper 40's Fahrenheit.

WSP Commercial Vehicle Enforcement Officers Keith Barton and Aaron Gustafson were traveling northbound behind Wosnack's bus in a white WSP van when they observed the Warren SUV veering across the southbound lanes into and through the median towards them and the bus. The Infiniti struck the southbound high tension barrier at an approximate 22 ~ 25° angle and overrode the barrier bending one post over, dislodging a second. The vehicle continued in a southeasterly direction and impacted the northbound low tension barrier interacting with the top two cables, carrying the top cable into the northbound left lane where the SUV and Wosnack's bus collided head-on. The right front of the SUV impacted the left front of the bus causing the SUV to be redirected north while rotating counter-clockwise up to its point of rest 177 feet to the north. Impact to the bus caused the brakes to lock up and the bus skidded to a stop at a slight angle to the right blocking lane one 201 feet from the POI. Officer Barton had to make an emergency stop and skidded to a stop in lane three just south of the damaged Infiniti.

Sigrid Wosnack was unrestrained by the equipped lap belt. She sustained a broken right femur and shattered knee cap. The massive intrusion at maximum engagement caused Clifford Warren's head to contact the left windshield wiper mount on the bus. Within seconds of impact a fire engulfed the SUV with Warren's body still in the driver seat restrained by his combination lap and shoulder seatbelt. The Snohomish County Medical Examiner found that

[1] WSP investigators' communication with the Warren family as well as information provided by two anonymous sources

Clifford Warren died of blunt impact trauma. Analysis by the State Toxicology Lab on a blood sample from Warren revealed he had a BAC of 0.07 g/100mL at the time of his death.

Officers Barton and Gustafson advised WSP Communications of the collision at 3:08 p.m. They attempted to put out the fire that had started in or on the Infiniti. Officer Gustafson observed that Warren had a gaping hole in his head and was not responsive. Area troopers and emergency personnel responded to the scene followed by investigators from the MAIT and local Criminal Investigation Unit. Trooper Rob Nance began the preliminary investigation by gathering witness statements and driver and vehicle information. The scene was documented with photographs and two total stations. The physical evidence matched the description of witness accounts of how the vehicles came together. (See dynamics report). Engineers from the Washington State Department of Transportation also responded to the scene to inspect the cable barrier system. The MAIT assumed primary investigative responsibility of the collision with the WSDOT engineers handling the roadway environment dealing with the interaction of the vehicle and cable barriers. The WSDOT completed an analysis report describing their findings.

CAUSE ANALYSIS

Speed reconstruction determined that Clifford Warren was traveling approximately 58 mph at impact with the bus. Witnesses describe Warren's SUV initially moving at or above freeway speeds with no evidence of slowing, i.e. brakelights or any reason for veering across all southbound lanes. A mechanical inspection on the vehicle showed no defects that would have caused this maneuver. Traveling south on 34th Ave NE from the casino to the crash location, Clifford Warren would have traveled at least 1.5 miles. He would have had to negotiate numerous curves and turns in the path on 34th Ave, 88th St NE and the onramp to the interstate. The onramp itself begins with a curve to the left followed by a sweeping right curve; the ramp straightens as you descend towards the mainline of I-5 prior to the entrance to the freeway. Investigators did not locate any scuffmarks consistent with a yaw leading to the median. Marks such as these would be indicative of over steer as in an avoidance maneuver. Projecting the tiremarks left on the inside southbound shoulder back in a straight path shows that Warren would have to approach at an angle well beyond the onramp. This is inconsistent with witness testimony.

The Snohomish County Medical Examiner determined that Warren died from blunt impact injuries due to the collision and did not find any medical conditions that would have caused his death. Investigators were unable to determine a specific reason why Clifford Warren drove his 2001 Infiniti QX4 from the 88th Street on ramp across all southbound lanes leading to the collision with the bus that claimed his life and seriously injured Sigrid Wosnack. However a likely contributing factor was the alcohol he had consumed prior to driving. Studies show that driving skills are significantly affected at a 0.07 BAC. According to the Washington State Liquor Control Board brochure[2] "How Drinking Impairs Driving", having a lesser BAC of 0.05, one's thoughts, judgment, and restraints are more lax, steering errors increase, and vision is impaired. This condition significantly increases the potential for driving failure and the likelihood of a crash.

At a minimum, Clifford Warren drove his vehicle in a negligent manner, unable to control his Infiniti as he entered the highway. RCW 46.61.5249 1)(a) states in part that: A person is guilty of negligent driving in the first degree if he or she operates a motor vehicle in a manner that is both negligent and endangers or is likely to endanger any person or property, and exhibits the effects of having consumed liquor or an illegal drug. The result being he crossed his entire intended direction of the freeway, crashed through the median barriers, and collided with the opposite direction bus, clearly endangering all drivers in the immediate area.

[2] (http://www.brad21.org/bac_charts.html)

While not a cause of the crash, Wosnack was traveling unrestrained and in violation of the left lane law and speed analysis showed her to be traveling approximately 68 mph. Wosnack was in violation of the following RCW's:

- 46.61.100 "Keep right except when passing, etc." Section (3)
- 46.61.400 Speed Basic Rule and maximum limits
- 46.61.688 Safety Belts, Use Required

SAFETY QUEST, INC.
21 RANCHERO ROAD
COLLEGE STATION, TEXAS 77845
TEL: (979) 777-2647

April 17, 2007

Mr. Richard B. Albin
Assistant State Design Engineer
Washington Sate Department of Transportation
Transportation Building
310 Maple Park Avenue
P. O. Box 47329
Olympia, Washington 98504-7329

RE: Warren cable guardrail accident on I-5

Dear Mr. Albin:

This letter report documents my investigation and findings of the Warren accident of February 13, 2007 along Interstate 5.

Background

As reported by State of Washington Police Traffic Collision Report No. 2808176, on February 13, 2007 at 1508 hours, Mr. Clifford F. Warren of Everett, Washington sustained fatal injuries in a traffic accident. Mr. Clifford was traveling southbound on Interstate 5 (I-5) when his vehicle traveled from lane number 1 across all three southbound travel lanes, the paved shoulder, and into the median at approximately mile point (MP) 200.4. Upon entering the median Mr. Warren impacted the southbound cable barrier, breached the southbound cable barrier, continued through the median, impacting the northbound cable barrier, where upon continuing his trajectory collided into a commercial passenger bus traveling northbound on Interstate 5 in lane number 4 of 4 lanes. Mr. Warren's south-easterly trajectory ceased upon impact with the bus and he was accelerated northerly and came to rest on the I-5 inside northbound shoulder, where his vehicle caught fire and burned. The bus, operated by Ms. Wosnack, came to rest in lane number 2.

Accident Facts

<u>WSP Investigating Officer</u>

- R. S. Nance
  Badge Number: 1009

<u>Vehicle unit 01</u>

- Driver: Clifford F. Warren
  DOB: 01/01/1943

Address: 609 40th Place, Everett, Washington 98201
Driver's License No.: WARRECF574BA
Vehicle: 2001 Infinity QX4 4-wheel drive
VIN: JNRDR09Y21W217774
License plate: 360MEH
Injuries: Fatal

Vehicle unit 02

- Driver: Sigrid Wosnack
  DOB: 09/30/1958
  Address: 13610 112 Avenue, Surrey, BC V3R2G3
  Driver's License No.: 2743635
  Vehicle: 1998 Prevost Commercial Bus
  VIN: 2PCH33416W1012214
  License plate: 2423ES
  Registered Owner: Malaspina Coach Lines LTD.,
  5653 Wharf Rd, Sechelt, BC VON3EO
  Injuries: Leg injuries

Roadway

- U.S. Interstate 5,
  Posted speed 60 mph,
  Three southbound lanes nominally 12 ft wide,
  Four northbound lanes (1 dedicated exit lane), dropping to three lanes just north of the accident site. Lanes are nominally 12 ft wide and nominally 5-6 ft inside paved shoulders adjacent to median.
  Asphalt travel surface

Median

- Median width: nominally 40 ft wide,
  Median surface is grass covered,
  Slopes nominally 1:6 or flatter from MP 200.355 to MP 200.492

I-5 Southbound Median Cable Barrier

- Trinity Industries Cable Safety System (CASS) Cable Guardrail Safety System Specifications:
  ¾ inch diameter pre-stretched 3x7 cable,
  16 ft-5 in (5.0 m) post spacing,
  2 in x 4 in x 8 gage (50 mm x 100 mm x 4 mm) C-shaped posts,
  National Cooperative Highway Research Program (NCHRP) Report 350 Test Level 3 compliant; crash tested 01/31/2003, Texas Transportation Institute Report 400001-TCR2[(1)]
  United States Department of Transportation Federal Highway Administration (FHWA) - National Highway System (NHS) Acceptance Letter B-119, dated May 13, 2003,[(2)]

Cable guardrail placed approximately 12 ft from the edge of the southbound travel lane.

I-5 Northbound Median Cable Barrier

- Washington State Type 3 Cable Barrier, also referred to in the American Association of State Highway Transportation Officials (AASHTO), et al, "*A Guide to Standardized Highway Barrier Hardware*" to as "Weak Steel Post Cable Guardrail – SGR01a-b"
  Specifications:
  ¾ inch diameter 3x7 cable,
  16 ft-5 in (5.0 m) post spacing,
  S3 x 5.7 x 63 in (S75 x 8.5 x 1600) posts,
  National Cooperative Highway Research Program (NCHRP) Report 350 Test Level 3 compliant; tested 02/16/2000, Texas Transportation Institute Report 404211-8[3],
  United States Department of Transportation Federal Highway Administration (FHWA) - National Highway System (NHS) Acceptance Letter B-64, dated February 14, 2000[4],
  Cable guardrail placed approximately 17 ft from the edge of the northbound travel lane.

Design

The discussion hereafter is based on generally accepted design practices commonly recognized by the American Association of State Highway and Transportation Officials (AASHTO) and frequently adopted either wholly or in part in individual State Department of Transportation design manuals. AASHTO produces design guidelines for the intent of providing…"guidance to the designer by referencing a recommend range of values for critical dimensions. Sufficient flexibility is permitted to encourage independent designs tailored to particular situations."[5] The AASHTO Roadside Design Guide …"is not a standard, nor is it a design policy. It is intended for use as a resource document from which individual highway agencies can develop standards and policies. While much of the material in the guide can be considered universal in its application, there are several recommendations that are subjective in nature and may need modification to fit local conditions. However, it is important that significant deviations from the guide be based on operational experience and objective analysis".[6]

Median

Medians are provided to reduce the frequency of cross over accidents and headlight glare. The median provides the errant motorist a place and opportunity to recover and return to the roadway. The AASHTO 2002 Roadside Design Guide[2], shown in Figure 1, indicates that barriers in medians were optional and often not generally considered for placement in medians greater than 30 feet in width. It was believed that 80 percent of errant motorists were able to recover within 30 feet of the traveled way. When barriers are placed in the median, a conundrum exists between

placing the barrier immediately adjacent the travel lane or shoulder area versus placing the barrier further away from traffic. In the case of barrier immediately adjacent travel lanes, the effects of slope and terrain will not have the potential to affect barrier performance. However, the incident of errant vehicles impacting the barrier will increase because the recovery room has been reduced. When the barrier is moved further away from the travel lanes, a greater recovery area is provided, thus reducing the accident occurrence with the barrier.

In 2004, FHWA conducted a nationwide survey of state DOTs regarding cross median crashes and received responses from 25 states. It was discovered that a significant percentage of fatal cross median crashes were occurring in medians having a width greater than 30 feet. Approximately two-thirds of the cross-median crashes occurred in medians less than 50 feet in width.

