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EVALUATION OF CROSS MEDIAN CRASHES

Final Report

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16. Abstract

The objective of this research project has been to evaluate the post-impact performance of two different median barrier systems installed in New Jersey: (1) a three-strand cable median barrier system installed on I-78, and (2) a modified thrie beam median barrier system installed on I-80. The subject research program has evaluated the performance of the I-78 and I-80 median barrier designs in three ways – (1) through finite element modeling, (2) through field investigation of crashes into the subject barriers, and (3) through a survey of the median barrier experience of other state DOTs. Although the focus of this study has been on the I-78 and I-80 median barrier designs, the results of this study are expected to provide new insight into the performance of and potential improvements to the design of future median barrier in New Jersey.

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1. Summary

Cross-median accidents are one of the most dangerous types of highway crashes. When a vehicle crosses an interstate median, enters opposing lanes, and collides with oncoming traffic, closing speeds can easily exceed 100 mph. In response to several widely publicized cross median crashes, NJDOT has initiated a pilot program in which cross median barriers have been installed at the following locations:

- I-78 from approximately Milepost 23.3 to Milepost 24.48

- I-80 from approximately Milepost 27.25 to Milepost 28.16

The pilot project is evaluating the post-impact performance of two different median barrier systems: (1) the three-strand cable median barrier system installed on I-78 and (2) the modified thrie beam median barrier system installed on I-80.

The subject research program has evaluated the performance of the I-78 and I-80 median barrier designs in three ways – (1) through finite element modeling, (2) through field investigation in the event of a crash into the subject barriers, and (3) through a survey of the median barrier experience of other state DOTs. Although the focus of this study has been on the I-78 and I-80 median barrier designs, the results of this study are expected to provide new insight into the performance of and potential improvements to the design of future median barrier in New Jersey.

2. Introduction and Background

When a vehicle crosses an interstate median, and collides with oncoming traffic, the result is frequently fatal. On November 20, 2002, a tractor-trailer heading east on Route 78 suffered a blown-out front tire. The driver of the truck lost control, crossed the median and struck an oncoming car before crashing into a second tractor-trailer. The driver of the second tractor-trailer was killed in the crash, and two of the occupants of the car were critically injured. Police were forced to shut down Route 78, a major thoroughfare, for three hours to permit cleanup of the destroyed vehicles, spilled cargo, and other crash debris.

Figure 1. Median Barriers are designed to resist cross median crashes like this crash in Florida

Preventing Cross-Median Crashes

The purpose of a highway median is to separate lanes of opposing traffic, provide an area for emergency stopping, and provide a recovery area for out-of-control vehicles which run off the road. The primary method of preventing cross-median crashes is to provide a sufficiently wide median to allow drivers who leave the road to recover control of their vehicles and re-enter the highway in the correct direction. Although there is to date no accepted analytical relationship between median width and probability of recovery, it is well established that wider medians lead to fewer cross-median crashes. Median widths of 50- to 100-feet are not uncommon on rural interstates.

When there is insufficient space for wide medians, longitudinal median barriers can be installed in the median to prevent cross-median crashes. The AASHTO Roadside Design Guide [(1)] provides recommendations for when median barriers are warranted based upon median width and average traffic volumes. No matter how high the average traffic volumes, the guidelines state that median barriers are normally not considered when median widths exceed 50-feet.

State DOT experience with Median Barriers

It is interesting to note that the median width at the site of the Route 78 crash exceeds 50-feet. In compliance with the AASHTO guidelines, NJDOT had not installed a median barrier at this site. Because of cross median crashes like those experienced in New Jersey, many state DOTs use or are considering more stringent median barrier warrants than AASHTO. [(2)] Cross median crashes are the subject of active research programs in several states. The issue is also under study at the national level through NCHRP 17-14(2), "Improved Guidelines for Median Safety".

Several states have found median barriers to be a superb countermeasure against cross median crashes. The North Carolina DOT conducted a study on the effectiveness of a cable barrier system along a length of Interstate 40, and found that the average crash severity in median crashes decreased by 50% after installation of the system. [(3)] In another study of median crashes in North Carolina, Hunter et al [(4)] found that serious injury and fatal accidents decreased after the installation of three-strand cable median barrier. However, the study also showed that the frequency of less-severe median incursions in which the car struck an object increased. This was presumably because the presence of the median barrier reduced the clear zone.

Median Barriers in New Jersey

In response to several widely publicized cross median crashes, NJDOT has initiated a pilot program in which cross median barrier has been installed at the following locations:

- Route 78 from approximately Milepost 23.3 to Milepost 24.48

- Route 80 from approximately Milepost 27.25 to Milepost 28.16

The goal of the pilot project is to evaluate the post-construction performance of two different median barrier systems: (1) a 3-strand cable design and (2) a modified thrie beam barrier system.

3. Objective

The goal of this research program is to evaluate the effectiveness of cross median barriers, installed as a pilot project in New Jersey on Interstate 78 and Interstate 80. The specific objectives are to:

1. Perform a 3-D finite element analysis of the barriers under impact loading.
2. Develop an analysis plan for any accidents that may occur.
3. Perform an analysis of any vehicle crashes into the subject median barriers and report on their effectiveness.

4. Literature Survey of Current Practices and Field Experience

Scope

The intent of this section is to summarize the effectiveness of the various available median barrier designs. A specific objective is to determine the effectiveness of cable median barriers (e.g. the system installed at the I-78 site) and the modified thrie-beam median barrier (e.g. the system installed at the I-80 site).

Methodology

Median barrier effectiveness is first presented based on published results of full-scale crash tests. These tests are intended to test the barriers at practical worst-case impact scenarios. As they are staged events, detailed engineering data is collected allowing for a thorough investigation of the performance of the barrier. Although there is an attempt to quantify the potential for occupant injury in the test, the occupant injury resulting from the tested impact conditions are unknown. In addition, the few impact scenarios examined with full-scale testing cannot completely describe the performance of a barrier under field conditions.

Secondly, median barrier effectiveness is presented based on published results of barrier in-service evaluations. For these evaluations, the occupant injury and resulting costs are known. Also, the performance of the barrier can be evaluated based on actual field performance. These investigations, however, lack the detailed engineering data that is collected during full-scale crash tests.

An annotated bibliography of selected sources used in this literature review is provided in Appendix A.

Crash Testing Experience

Test Procedures and Philosophy

All roadside hardware, including median barriers, must meet a minimum set of criteria based on full-scale crash testing prior to actual field installation. The development of full-scale crash testing guidelines for these devices has been an evolutionary process with the first guidelines published in 1962. [(5)] A significant amount of the roadside hardware testing has been completed under National Cooperative Highway Research Program (NCHRP) Report 230 [(6)] guidelines, which were published in 1981. Currently, NCHRP Report 350 [(7)] provides the framework for the evaluation of these roadside safety devices. To facilitate this objective, the guidelines provide specifications for the test configuration (e.g. device installation), impact conditions (e.g. vehicle speed, approach angle, and impact point on the device), standardized test vehicles, data collection procedures, and evaluation procedures.

As countless installation configurations of these devices are possible, the guidelines recognize that crash testing of each configuration is not viable. Instead, the deliberate approach is to test at specific “normalized” conditions. For instance, all longitudinal barriers are to be installed straight on a flat slope although some roadways have these devices installed in a curved configuration, or on a slope, or both. Similarly, for practical testing purposes, the infinite vehicle impact conditions possible are narrowed to a few which represent the practical worst-case scenario for each device. The assumption is that if the device can perform satisfactorily under these severe conditions, then the performance will be appropriate for the spectrum of impacts, including all less rigorous impacts.

An analogous situation exists for the selection of test vehicles, as testing each device with each production vehicle model is impractical. To provide a reasonable number of standard test vehicles while incorporating the performance characteristics of the entire fleet, selection is such that each extreme of the vehicle fleet is represented. This “standardized” approach to testing of roadside features allows for a valid comparison between roadside safety hardware devices. Table 1 lists the current test vehicles designated by NCHRP Report 350.

Table 1. NCHRP 350 Test Vehicles [7]

Test Vehicle Designation	Description
700C	Mini Passenger Car
820C	Small Passenger Car
2000P	Large Pickup Truck
8000S	Single Unit Truck
36000V	Tractor Van-Trailer Truck
36000T	Tractor Tanker-Trailer Truck

Recognizing a need for varying performance requirements for the diverse roadway types, the guidelines specify up to six test levels (1 through 6), which differ primarily by impact conditions. Although these test levels are provided, the document does not specify warrants for the various test levels (i.e. devices meeting a particular test level are not specified appropriate for a given roadway or purpose). This decision is left to the discretion of the user agency (e.g. a State Department of Transportation). In general, however, the lower test levels are typically for lower traffic, lower speed applications while the higher test levels are for higher traffic, higher speed applications. [7] Table 2 summarizes the longitudinal barrier tests required for each specified test level. Figure 2 is a plan view schematic of a typical longitudinal barrier crash test.

Test level three (3) corresponds to the level typically used for most roadside hardware applications. To ensure barrier strength, test 3-11 requires that the barrier contain and redirect the 2000P test vehicle (typically a Chevrolet 2500 pickup truck) impacting at a speed of 100 km/hr and an angle of 25 degrees. To ensure proper performance with smaller vehicles and adequate occupant protection, test 3-10 requires that the barrier contain and redirect the 820C vehicle (typically a Geo Metro) impacting at a speed of 100 km/hr and an angle of 25 degrees. Test levels 4 through 6 require acceptable performance in tests 3-10 and 3-11 as well as one supplemental test with a heavy vehicle impacting at a speed of 80 km/hr and an angle of 15 degrees. For test level 4, 5 and 6, the heavy vehicles are an 8000S single unit truck, a 36000V tractor van-trailer truck, and a 36000T tractor tanker-trailer truck, respectively.

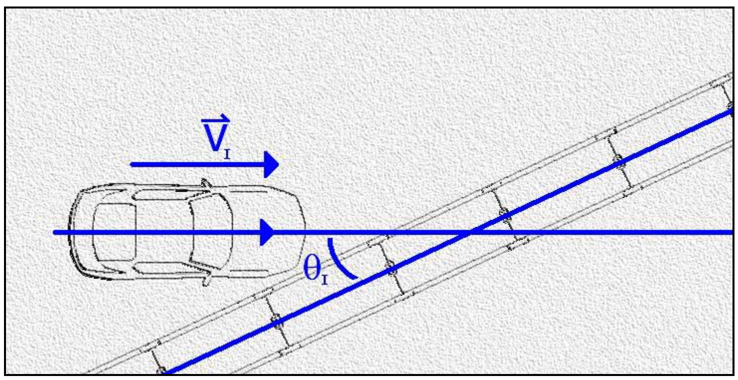

Figure 2. Plan View of Longitudinal Barrier Tests

Table 2. NCHRP 350 Longitudinal Barrier Test Conditions Summary [7]

Test Level	Test Designation	Impact Conditions		
		Vehicle	Nominal Speed (km/hr)	Impact Angle (degrees)
1	1-10	820C	50	20
	S1-10*	700C	50	20
	1-11	2000P	50	25
2	2-10	820C	70	20
	S2-10*	700C	70	20
	2-11	2000P	70	25
3 (Basic Level)	3-10	820C	100	20
	S3-10*	700C	100	20
	3-11	2000P	100	25
4	4-10	820C	100	20
	S4-10*	700C	100	20
	4-11	2000P	100	25
	4-12	8000S	80	15
5	5-10	820C	100	20
	S5-10*	700C	100	20
	5-11	2000P	100	25
	5-12	36000V	80	15
6	6-10	820C	100	20
	S6-10*	700C	100	20
	6-11	2000P	100	25
	6-12	36000T	80	15

* Optional Test

Based on detailed data collected during the full-scale crash test, the evaluation of a device is a three-tiered approach as specified by NCHRP Report 350 [7] and outlined below:

- Structural Adequacy
- Post-Impact Vehicle Trajectory
- Occupant Risk

Structural adequacy refers to how well the device performs its intended task. In the case of longitudinal barriers, the vehicle must be contained and redirected with no vehicle underride, override or penetration (controlled lateral deflection is permissible, however). Post-impact vehicle trajectory ensures that the device will not cause subsequent harm (i.e. a vehicle being redirected into opposing traffic). For longitudinal barrier tests, NCHRP 350 requires a vehicle exit angle of less than 60% of the impact angle and prefers that the vehicle does not intrude into adjacent traffic lanes. The occupant risk criteria attempts to quantify the potential for severe occupant injury. This criterion requires that detached elements do not penetrate the occupant compartment, occupant compartment intrusion is not sufficient to cause serious injury, and that the vehicle remains upright during and after the impact. In addition, the flail space model, an occupant injury criterion, is utilized to convert the vehicle kinematics into two distinct occupant risk metric values: the occupant impact velocity and the occupant ridedown acceleration. Each computed value is required to be below the corresponding maximum threshold value illustrated in Table 3. The crude assumption is that these metric values are proportional to the risk of injury; larger occupant risk values correspond to an increased potential for severe occupant injury.

Table 3. Current Occupant Risk Threshold Values [7]

Occupant Impact Velocity Limits

Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	9 m/s	12 m/s

Occupant Ridedown Acceleration Limits

Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	15 g	20 g

Crash Test Experience Results

Although many of the median barrier systems are long-standing devices that have been tested under previous crash testing guidelines, the crash testing experience will focus mainly on most recent NCHRP Report 350 compliant tests.

NCHRP Synthesis 244: Guardrail and Median Barrier Crashworthiness [8] contains a large amount of information regarding the crash test experience with roadside barrier systems. Information has been summarized from this report and appended with more recent crash testing results. The discussion of median barrier crash testing experience is divided into three categories based on stiffness: flexible systems, semi-rigid systems, and rigid systems.

<u>Flexible Systems</u>

Three-Strand Cable Barrier

The three-strand cable barrier consists of three steel cables (typically 19 mm in diameter) mounted on weak posts spaced 5 meters on center. [1] For roadside barrier applications, all three cables are mounted on the traffic side of the posts while the median barrier variation has the middle cable mounted opposite the side of the top and bottom cables. Most versions provide anchorage for the cables via a turnbuckle and breakaway anchor angle that is rigidly attached to a concrete footing. When a vehicle impacts this type of barrier, tension developed in the cables gradually redirects the vehicle while producing a significant amount of barrier deflection. [1] Figure 3 is a photo of the pilot section of three-strand cable median barrier installed on New Jersey Route 78 between mileposts 23 and 24 in Hunterdon County.

Figure 3. Three Strand Cable Barrier – New Jersey Route 78, Hunterdon County

The roadside barrier version of the three-strand cable barrier is NCHRP Report 350 test level 3 compliant. [8] Both 820C and 2000P vehicles were smoothly redirected in the 3-10 and 3-11 crash tests, respectively. All occupant risk values (3.4 m/s occupant impact velocity and 5.6 G ridedown acceleration) were within preferred limits and the dynamic deflection for the 820C test and the 2000P tests were 1.8 meters and 2.4 meters, respectively. Note that the roadside version of the three-strand cable barrier is sometimes utilized on both inside shoulders of a divided roadway in lieu of a single run of the median barrier version.

More recently, Washington State Department of Transportation in cooperation with Texas Transportation Institute (TTI) tested the three-cable median barrier under NCHRP 350 guidelines with favorable results. [9] In each test (3-10 and 3-11), the vehicle was contained and smoothly redirected with all occupant risk values well within the preferred limits set by NCHRP 350. For test 3-10, the occupant impact velocity and occupant ridedown acceleration values are 4.1 m/s and 3.9 G, respectively. Note that both tests produced larger deflections than the tests involving the roadside barrier version: a deflection of 2.6 meters was observed in the 820C test (small passenger vehicle) test and 3.4 meters in the 2000P test (full-size pickup truck), which is most likely a result of the different cable configurations.

Trinity CASS Cable Safety System

A proprietary version of the three-strand cable barrier, the Trinity CASS™ system utilizes channel section posts with slots for the cables to pass, resulting in a symmetric barrier that can be used for roadside or median applications. [10] The cables are spaced 110 mm apart vertically, approximately the same as the three-strand cable median barrier. Note that the vertical cable spacing for the three-strand cable roadside barrier is smaller (75 mm). [1] In addition, this barrier employs tensioned 19 mm diameter cables; depending on the ambient temperature, the recommended tension varies from 14 to 36 kN. [10] Figure 4 is an image of the Trinity CASS system.

Figure 4. Trinity CASS Cable Safety System (10)

All three versions of this barrier, differing only by post spacing, have been successfully tested to NCHRP 350 test level 3. (11,12,13) For the 2-meter, 3-meter and 5-meter versions, the dynamic deflection is 2.04 meters, 2.4 meters, and 2.8 meters, respectively. (11,12,13) Also, the occupant risk criteria values are comparable to that of the non-proprietary three-strand cable barrier.

Brifen Wire Rope Safety Fence

Developed by Brifen Limited in the UK in 1989, the proprietary Brifen Wire Rope Safety Fence consists of four interwoven, pre-stressed wire cables. (14) Similar to the three-strand cable barrier, the Brifen system relies on the elongation of the tensioned wire ropes to redirect an errant vehicle. The Brifen system is symmetric and can be used either as a median or roadside barrier. Due to a 3.2-meter (10.5 foot) post spacing and cable tension 4-5 times greater than the three-strand cable barrier, the Brifen system redirects vehicles with less deflection than three-strand cable barrier. (15) The European and US versions of the Brifen system are shown in Figure 5 and Figure 6, respectively; note that the US version has only a single cable passing through the posts while the fourth cable is interwoven between the posts.

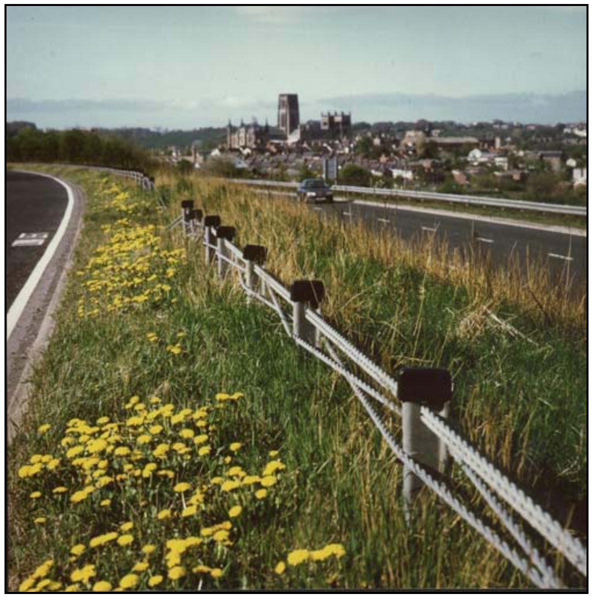

Figure 5. Brifen Wire Rope Safety Fence – UK Version [(16)]

Figure 6. Brifen Wire Rope Safety Fence – US Version [(14)]

The Brifen system has been successfully tested to NCHRP Report 350 test level 3. [(15)] Dynamic deflection for the 820C (test 3-10) and 2000P (test 3-11) vehicles was 1.04 meters and 2.4 meters, respectively. The dynamic deflection is equivalent to that of the three-strand cable roadside barrier and significantly less than the three-strand cable median barrier. Occupant risk criteria values (4.6 m/s occupant impact velocity and 4.0 G occupant ridedown acceleration for test 3-10) were well within NCHRP 350 limits and comparable to those experienced in the tests with the three-cable median or roadside barrier. An end terminal for this system, the Brifen Wire Rope Gating Terminal (WRGT), has recently been tested to NCHRP 350 test level 3. [(17)]

Safence 350 4RI Barrier

A proprietary system developed in Sweden, the Safence cable barrier consists of four evenly spaced cables (150 mm apart) mounted on weak posts to redirect errant vehicles.[18] Due to the vertical slot cut into each post, the cables are aligned vertically creating a symmetric barrier. Similar to the Brifen System, the Safence utilizes tensioned cables to reduce dynamic deflections caused by an impacting vehicle. Depending on the allowable lateral deflections, post spacing can vary between 1 and 3 meters, with the typical spacing at 2.5 meters. [18] Figure 7 is a photograph of an installed Safence 350 barrier.

Figure 7. Safence 350 4RI Barrier [18]

The Safence system with elliptically-shaped posts (2.5 meter spacing) has been successfully tested to NCHRP 350 test level 3. [19] Dynamic deflection for the 820C (test 3-10) and 2000P (test 3-11) vehicles was 1.1 meters and 1.8 meters, respectively. Although the dynamic deflections for the small passenger vehicles are equivalent, the dynamic deflection of the Safence barrier for the pickup is approximately 25 percent less than observed in the Brifen barrier crash test. Occupant risk criteria values (5.0 m/s occupant impact velocity and 8.1 G occupant ridedown acceleration for test 3-10) were within NCHRP 350 limits. A similar barrier with I-section posts instead of elliptical posts has also been successfully tested to NCHRP 350 test level 3. [20] Dynamic deflection for the 820C (test 3-10) and 2000P (test 3-11) vehicles was 0.8 meters and 2.7 meters, respectively. Occupant risk criteria values (5.5 m/s occupant impact velocity and 6.0 G occupant ridedown acceleration for test 3-10) were also within NCHRP 350 limits. No evidence has been found indicating an NCHRP 350 approved end terminal for this barrier system.

Weak Post W-Beam Barrier

As with the three-strand cable barrier, the weak post w-beam barrier was pioneered by the state of New York in the early 1960s. The redirection mechanism for the weak post w-beam barrier is also similar to that of the three-strand cable barrier: the posts serve to hold the w-beam at the proper height to engage the vehicle and the tension developed in the beam redirects the vehicle. [1] Although the posts are the same for both systems, the weak post w-beam barrier has a reduced post spacing of 3.8 meters (12 feet). The roadside barrier version of this barrier is shown in Figure 8.

Figure 8. Weak Post W-Beam Roadside Barrier – Southbound New York Thruway

NCHRP 350 test 3-10 was successful with vehicle containment and smooth redirection with a maximum dynamic deflection of 0.8 meters.[8] The occupant risk criteria values (4.5 m/s occupant impact velocity and 9.4 G occupant ridedown acceleration) were within the preferred limits, although slightly higher than those of the cable barrier. Test 3-11, however, was not satisfactory as the 2000P vehicle rode over the barrier. [8] Failure of this system to comply with test level 3 requirements prompted testing to ensure compliance with the less stringent test level 2 requirements. Both test 2-10 and 2-11 were successful with the respective vehicles contained and smoothly redirected. [8] Dynamic deflection for the 820C and 2000P test vehicles was 0.8 meters and 1.4 meters, respectively and all occupant risk values were within the preferred range (test 2-10 and 3-10 are identical).

Recently, modifications have been made to this system so that this barrier satisfies NCHRP 350 test level 3 specifications. [21] The modifications include raising the rail mounting height by 50 millimeters, redesigning post-rail connection, and relocating the rail splices to mid-span. [21] Dynamic deflections for the test 3-10 and 3-11 of the improved barrier were 1.03 meters and 1.65 meters, respectively. Compared to original design, the modified system has an equivalent occupant impact velocity value (4.5 m/s) and a lower occupant ridedown acceleration value (6.0 G).

Although the median version is expected to perform in a manner similar to the roadside version, we have found no full-scale crash tests involving the median barrier version. Another complication with this system is the lack of a crashworthy end terminal; the only approved termination is to bury the end in a backslope or attach to a rock cut (both options that require site specific conditions). [8]

Semi-Rigid Systems

Weak Post Box-Beam Barrier

Developed concurrently with the three-strand cable barrier and the weak post w-beam barriers, the weak post box-beam barrier consists of a rectangular steel tube mounted on weak posts via angle brackets. [1] Unlike most barrier systems that utilize the mirror reflection of the roadside barrier to generate the median barrier, the median version of the box-beam barrier is a significant departure from the roadside barrier version. Instead of dual rectangular beams mounted on either side of the weak posts, the weak post box-beam barrier has a single rail element held in place by protruding paddles that are bolted to the webs of the posts. Vehicle redirection in both systems, however, is accomplished through the tensile and flexure strength of the box-beam rail. [8]

The roadside version of the weak post box-beam barrier has satisfied NCHRP Report 350 test level 3. [22] Test 3-11, performed by TTI in 1995, demonstrated the ability of this barrier to contain and smoothly redirect the 2000P test vehicle with a maximum dynamic deflection of 2.08 meters. Although the median barrier is expected to perform in a similar manner, we have found no published test results utilizing the 2000P test vehicle. Note that the NCHRP 230 small car test (820C) is identical to test 3-10 and both the roadside and median barrier versions of the weak post box-beam have passed these tests previously. [8] The dynamic deflection for the 820C vehicle is 0.40 meters and 0.31 meters for the roadside barrier and median barrier, respectively. In both tests, the occupant risk values are almost identical. The occupant impact velocity is 5.9 m/s and 5.4 m/s for the roadside barrier and median barrier, respectively, while the occupant ridedown acceleration is 8.7 G and 9 G for the roadside barrier and median barrier, respectively. One proprietary terminal (BEAT) and one non-proprietary terminal (WYBET) have been tested to NCHRP 350 specifications for both the median and roadside barrier versions of this system. [23,24,25]

Strong Post W-Beam Barrier

The strong post w-beam barrier is the most common barrier system in use today. There are two main variations of this barrier system: wood post and steel post. Either type of post is used to support a w-beam rail element that is spaced from the posts using block-outs. Manufactured from timber, steel, or recycled plastic, the block-outs reduce the tendency of the vehicle wheels to snag on the posts and ensures proper rail height during an impact. [1] In contrast to the weak post systems, the redirection mechanism for this barrier involves the bending and shearing resistance of the posts as well as the tensile and flexural strength of the w-beam.

Despite its extensive usage, the steel post/steel block-out version failed to satisfy the NCHRP 350 test level 3 criteria. During test 3-11, the 2000P vehicle severely snagged on the posts and ultimately rolled over. [26] This system currently only satisfies test level 2. [8] More recently, however, a modified steel post system that utilizes routed wood block-outs instead of steel block-outs, has been successfully tested to NCHRP 350 test level 3.[27] Note that the maximum dynamic deflection for test 3-11 was 0.82 meters, significantly less than any flexible system or the box-beam barrier. Although the steel post and wood post versions have traditionally been considered equivalent, the wood post version was evaluated as a marginal pass for NCHRP 350 test level 3. There was wheel snagging present, however, it was not sufficient to cause vehicle rollover.[26] Dynamic deflection was 0.27 meters and 0.82 meters for tests 3-10 and 3-11, respectively. For test 3-10, the occupant impact velocity was 7 m/s while the occupant ridedown acceleration was 13 G. Although there has been testing on both the wood and steel strong post w-beam roadside barrier, we have found no published NCHRP Report 350 test results of either median barrier version.

Strong Post Thrie Beam and Modified Thrie Beam Barrier

The thrie beam concept was explored in the late 1970's in response to the emergence of smaller passenger cars and special purpose vehicles such as vans and pickup trucks.[8] The intent was to expand the performance of the popular strong-post w-beam barrier. Initial testing was done by Olsen et al at TTI using two lapped w-beam rails, resulting in a total of three corrugations. [28] Poor performance of this barrier system for heavy vehicles led to the development of the modified thrie beam barrier system. [29] Improvements to the original strong post thrie beam system included increasing the rail mounting height by 60 mm and the use of a deeper steel block-out. The block-out also contains a notch at the bottom to ensure that the rail remains essentially vertical and at the same height during a vehicle impact with the system. [8]

Figure 9. Modified Thrie Beam Median Barrier – New Jersey Route 80, Morris County

The steel strong post thrie beam barrier failed to meet NCHRP 350 test level 3.[8] Test 3-10 was successful with a dynamic deflection of 0.39 meters and occupant risk values within preferred limits (occupant impact velocity of 5.7 m/s and an occupant ridedown acceleration of 11.4 G). Test 3-11, however, resulted in severe wheel snagging and caused the 2000P test vehicle to rollover. Although the median barrier version has been satisfactorily tested to the NCHRP 230 requirements, we have found no published tests of the strong post thrie beam median barrier, which meet NCHRP Report 350 standards.

Performance of the modified strong post thrie beam barrier has been more successful and has fulfilled NCHRP test level 3.[8] Although test 3-11 resulted in the front right wheel being torn from the 2000P test vehicle, the modified thrie beam roadside barrier successfully contained and redirected the vehicle with a maximum dynamic deflection of 1.02 meters. More recently, the modified thrie beam roadside barrier has been tested to NCHRP 350 test level 4 using the 8000S single unit truck test vehicle.[30] Dynamic deflection in this rigorous test was a mere 0.71 meters. For the modified thrie beam median barrier, testing has also been satisfied to NCHRP Report 350 test level 4. [8] Deflection due to the 8000S vehicle was 0.70 meters, equivalent to the deflection in test 4-12 with the modified thrie beam roadside barrier.

Rigid Systems

NJ Shape Concrete Barrier

Consisting of a small vertical face near the bottom and two differing slopes for the remainder of the height of the barrier, the 810 mm tall NJ shape concrete barrier is the most widely used concrete barrier in the United States.[8] The intersection point of the lower 55-degree and upper 84-degree slope, or breakpoint, occurs 13 inches from the base of the NJ shape barrier.[1] Because of the high compressive strength of the concrete, barrier penetration is not an issue in a majority of the collisions; thus, the intent of the barrier is to redirect the vehicle while generating the smallest amount of vehicle damage.[8] As these barrier types are generally maintenance free and designed for no deflection in the event of a collision, they are ideal for narrow median applications. Reinforcement is typically utilized near the top of the barrier to prevent concrete fragments from being ejected from the barrier in a severe collision.[8] A 1070-mm tall version of the NJ shape barrier, known as the Ontario tall-wall, is also available. Although the profile of the barrier is the same as the NJ shape barrier, the Ontario tall-wall is typically set 75 mm below the pavement surface resulting in a lower breakpoint.[1]

Although the NJ shape barrier is used for roadside applications, a majority of the testing has traditionally been done on the median barrier version. The AASHTO Roadside Design Guide [1] indicates that the 810 mm NJ shape median barrier is compliant to NCHRP 350 test level 4; however, the literature review produced only tests for compliance with test level 3. For test 3-11, the NJ shape satisfactorily redirected the 2000P test vehicle. [31] Note, however, that the 2000P test vehicle climbed to the top of the barrier and had a maximum roll of 34° away from the barrier.

The 1070 mm Ontario tall-wall median barrier is compliant to NCHRP test level 5. [1] Test 5-10 was successful with containment and smooth, upright redirection of the 820C test vehicle. [8] As this is a rigid system, occupant risk values are higher than those obtained from the flexible and semi-rigid systems; the occupant impact velocity was 6.0 m/s and the occupant ridedown acceleration was 13.9 G. Similar to the 810 mm version, the 2000P vehicle was successfully redirected by the 1070 mm NJ shape median barrier.[32] To complete the test level 5 requirements, the barrier adequately redirected the 36000V van tractor-trailer truck impacting at 80 km/hr and an angle of 15 degrees. [33]

F-Shape Concrete Barrier

Developed by the Southwest Research Institute in the late 1970's, the F-shape barrier has a similar profile to the NJ shape with the exception of the location of the breakpoint. For the F-shape, the breakpoint is 255 mm (10 inches) from the bottom of the barrier instead of 330 mm (13 inches) for the NJ shape. The intent of this lower breakpoint is to improve vehicle stability and trajectory during redirection. NJ shapes, due to the higher breakpoints, tend to cause a vehicle, especially smaller cars, to climb the barrier during redirection.

Although we have found no published NCHRP Report 350 tests, the F-shape barrier system is believed to perform to test level 4 for 810 mm heights and test level 5 for 1070 mm heights. [1] Tests have been successfully performed, though, on the F-shape bridge railing to ensure compliance with the AASHTO Guide Specifications for Bridge Railings. [34] Since these tests are similar to the NCHRP 350 test level 4 tests and the F-shape barrier is not radically different from the already tested NJ shape barrier, the F-shape is considered acceptable by NCHRP 350 standards.[8] The bridge rail tests performed with the F-shape resulted in better vehicle stability during redirection in comparison to the NJ shape but other research [35] suggests that the F-shape offers only a slight performance advantage over the NJ shape.