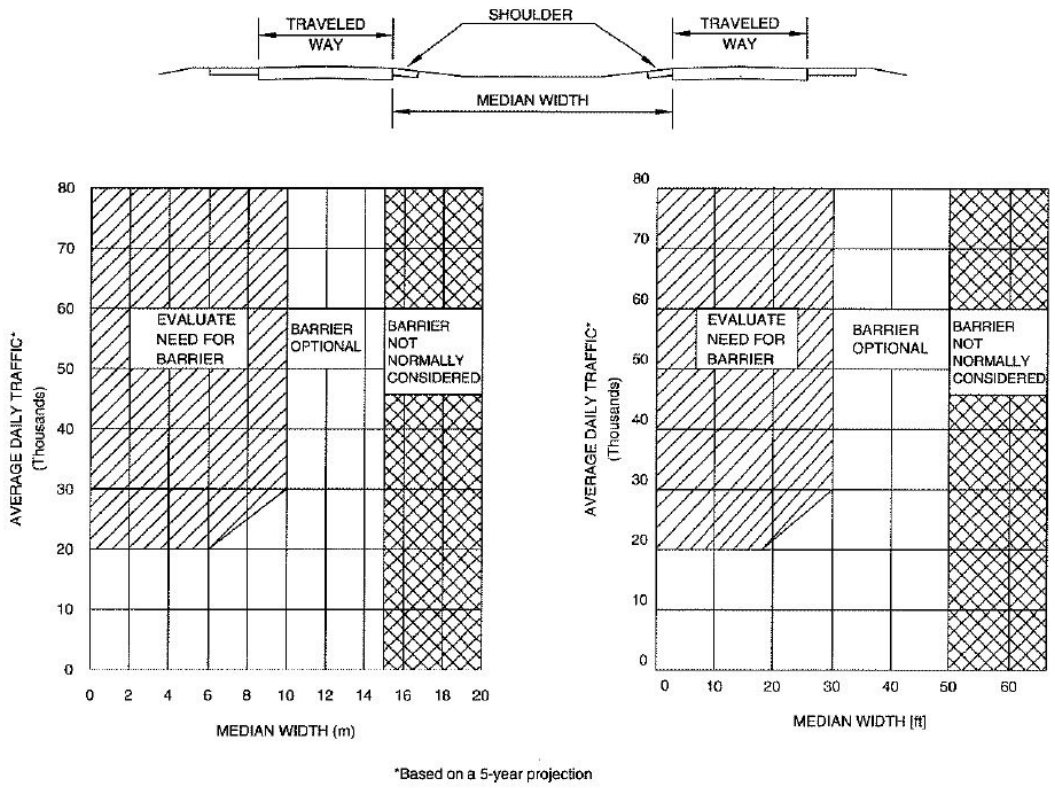


FIGURE 6.1 Suggested guidelines for median barriers on high-speed roadways

Fig 1. AASHTO Roadside Design Guide Median Barrier Guidance

Recognizing the severity of cross-median crashes and solely from a safety perspective, simply increasing the use of median barriers will generally (1) increase the number of reported crashes as the recovery area is reduced, (2) reduce the number of opportunities for emergency vehicles to cross the median, and (3) potentially reduce the area available to store snow in colder climates. In consideration of the severity of cross-

median accidents and accident data gathered by FHWA, recommendations for placement of median barriers on high-speed, fully controlled-access roadways were made based on median width and average daily traffic count. The guidelines shown in Figure 2, from page 6-2, figure 6.1, of the 2006 AASHTO Roadside Design Guide is shown below. "For locations where the median widths are greater than 10 m (30 ft) but less that 15 m (50 ft), and where ADT is greater than 20,000 vehicles per day, a cost benefit analysis or an engineering study evaluating such factors as traffic volumes, vehicle classifications, median crossover history, crash incidents, vertical and horizontal alignment relationships, median/terrain configurations may be conducted at the discretion of the transportation agency to determine the appropriate application for median barrier installations."[2]

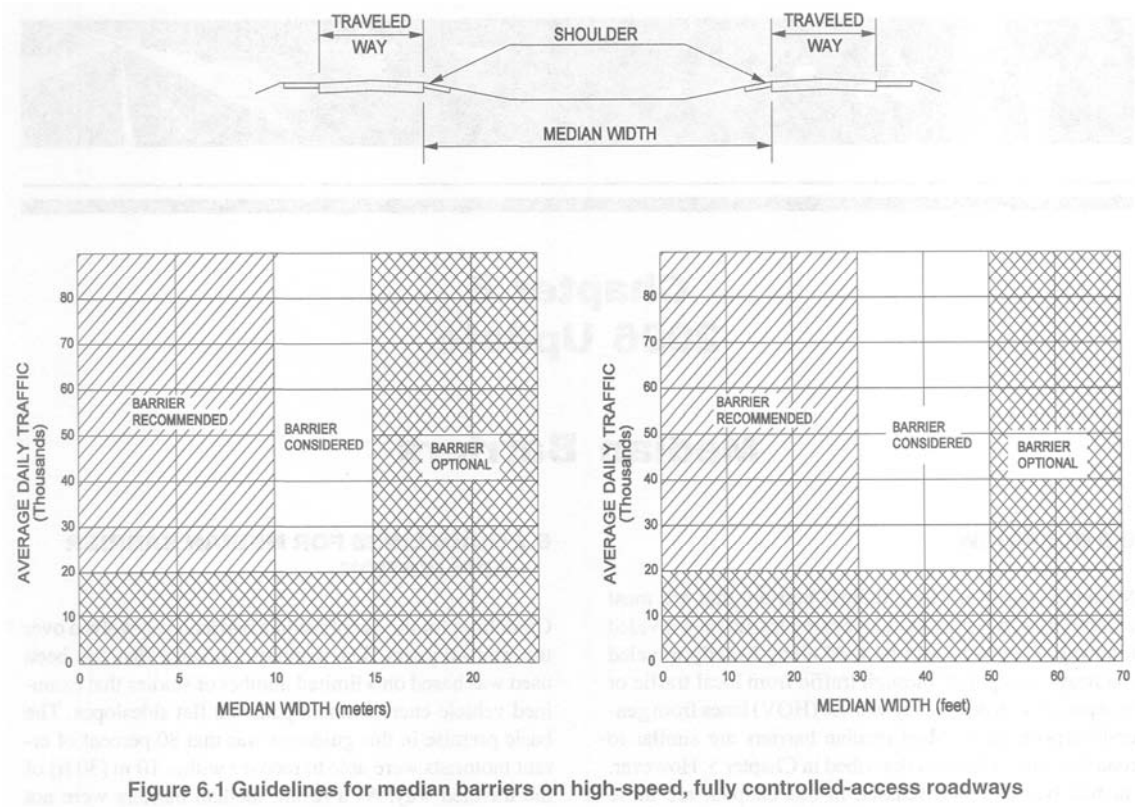


Figure 2. AASHTO Roadside Design Guide Median Barrier Guidance

The median in the area of the Warren accident on I-5 was nominally 40 feet wide, the traffic volume was 110,000 vehicles before day. At the time the cable barrier on I-5 in the Marysville area was constructed, the Washington State Design Manual did not require a median barrier for median widths greater than 30 feet. However, based on a history of cross-median crashes, Washington Department of Transportation decided to install cable guardrail in the median to enhance safety. The current Washington State Design Manual, section 700.06 states "Provide median barrier on full access control, multilane highways with median width of 50 feet or less and posted speeds of 45 mph or more".[7] In accordance with guidance provided in both the 2002 and 2006 AASHTO Roadside Design Guide, engineering judgment is necessary in determining the need for median barrier in medians greater than 30 feet wide. As appropriate for the roadway

conditions and environment today, Washington State Department of Transportation provided additional protection for cross-median accidents in the form of a cable guardrail system along both the north and southbound travel lanes.

Slopes

The roadside is generally not flat and at the same elevation as the roadway. Differential elevations may be due to topography or intentionally created to accommodate draining and channeling water from the travel way. A change in elevation is accommodated by transitioning the roadway elevation to the roadside elevation using cut and fill slopes. Roadside slopes are divided by AASHTO into three categories; recoverable, non-recoverable, and critical. Recoverable slopes are 4:1 or flatter. Recoverable slopes that are smooth permit an errant vehicle to maintain control, recover, and return to the travel way safely. Non-recoverable slopes are between 3:1 and 4:1. Non-recoverable slopes are traversable but an errant vehicle will not be able to return to the roadway. Slopes steeper than 3:1 are referred to as critical slopes and a vehicle risks overturning during traversal. Guidelines have been established by AASHTO for determining clear zone distances based on design speed, backslopes and foreslopes, and design average daily traffic.

When a barrier is warranted to protect the motorist from encroaching onto a steep slope, to shield a fixed object, or divide opposing high-speed traffic, the barrier itself usually can not be placed on the slope but rather in advance of the slope break. Barriers such as w-beam guardrail and concrete barriers are not permitted to be installed on slopes steeper than 10:1. If these barriers are installed on slopes, they should be placed 12 feet or further from the slope break. However, cable guardrail systems have successfully been tested on slopes as steep as 6:1 and are permitted for installation on slopes up to 6:1. Placement guidelines for barriers on slopes are presented in the AASHTO Roadside Design Guide.[2] Additionally, there are currently projects being conducted to continue researching placement of barriers on slopes at the state and federal level.

Cable Guardrail

New York has a long history of cable guardrail use. Much of the early research on cable guardrail systems was conducted by New York Department of Transportation (NYDOT). The Washington State cable guardrail is a derivative of the New York cable guardrail and in fact utilizes the New York terminal. Cable guardrail has a long and successfully history on the roadside and median for redirecting errant vehicles.

The safety performance and lower installation cost of cable guardrail often makes it more attractive than other barrier types due to the effective containment of a wider range of vehicle sizes, the lower acceleration levels experienced by the occupants of the errant vehicle and the vehicle is often not redirected back into the traffic. Less flexible barriers, such as W-beam guardrail and rigid barriers, such as concrete barriers, often result in higher levels of deceleration and redirect the errant vehicle back into traffic.

Additionally, the open design of cable guardrails makes it more aesthetically pleasing in scenic areas.

Additionally, cable guardrails may be installed on steeper slopes than other types of roadside barriers. Most roadside barriers are tested on level terrain and are typically installed on 10:1 slopes or flatter. Slopes steeper than 10:1 have shown for certain encroachment angles and speeds an errant vehicle may go over or under the barrier. According to FHWA, cable guardrail is the exception and may be placed on slopes as steep as 6:1 and some proprietary cable guardrails have been tested and accepted for use on slopes as steep as 4:1. The difference in performance between w-beam and cable guardrail on slopes is the w-beam rail G4(1S) may rotate rearward and down during an impact, while cables engaged approximately near bumper height remain essentially at the same height following the impact into the cable guardrail system. Simulation performed on the G1 roadside cable barrier concluded that…"(a) vehicle override of a cable barrier is likely if the midheight of the bumper is above the top cable on impact, and (b) vehicle containment and redirection is likely if at impact the midheight of the bumper is below the top cable and the upper corner of the impacting fender is above the lower cable. Analysis showed that upon contact the cable(s) creases the sheet metal and it typically remains in the crease during contact. Such behavior enables a cable barrier to redirect a vehicle even if the bumper is below the cable. When the upper corner of the impacting fender is below the lower cable, it is assumed that the vehicle will underride the barrier". [8]

Cable guardrail contains an errant vehicle by developing lateral restraining forces through interaction of the cables with the support posts, cable/post attachment hardware, the anchorage of the posts into the ground, and the concrete end anchors that terminate the cables at ground level. The lateral interaction of a vehicle impacting a cable guardrail occurs as the cable(s) wrap around the vehicle's bumper and contact the front fender of the vehicle. These lateral restraining forces gradually redirect the errant vehicle toward the roadway by the cables engaging the bumper and front fender of the vehicle. Often, the errant vehicle is redirected and contained within the cables of the guardrail system.

Details of Cable Guardrail Systems

Cable guardrail systems are available as non-proprietary, which is a low-tension system like the Washington cable guardrail and proprietary systems, which are all high-tension systems. Currently there are five high-tension cable guardrail systems that have been accepted by FHWA for use on the National Highway System. The CASS system is one of the five approved systems. All cable guardrail systems in use today use ¾ inch diameter 3 x 7 galvanized steel cables with a minimum tensile strength of 25,000 pounds. Some of the proprietary cable guardrail systems use prestretched cable.

The Washington State Type 3 cable guardrail system uses S3 x 5.7 x 5 ft-3 inch steel posts spaced 16 ft-5 in on center to support the cables. The top of the ground to the top of the highest cable is 30 inches. The distance between each cable is 4-1/2 inches, thus making the heights to the middle and bottom cables, 25-1/2 and 21 inches,

respectively. The cables are attached to the posts using 5/16" x 2 ¾" x 2" x 1" x 1" round bend hook bolt and hex nut. The cables (RCM01[9]) are attached to compensating spring cable end assemblies (RCE01[9]) and cable end fittings (RCE03[9]) using cable wedges (FMM01[9]). The compensating spring cable end assemblies are used to compensate for year around temperature fluctuations and prevent excessive sag in the cables. In addition, a turn buckle is attached to the compensating spring assemble to initially tension the cables during installation and maintenance. Periodic maintenance of cable guardrail is necessary on new installations to remove the construction stretch from new cables as they experience seasonal temperature cycles. Tables have been established for establishing the proper cable installation tension based on ambient temperature. Compensating spring cable end assemblies are used on one end of the cable and a turnbuckle only on the other cable end for installation lengths up to 500 ft in length. Cable installation lengths greater than 500 ft and up to 2000 feet use the compensating spring assembly on each cable end.

As previously noted, cable wedges are used to attach the compensating spring assemblies and cable end fittings. The cable wedges permit field applied end fittings to the cables, anchor the ends of the cables and permit the cable to be spliced or additional spring compensating assemblies to be added on long runs of cable. The wedge is driven into the splayed end of the cable and one wire is bent/crimped over to ensure the wedge does not back out of the cable and associated fitting. When the cable is loaded in tension, the wedge is pulled into the fitting creating large lateral loads between the cable, fitting, and wedge and thereby creating the restraining force necessary to hold on to the cable.

The CASS is a high tension proprietary cable guardrail system that uses a C-shaped 2 in x 4 in x 47 ¼ in 8 gage steel posts spaced 16 ft-5 in on center to support the cables. The top of the footing to the top of the post is 32-1/4 in. The top of the footing to the top of the highest cable is 29-13/16 inches. The distance between each cable is 4-5/16 inches, thus making the heights to the middle and bottom cables, approximately 25-1/2 and 21-3/16 inches, respectively. The CASS posts are alternately rotated 180 degrees. The CASS system is a socketed system, meaning the posts are inserted into sleeved concrete footings that allow the posts to be easily removed and replaced when damaged. The concrete footings are 12 in diameter x 30 in deep. The sleeve cast into each of the concrete footings is 3 in x 4 in x 15 in. The cables are attached to the posts by laying the cables in a wavy slot that is cut into the upper portion of the post. The cables maintain their appropriate spacing using plastic spacer blocks between the cables. The upper open section of the post has two flanges that are restrained together after the cables are placed into the slot with a stainless steel strap. The cables do not use compensating spring cable end assemblies due to the fact the cable is highly tensioned using turnbuckles. The high tension in the cable compensates for year around temperature fluctuations and keeps the cables always tensioned. Tables have been established for establishing the proper cable installation tension based on ambient temperature. For a temperature range of 0 to 99 degrees, the cable tension is nominally 6900 lb and 3700 lb, respectively. Turnbuckles are used on the end of the cables and at splices. A minimum of one turnbuckle is placed on installation lengths of 600 ft or less. For non-pre-stretched cable a turnbuckle is recommended every 750 feet. For pre-stretched cable a turnbuckle is recommended every 1000 feet.

Cable Guardrail Crash Testing

Level Terrain Testing

Roadside safety hardware, such as guardrails, bridge rails, crash cushions, and sign supports placed within the clear zone of the roadway on the National Highway System must be crash tested in accordance with the appropriate Federal Highway Administration accepted evaluation criteria. Since its adoption in 1993, the National Cooperative Highway Research Program (NCHRP) Report 350 "Recommended Procedures for the Safety Performance Evaluation of Highway Features"[10] is the evaluation criteria used for cable guardrail and other roadside safety appurtenances. The basic level of service for the National Highway System is Test Level 3.

According to NCHRP Report 350, two crash tests are required for the safety performance evaluation of the length of need of longitudinal barriers (guardrails).

> **NCHRP Report 350 test designation 3-10:** An 1808 lb (820 kg) passenger car impacting the cable guardrail at a nominal impact speed and angle of 100 km/h and 20 degrees with initial contact at the critical impact point (CIP) of the length of need. The primary objective of this test is to evaluate the risk to the occupants and post impact vehicle trajectory.
>
> **NCHRP Report 350 test designation 3-11:** An 4408 lb (2000 kg) pickup truck impacting the cable guardrail at a nominal impact speed and angle of 100 km/h and 25 degrees with initial contact at the critical impact point (CIP) of the length of need. The primary objective of this test is to evaluate the ability of the guardrail to contain and redirect the vehicle, while minimizing risk to the occupants while maintaining vehicle stability and a safe post impact trajectory. The pickup truck test vehicle is used as a surrogate for sport utility vehicles (SUV).

If the lowest cable in a cable guardrail is approximately the same nominal height as the U.S. generic cable guardrail system, FHWA has generally waived NCHRP Report 350 Test 3-10.

NCHRP Report 350 Test 3-11 has been performed on both the Washington and CASS cable guardrail systems. Each guardrail system successfully contained and redirected a 4408 lb ¾ ton pickup truck traveling nominally 62 mph and impacting the guardrail at 25 degrees. The test reports and FHWA acceptance letters for each cable guardrail are referenced at the end of this report [3,4,5,6]. Following the successful completion of the required NCHRP Report 350 crash tests, safety hardware is permitted to be installed. Thereafter, the in-service performance evaluation of new hardware begins. It should be noted, NCHRP Report 350 tests are performed with the test installation and approach travel lane level. Highway safety appurtenances tested on level terrain are accepted for installation on slopes up to 10:1.

Barriers on 6:1 Slope - Crash Testing

In 1978 FHWA sponsored crash testing to evaluate the G1 cable guardrail and other commonly used guardrails installed on a 6:1 slope. The objective of the study was the development of guidelines for the placement of barriers on slopes [11]. Seven full-scale were performed to evaluate the impact behavior of three widely used roadside barriers when placed on a 6:1 slope. Four tests involved the standard w-beam guardrail (G4(1S) system), two tests involved the three cable guardrail (G1 system), and one test involved the thrie beam guardrail (G9 system). All three guardrail types were mounted on steel posts. Vehicle override of the barrier occurred in 25 degree, 60 mph tests of the w-beam and thrie beam guardrails. The vehicle was contained and smoothly redirected for the same conditions when impacting the cable guardrail system.

The G1 cable guardrail is constructed similar to the Washington State Type 2 cable guardrail system. The G1 system uses the same S3 x 5.7 x 5 ft-3 inch steel posts spaced 16 ft on center to support the cables. The top of the ground to the top of the highest cable is 30 inches. The distance between each cable is 3 inches, thus making the heights to the middle and bottom cables, 27 and 24 inches, respectively. The cables are attached to the posts using 5/16" x 2 ¾" x 2" x 1" x 1" round bend hook bolt and hex nut. The cables (RCM01) are attached to compensating spring cable end assemblies (RCE01) and cable end fittings (RCE03) using cable wedges (FMM01).

Investigation

On February 16, 2007, I visited the I-5 accident site to inspect the Washington and CASS cable guardrail installations. Upon arriving, it was discovered repairs to the CASS system had already been completed and the system was back in full service. Likewise, the Washington guardrail system was disassembled and in the process of being repaired. Measurements of the repaired CASS system were recorded and measurements of the exemplar Washington cable installations were recorded at various locations traveling southbound of the accident site along I-5. Data Tables follow that present measurements recorded and make comparison to specified design dimensions. The compensating spring cable end assemblies, cable end fittings, and cable wedges from the I-5 accident site were inspected at Washington State DOT maintenance facility.

DESCRIPTION							
CASS CABLE GUARDRAIL	**Specified**	**Measured Midspan - impact P1-P2**	**Difference**	**Measured Midspan -P2&-P1& P1; P2 & P3**	**Difference**	**Exemplar Midspan MP 208**	**Difference**
Post Height, in	32 ¼	32 ¼ P1 & P2	None	32 ¼	None	32 1/4	None
Top Cable Height, in	29 13/16	28 ¾	1 1/16 low	28 ¾	1 1/16 low	30 3/8	9/16 high
Center Cable Height, in	25 ½	24 11/16	13/16 low	26 1/8	5/8 high	26 7/16	15/16 high
Bottom Cable Height, in	21 3/16	20 ¾	7/16 low	20 7/8	5/16 low	22 1/2	1 5/16 high
Tension, lb for 50° to 60° F	5300 to 4942					5720 top, 6340 center, 6160 bottom	

*Cable heights measured to top of cable

DESCRIPTION						MP 208	
WASHINGTON TYPE 3 CABLE GUARDRAIL	**Specified**	**Measured Midspan exemplar**	**Difference**	**Measured Midspan Exemplar**	**Difference**	**Measured Midspan exemplar**	**Difference**
Post Height, in	33 1/8						
Top Cable Height, in	30	29 ¾	1/4 low	30 1/8	1/8 high	29 1/16	15/16 low
Center Cable Height, in	25 ½	25 ¼	1/4 low	25 13/16	5/16 high	24 7/16	1 1/16 low
Bottom Cable Height, in	21	20 11/16	5/16 low	21 1/16	1/16 high	20 1/4	1/4 high
Tension, lb						960 top, 1380 center, 1480 bottom	

*Cable heights measured to top of cable

Table 1. Cable Guardrail Field and Design Measurements.

Data Description	Warren Accident	Washington State Cable Guardrail Crash Test	Trinity CASS Cable Guardrail Crash Test
Year, Make & Model	2001 Infinity QX4 4x4	1995 Chevrolet C2500	
Curb Weight, lb	4275	4408	4408
Weight distribution F/R	56/44	58/42	58/42
Wheelbase, in	106	132	132
Track width, in	59	65	65
Overall length, in	184	213	213
Overall width, in	72	77	77
Front bumper to front axle, in	30	35	35
Front bumper to front of hood, in	5	4	4
Height – Ground to:			
Top of Front Bumper, in	27	24.4	23.4
Headlight Center, in	34	34	34
Hood Front Top, in	39	40	40
Moments of Inertia			
Yaw Moment of Inertia, lb-ft-sec^2	3060.25	2774.94	2774.94
Pitch Moment of Inertia, lb-ft-sec^2	3131.00	2820.76	2820.76
Roll Moment of Inertia, lb-ft-sec^2	705.50	644.56	644.56
Center of Gravity			
From Ground, in	28.33	28.07	28.07
Behind Front Axle, in	46.24	55.44	55.44
Static Stability Factor	1.04	1.16	1.16

Table 2. Accident and Test Vehicle Dimensional Data.

Conclusions

Washington State Department of Transportation in accordance with the guidelines presented in with the Washington State Design Manual and the American Association of State Highway Transportation Official Roadside Design Guide provided a 40 ft wide median with traversable slopes and protected for crossover accidents by installing two different cable guardrail systems.

CASS Guardrail

The Trinity Industries Cable Safety System (CASS) Cable Guardrail Safety System was installed in the median along the I-5 southbound travel lanes. The CASS was properly installed in accordance with the manufacturer's specifications and construction tolerances. In the span of cable where the Warren vehicle breached the cable guardrail, the top cable was 1-1/16 inch low due to a combination of rotation and localized crushing of the plastic spacer with in the post. The top cable height was 28 ¾ to the top of the cable. This height is considered within construction tolerances and should not have affected the performance of the system. The G1-b is a three cable, steel post guardrail accepted for use by FHWA on the National Highway System and has a top cable height of 27 inches.

The Warren 2001 Infinity QX4 was a four wheel drive vehicle with a top of bumper height 3.6 inches taller than the test vehicle used in the crash test performed on the CASS system. The top of the bumper of the Warren vehicle is reported to be 27 inches from the ground. The top cable in the CASS cable guardrail was measured to be 28 ¾ inches from the ground. In crash tests performed on cable guardrail it has been observed that it is desirable for the vehicle's front bumper to engage the cables such that the cable(s) ride up and over the top of the front bumper. Cables that do not engage above the bumper have the opportunity to engage the impact side front tire and be ridden down. The lowest cable is frequently ridden down and not effective for containing and redirecting high center of gravity vehicles such as sport utility and pickup trucks. The lower cable is used to prevent small vehicles from under-ridding the cable guardrail.

The bumper of a vehicle leaving the pavement is at an effective higher height relative to the ground as it leaves the shoulder and traverses out onto a negative slope. This condition is exacerbated as the slope rate increases. The slopes in the vicinity of the impact were very moderate and varied from 13.5:1 to 9.8:1. The slope was nominally 6:1, 18 inches to 24 inches in advance of the post. Example bumper trajectory data is given in the AASHTO Roadside Design Guide. For an undisclosed vehicle type traveling 60 mph and encroaching 25 degrees onto a 10 ft wide, 5 percent sloping shoulder and continuing off onto a 6:1 slope, the change in bumper height was determined by simulation to be 4 inches at the edge of the shoulder and 4.8 inches 2 ft from the edge of the shoulder. In the example, the maximum change in bumper height is 6.9 inches and occurs 20 ft from the departed edge of travel lane. If a similar trajectory occurred with the Warren vehicle it would explain the vehicle overriding the cable guardrail system.