Single Slope Concrete Barrier

The most recent development in the evolution of the concrete barrier, the single slope barrier, consists of a single sloping face of either 9.1 or 10.8 degrees. [1] Similar to the NJ shape barrier, this barrier is available in two heights: 810 mm and 1070 mm. Note, however, that California utilizes even taller sections, 915 mm and 1420 mm, to allow for future pavement overlays. In terms of vehicle stability, a vertical concrete wall offers the greatest vehicle stability but the occupant risk values are only marginally acceptable. Adding a continuous slope to the barrier face is an attempt to reduce the potential for occupant injury while retaining the vehicle stability characteristics of the vertical barrier face. [8]

California's version of the single-slope concrete barrier (constant slope of 9.1 degrees), the Type 60 barrier, has been tested to NCHRP 350 test level 3. [36] Based on the results of the tests, both the 1420 mm version and 810 mm version of the Type 60 barrier is test level 3 acceptable. Note that the 810 mm version tested was intended to represent a 915 mm Type 60 barrier with pavement overlays reducing the effective barrier face height to 810 mm. Similar to the F-shape concrete barrier, the bridge rail version of this barrier has been tested to NCHRP 350 test level 4 and it is reasonable to assume that the median and roadside versions would perform accordingly. [8] Unfortunately, the anticipated improvement in vehicle stability has not been observed in any of the crash tests with the single slope barrier. [8]

In-Service Performance

Perhaps more important than the full-scale crash testing of a particular barrier is how the barrier performs after field installation. As there are an infinite number of impact scenarios possible with any roadside hardware device, full-scale crash testing cannot practically be utilized to ensure a devices' compliance with all impact conditions. The intent of the in-service evaluations is to ensure that a particular device performs properly in actual field installations and in impact scenarios other than those simulated by full-scale crash testing. Although detailed in-service evaluations are rarely performed, researchers (37,38) have long stressed the importance of these evaluations.

Although research does suggest that median barriers are effective on the whole (39), it is advantageous to discriminate between the relative effectiveness of the different types of median barrier. The following summarizes state experience regarding performance and effectiveness of median barriers.

In addition to the prose information presented herein, charts have been generated to provide a quick reference and summary of the in-service studies done for a particular barrier. Refer to Appendix B for the Barrier Performance Summary Charts.

<u>Flexible Systems</u>

Three-Strand Cable Barrier

A number of States have evaluated the effectiveness of the three-strand cable median barrier including New York State, Iowa, North Carolina, Washington State, Connecticut, and Oregon. The performance of both the roadside and median versions of the three-strand cable barrier have been included in this synthesis since there is a general lack of field studies with significant amounts of data and the roadside and median barrier versions of the three-strand cable barrier are very similar.

New York State was one of the earliest states to evaluate the performance of the three-strand cable barrier. Using police reported accidents between 1967 and 1969, Van Zweden and Bryden presented results of an investigation involving approximately 4,000 weak post guardrail and median barrier accidents. (40, 8) Out of 375 three-strand cable barrier (roadside version) collisions, barrier penetration occurred in 80 instances (20%). The high penetration rate noted in this study prompted the state to reduce the height of the barrier from 760 mm to 685 mm. Despite the high penetration rate, however, there were only 4 fatalities involving a three-strand cable barrier impact (2 involved penetration of barrier). In addition, the average repair cost of the three-strand barrier was found to be half that of the strong post w-beam barrier.

In 1977, Carlson et al. investigated the performance of three strand cable roadside barrier in their investigation of weak post barrier systems in the state of New York. [41] A total of 4 years of accident data was collected on 228 miles of state highway in the eastern portion of the state. In addition, 6 months of accident data was collected for 195 miles of the NY Thruway in 1973. Information for each accident was gathered using accident forms completed by DOT maintenance personnel. Regarding the three-strand cable roadside barrier, 23 collisions were analyzed; 21 on state roads and 2 on the NY Thruway. There were no fatalities reported and 91% of impacts resulted in no injury while the remaining 9% resulted only in minor injury. Although the observed three-strand cable barrier penetration rate was approximately 33%, little significance is attributed to this since only 12 length-of-need accidents were examined. Of the 11 incidents involving the end terminal, none resulted in any occupant injury. Examining the barrier repair costs, post damage on three-strand cable barrier is found to be statistically greater than w-beam or box-beam barriers. Despite this, however, the authors found that the overall repair cost differences between barrier types was minor.

In 1979, Iowa performed a historical collision study to evaluate three-strand cable barrier (roadside barrier version only) performance within the state. [42,8,38] For two years of accident data, the researchers matched police accident reports with barrier maintenance reports. From the 60 cable barrier maintenance reports available, 31 were matched to police reported collisions. Cable guardrail collisions were found to be less severe and involve less property damage than other guardrail impacts. Consistent with the Van Zweden and Bryden study, the penetration rate for the three-strand cable barrier was approximately twenty percent (7 of 31). The study also suggests that approximately half the collisions with guardrails are unreported. Although a nuisance from a maintenance standpoint, the unreported collision rate suggests that the cable barrier works as intended in 50% of the collisions (i.e. prevents serious injury and does not disable the vehicle).

Tyrell and Bryden investigated the effectiveness of the three-strand cable barrier installed in the median of divided roadways in the state of New York. [43, 38] Utilizing police accident reports for a 3-year period, a total of 15 sites were monitored for cable barrier collisions. Note that all sites were roadways that allowed only passenger vehicles and that there was no attempt to quantify the extent of unreported collisions. Of a total of 99 investigated collisions, occupant injury was reported in only 24 cases. The cable barrier failed to contain the vehicle in 4 instances; two of which were attributed to improper height of the barrier. Although there was no attempt to determine installation or usage problems through maintenance personnel, the authors concluded that the cable barrier was satisfactory based on the collected performance data and known installation costs.

A few years later in 1992, Bryden and Hiss published results of the performance of weak post barriers in New York State. (44, 38) Investigating 427 cable guardrail collisions and 16 median barrier collisions, the researchers determined the optimal barrier height range to be between 580 and 700 mm. For this height range, vehicle trajectory problems and the incidence of secondary collisions were lowest. The small number of collisions, however, prevented any conclusions regarding the performance of the three-strand cable median barrier.

North Carolina has an extensive documentation of its use of the three-strand cable barrier in median applications. A study completed in 1993 utilized 3.5 years of state accident data (751 cross median accidents) to characterize cross median accidents and prioritize locations that have a high propensity of these events. (45) The study found that cross median collisions are over-represented in terms of fatalities (they account for 3% of all interstate accidents in the study but represent 32% of interstate fatalities). Also, the study indicated a steady increase in the number of cross-median fatalities and injuries during the study period and that the largest number of cross median accidents occurred on interstates with median widths between 20 and 40 feet.

To combat cross median collisions in North Carolina, 13.7 km of three-strand cable barrier has been installed on Interstate 40. Mustafa describes the installation costs and preliminary maintenance and accident experience with the system. (46) Of the 125 reported cable barrier strikes between January 1994 and September 1995, none involved a fatality and 88 involved no injury at all. Hunter et al. presents an updated version of the performance of the same section of cable barrier based on accident data 4 years prior to and 3 years after the installation of the cable barrier (a total of 1478 barrier impacts). (47) Several regression-type models are developed to predict the number of accidents at the locations with cable barrier and then compared to the actual number of collisions observed at the sites. Examining the available data, a statistically significant increase is found in the total number of crashes on the sections with cable barrier (after installation of the barrier). Despite this increase, the installation of the cable barrier produced a significant reduction in the combination of serious and fatal collisions and has eliminated cross median collisions.

In Oregon, Sposito and Johnston evaluated the effect of 14.5 km of three-strand cable barrier installed on Interstate-5 (I-5). (48) Comparing accident frequency/severity data from 1987 through 1996 (pre-barrier installation) to the accident frequency/severity data from 15 months post-barrier installation, the three-cable median barrier was found to reduce both the number of fatalities (6 pre-barrier fatalities and no post-barrier fatalities) and susceptibility to cross-median collisions (10 cross median accidents pre-barrier and 3 post-barrier). The rate of injury-producing minor accidents since the barrier installation, however, increased from 0.7 to 3.8 injury accidents per year. Of a total of 53 accidents post-barrier installation, only three had some form of barrier penetration. In two cases, the vehicle underrode the barrier but did not cross into the opposing traffic lanes while the third case was a tractor-trailer that completely penetrated the barrier and crossed the opposing traffic lanes. Based on a subjective analysis of the investigated accidents, the researchers estimated that the three-strand cable median barrier prevented 21 potential cross median collisions. In addition, a cost-analysis incorporating the maintenance costs indicates that the annual cost of the three-cable median barrier is less than that of concrete median barrier. More recently, Oregon Department of Transportation released information regarding the effectiveness of an additional 20.7 km of three-strand cable barrier installed along I-5. [(49)] Although the new section of barrier has experienced 59 impacts in just less than two years, there have been no cross median collisions.

Through NCHRP Project 22-13 [(38)], Ray and Weir [(50)] investigated the in-service performance of guardrail systems in Connecticut, North Carolina, and Iowa. Although the focus of the study was to document the extent of unreported collisions, the researchers also collected information on police-reported accidents. Data in Iowa and North Carolina was collected over a two-year period (1997-1999) while data in Connecticut was collected over a year period (1997-1998). Of 87 police-reported collisions with the cable barrier, only 3 percent of the collisions resulted in severe or fatal occupant injury. Also, the researchers report no statistically significant performance difference between the three-strand cable barriers in the three different states. There is no indication of the penetration rate of the cable barrier.

Carlsson investigated the safety performance of the three-strand cable barrier 13 meter, 2+1 roadways in Sweden. [(51)] Although there are several variations of the 13-meter road in Sweden, the 2 + 1 design contains two 3.75-meter lanes, 1.0-meter paved outside shoulders, and a 3.50-meter center lane that changes direction every 1 to 2.5 kilometers. Previous research has found that the 13 m 2 + 1 roadway has a better safety performance than two-lane 9 meter roadways, however, there are a significant number of fatalities resulting from cross median collisions. In terms of safety benefits, the authors find that the implementation of cable median and roadside barrier reduces fatal and severe injuries by approximately 50% (no fatal accidents and 6 severe injury accidents after the implementation of the cable barrier). Also, as expected, the presence of cable median barriers on these roadways increased the total number of collisions.

Washington State has performed the most recent evaluation of the three-strand cable median barrier. Glad et al. used accident data to evaluate the current median barrier warrants utilized within the state. [(52)] Using cross median crashes from January 1996 through December 2000 on the divided state highway sections, a benefit/cost analysis is performed for three barrier types: three-strand cable barrier, w-beam guardrail, and concrete barrier. The study finds a barrier is cost effective in a median width up to 50 feet and that the cable barrier is the most cost-effective system. Another study by McClanahan et al. analyzes 43 km of cable median barrier installed along Interstate-5 from the perspective of installation costs, maintenance, and accident experience before and after installation. [53] The average bid price for the three-cable system is reported as 27,340 dollars per kilometer. Minimum and maximum repair costs per hit of the barrier range between 72 and 2800 dollars with an average of 733 dollars. Comparing the before and after installation accident experience, there was an increase in the total and fixed object accident rate (per hundred million vehicle miles traveled) from 6.50 and 3.40 to 13.35 and 12.17, respectively. The rollover and cross median accident rates, however, have been decreased from 1.51 and 2.12 to 1.25 and 0.51, respectively. In addition, there was a significant reduction in the total annual fatal accidents and there have been no cross median fatalities since the installation of the cable barrier. Although the study indicates a total of 10 barrier penetrations, the cable barrier contained heavy vehicles (type not specified) in 5 instances. Based on the examined data, the study concludes that the cable median barrier is a cost effective solution for the suppression of cross median collisions.

Trinity CASS Cable Safety System

As the CASS system is relatively new, the in-service experience is limited. The Utah Department of Transportation installed 13 km of this barrier along Interstate 15 in 2002 and intends to monitor its performance and maintainability. [54] Preliminary results from this study indicate that the CASS system is effective at preventing cross median collisions; the system prevented vehicle crossover in 12 instances with no barrier penetration. Also, there is evidence that this barrier can withstand multiple impacts as the system was impacted successively 4 times (in the same location, prior to repair) and prevented crossover in each case. Colorado Department of Transportation also plans to install and monitor approximately 5 km of the Trinity CASS barrier on Interstate 25. [55]

Brifen Wire Rope Safety Fence

Until recently, the in-service experience with the Brifen system has been limited to countries other than the United States. Although the manufacturers of the system boast at least two in-service studies that indicate the effectiveness of the system at preventing cross median collisions [56], we could not locate any published studies regarding the performance of this system overseas. There is also anecdotal evidence that this barrier can redirect tractor-trailer type vehicles. [57] Again, this information has been provided by the manufacturer and has not been substantiated by any peer-reviewed publication.

Although the Brifen system has been installed in over 30 countries, usage in the United States is rather limited. In July of 2001, Oklahoma Department of Transportation installed the Brifen system on an 11.3 km section of Lake Hefner Parkway in Oklahoma City. [58] Prior to this installation, a 305-meter test section was installed along the same roadway and was credited with preventing at least two cross median collisions. The Colorado Department of Transportation is also monitoring the in-service performance of this barrier that was recently installed on several Colorado highways. [55] Preliminary results indicate good impact performance with the ability to withstand multiple impacts. The report does indicate a Honda Accord underriding the barrier; however, the penetration was attributed to a cable height well in excess of the recommended installation height at the impact location. With respect to the Brifen System, the Utah Department of Transportation also indicates good impact performance with multiple impact capabilities. [54]

Safence 350 4RI Barrier

No in-service evaluations were found regarding the Safence 350 barrier.

Weak Post W-Beam Barrier

The in-service performance of the weak post w-beam barrier has been documented in the states of New York and Connecticut. Note that all in-service evaluations of this barrier have been performed prior to the improvements suggested by Ray et al. [21] to ensure compliance with NCHRP Report 350 test level 3.

In conjunction with the results of other weak and strong post barriers, Van Zweden and Bryden investigated the effectiveness of the weak post w-beam roadside barrier in New York. [40, 8] Compared to the three-strand cable barrier, the weak post w-beam barrier experienced a higher penetration rate; out of 212 collisions, barrier penetration was noted in 65 instances, or approximately 30 percent. The study also found the risk of occupant injury to be approximately 11 percent for collisions where the vehicle is contained by the weak post w-beam barrier. For comparison purposes, the injury rate for vehicles contained by the three-strand cable barrier was found to be approximately 3 percent. Given that a penetration occurs, however, the risk of injury is 15 percent, roughly equivalent to that of the three-strand cable barrier.

In 1977, Carlson et al. investigated the performance of weak post w-beam roadside and median barriers in their investigation of weak post barrier systems in the state of New York. [41] A total of 4 years of accident data was collected on 228 miles of state highway in the eastern portion of the state. In addition, 6 months of accident data was collected for 195 miles of the NY Thruway in 1973. Information for each accident was gathered using accident forms completed by DOT maintenance personnel. For the roadside barrier, 52 collisions were analyzed; 11 on state roads and 41 on the NY Thruway. There were no fatalities associated with weak post w-beam roadside barrier impacts. Approximately 4% of collisions resulted in severe occupant injury, 9% resulted in minor injury, and the remaining 81% of impacts resulted in no injury. Also, a penetration rate of 8% was observed in this study, much lower than that found in the earlier VanZweden and Bryden study. Based on two accidents, no problems with end terminal performance were identified. For the median barrier version, 89 collisions were analyzed; 3 on state roads and 86 on the NY Thruway. The injury severity profile associated with the median barrier version was similar to that observed for the roadside barrier: 2% of collisions resulted in severe injury, 16% resulted in minor injury, and the remaining 82% did not cause any occupant injury. Also, 6% of the median barrier collisions resulted in penetration, similar to the frequency observed in the w-beam roadside barrier. None of the median barrier accidents involved an end terminal.

Bryden and Hiss also observed the performance of the weak post w-beam barrier in their study of light post barriers in New York State. (44, 38) To relate barrier mounting height and performance, the researchers examined 306 roadside barrier collisions and 46 median barrier collisions. An increase in injury rates was observed for roadside barrier heights below 762 mm and the propensity for a secondary collision increased with when the barrier height was below 685 mm. The study also observed high redirection rates for roadside barriers with a height in excess of 584 mm. The small number of collisions, however, prevented any conclusions regarding the performance of the weak post w-beam median barrier.

As part of their investigation of the in-service performance of guardrail systems, Ray and Weir reported on the performance of the weak post w-beam barrier system in Connecticut. (50) Using data collected between 1997 and 1998, the study documented the extent of unreported collisions as well as barrier performance based on police-reported accidents. Of 102 police-reported collisions with the weak post w-beam barrier, only 1 percent of the collisions resulted in severe or fatal occupant injury. There is no mention of the observed penetration rate for this barrier type. The study also indicated no statistically significant difference between the performance of the three-strand cable barrier and the weak-post w-beam barrier.

<u>Semi-Rigid Systems</u>

Weak Post Box-Beam Barrier

In 1970, Galati examined the performance of the weak post box-beam median barrier in Pennsylvania. (59) Due to a previous cross median accident problem, approximately 15 km of box beam median barrier was installed on I-83 near Harrisburg. Examining accident data one year prior to the installation of the barrier and one year after the installation of the barrier, Galati notes that the number of cross median accidents have been reduced from 10 accidents (1 fatal) to a single accident in the after period (no fatalities). Note that the cross median collision after the barrier installation involved a tractor-trailer during snowy weather. In addition, there was an observed 120 percent increase in the number of median accidents in the period after barrier installation. Although there was an increase in the number of persons injured and number of property damage accidents, Galati notes the barrier has caused a reduction in the number of accidents involving injury.

Van Zweden and Bryden investigated the effectiveness of the weak post box-beam roadside and median barrier in New York. [40, 8] Of a total of 87 roadside barrier collisions, penetration was noted in 14 cases (16%). Given the occurrence of roadside barrier penetration, the risk of occupant injury is approximately 28%. The penetration rate for the box beam median barrier is lower than the roadside barrier: 2 penetrations in 43 collisions or approximately 5%. For the collisions where the vehicle is contained by the barrier, however, the median barrier version had a higher observed injury rate (22% compared to 10% for the roadside barrier).

Carlson et al. also investigated the performance of weak post box-beam roadside and median barriers in their investigation of weak post barrier systems in the state of New York. [41] For the roadside barrier, 37 collisions were analyzed; all occurred on state roads. There were no fatalities associated with weak post w-beam roadside barrier impacts. No fatalities or severe injuries were reported and only 10% of collisions resulted in only minor occupant injury. Of the 31 length-of-need impacts, none involved barrier penetration. Regarding the six accidents with roadside box-beam end terminals, only one collision resulted in minor injury and the terminals performed satisfactorily in each case. There were significantly more collisions investigated for the median barrier version: 191 impacts, 189 on state roads and 2 on the NY Thruway. As with the roadside barrier, no fatalities were reported. Approximately 2% of collisions resulted in severe injury, 5% resulted in minor injury, and the remaining 93% did not cause any occupant injury. Also, the median barrier version demonstrated good vehicle containment; only 1% of the median barrier collisions resulted in penetration. All ten box-beam median barrier terminal hits were not police reported and the maintenance reports suggested proper terminal performance.

Bryden and Hiss also observed the performance of the weak post box beam barrier in their study relating performance to the mounting height of light post barriers in New York State. [44, 38] A total of 623 roadside barrier collisions and 308 median barrier collisions were investigated. Unlike the cable and weak-post w-beam, the performance of the box beam barrier did not vary significantly for different mounting heights. Also, the containment rates for the barrier also exceeded 90% for all mounting heights.

Strong Post W-Beam Barrier

In conjunction with their study of longitudinal barriers in New York, Van Zweden and Bryden examined the effectiveness of the strong post w-beam roadside and median barriers. [40, 8] Of a total of 1045 w-beam roadside barrier collisions, penetration was noted in 293 cases (28%). Given the occurrence of roadside barrier penetration, the risk of occupant injury is approximately 33%, higher than all of the weak post systems observed in the study. Although there are significantly less cases involving strong post w-beam median barrier, the performance was similar to that of the roadside barrier. Median barrier penetration was noted in 35 of 145 cases (24%) and the risk of injury given a penetration was approximately 34%. For the collisions where the vehicle is contained by the barrier, both roadside and median versions had a roughly equivalent injury rate (14% for the roadside barrier compared to 18% for the median barrier).

Evaluating the field performance and maintenance costs associated with several impact attenuating devices, Outcalt assessed the usage of thicker 10-gauge w-beam rail at locations of high accident frequency. (60) Based on interviews with maintenance personnel, the thicker rail is found to be comparable in terms of ease of use but requires less maintenance than the standard 12-guage rails. There is no indication of any safety performance evaluation of the 10-guage rails other than performance with relation to minor impacts.

Ray and Weir reported on the performance of the strong wood post w-beam barrier in Iowa and the strong steel post w-beam barrier in North Carolina. (50) From July 1997 through June 1999, the study documented the extent of unreported collisions as well as barrier performance based on police-reported accidents. The risk of severe occupant injury given a collision with either system was approximately 4% (9 of 211 collisions resulted in severe or fatal occupant injury). Compared to the three-strand cable barrier, occupant injury is found to be more likely in collisions involving strong post w-beam barriers. There is no indication of the penetration rate for either the wood or steel post strong post w-beam barrier. The study also indicated no statistically significant performance difference between the wood or steel strong post w-beam barriers.

A French study by Huet et al. compares occupant injury risk for impacts with strong post w-beam median barriers and concrete median barriers. (61) The penetration rate for the strong post w-beam barrier was approximately 2% with 29 penetrations in 1452 median barrier collisions. To determine the effect of replacing metal median barrier with concrete, the researchers used a before-and-after approach that utilized 24 pairings of similar roadway sections. Based on a statistical analysis, the relative risk of occupant injury is found to be 1.9 times higher for impacts with concrete median barriers than for impacts with strong post w-beam median barriers. Another more recent study by Martin and Quincy highlights the relatively infrequent but severe cross median collisions on French roadways. (62) For strong post w-beam median barriers, the percentage of passenger car and large truck cross median accidents is 0.47% and 7%, respectively. In addition, the authors found that although occupant injury is usually less severe with metal barriers, there is no statistically significant difference in the fatality rate between metal and concrete median barriers.

Strong Post Thrie Beam and Modified Thrie Beam Barrier

As the strong post thrie beam and modified thrie beam barriers are relatively new systems, there have not been a significant number of in-service evaluations. Blost reported on modified thrie beam guardrail installed at two sites in Michigan. The intent was to evaluate the performance and installation problems of this system at locations that historically experienced frequent guardrail damage. [63, 38] As there were no impacts documented up to the time of publication, no performance evaluation of this system could be completed. The researchers do note that the installation cost of the modified thrie beam barrier was approximately double the cost of a typical w-beam system.

Woodham documented the field performance of modified thrie-beam barriers installed at three locations in Colorado: 500 feet on I-70 at Floyd Hill, 450 feet on US 550 near Silverton, and 3050 feet on Highway 160 west of Durango. [64] Accident data was collected between September 1983 and January 1988. A total of six accidents were police-reported during the observation period. None of the impacts involved barrier penetration and no injuries were reported in four instances. Both of the injury-causing accidents involved vehicle rollover not attributed to the performance of the barrier. In one case, a tractor-trailer rolled onto its side negotiating a curve and slid into the modified thrie-beam barrier. The other case involved a non-tracking passenger vehicle that rolled one and a half revolutions onto its top before coming to rest. There was also some evidence of minor unreported collisions, although the investigators were unable to discern the exact number of these events. A follow-up study that monitored the installations through 1989 included two more collisions, both involving barrier penetration.[8] Although this suggests a high penetration rate for this barrier, the high severity of the penetration accidents should be noted. Both barrier penetrations involved heavy vehicles traveling at high speeds and high angles.

Rigid Systems

NJ Shape Concrete Barrier

Utilizing 5 years of accident data, Seamons and Smith reviewed the median barrier warrant guidelines used in the state of California. [65] The observed penetration rate for the NJ shape is 0.10%, which is equivalent to the rates found for strong post metal beam barriers. For impacts with NJ shape concrete median barriers, only a slight increase in occupant fatalities was observed compared to impacts with metal beam median barriers. Also, a before-after study of 24 freeway sites and 5 non-freeway sites indicates that median barrier installation can be expected to increase median accidents 10 to 20 percent and 50 percent or more on freeways and non-freeways, respectively.

The study by Huet et al. provides a safety performance evaluation of concrete median barriers installed on approximately 200 km of French roadways. (61) Of 703 collisions involving NJ shape concrete median barrier, barrier penetration was noted in only 2 cases (0.3%). The researchers did not indicate whether these cross median collisions involved heavy vehicles. Based on a before-and-after study, the relative risk of occupant injury is found to be 1.9 times higher for impacts with concrete median barriers than for impacts with strong post w-beam median barriers. Also, roadway sections where strong post w-beam median barrier was replaced with NJ shape median barrier demonstrated an increase in redirections where the vehicle reentered the traffic stream. More recently, Martin and Quincy present data relating median barrier implementation to cross median collisions on divided French roadways. (62) For NJ shape concrete median barriers, the percentage of passenger car and large truck cross median accidents is 0.16% and 2.26%, respectively. Similar to the Huet et al. study, the authors find occupant injury is less severe with metal beam median barrier collisions but there is no statistically significant difference in the fatality rate between metal and concrete median barriers.

The most recent study in the United States focused on the extent of unreported collisions on divided highways equipped with concrete median barrier. (66) Fitzpatrick et al. utilized a videologging system coupled with police accident reports to perform the analysis on a small section of I-84 in Connecticut. Although there were fourteen police reported collisions during the 6-month data collection period, none involved any occupant injury. Based on the videologging results, the researchers estimated a total of 62 collisions into the study section of concrete median barrier. This suggests that the NJ shape concrete barrier performed adequately in 77% of the collisions (i.e. prevents serious injury and does not disable the vehicle).

F-Shape Concrete Barrier and Single Slope Concrete Barrier

No in-service evaluations were found regarding the F-shape or single slope concrete barriers.

Conclusions

The review of the available literature has provided insight to the crash test and in-service performance of the various median barriers available. General conclusions regarding median barriers are as follows:

- Installation of median barrier reduces the incidence of high severity cross median collisions while increasing the number of less severe collisions.

- With the exception of select concrete barriers, median barriers are not designed to contain and redirect heavy vehicles. Anecdotal in-service evidence suggests, however, that most barriers will redirect heavy vehicles under certain less severe impact conditions.

- The newer cable systems, the Brifen barrier, the Trinity CASS and the Safence 350, appear to be viable alternatives to the standard three-strand cable barrier.

Of particular interest to this project is the performance of the three strand cable and modified thrie beam barriers. Conclusions specific to these barriers are as follows:

- Crash testing suggests that the three strand cable barrier is capable of containing and redirecting passenger vehicles. For the modified thrie beam, crash testing suggests satisfactory performance with passenger vehicles as well as a limited number of heavy vehicles.

- Several studies corroborate that the three strand cable is effective at reducing the incidence of cross median collisions in wider medians. Despite typically increasing the total number of accidents, the cable barrier reduces the overall collision severity.

- Although there is a more limited amount of in-service performance information, the modified thrie beam barrier appears to perform adequately for all passenger vehicles.

5. Finite Element Modeling of Median Barriers

Introduction

A primary goal of this research program is to evaluate the crash performance of the I-78 and I-80 median barrier designs through finite element modeling. Although the focus of this study is on the I-78 and I-80 median barrier designs, the results of this study are expected to provide new insight into the performance of and potential improvements to the design of future median barrier in New Jersey.

Our approach is to use the LS-DYNA computer code to develop a finite element model of the median barrier systems at the pilot sites. LS-DYNA is used extensively by the roadside safety community to study the impact performance of roadside safety features, and by the automotive industry to study the crashworthiness of passenger vehicles. It is a general-purpose, explicit finite element program used to analyze the nonlinear dynamic response of three-dimensional structures. LS-DYNA has unique solution procedures which allow the code to simulate the physical behavior of 3D structures: nonlinear dynamics, thermal, failure, crack propagation, contact, quasi-static, Eulerian, arbitrary Lagrangian-Eulerian, fluid structure interaction, real-time acoustics, and multi-physics coupling. (67)

LS-DYNA is well suited to model the large deformations and high strain rates which are characteristic of vehicle crashes into roadside features. Other finite element codes, such as ANSYS, ABAQUS, COSMOS and SAP, are simply not suitable for this type of analysis – and are not used by the crash research community.

Description of the Model

Impact Configuration

A finite element model was constructed of a vehicle impact into a median barrier at an angle θ_I at an impact speed of V_I as shown in Figure 10. This impact configuration, used in NCHRP 350 crash tests, simulates an angled impact into either a median barrier or a guide rail at highway speeds. For example, NCHRP 350 test 3-11 prescribes a crash test in which a large pickup truck impacts a thrie beam median barrier at 100 km/hr at an angle of 25°.

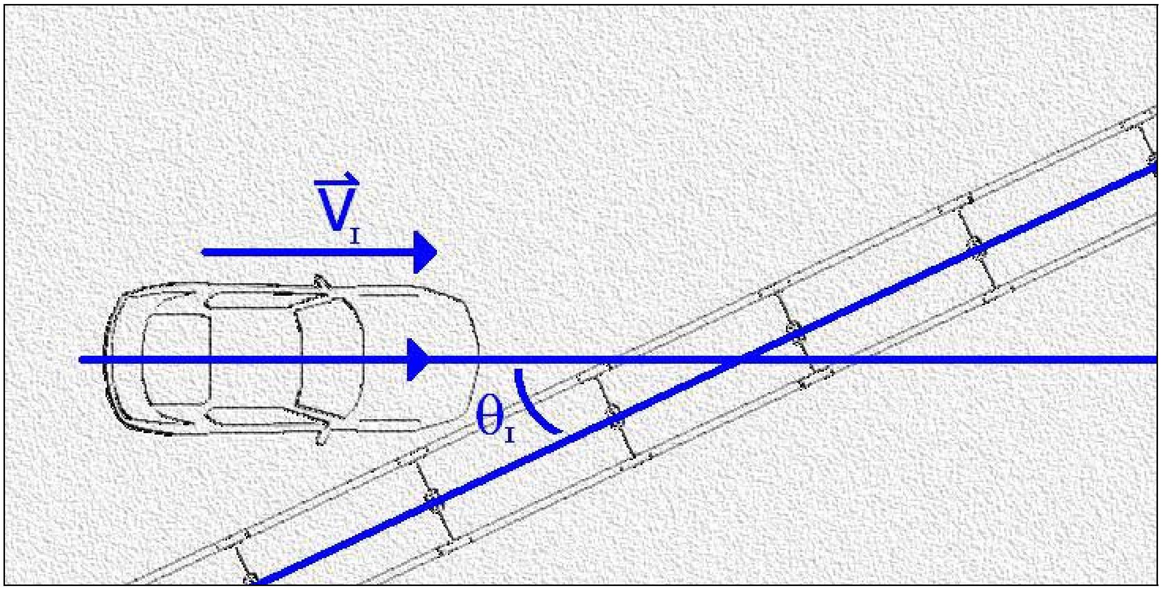

Figure 10. Impact Configuration: Vehicle into Median Barrier

Thrie Beam Median Barrier Model

The I-80 pilot site consists of approximately a one-mile length of thrie beam median barrier. A photograph of the thrie beam median barrier is shown in Figure 11.

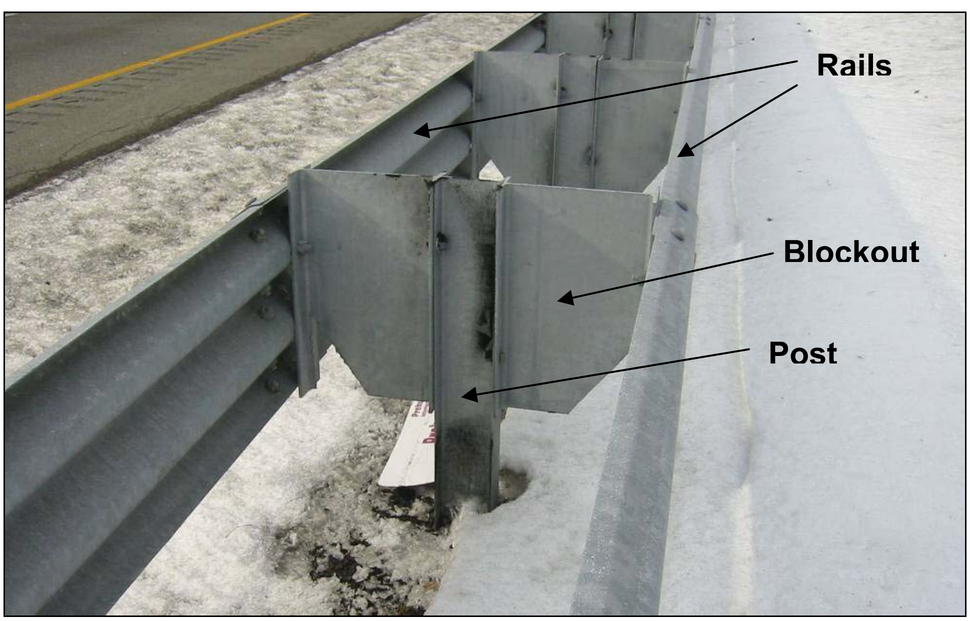

Figure 11. Thrie Beam Median Barrier

As shown in Figure 11, thrie beam median barrier consists of four major components: (1) the post, (2) the rail, (3) the blockout, and (4) the rail backplate. The backplate, installed between the blockout and the backside of the rail is not visible in this photograph.

A three-dimensional geometric model of the thrie beam median barrier was developed in the SolidWorks 3D solid modeling package. Dimensions for the model were obtained from the AASHTO Roadside Design Guide [1], and from an online database of roadside safety hardware descriptions maintained by Worchester Polytechnic Institute. [68] All dimensions on the figures which follow are given in millimeters.