During the impact event, the Warren vehicle directly impacted a CASS post (post 81) and the upper flange portions of the post that flank the cables in the slot bent over and closed together restraining the cable from lifting up and out of the slot. As CASS post 81 was struck and the post deformed at ground level, the partially restrained cables were pulled down as the post deformed over and thereafter the cables were overridden. The absence of an extensive number of post damaged, no movement in the terminal section, and no redirection or change in the vehicle's trajectory all indicate limited engagement with the CASS system and consistent with an overriding condition.

FHWA permits cable guardrail to be installed on the National Highway System on a slope of 6:1 or flatter. This guidance is from crash tests successfully performed in 1978 on the G1 cable guardrail system installed on a 6:1 slope and impacted by a 4500 lb 1974 Plymouth Grand Fury. The G1 cable guardrail system was installed such that the test vehicle departed the travel lane onto an 8 ft, 15:1 sloping shoulder, and then down a 6:1 slope. The G1 system was installed 6 ft down the 6:1 slope. The measured top of bumper height of the Plymouth was 18 inches. The lower passenger car bumper height permitted a large change in effective bumper height at the point of impact with the 30 inch top of cable height in the G1 system and permitted successful containment and redirection.

For cable guardrail installation, national guidance from FHWA is coming from antiquated test data that does not accurately reflect the current vehicle fleet on the roadway today. Crash testing guidelines have been updated to more accurately reflect the current vehicle fleet. However, previously performed crash tests have not been repeated for all hardware and site configurations using the new updated surrogate vehicles. The National Cooperative Highway Research Program has funded a project to study the placement of traffic barriers on roadside and median slopes[12]. The objective of this project is to produce comprehensive recommendations for placement of barriers on roadside and median slopes. The guidelines should address all of the common types of barriers used in the United States. The purpose of the study is to update the guidelines determined from the 1978 crash tests previously mentioned.

Washington State Type 3 Cable Guardrail

The Washington State Type 3 Cable Guardrail was installed in the median along the I-5 northbound travel lanes. The Washington Type 3 was properly installed in accordance with the state's specifications and generally accepted construction tolerances in locations where exemplar installations were measured. The Warren vehicle impacted the backside of the cable guardrail engaging the middle and upper cables. The lower cable was ridden down. Shortly after impact, at the northbound terminal, the middle and top cables pulled free from the compensating spring cable end assemblies and released the cables. At the southbound terminal, the top cable also released from the compensating spring cable end assembly as a result of becoming engaged with the front of the northbound bus. The release of the cables is indicative of the Warren vehicle being positively engaged in the cable guardrail system and tensile loading in the cables occurring. However, the middle and top cables could not develop the full strength of the

cable guardrail system and contain and redirect the Warren vehicle because the cable wedges failed to restrain the cable ends in the compensating spring cable end assemblies. The released top cable remained in contact with the Warren vehicle and was carried through its trajectory until the impact with the bus occurred. Thereafter, the top cable was carried with the front end of the bus to final rest.

Inspection of the cable ends, cable wedges and compensating spring cable end assemblies revealed little or no scarring or deformation. The absence of scarring or minimal witness marks on the inside of the compensating spring cable end assemblies and the cable wedges indicate the cable wedges were not fully seated during the installation process. When a cable is released during an impact with properly seated cable wedges, the failure mode may be one of the following: (a) the turnbuckle fails, (b) the nut strips the off of the threaded rod on the cable end assembly, or (3) the casting fails where the cable wedge is seated in either the cable end assembly, or the compensating spring cable end. When any of these failures occur, there is usually significant witness marks on the inside of the casting where the cable wedge is seated and loaded. Unfortunately there has been an absence of guidance for properly installing the cable wedge assembly during construction from FHWA or AASHTO. Additionally, visual inspection of the cable wedge will normally only indicate the wedge is present and a wire has been bent/crimped over the end of the wedge to prevent rearward dislodging.

Cable guardrail systems remain the most cost-effective method for providing roadside protection for errant motorist. Additionally, cable guardrail remains the most forgiving longitudinal barrier available to the highway designer. Frequently, accidents into cable barrier go unreported because of the lack of damage caused to the automobile and the absence of injuries sustained to the vehicle occupants. However, during the course of this investigation, the items identified that need additional research or in-field performance evaluation are the performance and placement of cable guardrails on all slopes when impacted with a test vehicle that more accurately represents the current sport utility vehicle on the roadway today. The high-center of gravity, tall bumper height, short front overhang and other metrics are very much different today on SUVs than the low and heavy passenger sedan used for testing 30 years ago. In addition, additional guidance is needed from FHWA or AASHTO for properly installing and inspecting the low-tension generic type of cable guardrail (Washington Type 3).

If you have any questions concerning this report, please contact me at (979) 777-2647.

Sincerely,

References

1. "A Policy on Geometric Design of Highways and Streets", 1990, American Association of State Highway and Transportation Officials.

2. "Roadside Design Guide", 2002/2006 American Association of State Highway and Transportation Officials.

3. Alberson, Dean, et al, NcHRP Report 350 Test 3-11 of Trinity Cable Safety System (CASS) with 5 m Post Spacing, March 2003.

4. Griffith, Michael S., "Federal Highway Administration Memorandum B-119 – Report 350 Nonproprietary Guardrails and Median Barriers", February 14, 2000.

5. Bullard, D. Lance, et al, "NCHRP Report 350 Test 3-11 of the Washington 3-Strand Cable Barrier with New York Cable Terminal, March 2000.

6. Horne, Dwight, "Federal Highway Administration Memorandum B-64 – Report 350 Nonproprietary Guardrails and Median Barriers", February 14, 2000.

7. Washington State Design Manual, May 2006.

8. Ross, Hayes E., Sicking, Dean L., "Development of Guidelines for Placement of Longitudinal Barriers on Slopes, Volume I. Executive Summary, FHWA DOT-FH-11-9343, May 1983.

9. American Association of State Highway and Transportation Officials, et al "A Guide to Standardized Highway Barrier Hardware, May 1995.

10. National Cooperative Highway Research Program Report 350 "Recommended Procedures for the Safety Performance Evaluation of Highway Features", May 1993.

11. Ross, Hayes, et al, "Development of Guidelines for Placement of Longitudinal Barriers on Slopes – Volume II. Full Scale Crash Tests, FHWA DOT-FH-11-9343, May 1983

12. National Cooperative Highway Research Program Research Project 22-22 "Placement of Traffic Barriers on Roadside and Median Slopes" Dec. 12, 2006 start date.

Summary report for investigation of the generic or low-tension cable barrier system

WSDOT acquired data;

Four WSDOT regions performed and reported the results of a field task to measure the cable anchors, within the cast-steel housing, that secure the ends of the ¾-inch cable of this cable barrier system.

There are three cables, top, middle and bottom, per system. Each end of each cable typically utilizes three anchor housing assemblies that each has a cast steel, fluted and tapered anchor that wedges the cable within the anchor housing assembly. Typically there are a total of 18 cable anchor wedges per installed section of this barrier system; three cables per section, with three anchor wedges per cable, per end.

The task was to measure the depth of the anchor wedge in the as-found condition. Next, the crews were to attempt to seat the wedge deeper into the anchor housing assembly with a drive pin and small sledge hammer. After the attempt to drive the anchor wedge deeper they were to remeasure the depth of the anchor wedge and document any achieved movement to the nearest 0.1 inch.

WSDOT checked 1,809 wedge locations:

- 1,224 locations on I-5
- 540 locations on I-90
- 27 locations on I-82
- 18 locations on SR 18

Table 1 shows the number of checked anchor wedges, by location and by the amount of measured movement in increments of 0.1 inch.

Table 1
Number of wedges moved

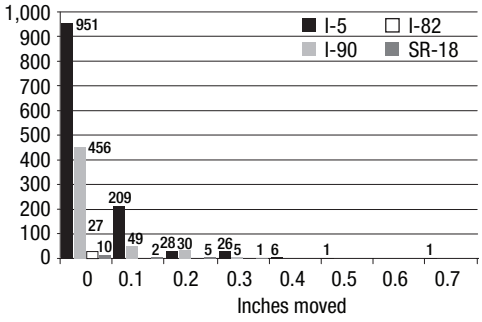
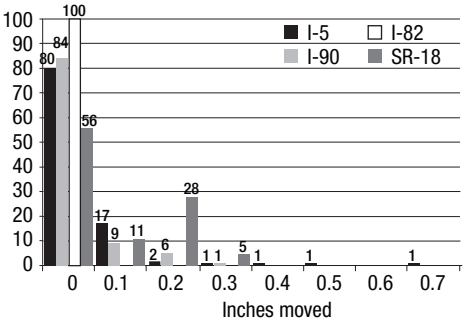


Table 2
Percent of wedges moved



Independent testing data: KBA

WSDOT hired independent consulting company, KBA Construction Management Inc. KBA representative Dick Rauscher traveled to the Everett vicinity to independently check, in the same fashion as WSDOT maintenance personnel did, the degree of additional "set" obtained after attempting to drive the anchor wedge deeper into the anchor housing. Rauscher was able to check the additional

set obtained on 30 anchor wedges. The results are shown in Table 3. WSDOT fabrication specialist David Harkema witnessed Rauscher performing the checks to ensure they were comparable to WSDOT procedure.

Table 3
KBA Anchor wedge movement achieved on I-5, by percentage

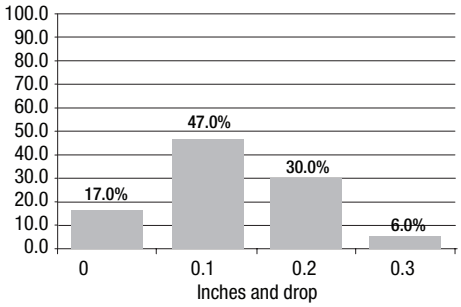
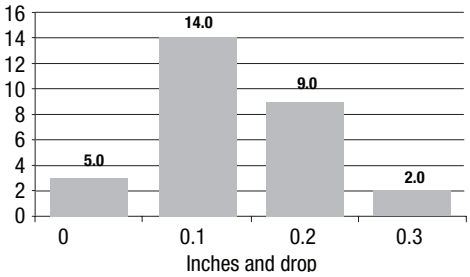


Table 4
KBA Anchor wedge movement achieved on I-5, by count



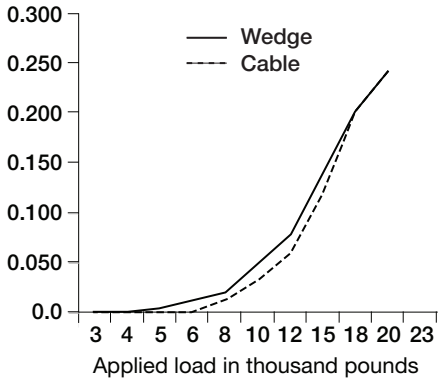
Noted inconsistencies:

1. Not all locations have a wire from a cable bent over the top of the anchor wedge to prevent it from backing out of the housing.
2. Some locations only have two anchor housing assemblies rather than the three depicted in the Standard Plans C-11b.
3. Some locations have the cables crossing over each other between the breakaway anchor angle and the first post.
4. At some locations, the two 3/4-inch hex nuts were not tight at the breakaway anchor angle.
5. Two anchor wedges were observed protruding beyond the opening of the anchor housing assembly.

Independent testing data: Mike Mayes Testing and Dwight Company, Inc.

WSDOT had Mike Mays Testing, an independent consulting company, perform a load test on four previously in-service, spring compensation anchor housing assemblies. Tables 5 through 7 graphically shows the Dwight Co. tension loading data and correlate it to the movement of the anchor wedge within the anchor housing assembly and the movement of the cable out of the anchor housing assembly, as the applied load increases;

Table 5
Spring compensation assembly CBSCA-1 (anchor housing assembly)
Movement in 0.001inches



The failure of each of the tested assemblies occurred at one side of the bale of the casting.