The rail, shown in Figure 12, is a little over 4.1 meters in length and is supported by three (3) posts. A cross-sectional view of the rail is shown in Figure 13. The rail was built using dimensions from Worchester Polytechnic Institute roadside safety hardware database. [68] The rail has a nominal thickness of 2.7 mm, and is composed of steel.

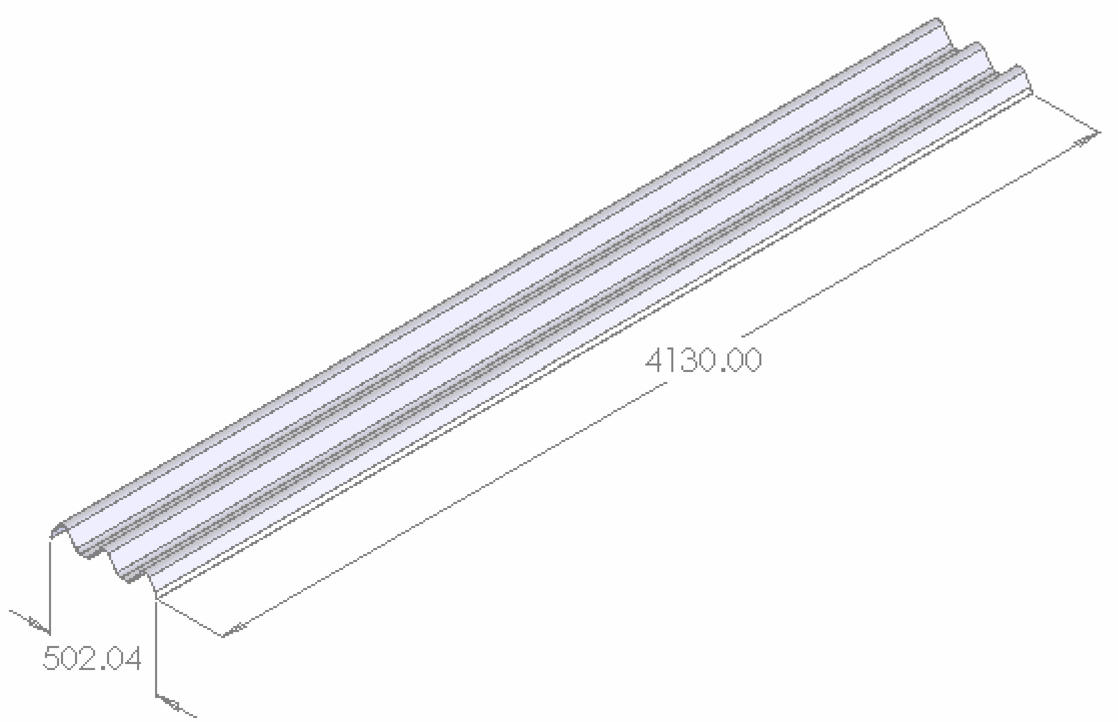

Figure 12. Thrie Beam Rail: Isometric View (dimensions in millimeters)

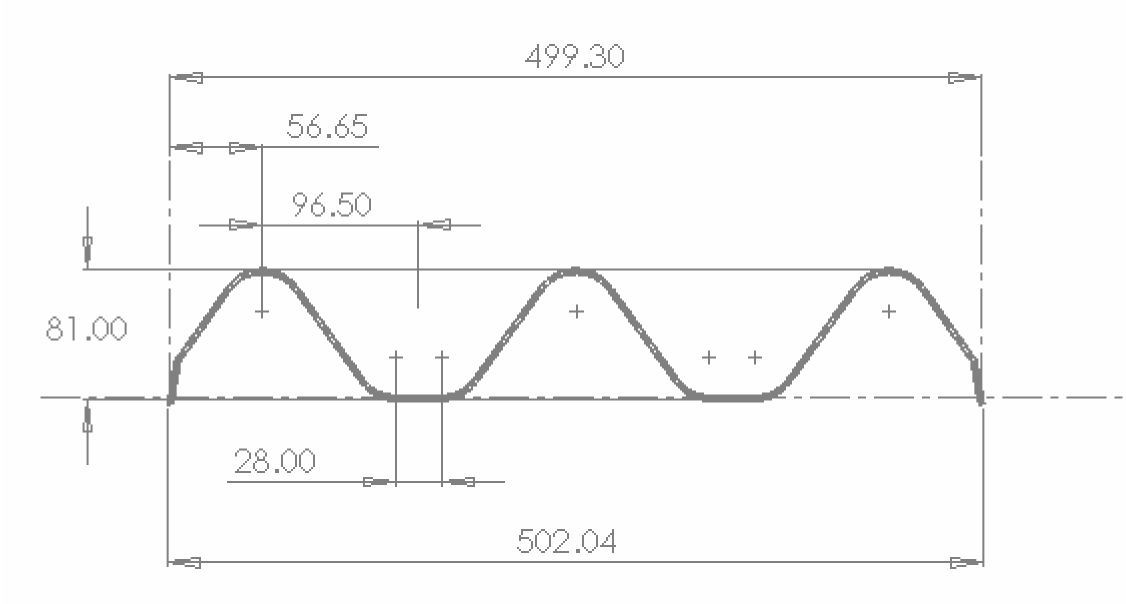

Figure 13. Thrie Beam Rail Cross-section (dimensions in millimeters)

The post shown in Figure 14 was built using the metric cross-section definition of a W150x13.5 wide-flange I-beam and the length definition from the design guide. These components were assembled using definitions from the design guide. Each post is driven to a depth of 1173 mm into soil on the roadside.

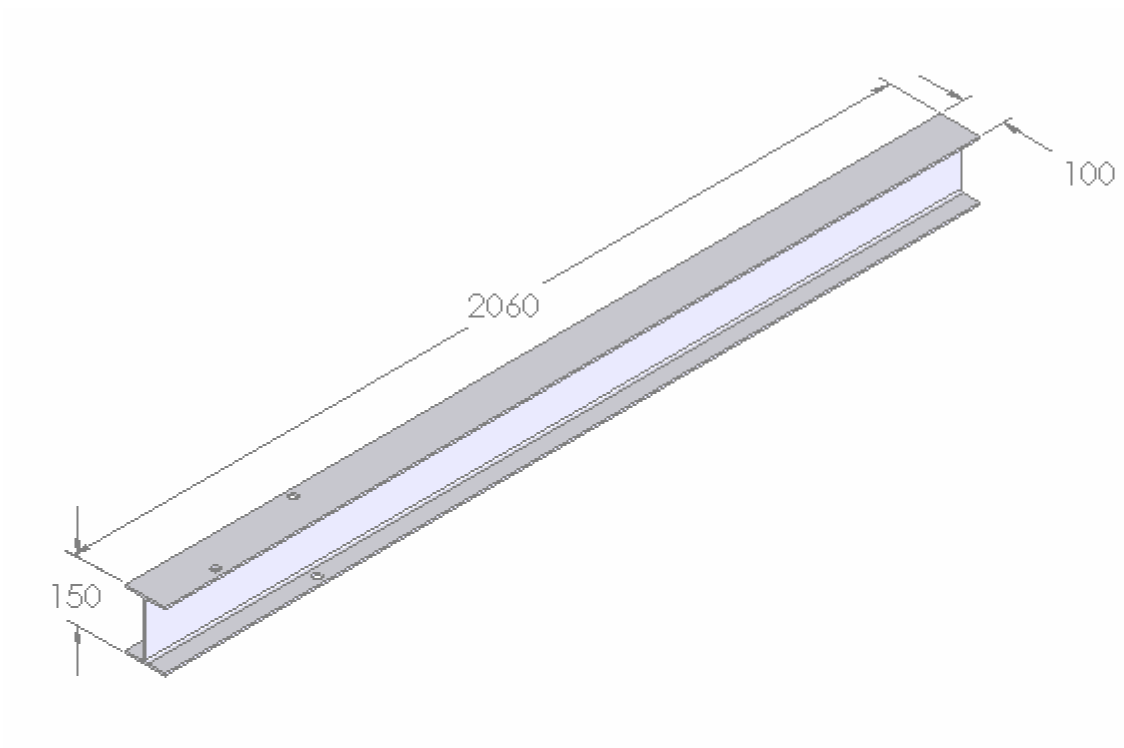

Figure 14. Thrie Beam Post (dimensions in millimeters)

The rail is connected to the posts by inserting a blockout, shown in Figure 16, and backup plate, shown in Figure 15, between the rail and post. The resulting rail-backup plate-blockout-post assembly is then bolted together. Note that there is no backup plate where two rails meet at the same post. The blockout was built using the metric cross-section definition of a W360x32.9 wide-flange I-beam and the length definition from the design guide. The rail and backup plate were built using dimensions from the Worchester Polytechnic Institute online database. [68]

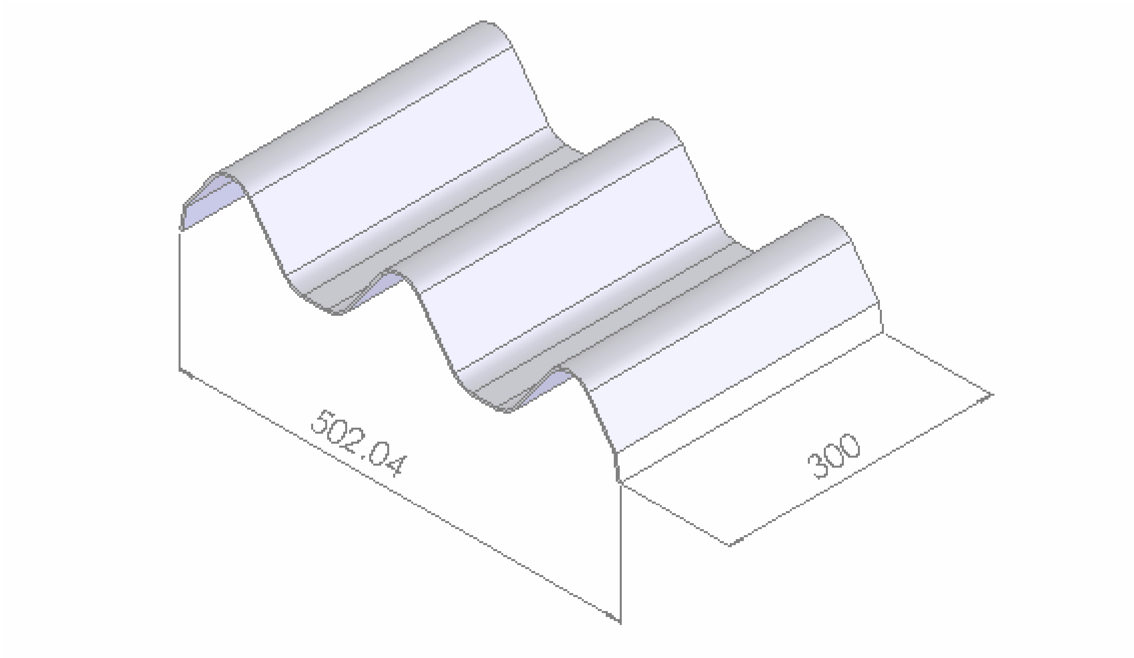

Figure 15. Thrie Beam Rail Backplate (shown without bolt holes) – dimensions in millimeters

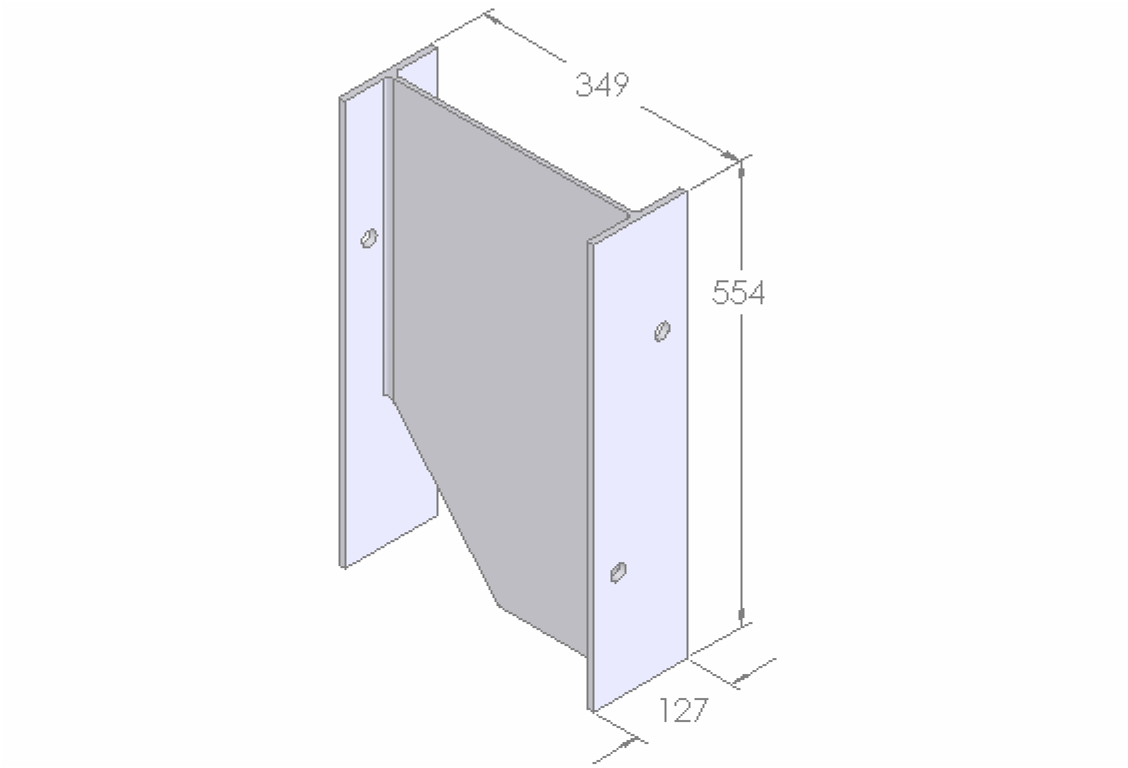

Figure 16. Thrie Beam Blockout (dimensions in millimeters)

Field Survey of I-80 System

The research team visited the I-80 site on February 5, 2004 to verify the accuracy of our geometric model through physical measurement of the as-built structure. The team took detailed measurements, photographs, and video of an arbitrarily chosen post, blockout, and rail at the pilot site. The research team found that the barrier was installed exactly as required in the AASHTO Roadside Design Guide. The dimensions of the I-beams and thrie beam components were found to be indistinguishable from the WPI specs used to develop the geometric model.

Assembly of a Simulated Section of Median Barrier

To reduce computational run times to a reasonable length, the entire one-mile section of the median barrier was not modeled. We hypothesized that in an actual collision only a 5-20 post section with associated rail would actually provide the restraining force necessary to redirect the vehicle. Preliminary simulations showed that an 8-post section of barrier was adequate to capture the dynamics of the crash. Although this greatly improved the run times, it should be noted that finite element simulation of a vehicle impact with an 8-post section of median barrier – a 500 millisecond event – still required over 40 hours of computational time.

Generation of the Finite Element Model

The FE model was built using HyperMesh, a computer package used to build complex finite element models. Each component of the geometric model's representative geometry was converted into IGES format using SolidWorks. Then, the geometry in IGES format was imported into HyperMesh. All shell geometry was converted from SolidWorks to HyperMesh in this way. The soil buckets described later in this report were re-created in HyperMesh manually because the soil bucket's pattern is essentially the cross-section of the to-be element mesh. The mesh for a single post of the model is shown in Figure 17.

To improve computational times, the thrie beam fasteners were modeled as LS-DYNA spotweld elements. Spotwelds are discrete elements that rigidly or semi-rigidly connect two nodes of the finite element model together. Despite the name, a spotweld element, has multiple uses including the modeling of simple fasteners especially if the fastener is not expected to bend or undergo large-scale deformation. There are many places in the thrie-beam that bolts are used to fasten two pieces together. Each bolt was represented by four spotwelds arrayed a sufficient distance apart to span the area of the bolt cross-section. The axial failure load in each spotweld was set to 290 kN (five times the yield load) to prevent intermittent spikes from causing failures and to compensate for the fact that spot welds are not compliant. The spotwelds were not allowed to fail in shear. As rails and posts under crash loading are expected to bend or shear long before a bolt fails, the use of spotwelds to model fasteners simplifies and speeds up a finite element simulation with minimal cost to the model accuracy.

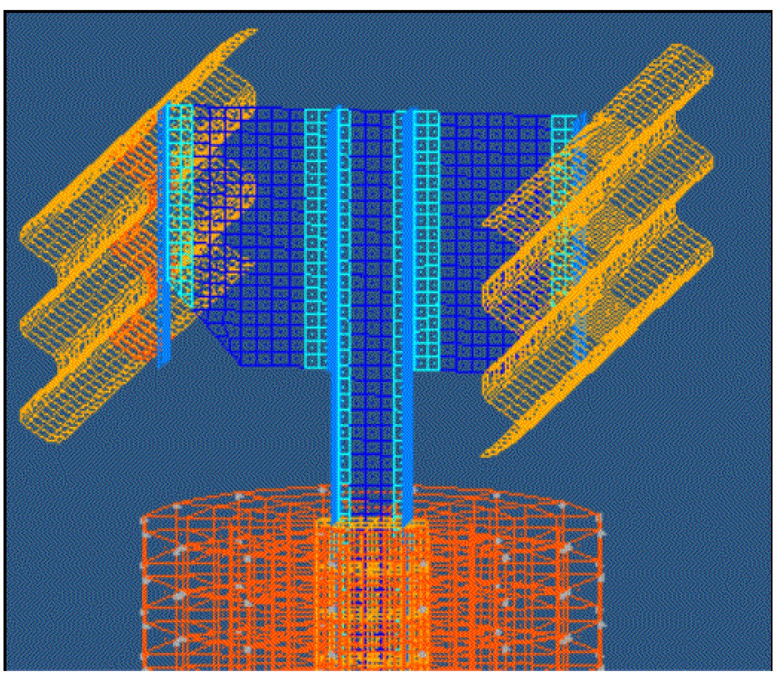

Figure 17. Finite Element Mesh of a Single Post of the Thrie Beam Median Barrier

Three-strand Cable Median Barrier Model

The I-78 pilot site consists of approximately a one-mile length of three strand cable median barrier. A photograph of the three strand cable beam median barrier is shown in Figure 18.

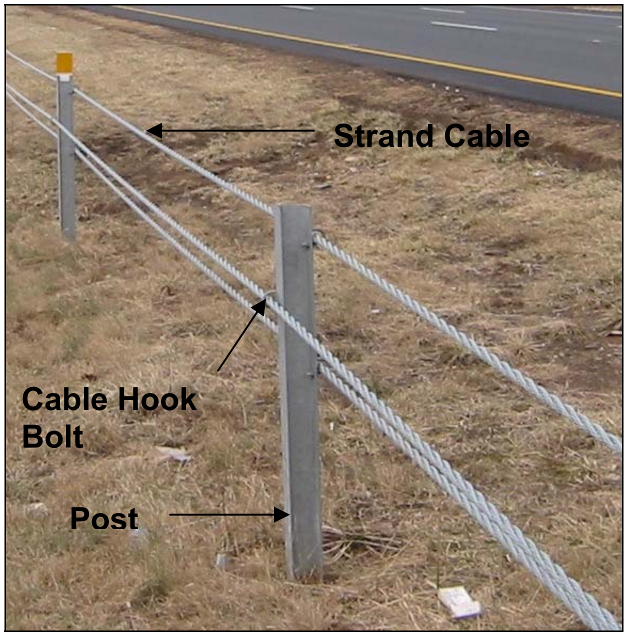

Figure 18. Three Strand Cable Median Barrier

As shown in Figure 18, three strand cable median barrier consists of four major components: (1) the post, (2) three strand cables, (3) the cable hook bolts, and (4) the soil plate. Note that the soil plate, installed directly to a portion of the post beneath ground level, is not visible in this photograph.

A three-dimensional geometric model of the three strand cable median barrier was developed in the SolidWorks 3D solid modeling package. Dimensions for the model were obtained from the AASHTO Roadside Design Guide [1], and from an online database of roadside safety hardware descriptions maintained by Worchester Polytechnic Institute. [68] All dimensions on the figures which follow are given in millimeters.

The cable, shown in Figure 19, consists of three steel cables stranded together into a composite cable with a nominal diameter of 19 mm. Each of the three cables is composed of seven smaller diameter cables as shown in Figure 20. The cable was built using dimensions from an online database of roadside safety hardware descriptions maintained by Worchester Polytechnic Institute. [68] Note that both strand cable images are from the WPI database as the cables were not modeled explicitly in the LS-DYNA model. Further discussion is provided in the model generation section.

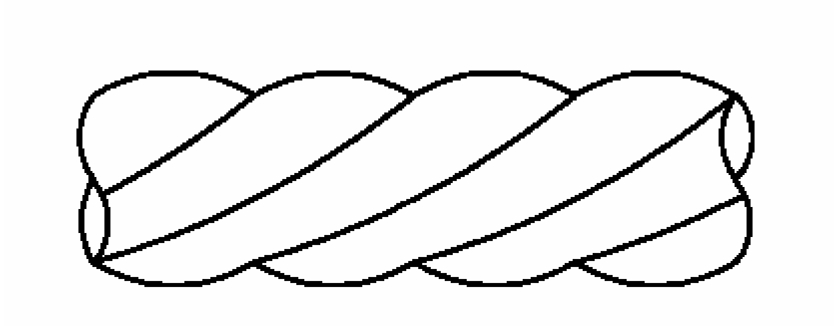

Figure 19. Three Strand Cable Barrier: Strand Cable[68]

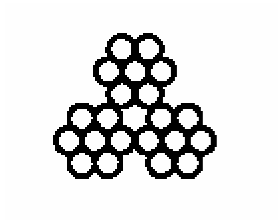

Figure 20. Three Strand Cable Barrier: Cross Section of Strand Cable [68]

The post shown in Figure 22 was built using the metric cross-section definition of an S75x8.5 I-beam and the length definition from the design guide. These components were assembled using definitions from the design guide. Each post is driven to a depth of 840 mm into soil on the roadside. The cable is connected to the posts by the cable hook bolts, shown in Figure 21. As with the strand cable, the cable hook bolts were not modeled explicitly in LS-DYNA, thus the image from the WPI database is shown.

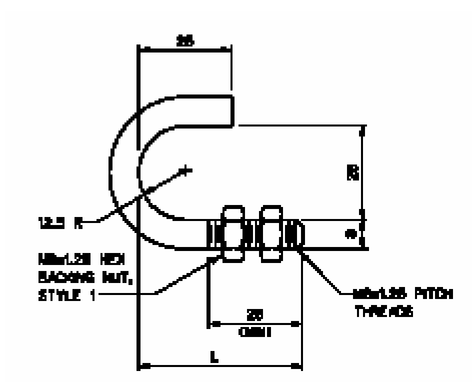

Figure 21. Three Strand Cable Barrier: Cable Hook Bolt [68]

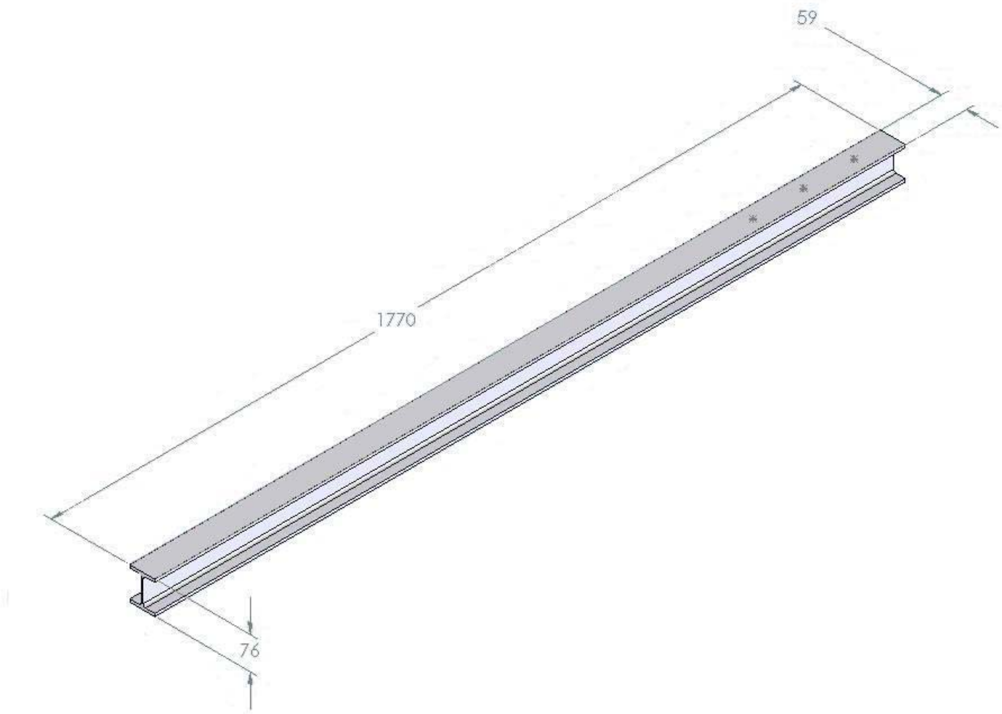

Figure 22. Three Strand Cable Barrier: Post (dimensions in millimeters)

A soil plate, shown in Figure 23, is attached to each post using three line welds; one at the top, middle and bottom of the soil plate. Note that the soil plate bottom edge is positioned 125 mm from the bottom of the post. The soil plate was built using dimensions from an online database of roadside safety hardware descriptions maintained by Worchester Polytechnic Institute. (68)

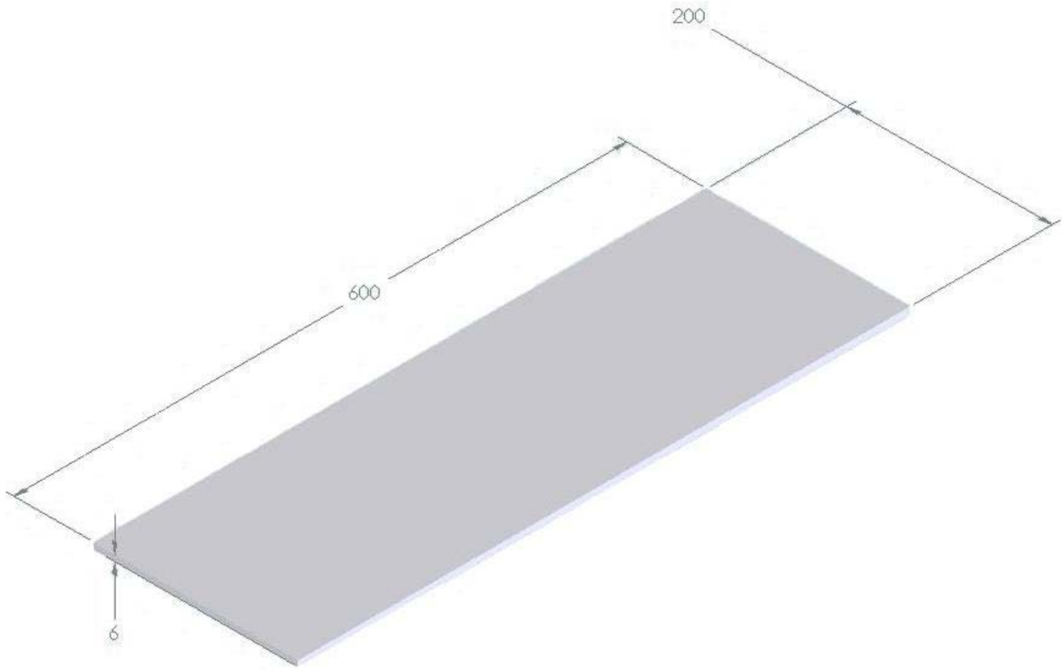

Figure 23. Three Strand Cable Barrier: Soil Plate (dimensions in millimeters)

Field Survey of I-78 System

The research team visited the I-78 site on February 5, 2004 to verify the accuracy of our geometric model through physical measurement of the as-built structure. The team took detailed measurements and photographs of an arbitrarily chosen post, cable hook bolt, and cable at the pilot site. The research team found that the barrier was installed exactly as required in the AASHTO Roadside Design Guide. The dimensions of the I-beams and components were found to be indistinguishable from the WPI specs used to develop the geometric model. Note that the dimensions of the soil plate were verified during an accident investigation on March 2, 2004. A post had been torn from the ground allowing the investigation team access to the soil plate.

Assembly of a Simulated Section of Median Barrier

As with the thrie beam model, the entire one-mile length of the cable median barrier was not modeled to ensure a reasonable computational time. Since the cable barrier is a flexible barrier system, collisions with the cable barrier are expected to involve more posts and, subsequently, longer impact durations than collisions with the thrie beam barrier. Although cable barrier collisions are longer, we hypothesized that an 8-post section would be sufficient to capture a large of enough portion of the kinematics to assess whether the barrier would redirect the vehicle. It should be noted that finite element simulation of a vehicle impact with an 8-post section of median barrier – a 500 millisecond event – still required over 40 hours of computational time.

Generation of the Finite Element Model

Similar to the thrie beam model, the FE model was built using HyperMesh. The post and soil plate components were converted into IGES format using SolidWorks. Then, the geometry in IGES format was imported into HyperMesh. All shell geometry was converted from SolidWorks to HyperMesh in this way. Due to the complex nature of the strand cable, the cables were modeled as long, thin shell elements or "ribbons" in Hypermesh. The trial ribbons were created that closely matched the cross sectional area and the moment of inertia of the actual strand cable. Trial runs were used to determine the ribbon that better mimicked the behavior of the strand cable. The soil buckets described later in this report were re-created in HyperMesh manually because the soil bucket's pattern is essentially the cross-section of the to-be element mesh. The mesh for a single post of the model is shown in Figure 24.

To improve computational times, the cable hook bolts were modeled as LS-DYNA spotweld elements. Each cable hook bolt was represented by two spotwelds located at the center of the flange of the post. Unlike the fasteners in the thrie beam model, the cable hook bolts are designed only to hold the cables in place to ensure that the vehicle engages the cables. As such, the hook bolts readily release the cable from the post during an impact. To mimic this behavior in the model, the axial and shear failure load for each spotweld was set to 50 kN to allow the cable to readily detach from the post. Again, the use of spotwelds to model fasteners simplifies and speeds up a finite element simulation with minimal cost to the model accuracy.

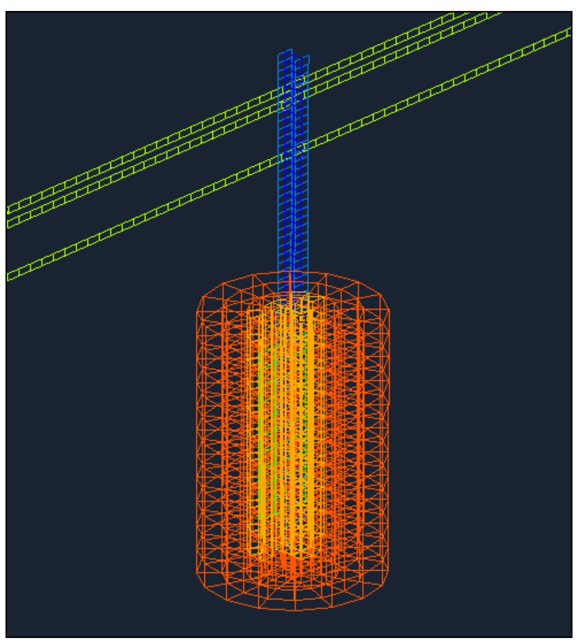

Figure 24. Finite Element Mesh of a Single Post of the Three Strand Cable Median Barrier

Soil Modeling

Each post has a region of soil surrounding it that will be included in the FE model. This region of soil is referred to as a “soil bucket”. Soil bucket is an FEA term and is used because these regions are typically shaped like a cylinder and are constrained on the side and bottom. Since FE models are discrete and the ground at the barrier site is continuous, only part of the ground can be modeled using elements. The constraints that interface with the soil bucket to model the rest of the ground are described below.

The soil buckets are constructed using a cross-section pattern. This pattern will be custom designed for the post’s cross-section and the post’s length below the ground line. Each soil bucket is a cylindrical region of elements, constrained on the side and bottom.

The mesh of elements in each soil bucket links the I-shape of the post with the circular shape of the outer rim. Therefore, the edge of the I-beam defines the inner edge of the soil bucket. The outer edge of the soil bucket is estimated through the observation of post deflection in previous crash tests. Typical values for the radius of a soil bucket are around five times the longest diagonal of the post’s cross-section. For very hard soils, this value can be reduced even further. However, for very soft soil or wet ground, typical values are around ten times the longest diagonal. The soil buckets in the thrie-beam model are just over five times the length of the longest diagonal of the post’s cross-section.

Material Properties

The wire rope used in the 3-strand cable median barrier is composed of steel. The constitutive properties of the steel in the cable were represented using the LS-DYNA Linear Elastic material model (Material type 1). The density was $7.89x10^{-9}$ tons (metric tons/mm^3. Young’s Modulus was set to $2x10^5$ MPa. Poisson’s ratio was set to 0.3.

The beams, rail, and backup plates of the thrie-beam and the posts of the 3-strand cable median barriers are composed of steel. The constitutive properties for these members were represented using the LS-DYNA Piecewise Linear Isotropic Plastic material model (Material type 24). The density was $7.89x10^{-9}$ metric tons / mm^3. Young’s Modulus = $2x10^5$ MPa. Poisson’s ratio was set to 0.3. The yield stress was set at 600 MPa. The plastic strain at material failure was set to 0.158. Plastic strain is defined to be zero at the yield stress. The LS-DYNA Piecewise Linear Isotropic Plastic material model is an 8 point piecewise linear fit to the plastic regime of the material. The eight points used to represent steel in our model are as follows:

Table 4. Plastic stress vs. strain curve for steel

Point	Plastic strain (in/in)	Stress (MPa)
1	0.0	600.0
2	0.01784	814.4
3	0.04018	989.
4	0.06204	1095.
5	0.08618	1155.
6	0.1178	1203.
7	0.1570	1258.
8	0.1600	1300.

The soil in the model was modeled using the LS-DYNA Soil and Crushable/Non-crushable foam material model (Material Type 5). The properties used to characterize the soil in our model were developed based on experiments performed to describe the behavior of guardrail posts in soil. [72] The shear modulus was set to 688 MPa. The bulk modulus was set to 1150 MPa. The yield function constants were set to a_0=1, a_1=0, and a_2 = 1. The value for a_2 in the NCAC models is a_2=0.722, however, preliminary simulations with our models showed better soil dynamic performance for a_2=1.0. The pressure cutoff was set to –0.1724 MPa. The volumetric strain vs. pressure relationship for our soil is as follows:

Table 5. Pressure vs. Volumetric Strain Curve for Soil Model

Point	Volumetric strain	Pressure (MPa)
1	0.0	0.0
2	$1.0x10^{-2}$	0.9550
3	$1.6x10^{-2}$	1.875
4	$2.0x10^{-2}$	2.565
5	$3.0x10^{-2}$	4.709

The fasteners in the thrie beam and the cable hooks in the 3-strand cable barrier models were represented by LS-DYNA spot weld elements. As discussed earlier, spotwelds are discrete elements that rigidly or semi-rigidly connect two nodes of the finite element model together. Spot welds were used to represent the cable hooks. A single spot weld holds each cable to the post. The failure loads were 50kN (yield stress times cross-sectional area) is shear and axial directions.

<u>Vehicle Models</u>

Three vehicles will be used in the finite element simulations – a small car, a large pickup truck, and a large truck. The vehicle models used in our simulations were obtained from the National Crash Analysis Center (NCAC). The NCAC, sponsored by NHTSA and FHWA, maintains a public finite element archive of LS-DYNA models. As shown in Table 6, the research team used three of these models. Our original plan was to use a tractor-trailer, however, at the time of this report, NCAC had not yet released this model. In its place, we used an 8000-kg single unit truck.

Table 6. LS-DYNA Models available from NHTSA / FHWA

Vehicle	Vehicle Category
1997 Geo Metro	Subcompact Car
1994 Chevrolet C2500	Full Size Pickup Truck
Ford F-800	Single Unit Truck

The small car was modeled using a 1997 Geo Metro shown in Figure 25 of mass 820-kg. The large pickup was a 1994 Chevrolet C-1500 pickup truck weighing 2000-kg shown in Figure 26. The single unit truck shown in Figure 27 weighed 8000-kg. Contact plates were added to each of the vehicles used in the three-strand cable models to ensure correct interaction between the vehicle and the cable.

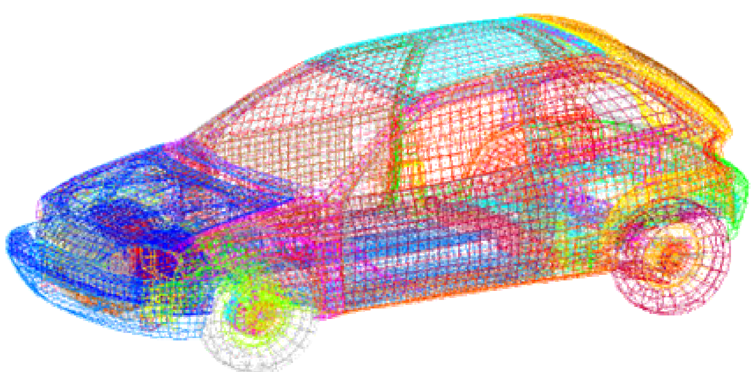

Figure 25. Finite Element Model of a 1997 Geo Metro

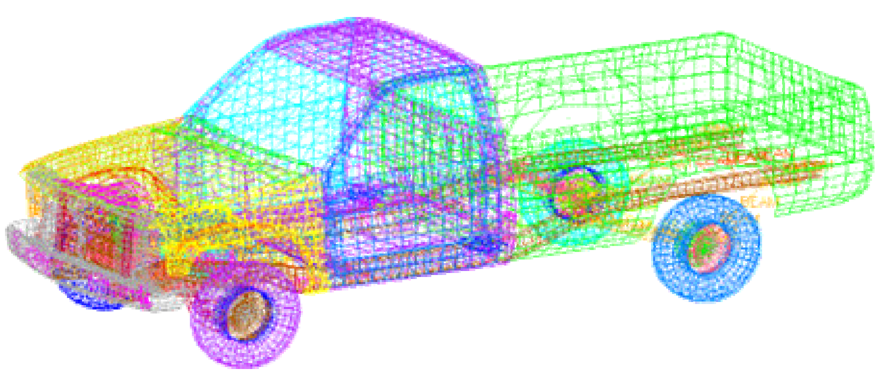

Figure 26. Finite Element Model of a 1994 Chevrolet C2500 Pickup Truck

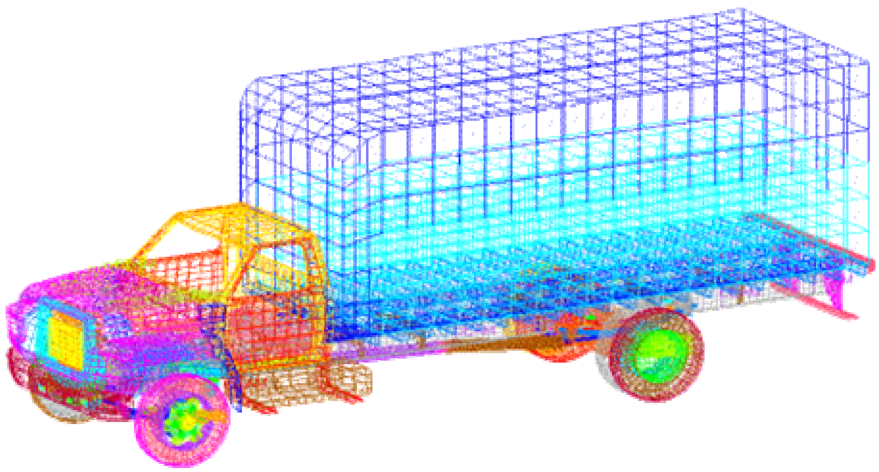

Figure 27. Finite Element Model of a Ford F-800 Single Unit Truck

Model Validation

To validate the finite element model, a simulated vehicle impact into a median barrier was conducted using at the same conditions as an actual crash test. The results of the computer simulations were compared with measured barrier and vehicle responses from the physical experiments. Ideally, the computer simulation should agree with the physical experiments.

The simulation and physical crash test were compared using the following metrics of performance:

- Test Article Deflections - Maximum Dynamic, Static Deflection, and Barrier Penetration if applicable
- Vehicle Exit Conditions – exit speed and exit angle of the test vehicle as prescribed by NCHRP 350
- Occupant Risk Factors – occupant impact velocity and occupant ridedown acceleration as prescribed by NCHRP 350 flail space model
- Trajectory – based on video footage and qualitative validation

<u>Validation of the Thrie-Beam Median Barrier Model</u>

The thrie-beam finite element model was validated against the results of a crash test conducted by Texas Transportation Institute on February 1995. [68] The test involved the impact of a 1989 Chevrolet C2500 pickup truck into the guardrail version of the thrie beam barrier. A crash test of a pickup truck into a median barrier version of thrie-beam was unavailable. The guardrail version of thrie beam is essentially one-half of the median barrier version. For the validation run, one side of the median barrier model, including the blockouts and rail, was removed from the LS-DYNA model. Unlike the I-80 blockouts, the blockouts in the TTI test do not span the entire width of the thrie-beam.

Table 7 summarizes the comparison between the LS-DYNA thrie beam model and the NCHRP Report 350 full-scale crash test (test 3-11). Note that the percentage values in the correlation column are computed using the following relation:

$$1 - ABS\left|\frac{Value_{Simulation} - Value_{Test}}{Value_{Test}}\right|$$

where $Value_{Simulation}$ and $Value_{Test}$ correspond to the values computed from the simulation and obtained from the test, respectively. There is a good correlation with respect to the vehicle exit conditions and generally, the model is indicative of the vehicle behavior observed in the full-scale crash test. Refer to Figure 28 for a side-by-side snapshot comparison of the LS-DYNA thrie beam model and corresponding crash test. In terms of occupant risk criteria, there is general agreement between the calculated occupant ridedown accelerations as well as peak 50 ms vehicle accelerations. The simulation did, however, under predict the occupant impact velocities by approximately 50 percent. Also, the barrier deflections found in the model are approximately half of those observed in the crash test.

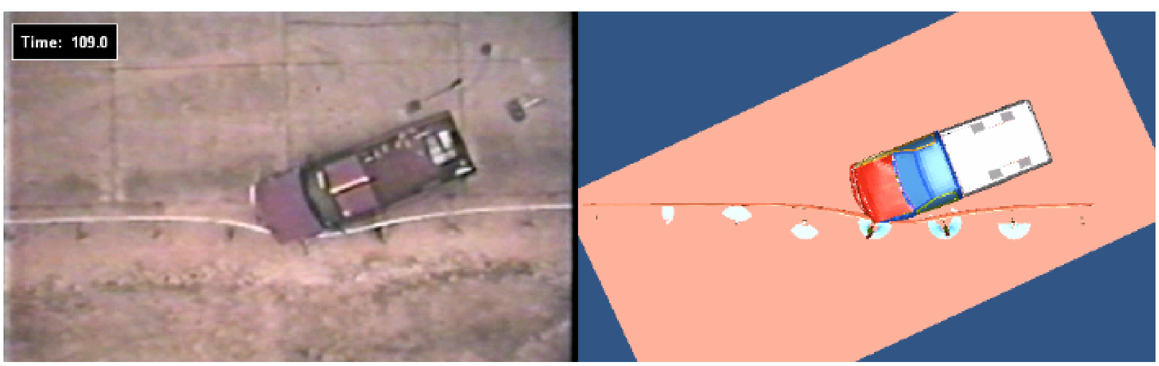

Figure 28. Thrie Beam Barrier Validation: Model and Crash Test

Table 7. Thrie Beam Model Validation Summary: Test 3-11

Category	Parameter	LS-DYNA Simulation	NCHRP Report 350, Test 3-11	Correlation
Impact Conditions	Speed (km/h)	100.7	100.2	100%
	Angle (degrees)	25.0	25.1	0.1°
Exit Conditions	Speed (km/h)	70.3	67.4	96%
	Angle (degrees)	12.2	11.1	1.1°
Occupant Risk	Occupant Impact Velocity, X-Direction (m/s)	3.9	7.8	50%
	Occupant Impact Velocity, Y-Direction (m/s)	2.1	5.2	40%
	Ridedown Acceleration, X-Direction (g's)	8.7	9.7	90%
	Ridedown Acceleration, Y-Direction (g's)	9.7	9.0	92%
	Peak 50ms Average Acceleration, X-Direction (g's)	5.9	6.2	95%
	Peak 50ms Average Acceleration, Y-Direction (g's)	6.0	5.2	85%
Test Article Deflections	Maximum Dynamic (m)	0.46	1.02	45%
	Maximum Static (m)	0.33	0.61	54%

Validation of the Three-strand cable Median Barrier Model

The 3-strand cable median barrier model was validated against the results of a crash test conducted by Texas Transportation Institute on June 1996. (70) The test involved the impact of a 1991 Ford Festiva small passenger car into a 3-strand cable median barrier. The test weight of the Ford Festiva was 820kg. For our simulation, we represented the small car using a Geo Metro, a small car in the same weight class as the Ford Festiva.

Table 8 summarizes the comparison between the LS-DYNA three-strand cable model and the NCHRP Report 350 full-scale crash test (test 3-10). Note that there is no comparison of vehicle exit conditions as the vehicle remained in contact with the barrier for the duration of the event for both the crash test and simulation. With respect to the occupant risk criteria, the peak 50 ms average

accelerations had the highest level of correlation. A good correlation was also observed with respect to the occupant impact velocity in the longitudinal direction; however, this strong correlation was not observed in the lateral direction. Also, compared to the thrie beam model, there is a much less agreement between the calculated occupant ridedown accelerations. Similar to the thrie beam, though, there is strong agreement between the peak 50 ms average accelerations. Also, similar to the thrie beam model, the LS-DYNA model under predicts the maximum and permanent deflection of the barrier. These larger discrepancies between the model and crash test may be attributed to the more complex nature of the interaction of the vehicle with the three-strand cable barrier. Refer to
Figure 29 for a side-by-side snapshot comparison of the LS-DYNA three-strand cable barrier model and corresponding full-scale crash test.

Table 8. Three Strand Cable Model Validation Summary: Test 3-10

Category	Parameter	LS-DYNA Simulation	NCHRP Report 350, Test 3-10	Correlation
Impact Conditions	Speed (km/h)	100.0	99.7	100%
	Angle (degrees)	20	20.4	0.4°
Occupant Risk	Occupant Impact Velocity, X-Direction (m/s)	3.4	4.1	83%
	Occupant Impact Velocity, Y-Direction (m/s)	0.5	2.9	17%
	Ridedown Acceleration, X-Direction (g’s)	6.8	3.6	11%
	Ridedown Acceleration, Y-Direction (g’s)	7.0	3.9	21%
	Peak 50ms Average Acceleration, X-Direction (g’s)	2.2	2.5	88%
	Peak 50ms Average Acceleration, Y-Direction (g’s)	2.6	2.8	93%
Test Article Deflections	Maximum Dynamic (m)	1.26	2.58	49%
	Maximum Static (m)	0.31	1.10	28%

Figure 29. Three Strand Cable Barrier Validation: Model and Crash Test

Additional Validation of the Models

To improve the confidence in the models, additional validation runs were performed; one for each pilot barrier. The additional simulation for the thrie beam barrier consisted of the 8000S test vehicle impacting the barrier at 80 kilometers per hour and at an angle of 15 degrees. This was validated against a corresponding crash test performed by the Texas Transportation Institute in June 1998 (30). The additional three strand cable barrier simulation consisted of a 2000P test vehicle impacting the barrier at a speed of 100 kilometers per hour and an angle of 25 degrees. This simulation was then validated against a corresponding crash test performed by the Texas Transportation Institute in February of 2000 (71).

Table 9 provides a summary of the additional validation simulation for the thrie beam barrier involving the 8000S test vehicle. Unlike the 2000P test validation with the thrie beam barrier, there was significant correlation to the occupant impact velocity and better correspondence in the barrier deflection values in the 8000S validation. For the occupant ridedown and peak 50 ms average accelerations, however, the thrie beam model appears to over predict based on the values observed in the full-scale crash test.

Table 9. Thrie Beam Barrier Model Validation Summary: Test 4-12

Category	Parameter	LS-DYNA Simulation	NCHRP Report 350, Test 4-12	Correlation
Impact Conditions	Speed (km/h)	79.2	78.8	99%
	Angle (degrees)	15.0	15.7	0.7
Exit Conditions	Speed (km/h)	57.0	64.0	89%
	Angle (degrees)	7.4	8.2	0.8
Occupant Risk	Occupant Impact Velocity, X-Direction (m/s)	2.62	3.5	75%
	Occupant Impact Velocity, Y-Direction (m/s)	1.96	2.4	82%
	Ridedown Acceleration, X-Direction (g's)	3.67	2.9	73%
	Ridedown Acceleration, Y-Direction (g's)	4.51	3.8	81%
	Peak 50ms Average Acceleration, X-Direction (g's)	1.56	1.4	89%
	Peak 50ms Average Acceleration, Y-Direction (g's)	3.50	2.3	48%
Test Article Deflections	Maximum Dynamic (m)	0.48	0.71	67%
	Maximum Static (m)	0.29	0.51	58%

Table 10. Three Strand Cable Model Validation Summary: Test 3-11

Category	Parameter	LS-DYNA Simulation	NCHRP Report 350, Test 3-11	Correlation
Impact Conditions	Speed (km/h)	100.0	101.4	99%
	Angle (degrees)	25.0	24.8	0.2
Occupant Risk	Occupant Impact Velocity, X-Direction (m/s)	3.4	2.2	45%
	Occupant Impact Velocity, Y-Direction (m/s)	0.5	2.9	17%
	Ridedown Acceleration, X-Direction (g's)	6.8	2.7	-52%
	Ridedown Acceleration, Y-Direction (g's)	7.8	4.9	41%
	Peak 50ms Average Acceleration, X-Direction (g's)	2.2	1.6	63%
	Peak 50ms Average Acceleration, Y-Direction (g's)	2.6	2.1	76%
Test Article Deflections	Maximum Dynamic (m)	2.1	3.4	62%
	Maximum Static (m)	0.4	0.7	57%

Table 10 provides a summary of the additional validation simulation for the three strand cable barrier involving the 2000P test vehicle. Similar to the test validation with the 820C vehicle, there was significant correlation in the peak 50 ms average acceleration values and the barrier deflection. Also, both showed a tendency to over predict the occupant ridedown acceleration values. Overall, however, the cable model appears to be less accurate for collisions involving pickup truck type vehicles.

Parametric Evaluation of Median Barrier Crash Performance

Since cross median collisions are relatively infrequent events, median barrier performance across the spectrum of potential impact conditions cannot be assessed based solely on anecdotal crash information. The purpose of the parametric evaluation is to determine the upper performance limits of the pilot barriers based on a wide variety of impact conditions. To accomplish this objective, the validated LS-DYNA models are utilized with varying impacting vehicles and impact angles. The intent is to ultimately find combinations of vehicle and impact conditions will induce barrier failure resulting in the vehicle crossing the median into opposing traffic lanes.

A total of 10 simulations were successfully conducted. The series of simulations included runs at NCHRP Report 350 conditions as well as test conditions at both higher and lower severity impact conditions. Simulations were conducted at impact speeds of 80 kph and 100 kph. Impact angles included 15, 20, and 25 degrees. The results for the Thrie Beam simulations are shown in Table 11. The results for the Three Cable Barrier are shown in Table 12.

Table 11. Thrie Beam Parametric Study Results: Occupant Risk

Vehicle	Impact Conditions		Impact Velocity		Ridedown Acceleration		Max 50 ms Vehicle Accelerations	
	Speed (kph)	Angle (deg)	X	Y	X	Y	X	Y
820C	100	20.0	4.3	1.9	4.8	10.2	5.1	8.4
820C	100	25.0	2.4	3.5	3.3	6.7	3.2	6.8
2000P	100.7	25.0	3.9	2.1	8.7	9.7	5.9	6.0
8000S	79.2	15.0	2.6	2.0	3.7	4.5	1.6	3.5
8000S	79.2	20.0	2.9	0.4	2.3	6.4	1.6	3.0
8000S	100	25.0	-	-	-	-	-	-

Table 12. Three Cable Paramtric Study Results: Occupant Risk

Vehicle	Impact Conditions		Impact Velocity		Ridedown Acceleration		Max 50 ms Vehicle Accelerations	
	Speed (kph)	Angle (deg)	X	Y	X	Y	X	Y
820C	80.0	25.0	4.1	1.5	4.4	6.6	2.5	3.9
820C	100.0	20.0	3.4	0.5	6.8	7.0	1.3	0.3
820C	100.0	25.0	5.0	1.4	5.2	9.3	5.0	4.28
2000P	100.0	25.0	3.4	0.5	6.8	7.8	2.2	2.6

Although the both models were validated against the full scale crash tests, extrapolating these models to other impact conditions was not straightforward. Models which were computationally stable at lower severities frequently became unstable at higher severities, and required modification. Occasionally, models which were stable at the NCHRP 350 conditions became unstable at lower severities. The three-strand cable barrier was particularly difficult to model. The LSDYNA contact algorithms were found to not be robust with the narrow contact impacts characteristic of cables. There were no stable models of the 8000s single unit truck impacting 3-strand cable. Likewise, the pickup truck model was only stable at the NCHRP Report 350 conditions. Extrapolation of these models to these higher severity crash conditions will require both additional model refinement, and additional physical crash tests against which to validate the models.

A number of observations can be gleaned from the available parametric study simulations. The thrie beam model suggests that the thrie beam barrier may be able to contain and redirect an 8000S vehicle at impact conditions slightly higher than NCHRP Report 350 test level 4 conditions. A satisfactory simulation was completed with the 8000S impacting at 80 km/hr and an angle of 20 degrees. With respect to the three-strand cable barrier, the simulations also suggest a higher level of performance than demonstrated through NCHRP Report 350 crash testing. A successful simulation was performed with the 820C small car impacting the three-strand cable barrier at 100 km/hr and an angle of 25 degrees (5 degrees greater than those specified in NCHRP Report 350). Also, a simulation involving the 8000S vehicle impacting the three-strand cable at 80 km/hr and an angle of 15 degrees suggests some ability of this barrier to redirect heavier vehicles. This simulation is not included in the preceding tables, however, as the 8000S spun out late in the impact event – a phenomenon which could not be experimentally verified.

Table 11 and Table 12 also summarize the occupant risk values for the satisfactory simulations on the thrie beam barrier and three strand cable barriers, respectively. The occupant risk criteria provide a measure of injury potential for a given set of impact conditions. Note that the 8000S vehicle test (100 kph and an angle of 25 degrees) does not have any corresponding occupant risk information. Although the barrier showed no signs of penetration, the 8-post section of barrier was not sufficient to fully contain and redirect the vehicle in this severe collision.

For simulations with both barriers, it is useful to compare occupant risk values for differing impact configurations to gauge the likelihood of occupant injury. The simulations involving the 820C vehicle and the thrie beam do not suggest a significant difference in occupant risk. An increasing in impact angle of the vehicle (from 20 to 25 degrees) only results in an increase in the lateral occupant impact velocity. This may attributed to the fact that a smaller impact angle allows for more vehicle-to-barrier interaction and more severe occupant risk values. However, the relatively consistent decline in the other occupant risk measures suggests that there may be an inconsistency in the model. Examining the simulation with the 2000P test vehicle, a more severe collision is evident by an increase in every value with the exception of the lateral peak 50 ms average acceleration value (comparing to the 820C test with the same impact conditions).

With respect to the 8000S simulations, both appear to subject the occupant to a lower potential for injury. This may be a result of the lower impact speed combined with the significantly larger mass of the vehicle.

For the three strand cable barrier, simulations involving the 820C test vehicle include three distinct impact conditions. Although the occupant risk values are relatively close to each other, the model appears valid as the risk values are greatest at the most severe impact conditions (100 kph and an angle of 25 degrees). In addition, the 2000P test vehicle does not exhibit substantially higher occupant risk values than the equivalent impact conditions with the 820C vehicle. This reinforces the fact that the 820C vehicle is more critical for occupant risk values and the pickup test is primarily utilized to test the strength of the barrier.

Conclusions

Based on the generation of the finite element models of the pilot median barriers, the validation process and the parametric study, the following conclusions are evident:

- Site inspections revealed that both as-built pilot barriers matched the requirements of the AASHTO Roadside Design Guide.

- There is satisfactory agreement between both LS-DYNA models and the corresponding full-scale crash tests used to validate the models. Additional validation suggests that the thrie beam model is more robust than the three strand cable barrier.

- Additional modifications and subsequent revalidation need to be performed on both models prior to extrapolating these models to higher severity crashes.

- The available simulations do suggest that both pilot barriers may perform to levels beyond which they are crash tested to under NCHRP Report 350 guidelines.

6. Field Investigation of Median Barrier Crashes

Introduction

One objective of this research program was to determine the effectiveness of the I-78 and I-80 pilot median barriers based on performance of these barriers in the event of a collision. To achieve this objective, a crash investigation team was formed to conduct an investigation in the event of a collision with either pilot barrier. In conjunction with NJDOT maintenance personnel, a crash notification structure was developed to inform the investigation team of impacts to the pilot median barriers. For each impact, the investigation was performed according to the developed data collection plan. The findings of each investigation were summarized in a crash investigation report and the associated data is stored in a database developed specifically for cross median crashes. A special focus was on the police reported collisions since these are more likely to test the upper performance limits of the barrier. Unreported collisions were also investigated to provide insight to median barrier damage in less severe impacts.

This section describes the development of the accident notification plan, the data collection plan, the Median Barrier Accident Database, and the results of the investigated crashes.

Accident Notification Plan

The purpose of this section is to present the notification structure for impacts to the median barrier pilot sections on I-78 and I-80.

Notification Process

Before an accident at the pilot site can be investigated, the research team must be notified that a crash has taken place. Establishing a reliable system of accident notification has proven to be one of the more challenging aspects of this project. The research team has developed contacts with personnel at two NJDOT Operations offices: Traffic Operations North as well as Maintenance and Equipment Operations Central. Traffic Operations North is responsible for an area that includes the modified thrie beam barrier test section on I-80, while Maintenance and Equipment Operations Central is responsible for an area that includes the three-strand cable barrier on I-78.

Test pilot impacts can be classified into two categories: Police reported and unreported collisions. The unreported accidents typically involve less severe hits on a section of the barrier. In many cases, the impact does not disable the encroaching vehicle and the vehicle leaves the scene. Police reported accidents, however, usually involve more severe impact conditions and a higher propensity for occupant injury. In many cases, the vehicle is disabled and is unable to be driven from the scene. Depending on the type of collision, the notification structure changes.

I-80 Modified Thrie-Beam Pilot Site

Figure 30 depicts the notification process for disabling accidents, where the police and/or emergency medical personnel are present at the scene. There are three main notification avenues: motorists, the NJ State Police, or the local police that notify NJDOT personnel of the incident. If the barrier impact occurs during normal business hours (8 am to 5 pm), NJDOT Traffic Operations North (TON) is notified directly of the incident. If the impact occurs outside of normal business hours, however, notification occurs through Northern Communications, a Trenton-based dispatch center that handles emergency calls during off-business hours.

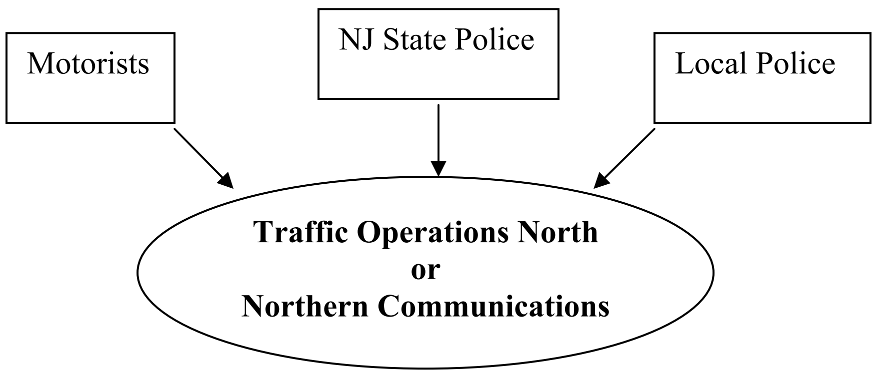

Figure 30. Route 80 Notification Structure: Disabling Accidents

In the event of a major collision with the Route 80 Thrie-Beam Pilot site, TON or Northern Communications will contact Rowan University directly. As a failsafe, TON will also contact Maintenance and Equipment Operations North, the department responsible for replacing damaged roadside hardware in the region that includes the Route 80 thrie-beam pilot site.

Figure 31 depicts the notification process typical for **non**-disabling accidents where the police and/or emergency medical personnel are **not** present at the scene. Again, these collisions include minor property damage only accidents where the vehicle drives away after impact. There are four possible notification avenues: motorists, NJ State Police, local police and NJDOT maintenance personnel. Although notification of these accident types can occur via motorists or local or state police, the typical avenue is through the observations of NJDOT maintenance personnel. Maintenance crews are required to make daily patrols of the roadways within their jurisdiction to check for damaged roadside safety hardware. A biweekly report of the length and nature of repair work needed is submitted to Traffic Operations North.

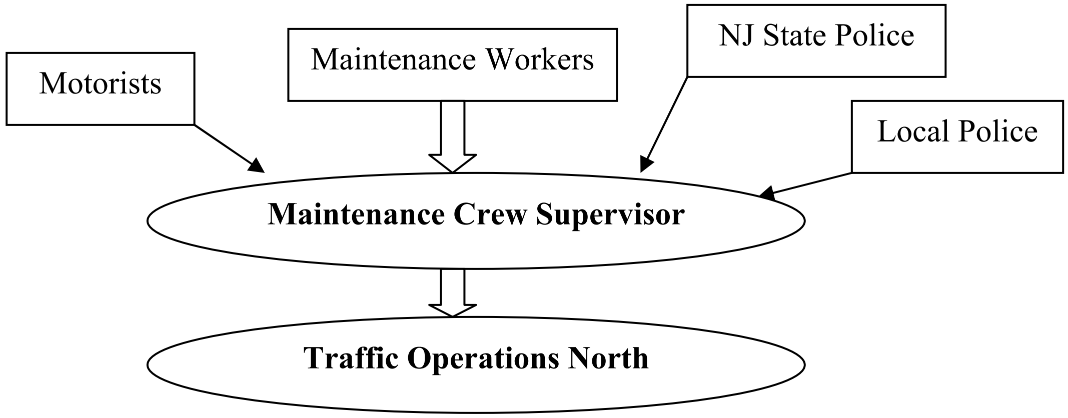

Figure 31. Route 80 Notification Structure: Non-Disabling Accidents

For these less severe collisions, the maintenance crew supervisor will contact Traffic Operations North regarding hits to the Route 80 thrie-beam pilot site. Traffic Operations North will then contact Rowan University.

I-78 Three-Strand Cable Pilot Site

Although similar to the I-80 notification process, the notification procedure for the I-78 test section is not as formalized. Figure 32 depicts the typical notification process for disabling accidents. Unlike the I-80 test section, though, the notification structure does not change for on and off-hour disabling collisions. If the impact occurs outside of normal business hours, Maintenance and Equipment Operations Central is notified of the collision, presumably through a dispatch center. Maintenance and Equipment Operations Central will then notify Rowan University directly of any hits to the I-78 three-strand cable barrier.

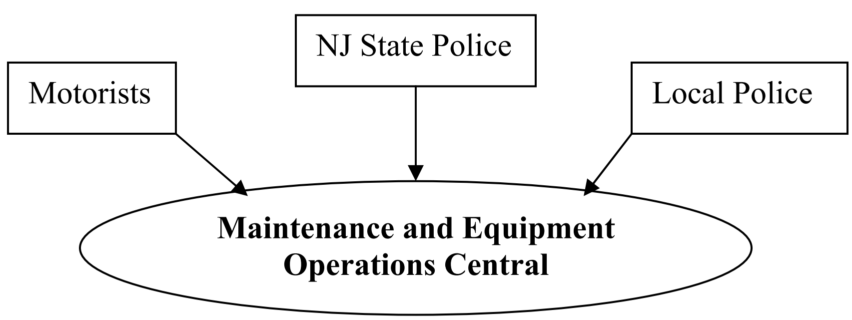

Figure 32. Route 78 Notification Structure: Disabling Accidents

Figure 33 depicts the notification process typical for **non**-disabling accidents where the police and/or emergency medical personnel are **not** present at the scene. There are four possible notification avenues: motorists, NJ State Police, local police and NJDOT maintenance personnel. Although notification of these accident types can occur via motorists or local or state police, the typical avenue is through the observations of NJDOT maintenance personnel while performing daily patrols of the roadways within their jurisdiction. Maintenance and Equipment Operations Central will then notify Rowan University directly of any impacts to the I-78 three-strand cable barrier.