The ultimate failure of CBSCA-1, occurred an anchor housing

Table 6
Spring compensation assembly
CBSCA-2 (anchor housing assembly)
Movement in 0.001inches

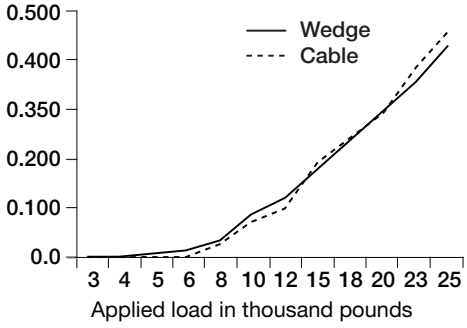
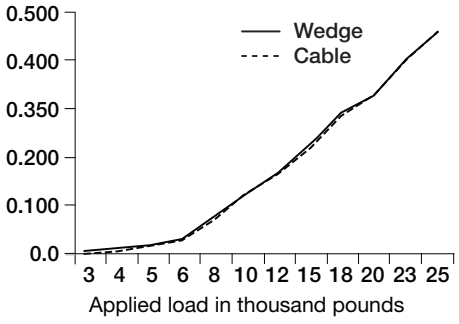


Table 7
Spring compensation assembly
CBSCA-3 (anchor housing assembly)
Movement in 0.001 inches



assembly, at a load of 21,564 pounds, partly was due to point loading within the test fixture. An initial set-up test was run, and with the data of four tests, the average ultimate loading to cause failure was 27,207 lbs.

Noted items;

During the initial loading, it typically took 4,500 pounds of load before the wedge would begin to move.

McKnight Laboratory Inc.

METALLURGICAL ANALYSIS OF CABLE MEDIA BARRIER COMPONENTS FROM BARRIER CROSSOVER COLLISION ON FEBRUARY 13, 2007, I-5 ACCIDENT IN MARYSVILLE, WASHINGTON

Report No. MTE070311

Prepared for:

Mayes Testing Engineers, Inc.

April 12, 2007

Prepared by:

McKNIGHT LABORATORY, INC.

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8. Addendum (Delivery Receipts)

April 12, 2007

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McKNIGHT LABORATORY, INC.
Report No. MTE070311

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Mayes Testing Engineers, Inc.
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Everett, WA 98204

SUBJECT: METALLURGICAL ANALYSIS OF CABLE MEDIA BARRIER COMPONENTS FROM BARRIER CROSSOVER COLLISION ON FEBRUARY 13, 2007, I-5 ACCIDENT IN MARYSVILLE, WASHINGTON

PROCEDURE

At the request of Mr. Thomas Baker, Department of Transportation, and Michael Mayes of Mayes Testing Engineers, Inc., the writer traveled to Seattle and met with Thomas Baker and Mel Reitz to examine the subject cable barrier components that were removed from the accident site related to the cable media barrier crossover collision that occurred on February 13, 2007, I-5 accident in Maryville, Washington. This accident reportedly involved an SUV which struck the cable media barrier and crossed over into the oncoming lane and struck a Canadian tour bus.

PROCEDURE (cont)

The accident event reported by DOT was as follows:

"On February 12, 2007, an Infinity Sports Utility Vehicle, proceeding Southbound on I-5 near Marysville, Washington, crashed through both a high tension cable barrier and a cable barrier, entering the Northbound lanes and causing a crash with a bus. The high tension cable barrier on the media side of the Southbound lanes was damaged involving approximately 5 posts. The cable barrier on the media side of the Northbound lanes experienced greater damage including pulling the wire rope out of three of the spring cable end assemblies, two North of the crash site (wire ropes 2 and 1, counting from top down) and one South of crash site (wire rope 1, again counting from the top down)."

The cable barrier components from the accident site and other samples of cable barrier components were examined at the Maintenance and Operations Warehouse in Everett, Washington,and a trip was also made to the site to examine the area where the accident had occurred.

Samples were selected at the Everett facility to be submitted to McKNIGHT LABORATORY for further metallurgical evaluation. The samples selected were subsequently shipped to McKNIGHT LABORATORY on 3-19-07 and received on 3-20-07. A copy of the items shipped and the items received at McKNIGHT LABORATORY are documented in the Addendum titled "Shipping Receipts". These components were subsequently examined at McKNIGHT LABORATORY on 3-30-07 and photographs taken of all of the components received and evaluated.

PROCEDURE (cont)

Prior to the inspection and evaluation of the cable media barriers from the Department of Transportation, a trip was made to Texas Transportation Institute at the Texas A&M University with Thomas Baker to witness pendulum testing of generic low tension cable guard rail wedge anchor assemblies. The cable and tension cable components that were tested at Texas Transportation Institute (TTI) were identical to the cable and hardware components used on the median barrier at the accident site in Marysville, Washington. Nineteen pendulum test assemblies were tested at TTI on 3-21 and 3-22-2007, and all of the testing was supervised and coordinated between personnel at TTI, Thomas Baker and the writer. The personnel in charge of the testing at TTI were Dr. Dean C. Alberson and Mr. Lance Bullard at TTI. The results of the testing are documented in Section 6 of this report. After the tests were conducted at TTI, the 19 cable and wedge component assemblies were shipped to McKNIGHT LABORATORY and photographs taken to document the cable markings on the wedge from the spring compensating housings and also the cable markings on the inside of the nose of the spring housing assemblies that were tested. This photographic evidence is documented in Section 7 entitled "Wedge and Spring Housing Nose Cable Markings." Copies of all photos and videos taken at TTI were submitted on DVD discs to the Department of Transportation and also McKNIGHT LABORATORY.

EXECUTIVE SUMMARY AND CONCLUSIONS

The cable barrier components from the accident site and other samples of cable barrier components submitted by the Department of Transportation in Everett, Washington were examined in Everett, Washington and then shipped to McKNIGHT LABORATORY for further evaluation. The photographs of the various components, which are shown in Section 3 of the report, documented the condition of the cable end and spring compensating housing and wedge from the South and North anchor spring compensating cable ends from the accident site. Examination of the cable, wedge and inside area of the spring compensating cable casting from the North top and middle barrier cable from the accident site revealed that the stranded cable and wedge had pulled out of the spring compensating casting and that the interference abrasion markings between the wedge and the inside of the spring compensating cast housing were very light. In other words, there was evidence of minimal interference between the wedge, cable and anchor housing at these two ends. On the inside of the spring housing assembly, there were minor scratch marks on the inside of the housing and on the wedges that were used there were cable markings only on the bottom end of the flutes of the wedge which indicated that the wedge had not been completely seated. Examination of the cable, wedge and spring compensating housing for the top South position from the accident site also revealed the same type of light interference fit between the cable, wedge and the housing consistent with the two pullouts that occurred at the top and middle North positions. At the South middle cable end and at the South bottom cable end attachment to the housings, the interference markings were also light. However, during the accident the cable barrier at the top middle position on the South end and at the South bottom location did not pull the wedge and cable out of the spring housing casting.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

Based on these preliminary findings, it was decided to conduct a full scale testing of 19 different cable barrier assemblies at the Texas Technical Institute at Texas A&M. The test cable assemblies that were tested at TTI consisted of a spring compensating housing, a length of ¾" cable, and an anchor cast housing at the opposite end of the assembly. These assemblies were then impact pulled at TTI under different testing conditions and testing parameters. The tests conducted at TTI essentially created a dynamic impact tensile test on the 19 different cable assemblies. These tests were conducted in an attempt to understand how and under what conditions the cable and wedge assemblies on the compensating end of the barrier assemblies would cause a pullout of the wedge and cable from the spring compensating end casting. In these different test assemblies, the method of installing the wedge in the stranded cable inside of the housing was evaluated.

The parameters of the tests involved changing the following parameters:

1) The embedment of the wedge at the wedge anchor assembly in the casting.
2) Varying the method of driving the wedge into the cable attachment.
3) Varying the amount of alignment of the wedge with the 3 stranded cables at the time the wedge was driven into the fittings.
4) Changing the velocity of the impact for the tests.
5) Changing the drop height of the bogey which was used to create the impact test on the cables.

During the testing at TTI, still photographs and video filming was conducted of each and every test by TTI and these have been submitted to McKNIGHT LABORATORY and the Department of Transportation for review.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

After all of the testing was completed at TTI, the test cable assemblies were submitted to McKNIGHT LABORATORY for examination. At McKNIGHT LABORATORY, the spring compensating end assemblies and companion cable and wedge from the nose of the spring compensating end castings were evaluated and documented. The markings on these components were compared to the markings that were found on the cable assemblies that were involved with the accident.

The typical dimensions of the wedge, cable and inside nose opening of the spring housing assembly revealed that the maximum cable diameter was approximately .730" and that the opening in the nose of the compensating spring housing varied from .760 to .785" in a triangular configuration which allowed the cable to be inserted into the nose of the spring compensating end casting. Once the cable strand was inserted into the housing, the 3 strands making up the cable were then splayed apart so that the wedge could be placed in-between the 3 strands and seated in the flutes or longitudinal grooves of the wedge. The wedge was then driven down into the housing to different depths to create the interference fit between the wedge, cable and the inside of the cast housing. The dimensions of the wedge were documented in the Standard Plan C11B. Measurements of the wedge were similar to the Standard Plan but varied somewhat from the Standard Plan specifications. The wedge, however, being of a cast configuration was basically in compliance with the general configuration of the cable wedge indicated in the Standard Plan C11B. When the wedge is installed in the assembly and driven into the 3 strands of the cable, the three strands tend to follow the 3 grooves or flutes in the wedge and as the depth of the wedge is increased, the frictional force between the wedge, cable and spring housing fitting is greatly increased so that during any type of tensile loading effect the cable and wedge should not pull out of the cast fitting.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

In order to determine the characteristics of the wedge, cable and the cast iron spring compensating end casting, each of the components was evaluated for chemistry, hardness and microstructure. Results of the analysis on the wedge showed that it was made from a ferritic malleable cast iron material consistent with ASTM A-47. The microstructure of the wedge was consistent with a ferritic malleable cast iron as specified in ASTM A-47. The hardness of the wedge was typically 64.7 to 68.8 Rockwell B which is equivalent to a Brinell hardness of about 114 and 119 which is also consistent with ASTM A-47 which specifies that the hardness shall not exceed 156 on the Brinell hardness scale. The results of the analysis on the spring compensating end casting revealed that the chemistry was consistent with a malleable iron type cast iron. However, the hardness and microstructure did not conform to the ASTM A-47. The typical hardness of the casting was equivalent to a hardness of approximately 240 on the Brinell hardness scale which is in excess of the 156 maximum hardness specified in ASTM A-47. The difference in the hardness between the casting and the wedge was due to the fact that the wedge had a ferritic microstucture with nodule graphite whereas the cast housing had a pearlitic matrix with nodular graphite. The analysis of the cable showed that it was made from a 1045 to 1050 carbon steel which was cold drawn to a hardness of approximately 39.5 to 43 Rockwell C which is equivalent to a Brinell hardness of 360 to 393.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

Based on these analyses, it's obvious that the wedge in the assembly has a lower hardness than the spring compensating cable end housing, and that the hardness of the cable exceeds the hardness of either the wedge or the cast housing. As a result of this difference in hardness, when the wedge is driven in-between the cable strands, cable markings are more prominent on the flutes of the wedge than they are on the inside surface of the cast spring housing fitting. Consequently, when the cable and wedge are pulled out of the cast housing, more prominent cable marks are made on the wedge than on the spring compensating housing. This criteria was therefore used to evaluate and compare the markings on the wedge and the cable ends and the inside of the cast housing on the assemblies that pulled out at the accident site and compared to the markings on the wedge, cable and housings from the test assemblies that were conducted at Texas Technical Institute.

Of the 19 tests that were conducted at TTI, there were 5 significant tests which created a situation where the wedge and cable pulled out of the spring compensating end assembly. These were Tests P2, P5, P9, P11 and P16. On Test P5, the wedge and cable pulled out of the spring housing assembly and left cable markings over the full length of the 3 flutes in the wedge. In this particular test, the wedge seat depth was 14mm and the impact speed of the bogey was 31.8 kilometers per hour. In test assemblies P9, P11 and P16, the depth of embedment of the wedge prior to the tests was respectively 6mm, 4mm and 7mm and the speed of the test bogey was respectively 19.9 kilometers per hour, 19.4 kilometers per hour, and 20 kilometers per hour. The examination of the wedge and cable and inside nose of the spring compensating casting from these three test assemblies showed that the cable markings on the flutes of the wedge were minimal and only present near the bottom or the small end of the wedge.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

In addition, the cable markings on the inside nose of the spring housing assembly casting were also light in comparison. The wedges from these three test assemblies were completely different than the cable markings on the wedge from the P5 test assembly where the wedge was completely seated to a depth of 14mm. The cable markings on the wedge, cable and inside nose of the spring housing casting from Test Specimens P9, P11 and P16 were virtually identical to the markings of the wedge, cable and spring housings from the cable barrier assembl'ies removed from the accident site; specifically the appearance of the wedge, cable and housing from the top North position and middle North position and top South position where the wedge and cable pulled out of the spring compensating cast housing. In other tests where the depth of the wedge embedment was increased from 7mm up to 9mm to 14mm and at the lower speed of testing the cable and wedge did not pull out of the spring compensating end casting.