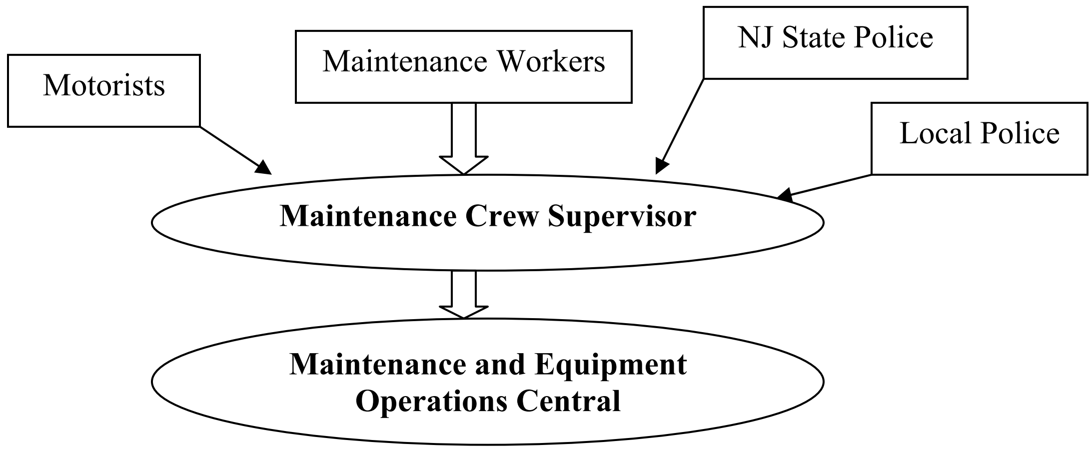

Figure 33. Route 78 Notification Structure: Non-Disabling Accidents

Response Logistics

After a crash notification has been made, a team of a least two investigators will visit the site and begin the data collection process. We currently have several data collection teams assembled and on call in case of notification. Each team is equipped with the proper onsite inspection tools including safety gear, various measuring instruments, and a digital camera.

Data Collection

In the event of an impact with either pilot barrier section, the research team will perform a detailed site investigation. This section presents the data collection protocol to be utilized during each site investigation. Data collected from onsite inspections will be analyzed to evaluate the effectiveness of the pilot median barrier systems. Onsite data collection can be broken out into three main categories: general site information, site photography, and barrier performance measures.

General Site Information

Since the barrier sites remain constant, the research team has performed a preliminary investigation at both locations to document the existing conditions. Also, the research team has acquired the as-built plans and barrier details for both sites.

Photography

Although they are not directly used in statistical analyses, photographic images are crucial to the accident reconstruction process. Investigators should document the following with photographs:

1. *General Scene*: Photograph the general scene, including roadway images up and downstream of the collision site. This will provide information about the general roadway environment and the relative location of the traffic barrier. Include these in the Supplemental Photo Data Sheet.

2. *Impact Site*: Photograph the median crash site including pictures of individual damaged posts. Each post should be identified with a number. Include these in the Impact Site Data Sheets.

3. *Component Damage*: Photograph every damaged component of the median barrier. Include these in the Supplemental Photo Data Sheet.

4. Photograph any tire marks or unusual terrain conditions that would indicate a crash. Due to the unique nature of each crash, it is important to photograph any other distinctive characteristics that may be present at the crash site.

Barrier Performance Measures

These measurements/descriptions are intended to provide detail regarding the performance of the barrier during the impact and will later be entered into data collection forms. Length is to be measured in millimeters and angles are to be measured in degrees. The following measurements will be essential to analyzing the barrier performance:

1. The approximate impact angle of the vehicle just prior to impact (with respect to the barrier)
2. Lateral offset or the perpendicular distance from the edge line to the barrier.
3. Rail height in undamaged area of barrier.
4. Total damaged length of barrier.
5. Component failures in the barrier system (rail element, posts, and connection).
6. Lateral and longitudinal displacement of each damaged post at the ground line.
7. Lateral and longitudinal displacement of each damaged post at post end.
8. Angle between post and ground.
9. Vehicle track width (if tracks present).

Data Organization

Data collection forms will serve as a crash investigation guide as well as an organizational tool for the collected information. Reference Appendix C for a copy of the data collection forms utilized for the crash investigations. The forms provide a clear and consistent record of the data that has been collected for each collision investigated. Note that each of the three forms has the same header information to ensure that corresponding forms remain associated.

The information to be included in the *Impact Site Overview* data collection form is summarized in Table 13.

Table 13. Impact Site Overview Form

Name	Description
Section Designation	Designate the name of the crash site (i.e. "Strike 1"). If there are multiple strikes in the barrier from different crashes, label them accordingly.
Location	Enter the location of the crash site inspection (i.e. route number, street name).
Date	Date of crash site inspection.
Date of Impact	Date of collision (if known).
Name of Investigator	Name of person(s) performing the inspection.
Description of Damaged Area	Fill in the number of damaged posts encompassing the crash, direction the vehicle was traveling, and whether the barrier redirected the vehicle.
Location of Reference Post	Fill in the distance and direction that the first and last reference posts are located from a known mile marker. The first reference post should be the closest undamaged post before the impacted section. The last reference post should be the closest undamaged post after the impacted section.
Location of Impact	Distance and direction of first damaged component from reference post #1.
Angle of Impact	The approximate angle that the vehicle was traveling just before impact (with respect to the barrier).
Number of Posts in Damaged Section	The total number of posts encompassing the crash site including the first and last reference posts.
Rail Type	Type of barrier (i.e. W-beam, cable barrier, etc).
Rail Height	Total distance (in millimeters) from the ground to the top of the rail.
Post Type	Fill in the type of post used in damaged section (i.e. S3x6 weak post). Include type of footing (i.e. soil, concrete, etc).
Vehicle Redirection/Barrier Performance	(Yes/No) Was the vehicle redirected?
Police Report	(Yes/No) If yes, include report number.
Post Spacing	Fill in the distance (in millimeters) between barrier posts.
Blockout	Fill in blockout type (if applicable).
Track Width	Distance (width) between vehicle tire tracks.
End Terminal Type	Fill in end terminal type (i.e. tied & anchored).
Barrier Penetration	(Yes/No) Did the vehicle penetrate the barrier?
Site Plan Map	Insert a sketch of the impact site. Include location of the barrier and location of the impact.

The *Supplemental Photos* form is included to capture additional images of the crash site that may be useful to the reconstruction of the crash event. This would include, but not be limited to, detached rail or post elements, unusual damage, or debris from the impacting vehicle. Note that each supplemental photo should have an associated description.

The information to be included in the Component Details data collection form is summarized in Table 14. Note that definitions for the first five "header" data elements are not repeated as they are identical to those on the *Impact Site Overview* form.

Table 14. Component Details Form

Name	Description
Post Number	Fill in post number.
Forward Displacement at Post End	Fill in the longitudinal displacement (parallel to barrier) at the top of the post (in millimeters).
Forward Displacement at Ground Surface	Fill in the longitudinal displacement of the bottom of the post (in millimeters).
Description of Damage to Post	Qualitative description of the damage to the post (including bending, shear, and torsion). Include whether or not the post-rail connection failed.
Lateral Displacement at Post End	Fill in the lateral (perpendicular to the barrier) displacement at the top of the post (in millimeters).
Angle Between Post and Ground	Use digital level to measure the angle between the post and the ground. (a vertical post would be 90˚)
Photo of Damaged Post	Insert photo of damaged post. Photo is to include post number designation.

Median Barrier Accident Database

In order to store and organize the data from the on-site field investigations a database was created utilizing the Microsoft ® Access Program. The goal of this database is to compile the on-site investigations so that users can sort the crashes based on desired criteria.

The New Jersey Barrier Performance database was based upon the database described in the NCHRP Report 490. [38] The overall five-form structure remains the same but the forms were modified to incorporate tabbed menus. This allows users to view the data without scrolling up or down to view the contents of the entire form. Some of the data fields were changed to satisfy the guide rail damage focus of the on-site field investigations. The table structure was unchanged, but some fields were tailored to meet the changes made to the forms.

The database consists of five main tables: (1) General Information, (2) Barrier Data, (3) Terminal Data, (4) Transition Data, and (5) Concrete Barrier Data. The General Information table consists of three sub-tables: Collision Data, Hardware Data, and Vehicle and Occupant Data. The remaining four tables deal strictly with the roadside hardware. Each of the four forms consists of three sub-tables: Cross Section Data and Impact Damage Data. This allows for a complete description of both the existing barrier and damage resulting from the impact. Although this project does not involve concrete barrier collisions, the Concrete Barrier Data table was kept in the event that NJDOT would like to collect information regarding these collision types.

In addition to the table and form changes, the database was also password protected. This feature prompts for a user name and password before opening the database. Certain user names were created with administrator rights, allowing the user to enter and edit data. The second group of users was only granted read-only rights, which prevents any modification to the information in the database. This was an important feature since it prevents unwanted tampering with the database information. Another feature of the database is the search function which allows users to search through the cases in the database based upon selected criteria. The cases that meet the desired criteria will be displayed with basic information about the case. Users will then be able to open the full forms for any of the cases that resulted from their search.

Refer to Appendix D for screen shots from the New Jersey Barrier Performance Database.

Results of Field Investigation

<u>Site Conditions</u>

The research team performed an initial visit to each of the pilot barrier sites to gather information regarding existing site geometrics and conditions. The data is summarized in Table 15.

Table 15. Summary of Pilot Section Site Conditions

Pilot Section	# of Lanes	Average Median Width (ft)	Median Cross Slope (H:V)	Barrier Offset (ft)	2003 Traffic Volume	Interchange Locations (< 1 mile)
I-78	6 (3 East, 3 West)	50	10:1	14 (WB lanes)	98,800	MP 25.03
I-80	6 (3 East, 3 West)	42	Variable (4:1 to 8:1)	14 (WB lanes)	100,800	MP 27.18, MP 28.82

Crash Experience

The research team has investigated a total of 12 accidents at the two pilot barrier sites between November 2003 and November 2004. Table 16 summarizes the accident experience for each of the pilot barriers.

Table 16. Summary of Pilot Section Accident Experience

Pilot Section	Location (MP)	Damaged Posts	Impact Angle	Barrier Penetration?	Police Reported?
I-78 Three Strand Cable Barrier	24.2	9	9	No	No
	23.8	3	Unknown	No	No
	23.8	5	3.5	No	No
	24.4	1	15	No	No
	24.2	2	Unknown	No	No
	23.8	1	Unknown	No	No
	23.8	1	Unknown	No	No
	23.9	19	<5	No	Yes
	24.4	16	50	No	No
	23.3	1	Unknown	No	No
I-80 Thrie Beam	27.8	-	Unknown	No	No
	27.5	-	Unknown	No	No

Table 16 indicates a significant discrepancy in accident frequency between the two median barrier pilot sites. The modified thrie-beam barrier on I-80 only experienced two crashes while the I-78 site experienced ten impacts. Site geometrics do not seem to provide any reasonable explanation: the I-80 site has a steeper and narrower median situated along a horizontal curve while the I-78 site has flatter slopes and only has a slight horizontal curvature. Based on this information, the I-80 site would be expected to have a higher accident frequency. It should be noted, however, that even though the I-78 median is wider, the cable barrier is much closer to the westbound travel lanes (offset approximately 10 feet), which could provide some explanation of the higher accident frequency observed.

Another important facet evident in Table 16 is that there were no instances of barrier penetration at either pilot site. Note that only one of the investigated impacts was police reported. Although detrimental from a research standpoint, the lack of police-reported accidents suggests that the pilot barriers are performing correctly; vehicles are being redirected by the barrier and the driver (presumably only with minor injuries, if any) is able to drive the vehicle from the scene.

Individual Crash Performance

A brief synopsis of each crash investigation is provided below. Refer to Appendix E for copies of the detailed investigation reports for each crash.

I-78 Impact 1: A total of 9 posts were damaged in this collision (approximately 130 feet of barrier) which occurred roughly at milepost 24.2. Based on vehicle tire tracks in the median, the impact angle of the vehicle was estimated to be approximately 10 degrees and the maximum deflection of the barrier was approximately 2.5 feet. Figure 34 is a photograph of the crash damage facing westbound.

Figure 34. Impact 1: Barrier Damage

I-78 Impact 2 and Impact 3: These collisions occurred within close proximity and just westbound of milepost 23.8. In the first collision, a 3 post section of the barrier was damaged (approximately 35 feet of barrier) and appeared to be caused by a vehicle moving in the westbound direction. The angle of impact could not be determined based on the evidence at the time of investigation. Refer to Figure 35 for an image of the damaged barrier section.


Figure 35. Impact 2: Barrier Damage

The second damaged barrier section occurs after approximately 30 feet of undamaged barrier and consists of 5 damaged posts (approximately 60 feet of barrier). Again, the damage to the barrier suggested that the errant vehicle had been traveling in the westbound direction. Tire tracks suggested a low impact angle of approximately 4 degrees. Refer to Figure 36 for a photograph of the barrier damage. In both instances, the vehicle was redirected with no barrier penetration; however, the research team could not discern whether the damage had been caused by a single vehicle or by two different vehicles on separate occasions.


Figure 36. Impact 3: Barrier Damage

I-78 Impact 4 thru Impact 7, Impact 10: All of these incidents were very minor in nature. With the exception of impact 5 (involving 2 posts), each only involves damage to a single post. The research team could not determine whether the damage was due to an unintentional run-off road incident or maintenance activities.

I-78 Impact 8: This impact involved 19 damaged posts (approximately 300 feet of barrier) and occurred near milepost 23.9. Based on the tire tracks at the scene, the vehicle impact angle was determined to be approximately 5 degrees and the probable direction of travel was westbound. The vehicle appeared to be successfully redirected by the barrier although the tire tracks indicate that the vehicle may have spun 180 degrees towards the end of the impact. The accident diagram provided on the police report indicated that the vehicle was traveling westbound, impacted the barrier and came to rest facing east. It should be noted that the occupant of the Pontiac Grand Prix was not injured. Refer to Figure 37 for a photograph of the barrier damage.

Figure 37. Impact 8: Barrier Damage

I-78 Impact 9: A total of 16 posts were damaged in this impact occurring near milepost 24.4. Note that only 2 posts were damaged and the remainder of the posts had at least one cable detached. The impact angle is approximately 50 degrees based on the tire marks at the scene, much greater than the other investigated collisions. Despite the apparently high impact angle, the barrier appeared to contain and redirect the vehicle. Refer to Figure 38 for an image of the barrier damage.

Figure 38. Impact 9. Barrier Damage

I-80 Impact 1 and Impact 2: Both impacts to the thrie beam involved only minor beam deflection with no evidence of any significant post damage. Due to the minor nature, a complete investigation was not performed for either of these incidents.

Conclusions

The following conclusions are evident based on the field investigation of the pilot median barrier sections:

- A total of 12 accidents were investigated at the two pilot barrier sites between November 2003 and November 2004. Two of the accidents were at the I-80 thrie beam pilot median barrier site. Ten of the accidents were at the I-78 three-strand cable barrier site. This was an unexpectedly high number of accidents.

- Both pilot barriers successfully contained and redirected all impacting vehicles.

- Only one of the 12 accidents was police-reported. Non-police reported crashes are, in general, highly unlikely to involve injury. This indicates that the pilot barriers were able to successfully contain the impact vehicles without causing occupant injury.

- Based on the experience with the cable barrier installation on I-78, maintenance of the system appears to be a problem which can adversely affect barrier performance. The barrier was slow to be repaired after damaged. In our study, the cables were frequently left on the ground for weeks after the crash, and were hence may have not been always available to contain an encroaching vehicle.

7. Conclusions and Recommendations

This section summarizes the effectiveness of cross median barrier systems based on the investigation of barrier effectiveness in other states, the performance of the pilot barrier sections, and finite element modeling of median barrier impacts.

Literature Survey of Current Practices and Field Experience

The review of the available literature has provided insight to the crash test and in-service performance of the various median barriers available. General conclusions regarding median barriers are as follows:

- Installation of median barrier reduces the incidence of higher severity cross median collisions while increasing the number of less severe collisions.
- With the exception of select concrete barriers, median barriers are not designed to contain and redirect heavy vehicles. Anecdotal evidence suggests, however, that most barriers will redirect heavy vehicles under certain less severe impact conditions.
- The newer cable systems, including the Brifen barrier, the Trinity CASS and the Safence 350, appear to be viable alternatives to the standard three-strand cable barrier.

Specific conclusions regarding the three strand cable barrier and the modified thrie beam barrier are as follows:

- Crash testing suggests that the three strand cable barrier is capable of containing and redirecting passenger vehicles. For the modified thrie beam, crash testing suggests satisfactory performance with passenger vehicles as well as a limited number of heavy vehicles.
- Several studies corroborate that the three strand cable is effective at reducing the incidence of cross median collisions in wider medians. Despite typically increasing the total number of accidents, the cable barrier reduces the overall collision severity.
- Although there is a more limited amount of in-service performance information, the modified thrie beam barrier appears to perform adequately.

Field Investigation of Median Barrier Crashes

Based on the research team's effort to investigate impacts into the pilot barriers, the following conclusions are evident:

- A total of 12 accidents were investigated at the two pilot barrier sites between November 2003 and November 2004. Two of the accidents were at the I-80 thrie beam pilot median barrier site. Ten of the accidents were at the I-78 three-strand cable barrier site. This was an unexpectedly high number of accidents.

- Both pilot barriers successfully contained and redirected all impacting vehicles.

- Only one of the 12 accidents was police-reported. Non-police reported crashes are, in general, highly unlikely to involve injury. This indicates that the pilot barriers were able to successfully contain the impact vehicles without causing occupant injury.

Finite Element Modeling of Median Barriers

Based on the generation of the finite element models of the pilot median barriers, the validation process and the parametric study, the following conclusions are evident:

- Site inspections revealed that both as-built pilot barriers matched the requirements of the AASHTO Roadside Design Guide.

- There is satisfactory agreement between both LS-DYNA models and the corresponding full-scale crash tests used to validate the models. Additional validation suggests that the thrie beam model is more robust than the three strand cable barrier.

- Additional modifications and subsequent revalidation need to be performed on both models prior to extrapolating these models to higher severity crashes.

- The finite element simulations suggest that both pilot barriers may perform to levels beyond which they are crash tested to under NCHRP Report 350 guidelines.

Recommendations

- Both pilot barriers are viable solutions to reduce the occurrence of cross median collisions on divided highways.

- Although there is typically an increase in the total number of collisions, the installation of the barrier typically results in an overall reduction of accident severity.

- Based on the experience with the cable barrier installation on I-78, maintenance of the system appears to be a problem which can adversely affect barrier performance. The barrier was slow to be repaired after damaged. In our study, the cables were frequently left on the ground for weeks after the crash, and were hence not always available to contain an encroaching vehicle.

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Appendix A – Annotated Bibliography

Thirez, Kristin, Radja, Greg, and Gary Toth. Large Truck Crash Causation Study – Interim Report. Report DOT-HS-809-527. National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, D.C. September 2002.

Conducted by the National Highway Safety Administration (NHTSA) and the Federal Motor Carrier Safety Administration (FMSCA), the Large Truck Crash Causation Study (LTCCS) is a three-year project to create a first-of-a-kind national database describing the causes and factors relating to large truck crashes. Ultimately, a better understanding of the mechanisms of these crashes will allow for the development of effective countermeasures to prevent or reduce the severity of these events. This interim report describes the field data collection methodology for the study and presents preliminary tallies of the crash data collected to date. Utilizing National Automotive Sampling System (NASS) data collection structure, accident investigators will collect detailed crash information on a nationally representative sample of large truck accidents. Since large trucks tend to be moved quickly from the scene following an accident, this study uses an on-scene investigation response protocol, as opposed to the typical reactive approach used by NASS investigators. Another nuance of this study is the cooperation of NASS accident investigators, police investigators, and FMSCA state truck inspectors, which is believed to enhance data collection efforts. Information is provided regarding the accident notification sequence, on-scene data collection procedures, as well as the data elements collected. Preliminary tallies are presented for approximately 600 crashes investigated to date. Note that this information is only provided to illustrate the types of accidents being sampled under this study (i.e. no national estimates should be inferred).

Although only a preliminary analysis is available at this time, this study appears to collect information of sufficient detail to be useful in the determination of national trends in large truck cross-median accidents. Augmenting this data with state-collected data could provide valuable insight on reducing the frequency and severity of these types of accidents. Also, the data collection and notification protocol developed as part of this study could be used as a guide for accident investigations within the state.

Ross, H.E., Sicking, D. L., Zimmer, R.A., and J.D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. NCHRP Report 350, TRB, National Research Council, Washington, D.C., 1993.

Intended as an update and expansion to NCHRP Report 230, this report presents uniform procedures for evaluating the safety performance of candidate roadside hardware, including longitudinal barriers, crash cushions, breakaway supports, truck-mounted attenuators and work zone traffic control devices. Evaluation of devices is facilitated through the three main criteria: (1) structural adequacy, (2) occupant risk, and (3) post-impact trajectory. Structural adequacy refers to how well the device performs its intended task (i.e. a guardrail preventing a vehicle from striking a shielded object); the post-impact vehicle trajectory ensures that the device will not cause subsequent harm (i.e. a vehicle being redirected back into traffic), and the occupant risk criteria attempts to quantify the potential for severe occupant injury. The guidelines recognize the infinite number of roadside hardware installations and crash configurations; standardized installation configurations and practical worst-case impact scenarios are used to provide a basis of comparing the performance of similar devices. Of particular note is the multi-service level concept that provides six different test levels to allow for more or less stringent performance evaluation (ideally dependant on the ultimate usage/placement of the hardware). Other deviations from the previous guideline include the conversion to metric units, the use of the ¾ ton pickup test vehicle in place of the 4500-pound passenger vehicle, inclusion of supplementary test vehicles (700-kg mini-compact passenger car and the 8000-kg single unit truck), side impact testing guidelines (developed by others), and guidelines for selecting the critical impact for tests involving re-directional hardware.

With respect to cross median crashes, this report is the standard by which median barriers are tested. Although the report specifies six different test levels, the warrants for devices meeting an individual test level is outside the scope of the document and left to the judgment of the transportation agency implementing the hardware. Generally, however, devices tested to the lower test levels (1 and 2) are used on lower volume, lower speed roadways, while devices tested to higher levels (3 thru 6) are typically used on larger volume, higher speed roadways. Note that the 2000P test vehicle (¾ ton pickup) is used to evaluate the strength and redirective capabilities of longitudinal barriers up to and including test level 3. All impacts are performed at 25 degrees and at 50, 70 and 100 kph for test levels 1, 2 and 3, respectively. For test level 4, 5 and 6, the guidelines specify the 8000S vehicle (single-unit van truck), the 36000V vehicle (tractor/van trailer) and the 36000T vehicle (tractor/tank trailer), respectively. All tests are performed with an impact angle of 15 degrees and impact speed of 80 kph. Information is needed regarding the ability of median barriers (tested to specific NCHRP 350 test levels) to prevent cross-median crashes for different vehicle types.

Sposito, B and S. Johnston. Three-Cable Median Barrier Final Report. Report OR-RD-99-03, Oregon Department of Transportation, July 1998.

Following three fatalities from a cross median accident 1996, Oregon Department of Transportation (ODOT) installed weak-post three-cable median barrier along sections of Interstate 5 (I-5) to reduce the potential for future occurrences. This study evaluates the cost-effectiveness of this system at preventing cross-median crashes on I-5. A general overview of the three-cable system is presented including advantages and disadvantages of the system, installation costs, and design details. Comparing accident frequency/severity data from 1987 through 1996 (pre-barrier installation) to the accident frequency/severity data from pre- and post-barrier installation, the three-cable median barrier was found to reduce both the rate of fatalities and susceptibility to cross-median collisions. Note, however, that the prevalence of minor accidents has increased since the barrier installation (from 0.7 to 3.8 injury accidents per year) and that this study only considers police-reported accidents (accounting for approximately 51% of the total accidents). Of a total of 53 accidents post-barrier installation, only three had some form of barrier penetration. In two cases, the vehicle underrode the barrier but did not cross into the opposing traffic lanes while the third case was a tractor-trailer that completely penetrated the barrier and crossed the opposing traffic lanes. Performing a cost-analysis incorporating the maintenance costs, the annual cost of the three-cable median barrier is found to always be less than that of concrete median barrier (for the subject location, study period, and utilized inflation rate). To demonstrate the typical time, manpower, and materials involved in a repair, documentation of a single repair event is provided.

This report indicates the cost-effectiveness of three-strand cable median barriers for reducing the propensity for cross median crashes and is in agreement with similar studies performed in North Carolina, Iowa, and New York. Note, however, that this system is only applicable at redirecting most passenger vehicles and that a heavy truck penetrated the study system. The authors indicate that none of the median barriers in Oregon are designed to contain these heavy vehicles, as it is not cost-effective. This system is also not applicable in all median types. A minimum median width of seven meters is required since this “flexible” barrier is capable of large deflections.

Glad, R.W., Albin, R.B., McIntosh, D.M., and Olson, D.K. Median Treatment Study of Washington State Highways. Report No. WA-RD-516.1, Washington State Department of Transportation, Olympia, Washington, March 2002.

Performed by the Washington State Department of Transportation (WSDOT), this study analyzes cross-median crashes in an effort to update the guidelines for median barrier warrants and develop a methodology for ranking median barrier needs across the state. Background is provided on the current median barrier warrant guidelines (essentially those recommended by AASHTO, developed in the 1960's) and previous WSDOT research that indicates a need for revision of the current warrants. The study focuses solely on multilane, divided highways with full access control, depressed or unprotected medians, speed limits greater than 45 mph, and AADT values in excess of 5,000. Using cross median crashes from January 1996 through December 2000 on the selected roadway sections, a benefit/cost analysis is performed for three barrier types: three-strand cable barrier, w-beam guardrail, and concrete barrier. The study finds a barrier is cost effective in a median width up to 50 feet and that the cable barrier is the most cost-effective system (based on the assumptions of the analysis). Note that the original ASSHTO guidelines only require an evaluation for the need of a median barrier for median widths up to 32.8 feet and ADT values greater than 20,000. If the median is less than 32.8 feet in width and the ADT is less than 20,000, barrier is optional. For median widths between 32.8 and 50 feet, barrier is also considered optional.

Consistent with the Oregon study, this study finds the cable barrier to be more cost-effective than concrete or w-beam median barriers. Note that there are significant limitations inherent in this study due to the use of anticipated benefit information. Since no barriers have actually been installed in the subject locations, the number and severity of barrier accidents is impossible to predict. Thus, for the purpose of the analysis, the number of accidents has been assumed constant and the severity selected as "possible injury" (this category corresponds to an average societal cost value). The authors reason that these assumptions will underestimate the number of collisions after barrier installation but may overestimate the severity of the collisions resulting in a reasonable net value. Actual contract cost and maintenance data were used to determine the cost of each system assuming that only minimal grading is necessary at the time of system installation. Maybe additional information can be gleaned from this study by comparing the study benefit/cost analysis (performed with anticipated benefits) to a benefit/cost utilizing actual benefits based on accident data obtained after barrier installation. Based on the results of this study, however, WSDOT is revising the median barrier warrants to recommend barriers on full access control, multi-lane highways with posted speeds above 45 mph and median widths less than 50 feet.

Martin, J. and R. Quincy. Crossover Crashes at Median Strips Equipped with Barriers on a French Motorway Network. Transportation Research Record 1758, Transportation Research Board, National Research Council, Washington DC, 2001, p 6-12.

The authors present an examination of cross-median crashes on French interurban four and six lane highways. All subject roadways have uninterrupted median barrier with intermittent removable barriers (70-120 meters in length) to provide access. Median barrier types include the New Jersey shape concrete barrier, single w-beam guardrail, and double w-beam guardrail. Note that only small portions of the barrier included are tested higher than level N2 (1500 kg vehicle impacting at 110 km/hr with a 20° angle of incidence). The 2000 km of roadways examined have an average median width between 3 and 5 meters, a 130- km/hr legal speed limit, and are situated on relatively flat terrain. Examining accidents between 1996 and 1998 (45,000 including both injury and property damage only accidents), the authors find that, although infrequent, cross-median crashes are more serious than other accidents. Only 0.5 % of the total accidents were cross-median collisions but 19 % of these collisions were fatal (only 1.3 % for other accidents). The risk of a cross-median crash is 15 times greater for a large truck and 4 times more likely if the barrier is metal rather than concrete. In addition, concrete barriers are found to increase injury collisions (when compared to metal barriers) but have no significant effect on the number of fatalities.

The results of this report show that concrete barriers are the most effective at halting cross median crashes, but tend to increase injury-accident frequency. The recommendation of this report is to possibly use a concrete New Jersey type concrete barrier and a metal W-beam type metal barrier in conjunction to decrease the number of cross median crashes non-median-crossover accidents. Note that there are several important limitations of the data used in this study. Other than the number of lanes, there is no detailed roadway data such as roadway alignment, cross-slope, and median barrier location with respect to roadway. In addition, there is no information regarding the vehicle impact speed and impact angle. Both the distribution of roadway characteristics and impact conditions could have a significant effect on the number of cross median crashes and the selection of proper countermeasures.

Sickling, D.L, Reid, J.D., and J.R. Rhode. Flared Energy-Absorbing Terminal Median Barrier. *Transportation Research Record 1797*, Transportation Research Board, National Research Council, Washington DC, 2002, p 89-95.

This article presents the full-scale crash test results of the Flared Energy-Absorbing Terminal - Median Barrier (FLEAT-MT). An introduction to the design concept precedes a detailed description of the device, required materials, and installation procedures. Similar to the FLEAT guardrail terminal, the FLEAT-MT utilizes impact heads to "kink" the w-beam rail and absorb the kinetic energy of the impacting vehicle. In the FLEAT-MT, however, the impacting heads are staggered; the oncoming traffic side extends an additional three posts from the opposing traffic side and has a flare such that both impacting heads are nearly aligned. Three full-scale crash tests were performed to evaluate the impact performance of the FLEAT-MT: 2000P redirection test (3-35), 2000P head-on-test (3-31), and 2000P reverse-direction test (3-39). In accordance with NCHRP Report 350, all tests were passing for test level 3 median barrier terminals. The FHWA is currently evaluating the FLEAT-MT for approval to be used on national highway systems.

The FLEAT-MT is an economical end terminal for w-beam median barriers. From the construction details provided, the FLEAT-MT appears better suited for smaller width medians as the installation procedures have the opposing w-beams within a few feet of each other. Additional information regarding the placement of barriers and cross-median collisions is needed. For instance, is it more effective to position a w-beam at each edge of the opposing traffic stream or to position both together within the median?

Hunter, W.W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M., and Harkey, D. L. Three-Strand Cable Median Barrier in North Carolina: In-Service Evaluation. *Transportation Research Record 1743*, Transportation Research Board, National Research Council, Washington DC, 2001, p 97-103.

The authors present a safety evaluation of three-strand cable median barrier installed on a 9-mile stretch installed on Interstate 40, a freeway in North Carolina. Data was extracted from the Highway Safety Information System (HSIS) and includes only North Carolina data between 1990 and 1997. A before-after comparison is facilitated by the development of several regression-type models that use a reference population (e.g. all freeway locations without cable median barrier treatment) to predict the number of accidents at the locations with cable median barriers. The predicted number of accidents is then compared to the actual number of collisions at the sites with cable median barrier. Explanatory variables used to predict expected accident counts include AADT, median type, median width, number of lanes, and segment length. Examining the available data, a statistically significant increase is found in the total number of crashes on the sections with cable median barrier (after installation of the barrier). Also, the installation of the cable barrier produced a significant reduction in the combination of serious and fatal collisions. For other collision types, the models predict (and the accident data was in agreement) increases in rear-end crashes as well as overturn crashes for the treatment area. Since there were no cross median accidents after the installation of the barrier, the effect of the barrier on this crash mode could not be estimated.

Similar to the Oregon and Washington studies, this study of cable median barrier in North Carolina supports the effectiveness of this type of barrier (i.e. although there is an increase in accident frequency, the severity of those accidents is significantly reduced). Note that this study is limited, however, to barrier installation on a single freeway with a median width ranging from 44 to 64 feet and almost 80 percent of the cable was double-run (one barrier on each side of the median).

Fitzpatrick, M.S., Hancock, K.L., and Malcolm H. Ray. Videolog Assessment of Vehicle Collision Frequency with Concrete Median Barriers on an Urban Highway in Connecticut. *Transportation Research Record 1690*, Transportation Research Board, National Research Council, Washington DC, 1999, p 59-67.

The authors present a methodology to utilize video to investigate the in-service performance of concrete median barrier. Since these median barriers are typically installed on high volume, high-speed roadways with narrow medians, site inspections pose serious risk to investigators or require a disruption of traffic patterns. To solve this problem, the authors propose the use of video on board a modular van to determine the frequency of accidents with the concrete median barrier. A small portion of I-84 in Connecticut serves as the study section and a demonstration of the proposed methodology. The study section is 1.68 km in length with an average daily traffic of approximately 128,000 vehicles per day, median width of 0.78 meters, and number of travel lanes varying from 2 to 4. A baseline video was compared to 5 subsequent videos to determine the number of collisions with the concrete median barrier in the study section during the 6-month study period. The collected data indicates that approximately 1 in 4 concrete median barrier impacts in the study section are reported to the police. Comparing curved and tangent roadway sections, the study finds that the collision rates on curved roadway segments are approximately 3 times greater than on tangent sections. Since the median width in the study section is so narrow, the authors assume that the collision rate observed is not much different than the median encroachment rate. The encroachment rates are then compared to estimates provided by widely used roadside hardware benefit/cost analysis programs, Roadside and RSAP. Neither Roadside nor RSAP, however, provided a realistic estimate of the encroachment rates observed on the study section.

This paper illustrates a safe and effective method to perform an in-service evaluation of concrete median barrier installed on high-volume, high-speed roadways. Although the authors modified an existing modular videologging unit originally designed to acquire roadway data, they indicate that videologging is cost-effective even if a particular agency does not currently have such a device. Note that the Roadside and RSAP estimates of median encroachments are based on data collected on much lower volume roadways than the study section.

Miaou, S., Hu, P., Wright, T., Davis, S., and A. Rathi. *Development of the Relationship Between Truck Accidents and Geometric Design: Phase I*. Federal Highway Administration, August 1993.

The purpose of this study was to develop preliminary relationships between large truck accidents and roadway geometric features to address the following issues: (1) how safe a given roadway section is in terms of truck accident rate and truck accident probability, (2) identification of geometric design elements that have a greater impact on safety based on large truck accidents, and (3) quantification of large truck accident reductions expected by a given geometric design improvement. Two models were developed based on the Poisson and negative binomial regression models using data from Utah collected under the Highway Safety Information System (HSIS). Each model considered three classes of roadway: rural interstate, urban interstate, and rural two-lane undivided arterial. Preliminary relationships have been developed for number of lanes, annual average daily traffic (AADT) per lane, horizontal curvature, length of curve, vertical grade, length of grade, and shoulder width. Based on the developed models, the authors make suggestions with respect to the collection of additional variables and the sample collection procedures required for a model applicable to different geographical regions.

Although this study focuses on the development of relationships between various geometric design features and all accidents involving large trucks, there is little that can be gleaned regarding cross-median accidents. One finding of interest, however, is that as paved inside shoulder width increases in each direction on a rural interstate, truck accident involvement rate decreases by approximately 8 percent.

Lynch, J. M., N. C. Crowe, and J. F. Rosendahl. *Across Median Accident Study: A Comprehensive Study of Traffic Accidents Involving Errant Vehicles Which Cross the Median Divider Strips on North Carolina Highways*. North Carolina Department of Transportation, Raleigh, 1993.

The objectives of this study were to identify interstate locations with a high propensity for cross-median crashes (using existing accident data), determine possible safety improvements, and develop a prioritized listing of these sites and recommended improvements. Examining North Carolina accident data from April 1988 through October 1991, the authors identified and performed site investigations for a total of 751 cross-median accidents. Cross-median accidents, although occurring less frequently (3% of all interstate accidents in the study), represent a significant portion of the interstate fatalities (32%). The available data suggests that cross-median crashes are generally more severe than other interstate accidents; 9% of cross-median accidents were fatal (3% for other interstate accidents) while 31% resulted in severe injury (15% for other interstate accidents). Also, the study indicated a steady increase in the number of cross-median fatalities and injuries during the study period and determined that alcohol is not a significant factor in these types of crashes. For the identification of potential problem areas in North Carolina, the authors ranked a total of 24 sections of interstate highway based on a benefit/cost analysis and an incremental analysis. Note that, for majority of these interstate sections (15 of 24), double-faced guardrail is proposed. Single-faced guardrail and concrete barrier (NJ shape) is proposed for the remainder of the sections.

The findings of this study are consistent with other cross-median crash studies (i.e. cross median crashes are found to be less frequent but more severe than other crash types on divided roadways). It is interesting to note that none of the proposed median barriers are three-strand cable systems although all of the median widths are in excess of the required 7 meters (for cable systems). Other findings of interest relate to the divided roadway characteristics. The cross median accidents per mile are significantly higher (almost 3 times) for interstates with a posted speed limit of 55 mph than for interstates with a posted speed limit of 65 mph. Also, from the available data, the largest number of cross median accidents is on interstates with median widths varying between 20 and 40 feet.

Seamons, L. L., and R. N. Smith. *Past and Current Median Barrier Practice in California. Report* CALTRANS-TE-90-2. California Department of Transportation, Sacramento, 1991.

The objective of this research is to review California Department of Transportation's (Caltrans) past and current median barrier warrants and, using accident data, determine if they are still reliable. A brief history of median barrier policy is presented up to and including the current (1991) practice. To determine the need for a median barrier on a divided freeway, Caltrans utilizes a two-tiered approach involving the number of cross-median accidents and the combination with traffic volume and median width. Examining California cross-median accidents for a 5-year period (1984 through 1988), no changes are suggested to either warrant. The accident data is also used to investigate differences in accident severity, penetration rates, and proportion of rebound accidents for various barrier types. A comparison between concrete and metal median barriers reveals a slight increase in severity for concrete barrier impacts (55% fatal or injury versus 53% fatal or injury for metal barrier in medians 36 to 41 feet). An analysis of barrier penetration indicates the effectiveness of median barriers at preventing cross median crashes; the cable barrier is found to have a penetration rate of 0.70% while concrete, w-beam, and thrie beam have penetration rates of approximately 0.10%. For rebound collisions, cable barriers are found to have the lowest proportion while no significant differences are found between w-beam, thrie beam and concrete median barrier. Also, a before-after study of 24 freeway sites and 5 non-freeway sites indicates that median barrier installation can be expected to increase median accidents 10 to 20 percent and 50 percent or more on freeways and non-freeways, respectively.

The volume/median width warrants reviewed call for median barrier to be installed on all divided roadways with an excess of 40,000 annual average daily traffic (AADT) and median widths less than or equal to 45 feet. For AADT values less than 40,000, the warrant is proportional to the median width (the wider the median, the more traffic is required to warrant a barrier). For the accident warrant, Caltrans utilizes a cross median accident rates of 0.50 (total accidents) and 0.12 (fatal) accidents per mile per year with a minimum of three cross median accidents at a particular site in a five year period. A yearly median barrier monitoring system is implemented by Caltrans to monitor the California freeway system (including multi-lane non-freeway roads) against both established median barrier warrants. Personnel at each district perform a detailed review and field investigation for those sites meeting either warrant. Caltrans headquarters assembles the reports from each district and determines the funding allocation. Another interesting facet of the Caltrans median barrier approach is the phasing out of cable and w-beam median barriers in favor of concrete barriers and thrie beam metal barriers. Note that concrete barriers are used in median widths up to 36 feet while thrie beam is used in median widths between 20 and 45 feet.

Khorashadi, A. *State Route 37 Safety Evaluation Report*. Report FHWA/CA/TE-99/12, California Department of Transportation/Federal Highway Administration, May 1999.

Khorashadi presents a before and after type safety evaluation of various improvements to State Route 37, which include the elimination of existing passing lanes and replacement with concrete median barrier. An approximately 3-mile section is analyzed and the final roadway cross-section consists of two 12-foot lanes separated by concrete barrier, two 5-foot inside shoulders, and has two 8-foot outside shoulders. Accident data for 11 months after the improvements are compared to corresponding time periods in the five years prior to the implementation of the improvements. The raw data indicates a reduction in total, fatal, sideswipe, head-on, run-off road accidents, and an increase in rear-end accidents. Developing a statistical model based on the Poisson distribution, the author compares the predicted number of accidents from the model (if no improvements to the roadway are made) with the actual number of accidents on the improved roadway. For fatal, head-on, and sideswipe accidents, the observed decrease in accidents is found to be statistically significant with 95 percent confidence.

The results of this study suggest that the implementation of concrete median barrier can decrease fatal and head-on accidents on two-lane roadways. Khorashadi cautions the influence of other improvement projects undertaken on or near the analysis roadway section in the analysis period. These include a superelevation improvement and the implementation of a double fine zone. Also note that the average annual daily traffic (AADT) for the analysis section does only varies slightly over the analysis period, thus, the accident counts have not been adjusted based on traffic volume.

Nystrom, K. *Median Barrier Study Warrant Review – 1997*. Report CALTRANS-TE-97-02, California Department of Transportation, December 1997.

This report is part of the ongoing study/review of the median barrier warrants used in the state of California (Seamons and Smith, 1991 is the preceding study). Prompted by significant changes in vehicular traffic (more than a 25% increase in freeway travel and speed limit increase from 55 to 65 mph or more), the objective of this research is to review the current median barrier warrants using current California accident data and evaluate the need for an update. Following a comprehensive history of previous median barrier practices and related Caltrans studies, Nystrom indicates that the study is specifically focused on investigating the volume/width warrants for median widths in excess of 45 feet, as an increasing number of roadways with wider medians are meeting the accident frequency warrants. An analysis of California freeway accident data from 1991 through 1995 indicates that the installation of median barrier decreases fatal accident rate by approximately 40% while increasing both the injury accident and total accident rate by approximately 75% and 100%, respectively. The study employed two methods of evaluating the cost effectiveness of potential modifications to the current warrants. A benefit-cost approach is utilized to quantify the balance of benefits from a decrease in cross-median accidents with the consequences of increased injury accidents (due to the presence of the barrier) while the diminishing return analysis is used to identify the barrier warrant(s) that will produce the greatest return (i.e. reduction in cross median accidents). Using the benefit/cost approach, the study determines that extending the current barrier warrants to include median widths up to 75 feet is cost effective. In accordance with a previous Caltrans study done in 1968, the diminishing return analysis indicates that a combination of the traffic volume and median width as a warrant for median barrier will produce the greatest benefit. Note that this study recommends that the accident warrant portion of the Caltrans median barrier warrant remain unchanged.

This study outlines a methodical approach to determining the effectiveness of median barrier warrants. California utilizes the AASHTO median warrant recommendations as a guide but relies on analysis of state-specific data to develop the warrants that are used in implementing median barriers across the state. The result is warrants substantially different than those recommended by AASHTO, which are implemented by New Jersey. Perhaps a similar study done for freeways within New Jersey will result in the optimal set of median barrier warrants for the traffic conditions observed in this state.

Mustafa, M. B. *Use of Three-Strand Cable Barrier as a Median Barrier - Interim Report*. North Carolina Department of Transportation, Raleigh, August 1997.

The purpose of this interim report is to document the effectiveness of the three-strand cable median barrier in terms of required maintenance and repair. Due to a cross median accident problem, the North Carolina Department of Transportation (NCDOT) installed a three-strand cable median barrier along an 8.5-mile section of Interstate 40 (This stretch of median barrier is the focus of the study). A majority of the subject roadway is a 6 lane divided highway, including 12 foot outside shoulders and 10 foot inside paved shoulders, with median width varying from 39 to 64 feet. With the exception of a single mile segment of single-run cable median barrier, three-strand cable barrier is installed on both sides of the grassed median. Observation of the study section and maintenance procedures produced the following observations: (1) installation of the three-strand cable median barrier essentially eliminated the cross median crash problem at the study site, (2) installation of the barrier produced an increase in the overall number of crashes at the study site, and (3) the manufacturer does not provide a repeatable indicator of the tension in the cables.

The authors' note that since the three-strand cable barrier is utilized around the country for median applications, this report focuses solely on the maintenance and cost issues rather than crash performance. For the study section, the installation cost of the barrier was $8.82 per linear foot and $2,111.00 for each anchor terminal (1994 dollars). Other than periodic need to tension the cables, maintenance involves activities similar to the installation of the barrier (in the event that it is struck by an errant vehicle). According to study, an eight-man maintenance crew can replace 50 to 75 posts in approximately 2 hours. The average repair cost per post is cited between $60 and $65 (1996 dollars). Also note that the barrier repair is only done immediately following an accident if both sides of the median are damaged at once or when the barrier is damaged at a location where there is only a single barrier in the center of the median.

Griffith, Michael S. *Safety Evaluation of Continuous Shoulder Rumble Strips Installed on Freeways.* Masters Thesis, University of Maryland at College Park, 1998.

Griffith investigates the safety benefits (e.g. reduction of single vehicle run-off road collisions) and potential adverse effects of the installation of continuous shoulder rumble strips (CSRS) on urban and rural freeways. Although previous studies have been done to address the safety implications of CSRS, the author indicates a large variation in the study findings, possibly a result of limited samples and unsound methods of analysis. The purpose of this study is to provide an estimate of the safety effectiveness of CSRS based on a large sample and sound analysis methodology. Data from the Highway Safety Information System (HSIS) for Illinois and California was used to perform before-after evaluations of CSRS projects using different comparison groups. More emphasis has been placed on the Illinois data since it contains a larger sample and more detailed accident data. Based on the Illinois data, CSRS are found to reduce the total number of single-vehicle run-off-road accidents by 16 percent on all freeways and 21 percent on rural freeways. The investigation of potential adverse effects (e.g. potential multi-vehicle accidents due to CSRS startling a driver) indicates no significant adverse effect in the available data.

The study does not indicate whether cross-median accidents have been included in the analyses. Since CSRS are typically installed on both inside and outside shoulders of a freeway, the potential effect of these devices to deter cross-median crashes should be investigated. As they are relatively low-cost and maintenance free (compared to a barrier), they may provide another cost-effective alternate method of reducing cross median crashes. Or, in the least, can be used in conjunction with median barriers to reduce the amount of impacts with median barrier.

Mak, King K. and W.L. Menges. *NCHRP Report 350 Compliance Test of the New Jersey Safety Shaped Barrier*. Draft Report FHWA-RD-96-201, Texas Transportation Institute/Federal Highway Administration, March 1997.

Adoption of the revised procedures for roadside safety testing (NCHRP Report 350) raises questions regarding the performance of devices tested under the previous standard (NCHRP Report 230). The objective of this research is to evaluate the crashworthiness of the New Jersey safety shaped barrier with the new standard, specifically the new 2000P test vehicle (2000 kg Pickup). A single crash test was conducted at test level 3 specifications (100 km/hr impact speed and 25° impact angle) on a previously constructed NJ shape bridge rail barrier. According to the authors, the use of a bridge barrier has no bearing on the test results, as the vehicle stability was the factor of concern rather than the structural adequacy of the barrier. Based on the results of the crash test, the NJ safety shaped barrier is deemed acceptable on the basis of the NCHRP 350 evaluation criteria. Note, however, that the 2000P test vehicle climbed to the top of the barrier and had a maximum roll of 34° away from the barrier.

Hirsch, T. J., Fairbanks, W. L., and C.E. Buth. Concrete Safety Shape with Metal Rail on Top to Redirect 80,000-lb Trucks. Transportation Research Record 1065, Transportation Research Board, National Research Council, Washington, DC, 1986, p 79-87.

The objective of this research is to test a concrete barrier modified to contain and redirect an 80,000 lb van-type tractor-trailer for bridge and median applications. To obtain the strength required for the intended redirection, the authors modified the cross section of a Texas Type T5 concrete barrier (32-inch high) and mounted a modified version of the Texas Type C4 metal traffic rail on top resulting in a 50-inch high barrier. Although the vehicle ultimately rolled a quarter turn onto its side, the modified barrier successfully redirected the van tractor-trailer impacting at 48.4 mph and at an angle of 14.5 degrees. Note that the modified rail met all the required NCHRP 230 evaluation criteria and that the occupant risk values were within prescribed limits (although the occupant risk limits do not apply to large truck tests). The quarter turn roll of the vehicle has been attributed to the fact that the metal rail is set back approximately 10 inches from the front face of the concrete portion of the rail. Due to the slight increase in concrete cross section and modifications necessary to the metal rail, the modified rail cost is approximated at 80 dollars per linear foot compared to 35 dollars per linear foot for typical Texas Type T5 concrete barrier.

Although this research successfully identifies a median barrier that can redirect large vehicles, implementation of this device on freeways with large medians may not be cost effective. The modified barrier costs approximately ten times that of cable median barrier and, since cross median crashes are a relatively rare occurrence, the cost of installation for the system presented may be greater than the potential benefits. For high-volume roadways with a narrow median, however, this barrier appears to be a viable alternative.

Mak, King K., Bligh, Roger P., and W.L. Menges. *Testing of State Roadside Safety Systems, Volume I: Technical Report*. Draft Report 471470 – Vol. I, Texas Transportation Institute/Federal Highway Administration, September 1996.

A collaborative effort between the U.S. Department of Transportation and Federal Highway Administration, this research was aimed at evaluating new and modified roadside safety hardware, and, if necessary, improving their impact performance. To evaluate a total of 12 different types of appurtenances, a series of 36 full-scale crash tests were performed at the Texas Transportation Institute between November 1989 and December 1996. All tests were conducted in accordance with National Cooperative Highway Research Program (NCHRP) Report 230, NCHRP Report 350, and/or the AASHTO Guide Specifications for Bridge Railings, depending on the device tested. This report summarizes the findings of the entire effort while more detailed information regarding particular test sets is dispersed among 13 appendices. Note that this study focuses on the following three areas: (1) impact performance of the bridge railings, (2) performance of transition sections (from guardrails to bridge railings), and (3) impact performance of end terminals (for guardrails and median barriers).

Of particular interest is the crash testing and evaluation of existing guardrail systems in accordance with the relatively new NCHRP 350 guidelines. Using the 2000P (pickup truck) test vehicle, the following devices were tested: the cable guardrail system (G1), the weak-post w-beam guardrail system (G2), the box-beam guardrail system (G3), the strong-post w-beam guardrail system (G4), the thrie-beam guardrail system (G9), and the modified thrie-beam guardrail system. The w-beam weak-post system, w-beam strong-post (steel post) guardrail system, and the thrie-beam (G9) system failed the NCHRP 350 test level 3 conditions. Note that the cable guardrail, modified thrie-beam, w-beam strong-post (wood post) guardrail, and the box-beam (G3) system satisfactorily passed the NCHRP 350 test level 3 criterion.

Jewell, J., Rowhani, P., Stoughton, R. and W. Crozier. *Vehicular Crash Tests of a Slip-Formed, Single Slope, Concrete Median Barrier with Integral Concrete Glare Screen*. Report FHWA/CA/ESC-98/02, California Department of Transportation/Federal Highway Administration, December 1997.

The objective of this research is to determine if the Type 60G single slope concrete barrier satisfies the NCHRP Report 350 testing standards and to evaluate whether this barrier provides an equivalent alternative to the Type 50 (NJ Shape) concrete median barrier. California has used the NJ-shape concrete median barrier extensively on narrow median roadways since the 70's, however, have found several shortcomings of the design. First, thick pavement overlays change the geometry of the barrier and potentially increase the potential for vehicle to climb over the barrier. Also, there is no variation of this barrier high enough to provide a glare screen (from oncoming traffic). The proposed Type 60G single slope barrier is high enough to provide glare screen (1420 mm compared to the 820 mm NJ shape) and the geometry is not affected by road overlays. Note that the Type 60 barrier is similar to the Texas single slope barrier but has a vertical face angle of 9.1 degrees instead of 10.8 degrees; the reduced angle provides a design compatible with the more narrow medians present in California. A total of 5 crash tests were performed in accordance with NCHRP 350 Test level 3 conditions: 2 tests on a 1420 mm Texas barrier, 2 tests on a 1420 mm Type 60G barrier, and a single test with a 810 mm tall version of the Type 60 barrier. Note that the 2000P test with the Texas barrier failed due to guidance problems and was not repeated. The Type 60 barrier is deemed acceptable with respect to NCHRP 350 test level 3 and is recommended as a replacement for the NJ shape median barrier. Since none of the tests displayed significant vehicle climb (all under 250 mm), it is suggested that a Type 60 barrier 820 mm in height will perform as well as the 1420 mm Type 60G barrier.

Improved Guidelines for Median Safety: Summary of State Transportation Agency Survey. BMI, NCHRP 17-14(2) Draft Report, National Research Council, Washington DC, 2003.

A product of research conducted under National Cooperative Highway Research Project (NCHRP) 17-14(2), "Improved Guidelines for Median Safety", this report indicates the current practices, procedures, and policies of state transportation agencies with respect to the warrant and usage of median barriers. The overall objective of the project is to develop improved median barrier guidelines, for high-speed divided roadways, suitable for adoption in AASHTO's Roadside Design Guide. Presenting results from a questionnaire sent to each state transportation agency (50 + Washington, DC), the authors compare and contrast the median barrier guidelines of the responding states to the national recommendations contained in the AASHTO Roadside Design Guide. Approximately 74% (26 of 35 respondents) of the responding state transportation agencies followed the AASHTO recommendations. For the states not following the national recommendations, the report documents the deviations and the basis for the changes to the national recommendations.

With respect to the median width or side slope design criteria, the study finds only slight variation from the AASHTO recommendations for the states that deviate from those recommendations. For the same deviating states, however, the median barrier warrants utilized vary widely and are typically based on either on a safety or economic study. Although the three-strand cable and Brifen cable median barriers are gaining national attention, the two most commonly used median barriers are the concrete median barrier (New Jersey Shape or F-Shape) and the strong-post w-beam guardrail. In terms of median barrier placement, a majority of state transportation agencies attempt to place the barrier at the center of the median, if the median is symmetric. For asymmetric medians, the study finds that the AASHTO guidelines are generally followed. Despite a lack of exposure data, information is provided regarding the frequency and severity of cross median accidents for approximately 60% of the survey respondents. As expected, there is a large variation with the frequency of cross median collisions varying from 1 every 3-5 years to approximately 500 per year. The aggregate data suggests, as found in other studies, that cross median crashes are typically more severe. Also note that the most common mitigation measure for prevention of cross median crashes is the installation of median barrier.

Wiles, E. O., Bronstad, M. E., and C.E. Kumball. Evaluation of Concrete Safety Shapes by Crash Tests with Heavy Vehicles. *Transportation Research Record 631*, Transportation Research Board, National Research Council, Washington, DC, 1977, pp 87-91.

The authors detail three full-scale crash tests performed to evaluate the New Jersey shape concrete median barrier with respect to heavy vehicles. Each test utilized a 40,000 lb intercity bus impacting a 200-foot long NJ shape barrier installation at speeds of 67, 83, and 85 km/hr and at angles of 11.5, 6.6, and 16 degrees, respectively. Note that the damage attained by the bus on the first two tests was repaired prior to the subsequent tests. For each test scenario, the concrete barrier redirected the vehicle without a rollover (maximum of 24° roll towards the barrier in the 85 km/hr - 16° test). Although extensive barrier damage was documented in the 85 km/hr - 16° test, the authors conclude that the rear-end contact of the bus caused the damage and does not inhibit the ability of the barrier to redirect the vehicle. The authors hypothesize that the barrier failure could be remedied with sufficient embedment but that may cause roll of the barrier (rather than lateral displacement) and result in vehicle vaulting.

Ray, Malcolm H. and Richard G. McGinnis. *Synthesis of Highway Practice 244: Guardrail and Median Barrier Crashworthiness.* Transportation Research Board, National Research Council, Washington, D.C., 1997.

The purpose of this synthesis is to assimilate information regarding the current use of guardrail and median barrier among US states and how these barriers perform with respect to the current National Cooperative Highway Research Project (NCHRP) Report 350 testing standards. Comprehensive background information is provided for the evolution of testing procedures, selection and placement procedures and in-service evaluation of longitudinal barriers and median barriers. The results of a survey sent to all 50 states (only 39 respondents, however) provide general comparisons between barrier design, applications, and installation/maintenance costs among the states. A more detailed review is presented for each broad longitudinal barrier classification: weak-post systems, strong-post systems, concrete barriers, and aesthetic barriers. For each longitudinal barrier system, the authors provide a description of the system, a characterization of the distribution (which states utilize the system), results of relevant crash testing, and the typical in-service applications of the system. Ideally, this report is to provide a single resource to aid engineers in selecting the proper roadside hardware.

Examined weak post systems include the weak steel-post three-cable guardrail/median barrier, the weak wood-post three-cable guardrail/median barrier, the weak-post w-beam guardrail/median barrier, and the weak-post box-beam guardrail/median barrier. Notable advantages of the weak steel-post three-cable system include NCHRP Report 350 test level 3 compliance, inexpensive installation, minimized sight distance problems, reduced occupant forces in the event of a collision, and reduced snow drifting/accumulation. Disadvantages of this system include periodic monitoring of cable tension, a large clear area for barrier deflection, and increased barrier damage in the event of a collision. Due to a lack of an acceptable terminal and no crash testing for compliance with NCHRP Report 350, the weak wood-post three-cable barrier is expected to decline in use in the following decades. Similarly, the weak-post w-beam system no longer has an acceptable end terminal and usage is also expected to decline. Note that this system only passed NCHRP Report 350 test level 2 conditions. The weak-post box-beam system has passed Report 350 test level 3 (guardrail version only, however, the median version is expected to pass on that basis) and has a single proprietary end terminal. Although it appears to perform adequately, this barrier system cost may make the strong post w-beam guardrail a more cost effective option.

Examined strong post systems include the strong-post w-beam guardrail/median barrier, the strong-post w-beam with rubrail guardrail/median barrier, and the strong-post thrie-beam guardrail/median barrier. Although the strong-post w-beam guardrail is the most utilized barrier system, there are serious questions with regard to its Report 350 performance, specifically the 2000P test vehicle (¾ ton pickup). The strong-post w-beam with rubrail system is unlikely to be tested under Report 350 guidelines, as it not widely used. Other complications with this system include a higher cost (when compared to the higher-performance, lower cost modified thrie-beam system), sight distance obstruction, and the potential for accumulation of roadway debris. For the thrie-beam designs, only the modified thrie-beam has passed the NCHRP Report 350 test level 3 conditions. The modified thrie-beam is also effective for redirecting trucks and buses (test level 4 for the median version and test level 6 for the barrier version).

For concrete systems, the authors include the New Jersey shape barrier, F-shape barrier, and the constant slope barrier. Similar to the strong-post w-beam systems, the NJ shape concrete barrier remains one of the most widely used barrier systems in the United States. Relatively maintenance free with little or no dynamic deflection, this rigid barrier satisfies the NCHRP 350 criteria up to and including test level 5. Some notable disadvantages include vehicle redirection back into the traveled way, higher occupant forces, expensive construction cost, and possible sight distance problems. The F-shape barrier is similar to the NJ safety shape but with a lower break point (intersection of the two slopes). Since its usage is not as widespread as the NJ shape, the F-shape is more expensive than the NJ shape and has not been extensively tested to the Report 350 standards (although it is expected to perform adequately). The constant slope barrier shares many of the same characteristics as its rigid counterparts; however, the shape of the barrier is not compromised with overlays.

Knuiman, Matthew, Council, Forrest M., and Donald W. Reinfurt. Association of Median Width and Highway Accident Rates. *Transportation Research Record 1401*, Transportation Research Board, National Research Council, Washington DC, 1993, pp. 70-82.

Using statistical models, the objective of this research is to evaluate the effect of median width on median-related accident frequency and severity. Data for the study is extracted from the Highway Safety Information System (HSIS) for the states of Utah and Illinois. The analysis includes only homogeneous roadway sections at least 0.07 miles in length; a total of 982 sections in Utah (973.8 total miles) and 2,481 sections in Illinois (2,081.3 total miles). Note that the median widths of these sections vary from 0 to 110 feet and the posted speed limit is at least 35 mph on all sections. Accident data is available from 1987 through 1990 for Utah (37,544 reported accidents) and from 1987 through 1989 for Illinois (55,706 reported accidents). To isolate the effect of only median width, the available data has been adjusted based on other variables including roadway functional classification, posted speed limit, access control, average annual daily traffic (AADT), curvature, and section length. Fitting log-linear models to the available data indicates a general decrease in accident rate as median width increases. For median widths up to 25 feet, the study suggests only a small reduction in the accident rate (compared to 0 foot median). Although it is speculated that increasing the median width would result in a decrease in severe accidents, the data suggests that the median width effect is similar for all accidents regardless of severity.

The authors attempt to provide insight to the difficult association between accident frequency/severity and median width. Ideally, an understanding of this correlation may improve the warrants that designers use to determine the need for a median barrier on divided roadways. Although there have been a few previous studies, this study utilizes more recent data and a more comprehensive database than the previous studies. Important caveats to this study are that the control for the confounding variables are through statistical means rather than study design (actually constructing a highway with different median widths), and the omission of potentially important confounding variables such as vertical grade, median slope and type of traffic. Nevertheless, the results are important and appear to suggest that new highways should have medians considerably wider than 30 feet (unless a barrier is provided). Interestingly, the authors note that a gap in knowledge exists on when to install positive barriers in roadway medians.

Hirsch, T.J., and King K. Mak. Development of an IBC MK-7 Barrier Capable of Restraining and Redirecting an 80,000-lb Tractor Van-Trailer. *Transportation Research Record 1258*, Transportation Research Board, National Research Council, Washington, DC, 1990, p 82-91.

The objective of this research is the development of an International Barrier Corporation (IBC) MK-7 Barrier capable of restraining and redirecting heavy vehicles. Note that these barrier types consist of a standard corrugated steel shell that contains a specified fill material; the MK-7 is a larger version of the MK-9 that is typically used to redirect passenger vehicles. Using previous crash tests involving IBC-type barriers as a baseline, computer simulation was used to determine the required strength of the fill material to ensure redirection of an 80,000 van-type tractor-trailer. A series of laboratory soil tests determined that the optimum moisture content of the fill (to provide the required strength) was 10%, which was achieved by mixing 10 pounds of Portland cement and 10 pounds of water for each 100 pounds of sand fill. To test the design, a single crash test was performed with an 80,000 lb tractor-trailer impacting at an angle of 15 degrees and speed of 51 mph. Although there was a considerable amount of roll (towards the barrier), the vehicle was smoothly redirected by the barrier. Damage to the vehicle was severe but the barrier moved only a total of 7 inches laterally with a permanent deformation of 4.5 inches.

Elvik, R. "The Safety Value of Guardrails and Crash Cushions: A Meta-Analysis of Evidence From Evaluation Studies," *Accident Analysis and Prevention*, Volume 27, Issue 4, August 1995, pp 523-549.

Elvik presents a meta-analysis using information from 32 studies evaluating the safety effects of median barriers, roadside guardrails, and crash cushions. The objective is to determine how the installations of these devices affect the probability of an accident occurrence as well as the severity of a given collision. From the analyzed studies, there were 232 numerical estimates of the safety effects of these devices, where each estimate constitutes a unit of analysis. The funnel graph method is used to detect the presence of publication bias (the tendency to not publish unwanted results) and the logodds method is used to compute the weighted mean estimates of safety effects. Based on the available data, median barriers are found to increase the accident rate (by approximately 30%) but to decrease the severity (20% reduction of probability of fatal injury), given that a collision occurs. For longitudinal barriers situated at the roadway edge, the data indicates a reduction in both the accident rate and accident severity (45% reduction of probability of fatal injury). Although the data for crash cushions is limited, the study indicates that these devices reduce both accident frequency and severity. The random variation in the number of accidents for a given study is found to be the most significant contributor to variation in the study results (on the whole).

In contrast to other studies, the author utilizes a statistical approach to analyze the conglomeration of previous studies on the effectiveness of guardrails, median barriers, and crash cushions (rather than simply providing a synopsis of previous research). At least from an overall perspective, the study supports that the installation of median barriers increase the number of accidents but decrease the severity of accidents. Note that this observation includes results from all types of median barriers and not simply a specific type. The authors also make an interesting contrast between the focus of guardrail and median barrier research: a majority of the guardrail research has focused on the effects on accident severity while the focus of the bulk of median barrier research has been the effect on accident rate.

"Median Barriers Prove Their Worth" Public Works, Volume 123, Public Works Journal Corporation, New York, March 1992.

This article summarizes research conducted by the University of California Institute of Transportation Studies to determine the effect of NJ shape median barriers on accident frequency and accident severity. Contrary to other studies, the reviewed study found that the presence of the NJ shape median barrier did not affect the number of non-fatal/non-injury collisions. The study also found a significant reduction in the number of fatal accidents as well as the total number of fatalities (reductions of 36% and 43%, respectively). Using a benefit/cost analysis, the study finds that the implementation of NJ shape barrier results in a benefit to cost ratio between 1.1 and 1.2 over the project life cycle (for highways without previous median barriers).

Carlson, Arne. *2+1-Roads With Cable Barriers – Safety and Traffic Performance Results.* Torsten Bergh Swedish National Road Administration, April 2001.

The purpose of this research is to detail the use of three-strand cable barrier in Sweden to improve the performance of the 13 meter wide 2 + 1 roadway. Although there are several variations of the 13 m road in Sweden, the 2 + 1 design contains two 3.75-meter lanes, 1.0-meter paved outside shoulders, and a 3.50-meter center lane that changes direction every 1 to 2.5 kilometers. Previous research has found that the 13 m 2 + 1 roadway has a better safety performance than two-lane 9 meter roadways, however, there is a significant number of fatalities resulting from cross median collisions. The study focuses on roadway capacity effects, traffic speed effects, and safety effects of the installation of cable barrier to approximately 200 km of Swedish roadways (120 km are 13 m 2 + 1 roads while the remaining are 15.75 m 2 + 2 roads). Using floating car studies and before and after speed measurements, the researchers determined that, for one-directional volumes up to 1400 vehicles/hour, the speed difference is negligible and that the capacity of the 2 + 1 cable barrier roadway is approximately 300 vehicles/hour less than a typical 13 m roadway. In terms of safety benefits, the authors find that the implementation of cable barrier reduces fatal and severe injuries by approximately 50% (no fatal accidents and 6 severe injury accidents after the implementation of the cable barrier). Also, as expected, the presence of cable median barriers on these roadways increased the total number of collisions. In terms of maintenance costs, the authors indicate an increase of approximately 100%.