Based on these comparisons between the condition of the wedge, cable and markings on the inside of the spring compensating end castings, the results indicate that the wedge on the three cable assemblies that pulled out of the housings at the accident site were caused by the wedge not having been properly and completely seated in the cast housing assemblies at the time of installation. If the wedges had been seated to a depth of approximately 14mm or more, one would have expected that the wedge and cable would not have pulled out of the spring anchor assemblies. If the wedges had been seated to 14mm and if the speed of impact was in the neighborhood of 31.8 kilometers per hour, one might have expected the wedge and cable to pull out of the housing but, in that situation, one would have anticipated that there would be cable markings along the full length of the flutes in the wedge assembly consistent with the results of Test P5 that was conducted by TTI.

EXECUTIVE SUMMARY AND CONCLUSIONS (cont)

These results further indicate that the impact velocity at the accident scene was more in the neighborhood of 19 or 20 kilometers per hour as opposed to 31.8 kilometers per hour.

The final conclusion, therefore, is that the cable and wedge pulled out of the spring compensating end cast assemblies at the accident scene due to the fact that the wedges had not been adequately and completely driven into the assembly upon installation.

RESULTS

PHOTOS OF DOT CABLE ASSEMBLIES FROM THE ACCIDENT SCENE

The cable assemblies removed from the accident scene were sent to McKNIGHT LABORATORY. These were photographed and samples taken for detailed metallurgical analysis. FIGS. 1 through 4 illustrate the spring compensating cable end from the top North anchor assembly from the barrier. FIGS. 5, 6 and 7 illustrate the cable markings on the inside of the nose of the spring compensating housing. One can tell from the photographs that there are very slight scratch marks caused by the wire cable against the inside of the housing. This is one of the assemblies where the wedge and cable pulled out of the anchor assembly. FIGS. 8 through 17 illustrate the appearance of the wedge that was retrieved from this housing. There were cable markings or impressions along the lower bottom end of the wedge but no significant cable markings along the flute of the wedge towards the top end. This shows that the pressure between the interference fit between the wedge and the cable wires and the inside of the housing was very light which suggests that the wedge was not driven well into the housing at the time of installation. Subsequent testing of barrier cable assemblies at the Texas Technical Institute show much more significant impression markings on cable assemblies that were tested with well embedded wedges. These results will be discussed later in this report. FIGS. 18 and 19 illustrate the opposite end of the North top cable assembly which shows the cable anchor end. At this location, the wire and wedge did not come out of the anchor housing.

RESULTS

The wires of the cable end that was previously inserted into the spring compensating end of the North top cable assembly are shown in FIGS. 20 through 23. One can see that there is very little evidence of any significant abrasion markings on the wires of the stranded cable which again indicates that the interference fit between the wedge and the cable and the inside of the spring compensation housing was very low. This is consistent with the cable and wedge pulling out of the spring compensating end casting or housing.

FIGS. 24 and 25 illustrate the cable assembly from the North middle anchor assembly from the barrier, and FIGS. 26 and 27 illustrate the end of the spring compensating end housing from this assembly. FIGS. 28 through 32 illustrate the slight cable markings on the inside of the nose of the spring compensating assembly from the North middle position. The cable markings inside are very slight which indicates that the interference fit between the cable and the wedge and the housing was relatively low. FIGS. 34 through 42 illustrate the appearance of the wedge that was removed from the North middle anchor assembly barrier cable. One can see that there are virtually no significant cable markings from interference between the strands of the cable and the flutes of the wedge. The only cable markings that appear are near the bottom smaller end of the wedge which is consistent with the interference fit between the cable wedge cable and the inside nose of the housing being very slight. This is consistent with the wedge and cable pulling out of the cable barrier housing. FIGS. 43 through 46 illustrate the appearance of the wires of the cable from the North middle cable barrier location. One can see that there is very slight evidence of any significant abrasion marks on the individual wires of the cable end that pulled out of the housing.

RESULTS

If the wedge had been completely embedded in-between the three strands of the cable in the spring compensating housing, one would have expected a much greater interference fit and, consequently, more significant markings between the wedge, housing and wires on the end of this cable of the assembly.

FIGS. 47 and 48 illustrate the appearance of the top anchor assembly at the South end of the barrier cable. At this location, it was also reported that the cable and wedge pulled out of the spring compensating end housing. FIG. 49 illustrates the end of the spring compensating housing with tape over the end shown to the right. The appearance of the inside of the nose of the housing are shown in FIGS. 50 through 52. One can see again that there are only very light cable markings on the inside nose of the spring compensating assembly which indicates that the interference fit between the cable wires and the wedge and the spring housing was very light. This indicates that the pressure between these components was very light when the pullout occurred. FIGS. 53 through 61 illustrate the appearance of the wedge from the South top anchor assembly which again shows very minimal interference markings between the three stranded cables and the inside surface of the flutes. This supports the fact that the interference fit between the wedge, cable and inside of the spring compensating housing at the South top assembly was very light. Consequently, the abrasion marks were minimal when the cable pulled out of the housing. FIG. 62 illustrates the opposite cable anchor housing which did not pull out of the cable end fitting. FIGS. 64 and 65 illustrate where the South end cable was cut well away from the spring compensating housing.

RESULTS

FIGS. 66 through 70 illustrate the condition of the wire ends that pulled out of the spring compensating assembly at the South top location of the barrier cable. These markings on these individual wires are minimal suggesting that the interference fit and pressure between the stranded cables, the wedge and the inside of the housing was very slight.

FIGS. 71 and 72 illustrate the South middle anchor barrier cable assembly, and FIG. 74 illustrates the nose end of the spring compensating anchor assembly with tape covering the wedge inside of the housing. FIGS. 76 through FIG. 80 show the light cable markings on the inside of the nose of the spring compensating housing. FIG. 82 illustrates the appearance of the wedge from the spring compensating end of the assembly for the South middle location barrier. One can see that there is very little evidence of any wire impressions along the three flutes of the wedge from this assembly. Only very slight markings are apparent towards the smaller diameter end of the wedge. FIGS. 93 and 94 illustrate the appearance of the 4 ft. section of the cable cut from the South end middle barrier assembly and the end of the stranded cable. The housing is illustrated in FIGS. 95 through 99. One can see evidence of very slight distortion of the wires of the three strands of the cable end which indicates relatively light pressure or interference between the housing, the wedge and the stranded cable at this location. The one bent wire, shown in FIGS. 97 and 98, illustrates that one wire was bent over the top end of the wedge when the wedge was installed. This is typical of the type of installation that is called for when the wedges are placed in between the cables when they're driven into the housing assembly.

RESULTS

FIGS. 100 to 102 illustrate the spring housing end assembly from the South bottom anchor barrier cable that was removed from the scene, and FIGS. 103 through 108 illustrate the cable markings on the inside nose of the housing assembly. One can see some depression markings on the inside of the nose assembly made by the wire bearing against the inside of the housing at this location which indicates that there was more interference fit between the wedge cable and housing on this particular assembly. FIGS. 109 through 117 illustrate the appearance of the wedge from this barrier cable assembly. There did not appear to be any heavy markings along the flutes. Most of the markings were toward the bottom small diameter end, but there were some interference markings along the edge of the flute, as indicated by the arrow in FIG. 112. This apparently was caused by one of the wires from one of the strands slightly climbing out of the flute and creating greater compression loading between the edge of the flute, wire and the inside of the housing. The cable markings on the inside of the flutes appeared to be relatively light even at this location. FIGS. 118 through 120 illustrate the appearance of the three cable strands at the end of the cable where it was positioned inside of the spring housing assembly from the South bottom location. One can see that one of the wires had been bent over after the insertion of the wedge. This is indicated by the arrow in FIG. 119.

RESULTS

Two samples of a spring housing cable and wedge installation that were not from the accident scene were also submitted to the laboratory for comparative evaluation. These two assemblies were identified by DOT as No. 17 and No. 18 samples. FIGS. 123 and 124 illustrate Sample 17 that was submitted. The wedge and cable were still inside of the nose end of the spring compensating housing, as is illustrated in FIGS. 123 and 124. Before disassembling this particular unit, a measurement was taken from the edge of the opening, illustrated in FIG. 124, to the top end of the wedge to record the depth of the embedment of the wedge. On spring housing No. 17, the depth of the embedment of the wedge on this sample was estimated to be 18mm. The appearance of the wedge inside of the housing is illustrated in FIGS. 125 through 129, and the top end of the wedge is shown in FIG. 128. The cable and wedge were removed from the No. 17 housing by making A cut along the housing and then driving out the end of the cable and wedge. FIG. 130 shows the cut location. FIGS. 131, 132, 133 and 134 illustrate where longitudinal cuts were made in the spring housing for further examination. The wedge from this housing was removed and is illustrated in FIGS. 135 through 140. There is evidence of cable markings near the bottom half of the wedge and there is also evidence of interference markings between the edge of the cable and the wires in the cable. The markings on the wedge indicate that the wedge was well seated in the cable housing. FIGS. 141 and 142 illustrate the appearance of spring housing assembly No. 18 which also was not a part of the assemblies from the accident. FIGS. 143, 144 and 145 illustrate the wedge on the inside of this housing. The depth of the embedment of the wedge on this part was measured and found to be 7mm. The markings on the nose of the spring housing after cutting and removal of the wedge and cable are shown in FIGS. 147-149.

RESULTS

The appearance of the wedge removed from the No. 18 housing is shown in FIGS. 150 through 156..There are wire impressions at the bottom edge of the wedge and also some interference markings between the wire and the edge of the wedge near the top of the flute. These two examples would appear to be typical of the installation of the cable and wedge in prior spring compensation housings.

To illustrate the typical internal configuration of the wedge, the cable and the housing, a cross section of the assembly was photographed. FIG. 157 illustrates a half section of the spring compensator end housing and the sample of a new wedge and a new section of cable. FIG. 158 illustrates the wedge placed in-between the three wire strands in preparation for installation. FIG. 159 shows a higher magnification view of the initial installation, and FIGS. 160 and 161 illustrate the wedge being placed further into the housing. This gives one an idea of the wedging action of the wedge against the cable and then against the inside of the housing. FIG. 162 illustrates an end view of the wedge with the three cable strands seated in the flutes of the wedge, and FIG. 163 shows an additional view of the installation. When the wedge is pounded in against the cables, significant compression pressure is exerted between the wedge, cable and inside of the housing, thereby, locking the cable in the housing. Obviously, the further the wedge is driven in, the greater the compression and locking capability of the cable in the housing occurs.

FIG. 164 illustrates the appearance of a new wedge that was installed on test piece P-7 at TTI in Texas. This particular wedge was installed to a depth of 14mm at TTI and then removed so that the markings on the flutes could be documented. FIGS. 165 through 170 illustrate the typical cable markings that are imposed on this particular wedge. This is indicative of the type of markings that one might expect if the wedge is embedded to a depth of 14mm without any subsequent impact testing.

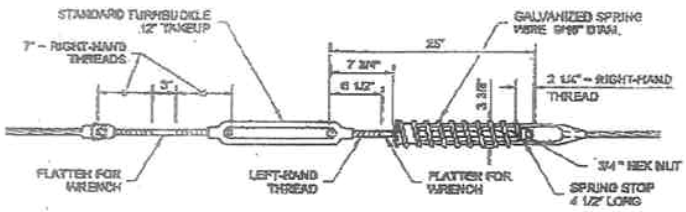
RESULTS (cont)

DIMENSIONS

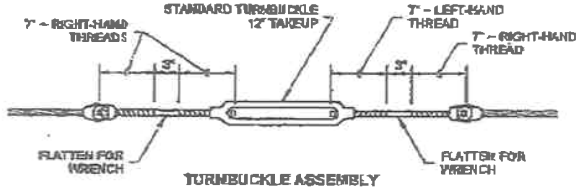
Some typical dimensions of the wedge, cable and the inside nose opening of the spring housing assemblies were taken. The typical dimensions of the wedge were documented on the cable barrier terminal Standard Plan C-11b which is illustrated in the following page. The second page illustrates the enlarged view of the wedge with the typical dimensions from Standard Plan C-11b shown and the actual measurements taken of various wedges. One can see that the actual measurements from several different wedges show dimensions that are similar but not exact in conformance with the dimensions given on the Standard Plan C-11b. However, the wedges are a cast material and are not precise. In other words, the wedges are not a machined finished part and, therefore, it is not unexpected that some of the actual measurements of the wedges would be somewhat different from the dimensions shown on the Standard Plan. In any case, these variations would not cause the cable assemblies to react adversely due to these slight dimensional differences in the writer's opinion.