Although this study does not include a benefit/cost analysis, the authors indicate significant benefits of the 13 m 2 + 1 roadway with cable barrier. These findings are in general concurrence with other three-cable median barrier studies done in the United States. A driver attitude survey, completed as part of this research, indicated a significant progression from a generally negative to generally positive attitude regarding the installation of cable barrier on the 2 + 1 roads. Potential concerns with the use of this roadway configuration, however, include work zone safety, emergency blockages, and an increase in emergency vehicle response times.

Zaouk, A. K., Bedewi, N. E., Kan, C., and Dhafer Marzougui. *Validation of a Non-Linear Finite Element Vehicle Model Using Multiple Impact Data.* FHWA/NHTSA National Crash Analysis Center, The George Washington University, American Society of Mechanical Engineers, Applied Mechanics Division, Volume 218, 1996, pp 91 – 106.

The authors describe the development of a multi-purpose finite element model of a 1994 Chevrolet C-1500 pick-up truck completed at the National Crash Analysis Center (NCAC). Note that the NCAC is a vehicle crash research center jointly funded by the Federal Highway Administration (FHWA) and the National

Highway Traffic Safety Administration (NHTSA). A detailed description is provided of the developed model including mesh generation techniques, associated materials testing, and utilized material properties. To validate the model statically, the researchers compared the weight of various components and the center of gravity location between the model and actual vehicle. The dynamic validation consisted of a comparison of the model to two full-scale crash tests: (1) a 35 mph frontal barrier collision and (2) a 62.5 mph, 25 degree collision with a 42-inch high vertical concrete barrier. To determine the validity of the model, the authors compared the crash deformation profiles (of high impact regions), velocity/acceleration time history records at different locations, energy absorption by different components, and general motion of the vehicle. The results of these comparisons indicate that the developed model is consistent with the full-scale crash tests.

This research suggests that the current complexity of finite element modeling technology is sufficient to provide a good comparison to results obtained from full-scale crash tests. To improve the current C-1500 model, the authors suggest the validation of other crash tests including a frontal offset collision, a side impact, and narrow object impacts. Nonetheless, the model appears to provide a reasonable surrogate for a full-scale crash test while costing a significant amount less and allowing the flexibility of infinite impact scenarios.

Carlson, Robert D., Joseph R. Allison and James E. Bryden. *Performance of Highway Safety Devices*. Report FHWA-NY-77-RR 57, New York State Department of Transportation, Albany, NY, December 1977.

Utilizing New York State accident and maintenance data over a 5-year period, the authors evaluate the performance of light-post roadside and median barrier, impact attenuation devices, slip-base sign supports, and frangible base luminaire supports. With respect to barrier performance, the objective was to document the performance at the higher rail mounting height (27" to center of rail). The study included five longitudinal barrier types: w-beam guiderail, cable guiderail, box-beam guiderail, w-beam median barrier, and box-beam median barrier. Total barrier mileage studied included 228 centerline miles of state roadway in the eastern portion of the state as well as 195 miles of the NY State Thruway (only for a 6-month period in 1973, however). For state roadways, data collection procedures consisted of accident forms filled out by DOT maintenance personnel. The NY Thruway data was collected in a similar manner but through the Thruway Authority's Traffic and Safety Engineer.

The observed roadside and median barriers are evaluated based on the resulting occupant injury severity, containment of the vehicle, performance of the end terminal (if applicable), as well as the amount of damage and repair costs. Considering all collected barrier accident data, there were no fatalities, 2% of the collisions involved severe injuries, and approximately 10% involved minor injuries. Thus, from an overall prospective, the barriers performed well. Because of the low number of injury cases, the study was not able to discern differences between injury rates for most of the individual barrier types. The only statistically significant difference (95% confidence level) in injury rate found was between the w-beam (higher injury rate) and box-beam (lower injury rate) median barriers. In terms of barrier penetration, all penetration rates (with the exception of the cable barrier) were lower than those in the previous state study (VanZweden and Bryden, 1977). Of the total of 15 length-of-need barrier penetrations, only two involved occupant injury (one minor and one severe). Although the small number of penetrations and barrier height inconsistencies prevented a statistical analysis relating the penetrations to barrier height, the barriers in this study have a higher average height compared to the VanZweden and Bryden study and also have a lower average penetration rate. A total of 29 end terminal accidents were present in the data set; only one resulted in minor occupant injury suggesting satisfactory performance. In terms of maintenance, the stiffer barrier systems are found to incur less damage in the event of a collision, however, there was not a large disparity observed in total repair costs between barriers.

Zweden, John Van and James E. Bryden. *In-service Performance of Highway Barriers*. Report No. NYSDOT-ERD-77-RR51 New York State Department of Transportation, Albany, NY, July 1977.

Early in the 1960's, New York State pioneered the development of weak-post barrier systems through analytical models and full-scale vehicle crash testing. In 1965, the state guardrail and median barrier standards were changed to include only weak-post barriers. The objective of this study was to evaluate the field performance of the older strong-post barriers and newly developed weak-post barriers based on New York State accident data. Data utilized in this study was from three sources: (1) State highway accidents from November 1967 to October 1969 (all barrier types), (2) median barrier impacts on the NY Thruway from 1967 to 1969, and (3) box-beam median barrier collisions on the Taconic State Parkway from September 1968 to December 1970. For barrier impacts on state highways and the Taconic Parkway, maintenance personnel (NYDOT and East Hudson Parkway Authority) collected the data. The NY State Police collected the information regarding collisions on the NY State Thruway. For the statistical analyses, the authors compared the performance of the investigated barriers based on the resulting occupant injury, reaction of the vehicle, and the maintenance required after impact.

From the utilized data sources, there were 4213 guiderail accidents from the statewide study (3496 strong-post, 717 weak–post), 324 median barrier accidents on the NY Thruway (141 strong-post, 183 weak-post), and 286 collisions involving weak-post box beam median barrier on the Taconic Parkway. The statewide study generated a number of significant conclusions comparing the performance of weak and strong-post barriers. Although there was no significant difference in fatality rates between strong and weak-post barriers, the weak-post barriers exhibited a combined fatality/serious injury rate significantly lower than that found for all strong-post barriers. The resulting occupant injury appears linked to barrier stiffness since the cable barrier (both strong and weak post versions) had lower injury severity rates while the stiffer median barriers had the highest injury rates. With respect to barrier penetration, the weak-post barriers demonstrated a lower penetration rate than the strong-post barriers (with the exception of the w-beam). Note that this may be due to the lack of consistency between early strong-post barrier designs; according to the authors, there were 22 combinations of rail, post type and post spacing identified between 1950 and 1965. The authors also indicated that barrier penetration (for the new weak-post systems) was typically resulted from a low rail height. Compared to cases where the barrier contains the vehicle, serious occupant injury is more likely in cases where the barrier is penetrated (this trend is evident for both weak and strong-post barriers). Barrier end terminals (includes first or last 50 feet of barrier) are observed to have higher penetration rates than their midsection counterparts and also resulted in higher serious injury rates. Barrier damage was linked to its stiffness, however, despite longer damage lengths, the weak-posts barriers were less expensive on average than strong-post barriers. For the NY Thruway investigation, the weak-post w-beam median barrier is found to have a significantly greater penetration rate than its strong-post counterpart, which is attributed to more severe impact angles (weak-post was generally located farther from the edge of traveled way). From the Taconic Parkway data, the box-beam median barrier displayed both low penetration and injury rates.

Erinle, O., Hunter, W., Bronstad, M., Council, F., and J. Richard Stewart. *An Analysis of Guardrail and Median Barrier Accidents Using the Longitudinal Barrier Special Studies (LBSS) File, Volume I: Final Report*. Report FHWA-RD-92-098, Scientex Corporation/Federal Highway Administration, February 1994.

The purpose of this study was to use the Longitudinal Barrier Special Study (LBSS) to determine the performance of longitudinal barriers in real-world crash situations. The LBSS is a specialized accident database within NHTSA's National Automotive Sampling System (NASS) system that has detailed information on collisions involving traffic barriers that occurred between 1982 and 1986. Specifically, the researchers used the LBSS to compare injury severity between length-of-need (LON) and end terminal impacts and examine failures of various barrier types. Since vehicle impact speeds were predominately missing from the LBSS data, the authors estimated this parameter from the available information (vehicle crush information, barrier permanent deformation, impact angle, etc.). Much of the analysis is based on 665 single vehicle impacts (450 LON and 215 end terminal) that involved only impact with a single barrier. Note that this study lacks vehicle exposure for the studied barriers.

For LON hits, significant differences among the studied barriers are found for driver injury versus no injury, however, non-significant differences for MAIS $\geq$ 2. Strong post barrier systems (median and guiderail) and concrete median barrier are found to present a significantly greater risk of occupant injury. For driver injury versus no injury, there was no statistically significant difference found between adverse barrier performance (snagged, overrode, vaulted, penetrated) and correct barrier performance (vehicle redirected). An analysis of impacts subsequent to a barrier impact indicates that rollover rate for concrete median barrier is double the overall rate for all barriers. Also, where rollover is the subsequent event, injury rates are found to be highest (although not statistically significant). Impacts with end terminals are found to be more likely to cause occupant injury than if the LON portion of the barrier is struck. End terminal hits are both more likely to induce vehicle rollover and, in the event that the vehicle does not rollover, produce more serious injuries than LON impacts.

Ray, Malcolm H., and J.E. Bryden. *Summary Report on Selected Guardrails*. Final Report: FHWA-SA-91-050. Momentum Engineering, Federal Highway Administration, June 1992.

This report details three relatively new longitudinal barriers: (1) the modified South Dakota three-strand cable barrier, (2) the modified Minnesota three-strand cable barrier and (3) the modified thrie-beam barrier. The modified South Dakota three-strand cable barrier is similar to the standard G1 three-strand cable barrier but utilizes a lighter flange-channel post. The modified Minnesota three-strand cable barrier is also a modified version of the standard G1 three-strand cable barrier but uses closer post spacing and wooden posts with a weakening hole. For each barrier, the authors present a brief history of barrier development, the design principles, the system components, construction costs, recommended applications, maintenance procedures, crash test results, and accident experience for field applications.

From the construction cost data provided, the modified South Dakota three-strand cable barrier is approximately 20% less expensive than the standard three-strand cable barrier. The field experience with this barrier, however, is limited. Although the barrier has been in use in South Dakota for a number of years, the authors indicate that there is only anecdotal evidence of its performance with no statistics provided. Based on similarities between the full-scale crash tests (Report 230), the authors speculate that this system will perform similar to the standard three-strand cable barrier. The modified Minnesota three-strand cable barrier appears to offer only a slight cost advantage in comparison to the standard three-strand cable barrier. Maintenance of this system, however, is more complicated due to the wood posts that fracture below the ground line and there is a lack of crashworthy end terminal for this system. As with the South Dakota version, the Minnesota three-strand cable barrier has only anecdotal in-service performance data and the authors provide no statistics. Modified thrie-beam barrier system was developed to improve the performance of the standard thrie-beam barrier with larger vehicles. The authors indicate three states that have installed this barrier on an experimental basis: Colorado at 4 locations, Rhode Island at 2 locations, and

Michigan at 3 locations. Accident experience, however, is only presented based on the Colorado installations and has been summarized from Woodham (1998) as well as from a follow-on unpublished report, also by Woodham. Good performance of the barrier is noted for passenger vehicles; all were redirected and none of the occupants were injured in four of the five collisions. Two heavy vehicle collisions were reported; one involving two army convoy single unit trucks and the other involving a tractor-trailer. The army convoy impacted the barrier at high angles and penetrated the barrier allowing the tucks to go over a steep embankment; two fatalities resulted from this accident. The other collision involved a tractor-trailer that had rolled on its side and slid sideways into the barrier. These test installations of modified thrie-beam have since been replaced by concrete barrier.

Appendix B – Barrier Performance Summary Charts

Charts summarizing the in-service performance of the following barriers are presented in herein:

- Three-Strand Cable Barrier
- Brifen Wire Rope Safety Fence
- Weak Post W-Beam Barrier
- Weak Post Box -Beam Barrier
- Strong Post W-Beam Barrier
- Strong Post Modified Thrie Beam Barrier
- NJ Shape Concrete Barrier

Barrier Field Performance Summary

Three-Strand Cable Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Agent	_	Kentucky	1976	_	_	_	_	_	_	_	_	_	_	_	_	_	Unable to locate a copy of this report.
Van Zweden and Bryden	Roadside	New York	1977	2	375	80 (21)	N/A	11	69	8	287	(4)	15	356			When there is no barrier penetration, chance of injury is less than 3%. Average repair cost is half the cost of strong post w-beam barrier despite the typically longer lengths of this barrier damaged.
Carlson, Allison, and Bryden	Roadside	New York	1977	4	23	4 (33)	N/A	_	_	_	_	0	0	2		21	Note that there were only 12 mid-section impacts with cable barrier. Out of these 12 impacts, 4 were penetrations (the data provided does not provide a link between penetration and occupant injury). The other 11 impacts involved the barrier end terminal (one case involved rollover).
Schneider	Roadside	Iowa	1979	2	31	7 (23)	N/A	_	_	_	_	1 (1)	4 (10)		_	_	Average property damage and collision severity were lower for cable barrier than for all guardrail collisions in the state. Average property damage loss for cable barrier is ~71% of property damage loss for guardrails in general. Approximately 60 maintenance reports were examined suggesting that about half of the collisions were unreported. Information summarized from NCHRP Synthesis 244 and NCHRP Report 490. Unable to locate a copy of this report.
Tyrell and Bryden	Median	New York	1989	3	99	4 (4)	15 Sites	_	_	_	_	_	_	24		75	Information summarized from NCHRP Report 490. Unable to locate a copy of this report.
Seamons and Smith	Median	California	1991	_	_	(0.7)	_	_	_	_	_	_	_	_	_	_	Study focuses mainly on metal beam and concrete median barrier effectiveness. Due to the higher incidence of penetration with cable barrier, California does not use three-strand cable median barrier.
Ray and Bryden	Roadside	South Dakota, Minnesota	1992	_	_	_	_	_	_	_	_	_	_	_	_	_	Two versions of the cable barrier are discussed: the modified South Dakota system which uses flanged channel posts and the modified Minnesota version that uses wood posts and a closer post spacing. Although the study indicates that these devices have been in use for several years in the respective states and anecdotal evidence of barrier performance is available, no statistics are provided in the report.
Hiss and Bryden	Roadside	New York	1992	1	427	84 (20)	_	_	_	_	_	38		178		211	Main objective of this study was to determine the effect of barrier height on performance. Injuries are found insensitive to rail heights in excess of 24 inches. For rail heights above 29 inches, a significant increase in adverse vehicle trajectories was observed.
Hiss and Bryden	Median	New York	1992	1	16	1 (6)	_	_	_	_	_	1		10		5	The small sample size precluded conclusions regarding this barrier type.
Yang et al.	Roadside/Median	New York	1993	3	_	_	_	_	_	_	_	_	_	_	_	_	This report examines tension loss in the cables in an effort to develop measures to the tension loss. Although the title of the document indicates the "performance" of cable guiderail, only the tension loss is examined with no relation to how this affects the ability of the system to contain and redirect vehicles.
LBSS	Roadside	National	1994	4	53	2 (4)	_	_	_	_	_	0	0	10	8	35	Note that the Total Injury Profile figures include ALL weak post barriers including weak-post w-beam and box-beam (the authors combined these barriers for analysis purposes). Although only 4% of collisions involved barrier penetration, 23% of the 53 collisions involved snagging while 7% involved barrier override.
LBSS	Median	National	1994	4	34	0 (0)	_	_	_	_	_	0	3	5	3	23	Total Injury Profile figures include ALL weak post barriers including weak-post w-beam and box-beam (the authors combined these barriers for analysis purposes). Although none of collisions involved barrier penetration, 12% of the 34 collisions involved snagging while 3% involved barrier override.
Mustafa	Median	North Carolina	1997	1.67	125	_	13.7 km/1 Site	_	_	_	_	0	2	9	28	88	Although the report states that there have been a total of 125 accidents, the total accidents (when described in terms of injury attained) add to 127.
Sposito and Johnston	Median	Oregon	1999	1.33	53	3 (6)	14.5 km/2 sites	1	2	4	46	0	5		_	_	2 of the penetrations involved passenger vehicles that underrode the barrier that did not encroach into the opposing traffic lanes. The other penetration was a tractor trailer crossover. Based on a subjective evaluation of the barrier accidents, the researchers indicated that the cable median barrier prevented 21 potential cross median accidents.
Sposito	Median	Oregon	2000	1.7	59	0	20.7 km/1 Site	_	_	_	_	_	_	_	_	_	An update to the Sposito and Johnston study that reports on the effectiveness of an additional 20.7 km of cable median barrier installed on I-5 in 1998. Out of 35 impacts/year with the barrier, the study indicates that 18 accidents/year are potential cross median accidents that have been prevented.
Ray and Weir	Roadside	Connecticut, Iowa, North Carolina	2000	1,2,2	87	_	111 Sites	_	_	_	_	3 (0.0045*)		12 (0.0226*)		72 (0.2163*)	(*Indicates the number of collisions per million vehicle kilometer past guardrail.) No statistical difference is found in three-strand cable barrier performance between the three states.
Carlsson	Roadside	Sweden	2001	Not Stated	121	1 (0.8)	200 km/Various	1	0	23	97	0 (0)	(6)	(31)	_	_	The single penetration was a passenger vehicle that overrode a roadside cable barrier. There is a discussion of median version of the cable barrier but there are no statistics provided for the effectiveness of the barrier in the median. Carlson merely states that the presence of the cable barrier in the median has prevented a number of cross median accidents.
Hunter, Stewart, et al.	Median	North Carolina	2001	4 before/3 after	1478	_	13.7 km/1 Site	_	_	_	_	_	_	_	_	_	Total accidents includes "before" and "after" period. Approximately 80% of the cable barrier is double run. Note that there have been no cross median accidents in three years after the installation of the barrier. A significant increase was observed in the total number of accidents, but there was a significant reduction in the overall accident severity.
McClanahan, Albin, and Milton	Median	Washington State	2004	5 before/1.5 to 5 after	58.56/year	_	43 km/4 Sites	_	_	_	_	0.33*	_	_	_	_	(*Annual fatal accident rate for cable guardrail collisions.) Data shown only applies to the "after" period. Although there was an increase in total accident rate in the period after the installation of cable median barrier, there was a reduction in the annual rate of all, fixed object, rollover, and cross median fatal accidents. Also, since the installation of the cable barrier, the annual rate of cross median collisions has been reduced from approximately 2 to approximately 0.5 per million vehicle miles traveled. There was a total of 10 cross median accidents but the study does not indicate the total number of barrier impacts. Five accidents involved heavy vehicles (type not specified) impacting the barrier; none resulted in barrier penetration and only one accident resulted in injury.

Barrier Field Performance Summary

Brifen Wire Rope Safety Fence

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/ Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Oklahoma DOT	Median	Oklahoma	2002	_	_	_	11.3 km/1 Site	_	_	_	_	_	_	_	_	_	Information extracted from a news article. Although it appears that a study is being conducted on the safety performance of this barrier, there is no evidence of a published report. The article indicates that a 305 meter test section of this barrier prevented at least 2 potential cross-median collisions.
Outcalt	Roadside/Median	Colorado	2004	1.75	9	1(11)	4 km/11 Sites	_	_	_	_	_	_	_	_	_	Preliminary results summarized here; research is still in progress. Note that the penetration was a Honda Accord that underrode the barrier due to improper cable height (at a drain location).
Sharp and Stewart	Median	Utah	2004	3	6	0	1.6 km/1 Site	_	_	_	_	_	_	_	_	_	Preliminary results summarized here; research is still in progress. Brifen System has withstood multiple hits (proir to repair) with no barrier penetration.

Barrier Field Performance Summary

Weak Post W-Beam Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/ Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Van Zweden and Bryden	Roadside	New York	1977	2	212	65 (31)	N/A	10	55	17	130	4	23	185			The injury rate of the weak post barriers is found to be 10 percent, half that of the strong post guardrails. For the study involving weak-post w-beam median barrier on the Thruway, however, barrier penetration is statistically greater than those observed for the strong-post w-beam (attributed to higher impact angles experienced by the weak post system).
Carlson, Allison, and Bryden	Roadside	New York	1977	4	52	4 (8)	N/A	_	_	_	_	0	2	8		42	Note that there were 50 mid-section hits of this barrier. The remaining 2 hits involved the end terminal. Both of the hits were unreported suggesting proper performance of the terminals.
Carlson, Allison, and Bryden	Median	New York	1977	4	89	5 (6)	N/A	_	_	_	_	0	2	14		73	No median barrier hits involved end terminals.
Hiss and Bryden	Roadside	New York	1992	1	306	34 (11)	_	_	_	_	_	36		140		130	Containment was high for all barrier heights in excess of 23 inches.
Hiss and Bryden	Median	New York	1992	1	46	1 (2)	_	_	_	_	_	5		18		23	The small sample size precluded conclusions regarding this barrier type.
LBSS	Roadside	National	1994	4	53	2 (4)	_	_	_	_	_	0	0	10	8	35	Note that the Total Injury Profile figures include ALL weak post barriers including three-strand cable and box-beam (the authors combined these barriers for analysis purposes). Although only 4% of collisions involved barrier penetration, 23% of the 53 collisions involved snagging while 7% involved barrier override.
LBSS	Median	National	1994	4	34	0 (0)	_	_	_	_	_	0	3	5	3	23	Total Injury Profile figures include ALL weak post barriers including three-strand cable and box-beam (the authors combined these barriers for analysis purposes). Although none of collisions involved barrier penetration, 12% of the 34 collisions involved snagging while 3% involved barrier override.
Ray and Weir	Roadside	Connecticut	2000	1	102	_	55 Sites	_	_	_	_	1 (0.0013*)		16 (0.0132*)		85 (0.0569*)	(*Indicates the number of collisions per million vehicle kilometer past guardrail.) Note that this study included weak post w-beam barriers both on the roadside and in the median.

Barrier Field Performance Summary

Weak Post Box-Beam Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Galati	Median	Pennsylvania	1970	1 before/1 after	33	1 (3)	15.1 km/1 Site	_	_	_	_	0	14		_	19	Data shown only applies to "after" period. Only 33 accidents reported to the police out of a total of 204 impacts identified by examining damage to the barrier. The single penetration was a tractor trailer in snowy conditions. Comparing the after data to the collected before data, there was a 120% increase in median accidents due to the presence of the barrier but there was a reduction in injury accidents as well as fatal accidents.
Van Zweden and Bryden	Roadside	New York	1977	2	87	14 (16)	_	4	10	7	66	1	10	76			No significant injury severity difference between end and mid-section hits (attributed to lack of data points for individual barrier types). Overall, however, the end hits are found to be more severe. The relatively small number of impacts prevented any other comparisons to the other barrier types.
Van Zweden and Bryden	Median	New York	1977	2	43	2 (5)	_	0	2	9	32	0	9	34			The relatively small number of impacts prevented any other comparisons to the other barrier types.
Carlson, Allison, and Bryden	Roadside	New York	1977	4	37	0 (0)	N/A	_	_	_	_	0	0	4		33	A total of 6 accidents involved the box-beam end terminal. The terminal performance was satisfactory and only one impact resulted in minor occupant injury.
Carlson, Allison, and Bryden	Median	New York	1977	4	191	2 (1)	N/A	_	_	_	_	0	4	10		177	A total of 10 accidents involved the median barrier end terminal. All were unreported with satisfactory performance indicated on the maintenance reports.
Hiss and Bryden	Roadside	New York	1992	1	623	23 (4)	_	_	_	_	_	62		353		208	Vehicle containment was better when the barrier was 24 inches or higher. In terms of injury and secondary events, performance of this barrier was equivalent for heights between 24 and 30 inches.
Hiss and Bryden	Median	New York	1992	1	308	7 (2)	_	_	_	_	_	30		171		107	Injury rates were uniform for barrier heights in excess of 23 inches.
LBSS	Roadside	National	1994	4	53	2 (4)	_	_	_	_	_	0	0	10	8	35	Note that the Total Injury Profile figures include ALL weak post barriers including three-strand cable and w-beam (the authors combined these barriers for analysis purposes). Although only 4% of collisions involved barrier penetration, 23% of the 53 collisions involved snagging while 7% involved barrier override.
LBSS	Median	National	1994	4	34	0 (0)	_	_	_	_	_	0	3	5	3	23	Total Injury Profile figures include ALL weak post barriers including three-strand cable and w-beam (the authors combined these barriers for analysis purposes). Although none of collisions involved barrier penetration, 12% of the 34 collisions involved snagging while 3% involved barrier override.

Barrier Field Performance Summary

Strong Post W-Beam Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Agent	_	Kentucky	1976	_	_	_	_	_	_	_	_	_	_	_	_	_	Unable to locate a copy of this report.
Van Zweden and Bryden	Roadside	New York	1977	2	1045	293 (28)	N/A	96	197	103	649	34	165	846			Average repair cost is twice the cost of the three-strand cable barrier. Aproximately 27% of the collisions with strong post barriers resulted in penetration. Displays significantly greater penetration rates for trucks (> 5000 lbs) than for cars (< 5000 lbs).
Van Zweden and Bryden	Median	New York	1977	2	145	35 (24)	N/A	12	23	20	90	5	27	113			Displays significantly greater penetration rates for trucks (> 5000 lbs) than for cars (< 5000 lbs).
Outcalt	Roadside/Median	Colorado	1993	2	_	_	3.3 km	_	_	_	_	_	_	_	_	_	The objective of this study was to determine if 10 guage w-beam was more advantageous from a maintenance standpoint at high accident frequency locations. From maintenance personnel interviews, the 10-guage rail is comparable in terms of ease of use but requires less maintenance than the 12-guage rail. Anecdotale evidence of performance is presented but only refers to minor hits involving snow plows.
LBSS	Roadside	National	1994	4	144	7 (5)	_	_	_	_	_	3	20	36	13	72	Note that the Total Injury Profile figures include ALL strong post barrier variations (steel and wood block-out) and thrie-beam (the authors combined these barriers for analysis purposes). Although only 5% of collisions involved barrier penetration, 7% of the 53 collisions involved snagging, 7% involved barrier override, and 4% involved vehicle vaulting.
LBSS	Median	National	1994	4	40	0 (0)	_	_	_	_	_	1	6	11	6	16	Total Injury Profile figures include ALL strong post barrier variations and thrie-beam (the authors combined these barriers for analysis purposes). Although none of collisions involved barrier penetration, 5% of the 34 collisions involved snagging, 2% involved barrier override, and 2% involved vehicle vaulting.
Huet et al.	Median	France	1997	7	1452	29 (2)	224 km/ 24 pairs of sites	_	_	_	_	_	_	_	_	_	The intent of the study was to determine the difference in severity between first impacts with concrete and metal median barriers. The relative risk of occupant injury is 1.9 times more likely when a concrete median barrier is hit rather than a strong post w-beam barrier.
Ray and Weir	Roadside (Wood Post)	Iowa	2000	1	10	_	48 Sites	_	_	_	_	1 (0.0000*)		2 (0.4694*)		7 (0.2347*)	(*Indicates the number of collisions per million vehicle kilometer past guardrail.)
Ray and Weir	Roadside (Steel Post)	North Carolina	2000	1	201	_	200 Sites	_	_	_	_	8 (0.0000*)		61 (0.0331*)		132 (0.0331*)	(*Indicates the number of collisions per million vehicle kilometer past guardrail.) Occupant injury was less common in collisions with the cable barrier than with the steel strong post w-beam barrier or both strong post systems combined.
Martin and Quincy	Roadside/Median	France	2001	2	11143	142(1.3)	2000 km	_	_	_	_	134	368	872	_	9769	Occupant injury is 1.9 times more likely in a collision with a concrete barrier rather than a metal barrier.

Barrier Field Performance Summary

Strong Post Modified Thrie-Beam Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Leonin and Powers	Roadside	_	1986	2	_	_	_	_	_	_	_	_	_	_	_	_	Unable to locate a copy of this report.
Blost	Roadside	Michigan	1986	_	_	_	2 Sites	_	_	_	_	_	_	_	_	_	Information summarized from NCHRP Report 490. Unable to locate a copy of this report.
Ray and Bryden	Roadside	Colorado	1992	5	7	1 (14)	4 Sites	2	0	1	4	1 (2)	_	_	_	_	The penetration involved heavy vehicles (2 army convoy single unit trucks) at high impact angles. Note that this report includes information from the Woodham (1998) study as well as information summarized from a later unpublished work from Woodham. There is mention of modified thrie-beam installed in Minnesota and Rhode Island, however, no data is provided for the experience of these states.
Woodham	Roadside	Colorado	1988	5	6	0 (0)	3 Sites	_	_	2	4	_	_	_	_	_	No vehicle penetrations observed. A tractor trailer that rolled onto its side prior to impacting the barrier was contained. Both collisions involving rollover have not been attributed to the performance of the barrier.

Barrier Field Performance Summary

NJ Shape Concrete Barrier

Study Designation	Roadside/Median	State	Year	Duration [Years]	Total Collisions	Total Penetrations (Percentage)	Total Barrier Length/Number of Sites	Penetration		Containment		Total Injury Profile [Accidents (Persons)]					Additional Information
								Injury	No Injury	Injury	No Injury	K	A	B	C	O	
Agent	_	Kentucky	1976	_	_	_	_	_	_	_	_	_	_	_	_	_	Unable to locate a copy of this report.
Seamons and Smith	Median	California	1991	5	_	(0.10)	_	_	_	_	_	_	_	_	_	_	Study focuses mainly on metal beam and concrete median barrier effectiveness. Concrete median barriers are found to have a slight increase in occupant fatality rates than metal barriers (55% compared to 53% for metal barriers).
LBSS	Roadside	National	1994	4	14	0 (0)	_	_	_	_	_	0	1	8	1	4	Although no accidents involved penetration, there were 2 cases of override noted.
LBSS	Median	National	1994	4	142	3 (2)	_	_	_	_	_	3	20	47	17	55	Although no accidents involved penetration, there were 8 cases of override noted. Vehicle rollover after impact with a concrete median barrier is found to be twice as likely when compared to the overall rollover rate for all barrier types.
Huet et al.	Median	France	1997	7	703	2 (0.3)	224 km/ 24 sites	_	_	_	_	_	_	_	_	_	The intent of the study was to determine the difference in severity between first impacts with concrete and metal median barriers. The relative risk of occupant injury is 1.9 times more likely when a concrete median barrier is hit rather than a strong post w-beam barrier.
Fitzpatrick et al.	Median	Connecticut	1999	0.5	14	0	1.68 km/ 1 Site	0	0	0	14	0	0	0	0	14	Although the intent of this study is to determine the extent of unreported collisions, the data summarized pertains to police reported collisions. Only about 23% of the collisions observed on the concrete barrier segment were reported to the police.
Martin and Quincy	Median	France	2001	2	2077	7 (0.33)	2000 km	_	_	_	_	27	77	330	_	1638	Although total injury is found to be more frequent (20% compared to 12%), there is no significant difference between fatality frequency (1.3% compared to 1.2%) when comparing concrete median barrier to metal beam barrier impacts.

Appendix C – Data Collection Forms

The data collection forms utilized during accident investigations are presented in this appendix and are as follows:

- Impact Site Overview Form
- Supplemental Photos Form
- Component Details Form

Note that for a given collision there may be multiple Supplemental Photo Forms as well as multiple Component Details Forms depending on the extent of barrier damage.