The third page illustrates the typical dimensions recorded from measuring the opening at the nose of the spring compensating housing on various assemblies. Samples 6, 7, 8, 9, 11 and 23 were checked, as illustrated in the sketch. Also recorded is the maximum cable diameter. One can see that the maximum cable diameter is approximately .730" as measured on a new cable segment, and the nose openings vary depending upon Location A, B or C from .760 to .785" amongst the various samples. The difference between the opening in the housing and the cable is compensated for by the driving of the wedge in between the strands of the cable during installation. This points to the importance of installing the wedge properly and driving the wedge in a sufficient distance to lock the cable inside of the nose of the housing.

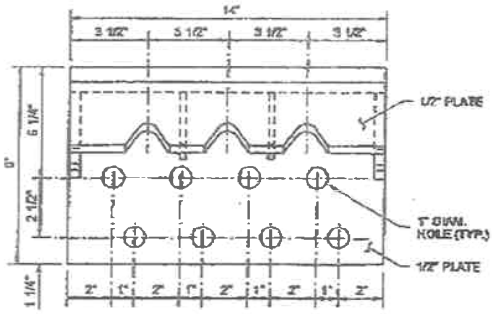
DRAWN BY: MARK BUJKA



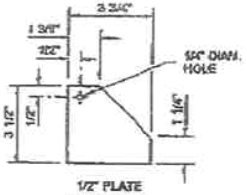
SPRING CABLE END ASSEMBLY



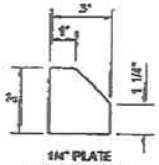
TURNBUCKLE ASSEMBLY



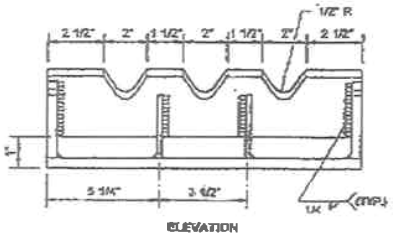
PLAN VIEW



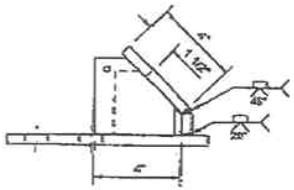
1/2" PLATE END GUSSET



1/4" PLATE INSIDE GUSSET

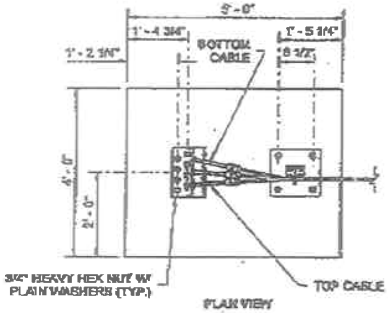


ELEVATION

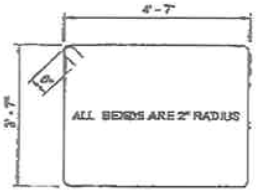


SIDE VIEW

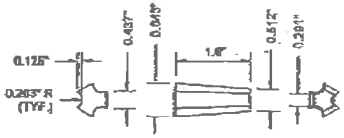
BREAKAWAY ANCHOR ANGLE



PLAN VIEW

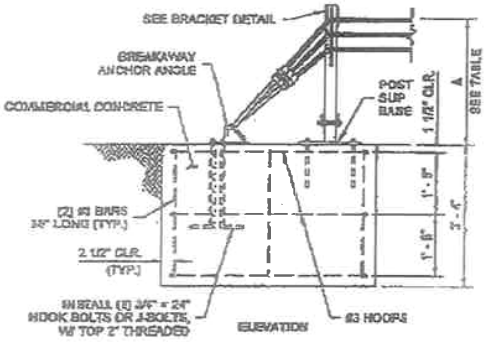


#3 HOOP



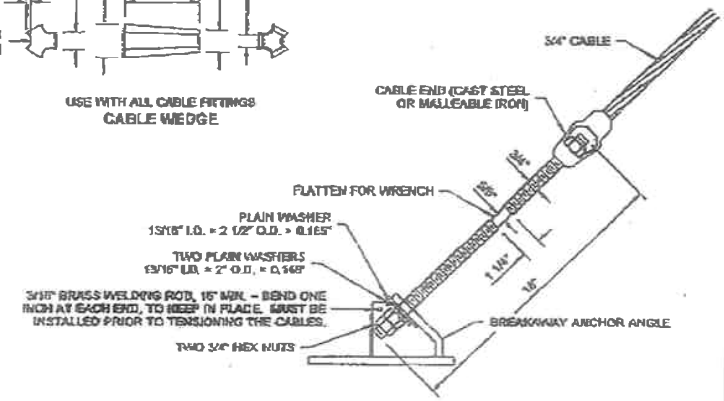
USE WITH ALL CABLE FITTINGS

CABLE WEDGE



ELEVATION

CAST-IN-PLACE FOOTING



CABLE END ASSEMBLY TO BREAKAWAY ANCHOR ANGLE DETAIL

EXPIRES JULY 24, 2004

CABLE BARRIER TERMINAL

STANDARD PLAN C-11b

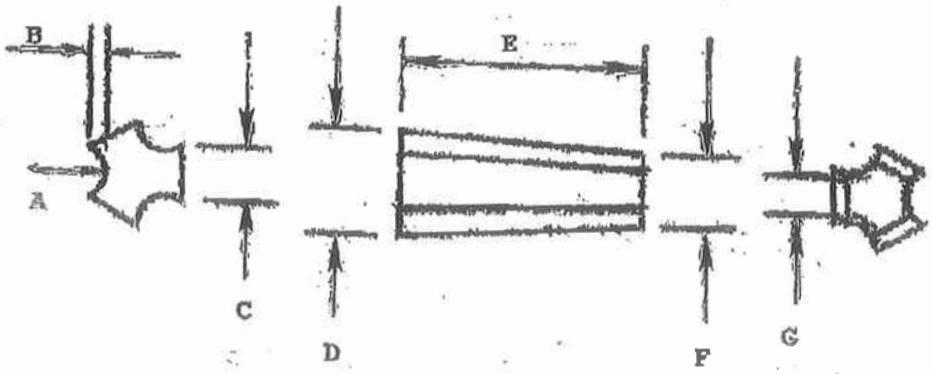
SHEET 2 OF 2 SHEETS

APPROVED FOR PUBLICATION

Harold Peterson 5-20-04

STATE CONSTRUCTION ENGINEER DATE

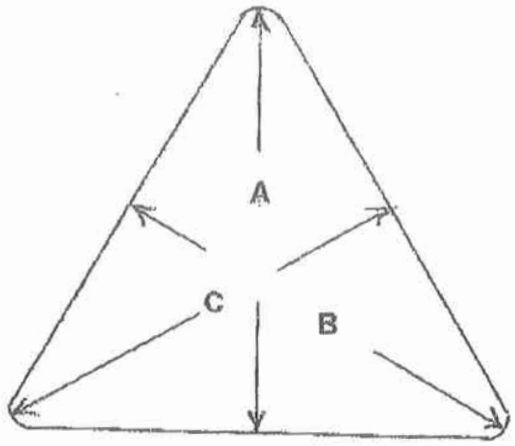
Washington State Department of Transportation



Dimensions from Standard Plan C-11b	Actual Measurements from Several Wedges
A - .203" R (Tyr)	.20"
B - .125"	.110"
C - .437	.50 - .52"
D - .842"	.885"
E - 1.8"	1.8 – 1.85"
F - .512"	.51 – .54"
G - .291"	.20 – .25" (approx.)

SPRING COMPENSATING HOUSING
CABLE NOSE – END OPENING DIMENSIONS

Cable Max. Diameter .730"



	A	B	C
Sample 7 – South Bottom Anchor Assembly	.785	.780	.785
Sample 8 – South Top Anchor Assembly	.780	.780	.780
Sample 9 – North Middle Anchor Assembly	.760	.766	.766
Sample 6 – South Middle Anchor Assembly	.761	.775	.766
Sample 11 – North Top Anchor Assembly	.780	.770	.764
Sample 23 – North Bound I-5 Cable Assembly Mile Post 205.1 3-13-07	.775	.775	.770

RESULTS (cont)

CHEMISTRY, MICROSTRUCTURE AND HARDNESS TESTING

FIG. 171 illustrates a typical new wedge that was cut so that a microsection could be prepared from the wedge. The rest of the wedge was used for quantitative chemical analysis. The typical cross section unetched microstructure of the wedge is shown in FIG. 172 which is typical of a malleable cast iron material, and FIG. 173 illustrates the typical etched microstructure of the wedge which is typical of a ferritic malleable cast iron material with the microstructure consisting of randomly dispersed graphite nodules in a ferritic matrix. The quantitative chemical analysis of the wedge was as follows:

Carbon	2.79%
Manganese	.28
Phosphorus	.020
Sulfur	.10
Silicon	1.47
Copper	.12
Chromium	.04
Nickel	.05
Molybdenum	.01
Iron	Balance

This chemical analysis is consistent with the analysis of a ferritic malleable cast iron.

RESULTS (cont)

The hardness of the wedge determined by taking Rockwell B hardness readings direct on the wedge cross section was 64.7 to 66.8 Rockwell B which is equivalent to a Brinell hardness of approximately 114 to 119.

FIG. 174 illustrates the location of the microsection prepared from the No. 11 spring housing assembly from the North top anchor assembly from the accident scene. This particular section was removed and a microsection prepared along with a quantitative chemical analysis and a hardness test. FIG. 175 illustrates the typical microstructure of the No. 11 housing assembly in the unetched condition, and FIG. 176 illustrates the typical etched microstructure of this part. The casting was typical of a malleable iron casting consisting of graphite nodules dispersed throughout a matrix consisting of pearlite and spheroidized pearlite platelets in the microstructure. The hardness of the casting was determined to be approximately Rockwell C 22 which is indicative of a Brinell hardness of approximately 240. Based on this information, the cast housing is a malleable iron casting but with a partially annealed pearlitic matrix microstructure. The chemical analysis of the spring assembly housing was follows:

Carbon	2.4
Manganese	.31
Phosphorus	.019
Sulfur	.12
Silicon	1.51
Copper	.16
Chromium	.06
Nickel	.06
Molybdenum	.01
Iron	Balance

RESULTS (cont)

This type of analysis is typical of what one would expect for a malleable cast iton. However, the microstructure is not typical of a ferritic malleable casting since the matrix microstructure is pearlitic. If one compares these requirements to the ASTM A47/A-47M-99 specification for ferritic malleable iron castings, the hardness and microstructure of the housing do not conform to the requirements of ASTM A47/A-47M. In the ASTM specification, the maximum hardness of the casting is designated as 156 Brinell. At a maximum hardness of 156 Brinell, the maximum hardness on the Rockwell B scale would be approximately 82. Obviously because of the matrix microstructure, the actual casting has a much higher hardness than that specified in A47. Because of the pearlitic microstructure, the actual cast housing would tend to exhibit more brittle characteristics than a ferritic malleable iron casting.

A sample of the new cable Sample 25 that was submitted was tested for microstructure, chemical analysis and hardness. FIG. 177 illustrates the typical cross section of one of the wires in the unetched condition which shows the zinc layer. FIG. 178 indicates the typical microstructure which consists of ferrite and cold worked pearlite matrix. The chemical analysis on the wire was as follows:

Carbon	.48
Manganese	.66
Phosphorus	.011
Sulfur	.012
Silicon	.23
Copper	.26
Chromium	.10
Nickel	.08
Molybdenum	.02
Iron	Balance

This indicates that the wire was made from an AISI 1045 to 1050 carbon steel.

RESULTS (cont)

The hardness of the wires determined by Knoop microhardness technique on the cross section showed the wire hardnesses to be 39.5 to 43 Rockwell C. This is equivalent to a Brinell hardness of 360 to 393 and an ultimate tensile strength of 177 to 199 ksi.

From the results of the chemical analysis, microstructure and hardness tests of the spring housing assembly segments, it's apparent that the wire is significantly higher in hardness and tensile strength than the wedge and the cast housing. In addition, the wedge is significantly softer than the cast spring housing assembly. Although the chemical analysis of the wedge and the spring housing assembly are virtually identical, the matrix microstructure of the wedge is ferritic and the matrix microstructure of the housing is pearlitic. This explains the difference in hardness between the wedge and the spring housing. The wedge conforms to ASTM A-47, but the spring housing does not conform to A-47.

RESULTS (cont)

The results of the testing by Texas Transportation Institute are included in this section of the report. Nineteen cable barrier assemblies were tested at TTI and in each case measurements were taken of the depth of the wedge in either the anchor housing fitting at the one end of the cable assembly or at the spring compensating cable end housing. In each case, the depth or embedment of the wedge was documented before the test and after the test was completed. Also, in cases where the cable pulled through, measurements were taken to determine the pull through of the cable and wedge at both the cable anchor end at the spring compensating cable end of the assemblies. The fold out sheet which follows documents all of the seat depth measurements and pull through measurements on all of the nineteen tests. In Tests P2, P5, P9, P11 and P16, the cable and wedge pulled completely out of the spring compensating end housing. The significance of these tests is very important because it shows that in situations where the wedge was not completely seated in the spring housing, the wedge and cable pulled out of the spring compensating end housing under the dynamic load testing that was performed at TTI:

On Test P2, which was conducted at an impact speed of 34.5 kilometers per hour, the wedge from this assembly pulled out and was ejected. Consequently, the wedge from this test was not found.

On Test P5, which was conducted at 31.8 kilometers per hour, the wedge was installed to a full seat depth of 14mm but under the dynamic high speed load, the wedge and cable on the compensating end still pulled out completely. The wedge from this assembly was saved.

RESULTS (cont)

On Tests P9, P11 and P16, the wedge and cable pulled out of the spring compensating end housing, but in all these cases the embedment or depth of this wedge seat was respectively 6mm, 4mm and 7mm, and the impact speed of these tests respectively were 19.9 kilometers per hour, 19.4 kilometers per hour and 20 kilometers per hour. These results show that where the embedment of the wedge was 4 to 7mm, the cable and wedge slipped out of the spring compensating housing at these lower impact speeds.

The wedge and cable ends and the end of the spring compensating housing from each of the tests, P1 through P19, were examined and photographed and are illustrated in Section 7 of this report.

RESULTS (cont)

The cable barrier test specimens P1 through P19 which were performed at Texas Transportation Institute were shipped to McKNIGHT LABORATORY for further examination. On these 19 test assemblies, the wedge and cable segments were removed from the end of the spring compensating cable housing for examination. In order to retrieve the wedge from the end of the spring housing assembly, it was necessary to make longitudinal cuts in the housing at the cable end so that the wedge and cable could be removed. The inside cable markings on the inside of the housing and the cable markings along the three flutes of the individual wedges were examined and photographed. FIGS. 179 through 257 are photographs which document the markings on the inside of the housing and the cable markings on the companion wedge from each of the test assemblies. FIGS. 179 through 182 illustrate the inside of the housing and the wedge from P1. In this particular assembly, the cable markings are very distinctive on the wedge and on the inside of the housing. This shows complete cable markings through the entire length of the wedge. On this test setup, the cable and wedge did not pull out of the spring housing assembly, but the interference fit between the housing and the wedge and the cable was very good.

On Test P2, the wedge was not found, but the markings inside of the nose of the housing are illustrated in FIGS. 183 and 184. There were some cable markings on the inside of the housing.

FIGS. 185 through 188 illustrate the inside of the housing and the wedge from Test P3. The wedge and cable did not pull out of the housing on this particular setup and the markings are very slight at the bottom nose end of the wedge. This is the test in which the cable was cut by wrapping around the post at the cable end assembly.

RESULTS (cont)

FIGS. 189 through 192 illustrate the inside of the housing and the wedge from Sample P4. On this particular test, the cable made significant marks on the inside of the housing and even more prominent cable marks over the entire length of the three flutes of the wedge. In this particular case, the depth of the wedge was 13mm and the wedge and cable did not pull out of the housing.

On Test P5, the spring housing casting broke and released the cable and the wedge. However, the wedge was well seated to a depth of 14mm and the cable markings along the wedge were significant over the full length of the flutes in the wedge.

On Test P6, the wedge was embedded to a depth of 15mm, but the wedge and cable did not release from the spring assembly housing. The cable marks were prominent over the full length of the flutes of the wedge, as illustrated in the photographs.

On Test P7, the wedge was seated to a depth of 12mm in the compensating spring housing assembly. On this assembly, the compensating cable end assembly broke, but the wedge and cable did not pull out of the housing. The cable markings on the wedge showed markings primarily towards the bottom end of the flute.

On Test P8, the wedge in the compensating cable end assembly was only 7mm and, although the wedge and cable did not pull out of the housing in the test, the markings were very slight on the bottom nose of the wedge. On this assembly, the nuts stripped off the bolt attaching the end cable to the post.

RESULTS (cont)

On Test P9, the wedge in the compensating cable end assembly was positioned at only 6mm and when tested the wedge and cable slipped out of the spring housing cable end assembly. The markings inside of the nose on No. 9 housing were very slight and the markings on the wedge showed only significant markings towards the bottom end of the flutes on the wedge from this assembly.

On Test P10, the wedge was tapped into the housing without trying to line up the three strands with the flutes of the wedge. In this particular test, the cable pulled out 33mm on the compensating cable end assembly and the seated wedge depth was 40mm. On this test, neither the wedge or the cable pulled out from the spring housing assembly or from the cable anchor fitting, but the markings on the wedge showed significant cable markings over the length of the flutes on the wedge. The wedge also showed significant damage marks on the top edge of the flute due to the fact that the three strands were not completely seated in the flute of the wedge on this particular setup. However, even though the three strands were not completely seated in the flute, there was a significant interference between the wires, the wedge and the housing which created a great enough friction in this assembly to prevent a pull out.

On Test P11, two of the strands were fully seated with only partial engagement of the third strand and the seating depth of the wedge on the compensating cable end was only 4mm. On this particular assembly, the cable pulled out completely from the compensating end assembly and left very slight markings on the inside nose of the housing and light marks at the bottom end of the flutes of the wedge.

RESULTS (cont)

On Test P12, the depth of the wedge seat in the compensating cable end assembly was only 3mm. However, when the test was performed, the compensating cable end assembly fractured and the cable pulled out 24mm and the wedge depth was 28mm. As a result, the markings on the inside of the cable markings on the inside of the housing were significant and the cable markings on the wedge were much more significant along the flutes.

On Test P13, the seated depth of the wedge was only 4mm, but one strand was fully seated in the flute, one strand partially engaged and the third with very little engagement in the flute of the wedge. The cable pulled out partially on the compensating cable end assembly and the wedge was seated at a depth of 28mm, but the cable and wedge did not pull out of the housing. The cable markings on the inside of the housing were significant and there were significant cable markings along the flute and top edge of the flute on the P13 wedge.

On Test P14, the wedge was seated to a depth of 12mm in the compensating cable assembly and during the test the cable pulled out 10mm on the compensating end assembly and the wedge depth was 28mm after the test. However, the cable and wedge did not pull out of the assembly. On the cable end fitting, the threads were stripped out of the bolt and part of the nut was pulled through the cable end fitting. The markings on the inside of the housing and along the wedge were present only at the bottom of the flute on the wedge.

RESULTS (cont)

On Test P15, the seated depth of the wedge and cable end assembly was 7mm and during the test the cable pulled out 23mm on the compensating cable end assembly and the seated wedge depth was 33mm. The cable markings on the inside of the spring housing assembly were slight and the cable markings on the inside of the wedge were present over approximately 50% of the length of the flutes.

On Test P16, the seated depth of the wedge on the compensating cable end assembly was 7mm and on this particular test the cable and wedge completely pulled out at the compensating end of the assembly. The markings on the inside nose of the spring assembly and housing were light and the markings on the wedge showed cable markings only very light on the bottom end of the flutes of the wedge.

On Test P17, the seated depth of the wedge on the compensating cable end assembly was 9mm and when this test was run the cable and wedge did not pull out of the housing. However, the cable markings on the flutes of the wedge were more prominent over the length of the wedge.

On Test P18, the seated depth of the wedge on the compensating cable end assembly was 9mm and when this test was run the cable end fitting casting fractured and released the cable. The cable wedge did not pull out of the housing. The cable markings were present over the full length of the flutes of the wedge from this particular test which is indicative of the fact that the wedge was properly seated.

RESULTS (cont)

On Test P19, the seated depth of the wedge in the compensating end assembly was 7mm and during the test the cable pulled out 15mm on the compensating cable end assembly and the seated wedge depth was 28mm. The cable and wedge did not pull out of the compensating end housing, but the cable marks on the flutes of the wedge were more prominent over approximately 50% of the length of the flutes.

TEST NO.	CABLE END WEDGE SEAT DEPTH mm	CABLE END WEDGE DEPTH AFTER TEST mm	CABLE END CABLE PULL THRU mm	COMPENSATING CABLE END WEDGE SEAT DEPTH mm	COMPENSATING CABLE END WEDGE DEPTH AFTER TEST mm	COMPENSATING CABLE END CABLE PULL THRU mm
P1.	14		20	14	35.	
P2.	14		10	15		pull out
P3	10		7	14	20	15
P4 .	11	20	7	13	30	
P5	10	27	22	14		pull out
P6	11	26	13	15	29	20
P7	17	14		12	14	9
P8	12	21	10	7	28	24
P9	10	13		6	52	pull out
P10	9	25	17	5	40	33
P11	11	16	6	4		pull out
P12	9	30	20	3	28	24
P13	12	26	15	4	28	28
P14	10	35	18	12	28	10
P15	6	37	32	7	33	23
P16	9	9	1	7		pull out
P17	11	28	19	9	34	25
P18	11			9	33	20
P19	8			7	28	15

WASHINGTON STATE DOT
FAILURE MODES OF TEST CABLES P1 THROUGH P19
McKNIGHT LABORATORY JOB NO. MTE070311

P1. Casting at cable end broke and released cable and wedge.

P2. Wedge and cable pulled out of spring compensating end.
Wedge not found.

P3. Cable looped around post and cable fractured.

P4. Threads on cable end fitting stripped and released cable end.

P5. Cable and wedge pulled out of spring compensating end.

P6. Threads stripped on cable end fitting and released.

P7. Casting on spring compensating end broke.

P8. Nut and threads stripped on cable end fitting.

P9. Cable and wedge pulled out of spring compensating end.

P10. Wedge and cable at cable end fitting did not pull out completely and the wedge and cable at the spring compensating end did not pull out completely. Cable assembly and bogie came to a stop.

P11. Wedge and cable pulled out completely at spring compensating end.

P12. Spring compensating end casting fractured.
No complete pullout at cable end or spring compensating end.

P13. Threads stripped at cable end fitting and released cable end.

P14. Nut and thread failure at cable end fitting.
No pullout of wedge or cable at either end.

P15. Threads on cable end fitting stripped and released cable end.
No complete pullout of wedge and cable at either end.

P16. Cable and wedge pulled out completely at spring compensating end.

P17. No complete pullout of wedge and cable at either end fitting.
Installation brought pendulum to a stop.

P18. Cable end fitting fractured and released wedge and cable.

P19. Casting at cable end fractured and released cable and wedge assembly.

WASHINGTON STATE DOT
FAILURE MODES OF TEST CABLES P1 THROUGH P19
McKNIGHT LABORATORY JOB NO. MTE070311

P1. Casting at cable end broke and released cable and wedge.

P2. Wedge and cable pulled out of spring compensating end.
Wedge not found.

P3. Cable looped around post and cable fractured.

P4. Threads on cable end fitting stripped and released cable end.

P5. Cable and wedge pulled out of spring compensating end.

P6. Threads stripped on cable end fitting and released.

P7. Casting on spring compensating end broke.

P8. Nut and threads stripped on cable end fitting.

P9. Cable and wedge pulled out of spring compensating end.

P10. Wedge and cable at cable end fitting did not pull out completely and the wedge and cable at the spring compensating end did not pull out completely. Cable assembly and bogie came to a stop.

P11. Wedge and cable pulled out completely at spring compensating end.

P12. Spring compensating end casting fractured.
No complete pullout at cable end or spring compensating end.

P13. Threads stripped at cable end fitting and released cable end.

P14. Nut and thread failure at cable end fitting.
No pullout of wedge or cable at either end.

P15. Threads on cable end fitting stripped and released cable end.
No complete pullout of wedge and cable at either end.

P16. Cable and wedge pulled out completely at spring compensating end.

P17. No complete pullout of wedge and cable at either end fitting.
Installation brought pendulum to a stop.

P18. Cable end fitting fractured and released wedge and cable.

P19. Casting at cable end fractured and released cable and wedge assembly.