IMPACT SITE OVERVIEW

Section Designation:	
Location:	**Date:**
Date of Impact:	**Investigators:**

Description of Damaged Area:	
Location of Reference Post (with respect to milepost):	
Location of Impact:	
Angle of Impact:	
Number of Posts in Damaged Section:	**Police Report:**
Rail Type/Block out Type:	**Post Spacing (mm):**
Rail Height (mm):	**Track Width (mm)**
Post Type (include footing):	**End Terminal Type:**
Vehicle Redirection / Barrier Performance:	**Barrier Penetration**

SITE PLAN / PHOTO OF DAMAGED AREA / LOCATION OF DAMAGED AREA

SUPPLEMENTAL PHOTOS

Section Designation:	
Location:	Date:
Date of Impact:	Investigators:

Auxiliary Photographic Information	

COMPONENT DETAILS

Section Designation:	
Location:	Date:
Date of Impact:	Investigators:

Post Number:	
Forward Displacement at Post End (mm):	Lateral Displacement at Post End (mm) (away from vehicle):
Forward Displacement at Ground Surface (mm):	Angle Between Post and Ground:
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):	Photo

Post Number:	
Forward Displacement at Post End (mm):	Lateral Displacement at Post End (mm) (away from vehicle):
Forward Displacement at Ground Surface (mm):	Angle Between Post and Ground:
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):	Photo

Appendix D – Median Barrier Accident Database

Included herein are screenshots from the New Jersey Barrier Performance Database. The screenshots are as follows:

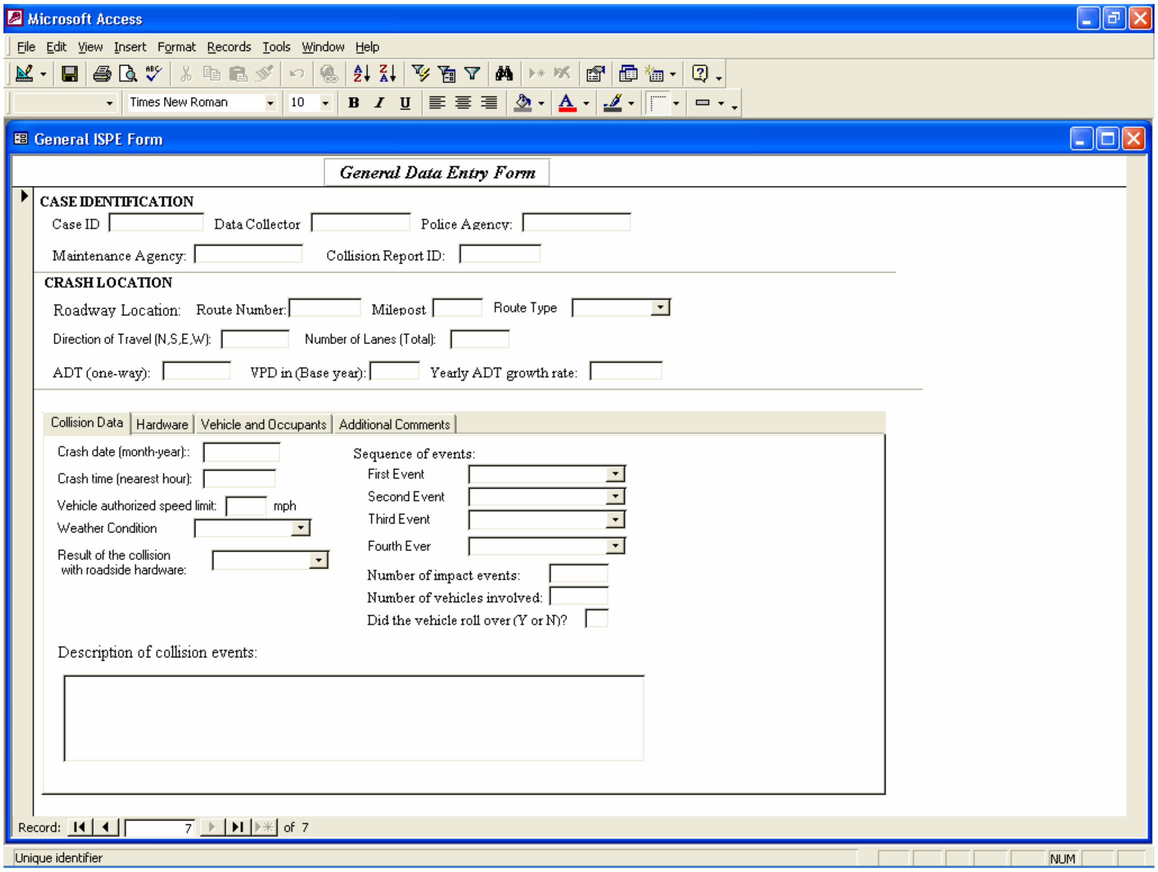


Figure D - 1. General Data Form: Collision Data

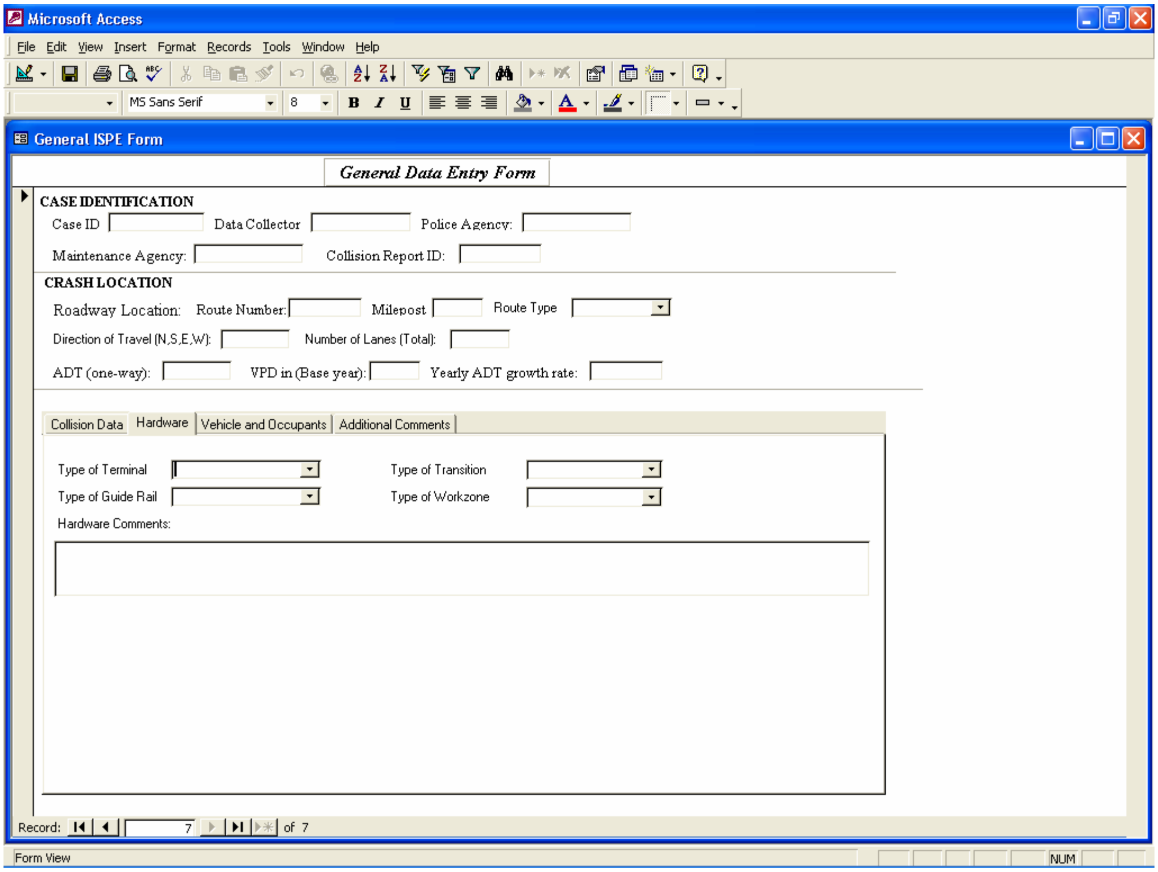


Figure D - 2. General Data Form: Hardware

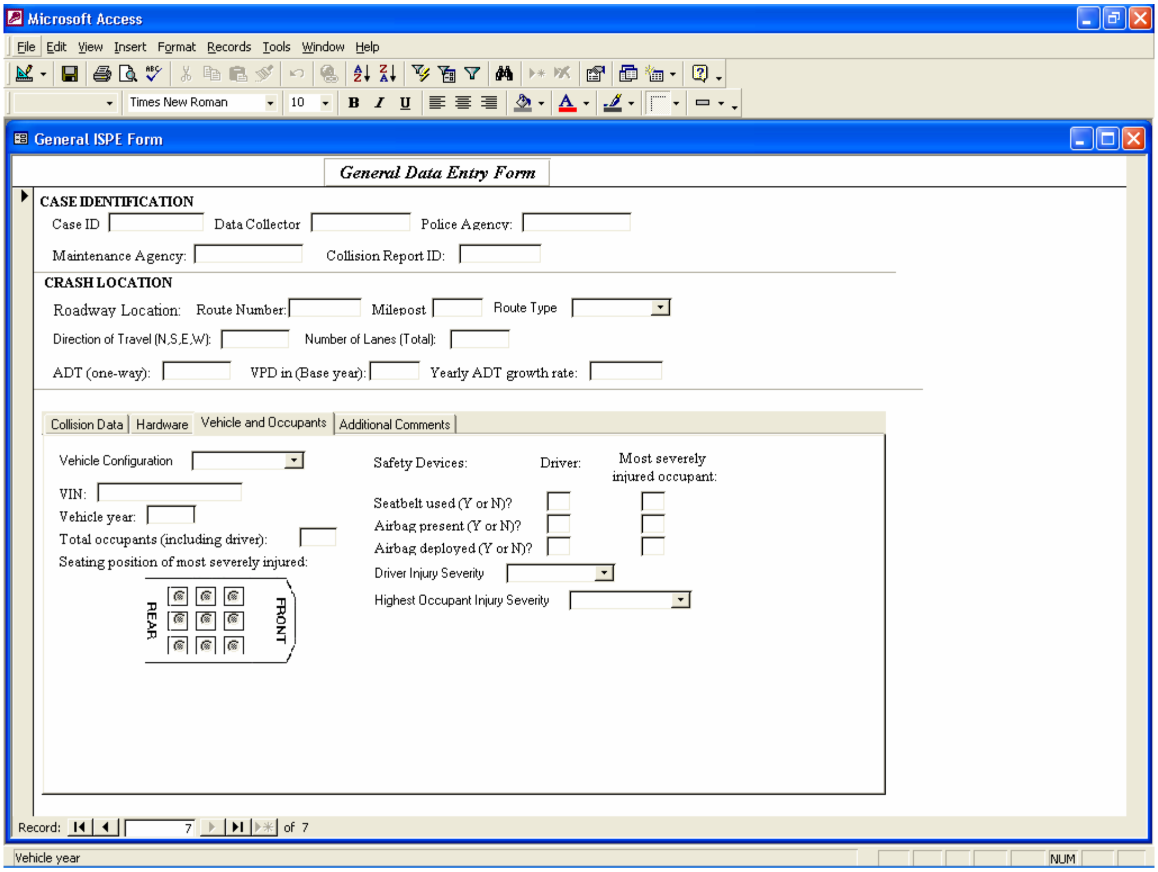


Figure D - 3. General Data Form: Vehicle and Occupants

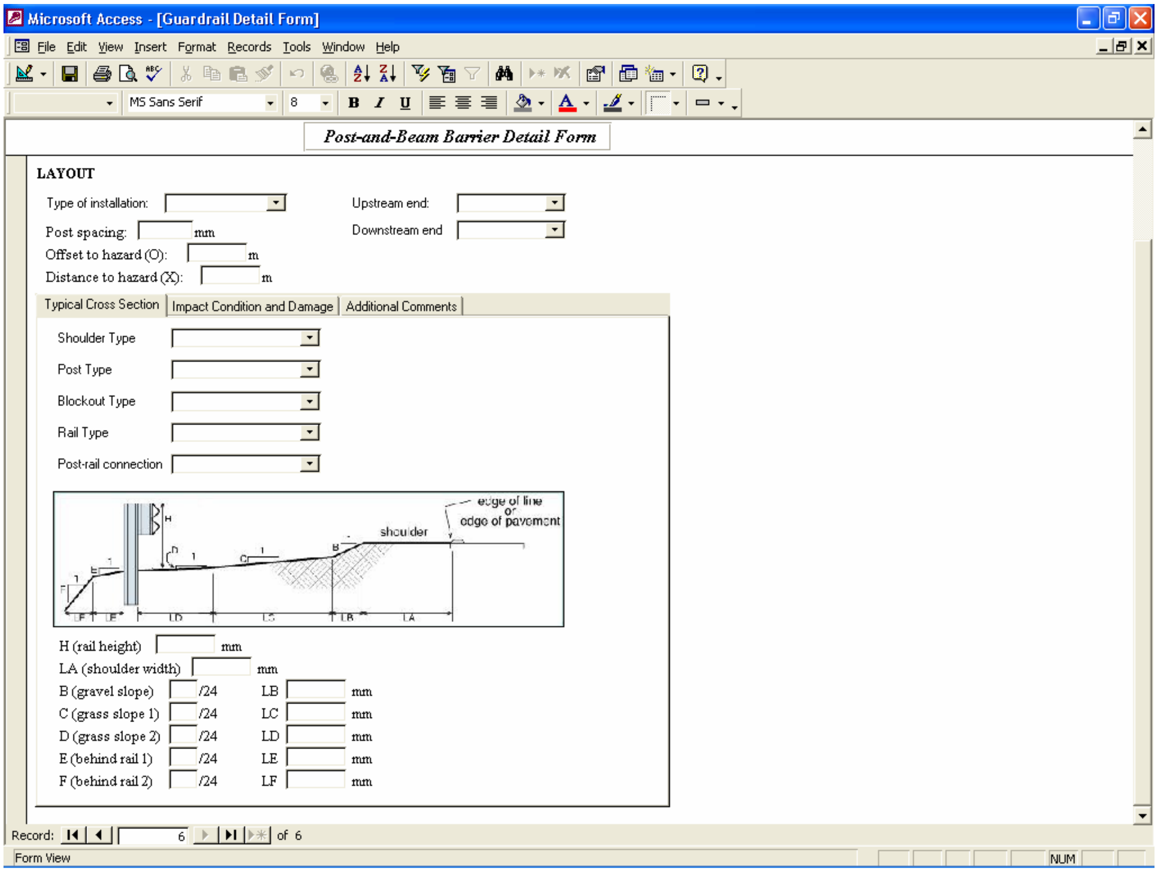


Figure D - 4. Barrier Detail Form: Cross Section

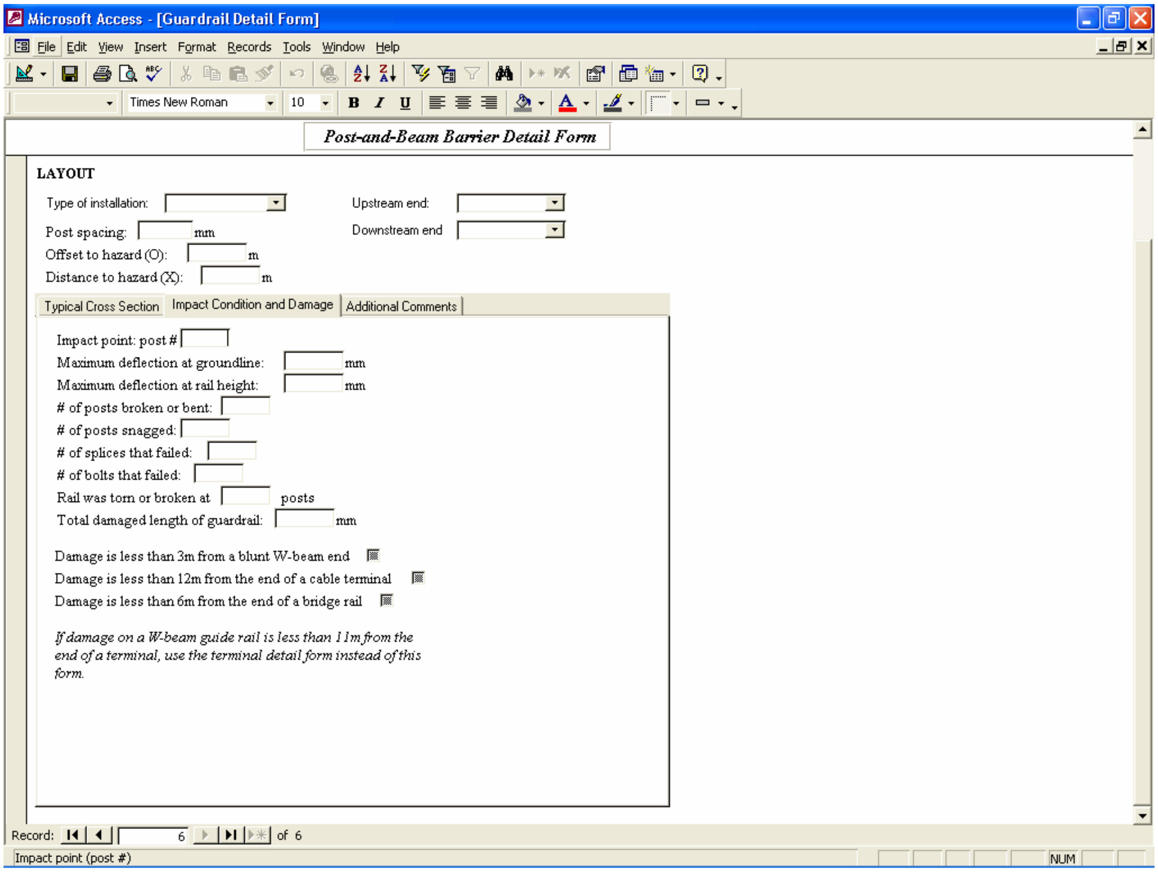


Figure D - 5. Barrier Detail Form: Impact Damage

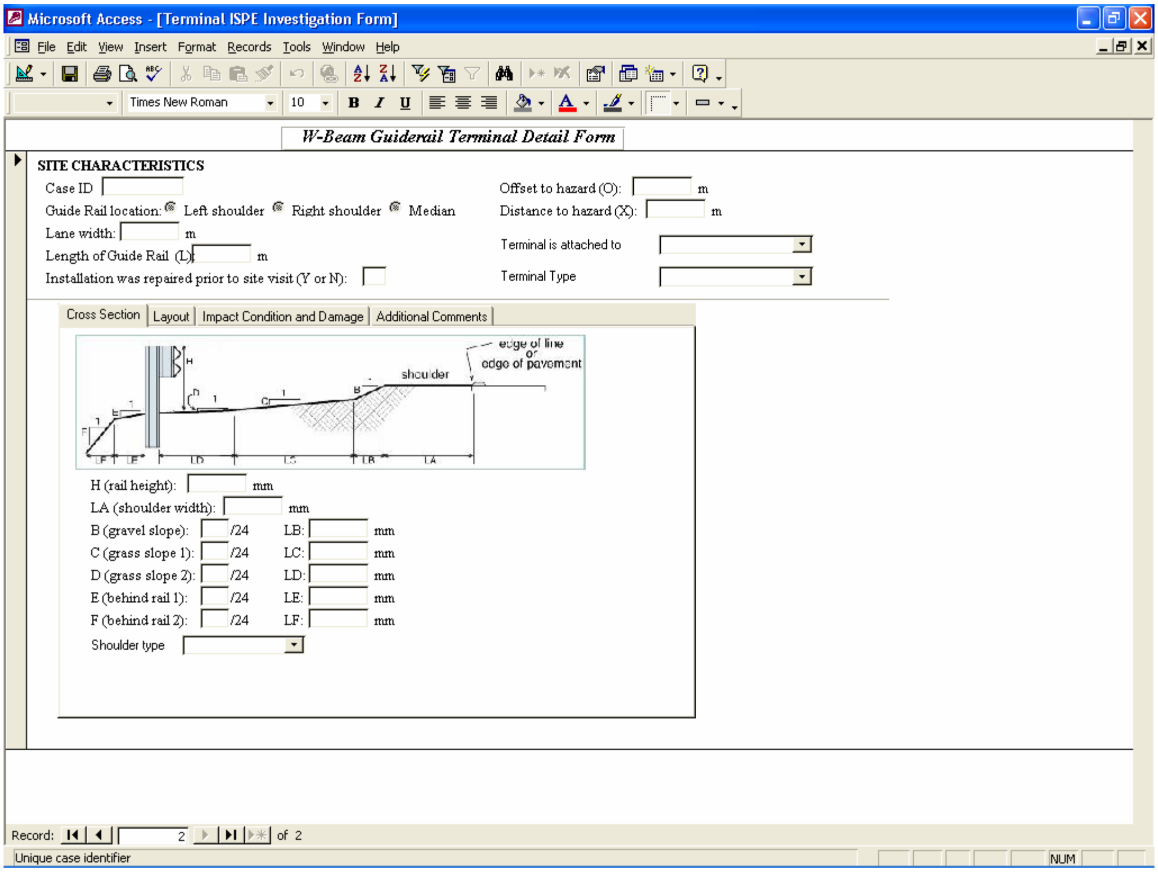


Figure D - 6. Terminal Data Form: Cross Section

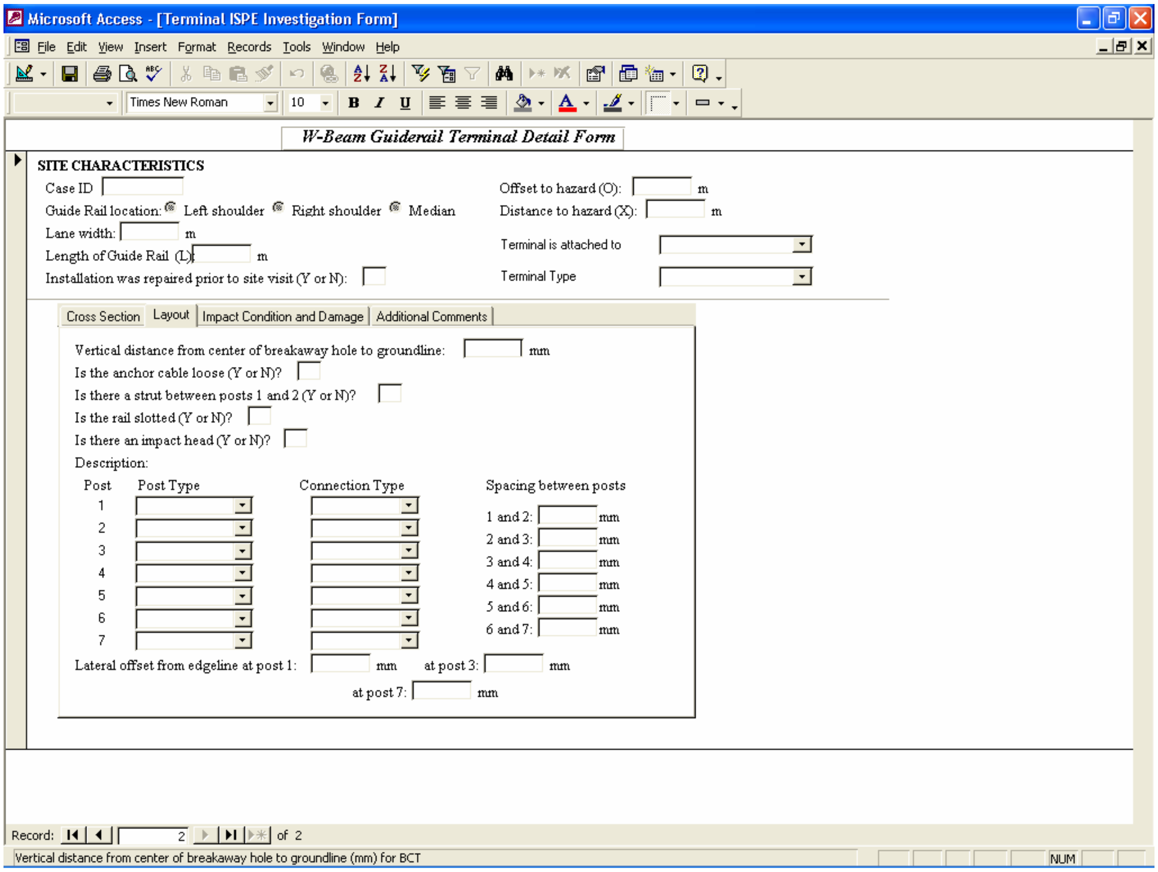


Figure D - 7. Terminal Data Form: Layout

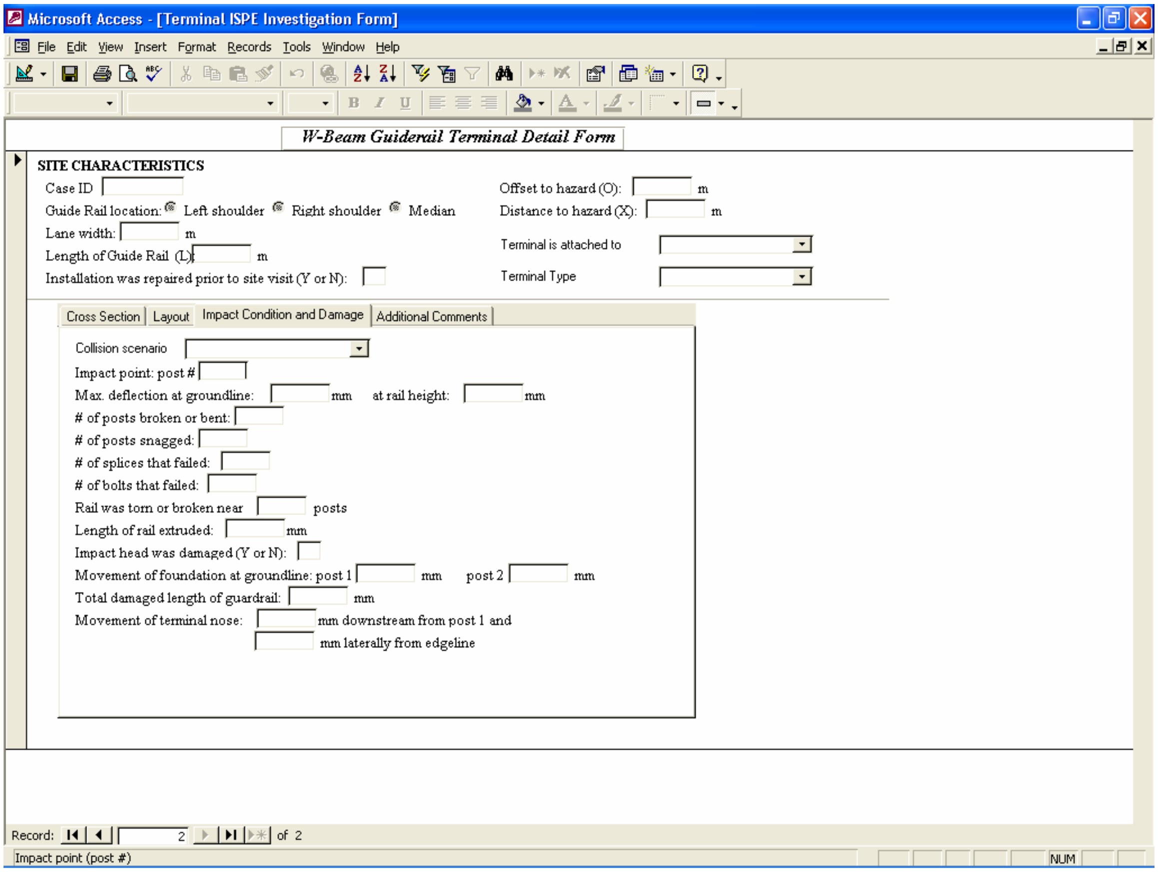


Figure D - 8. Terminal Data Form: Impact Damage

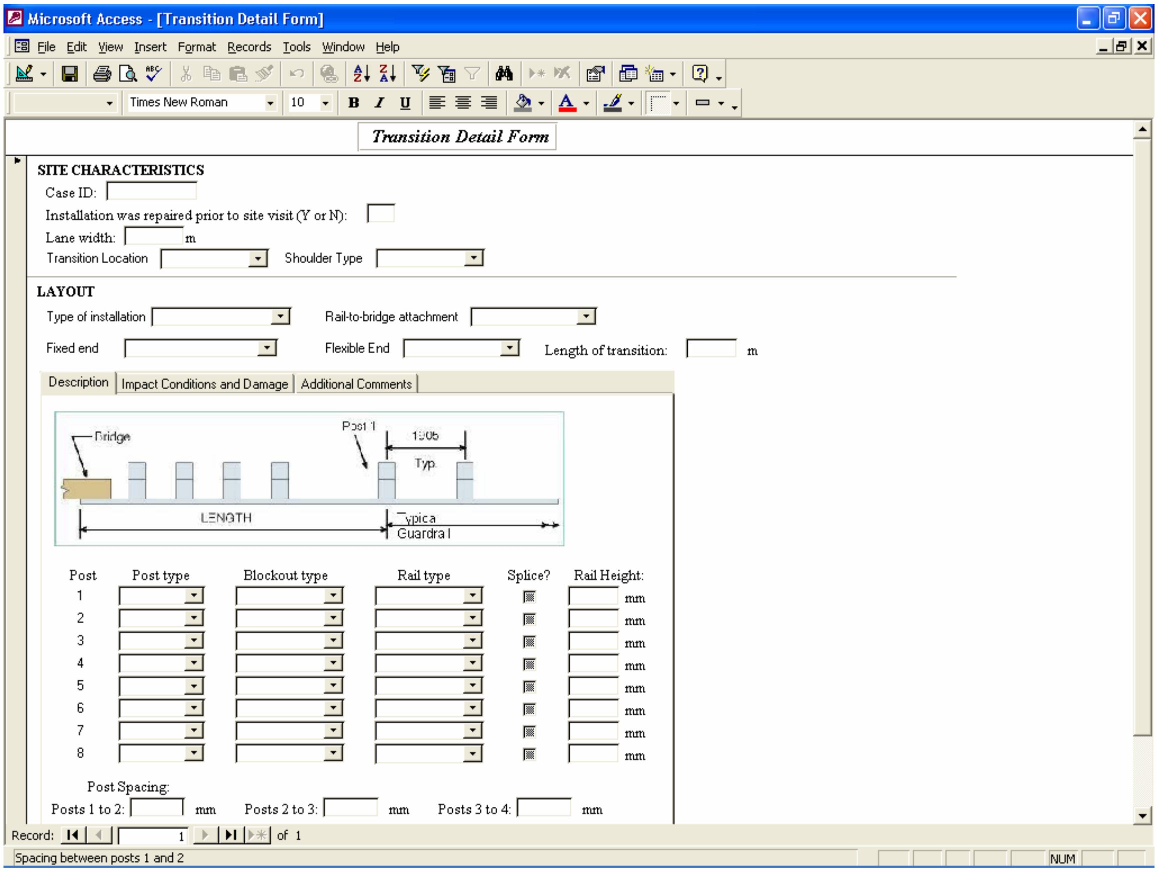


Figure D - 9. Transition Data Form: Description

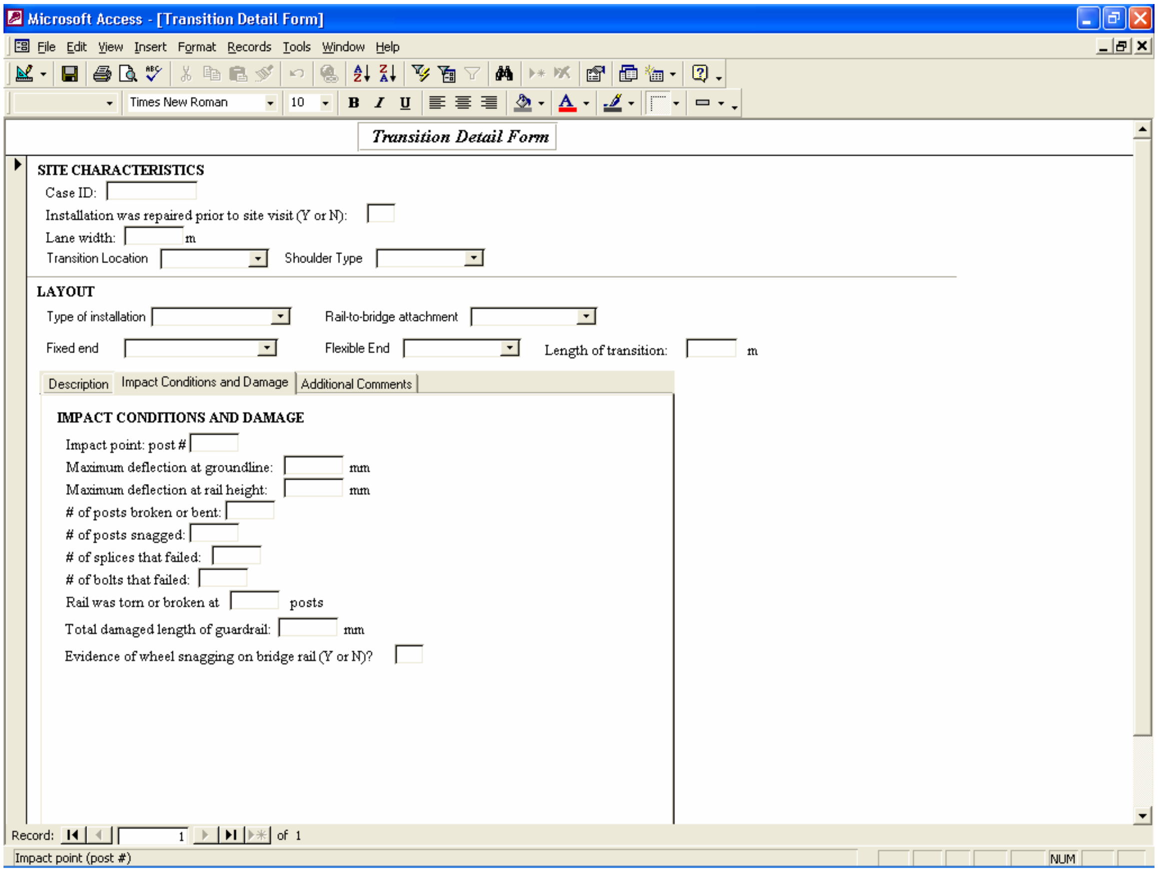


Figure D - 10. Transition Data Form: Impact Damage

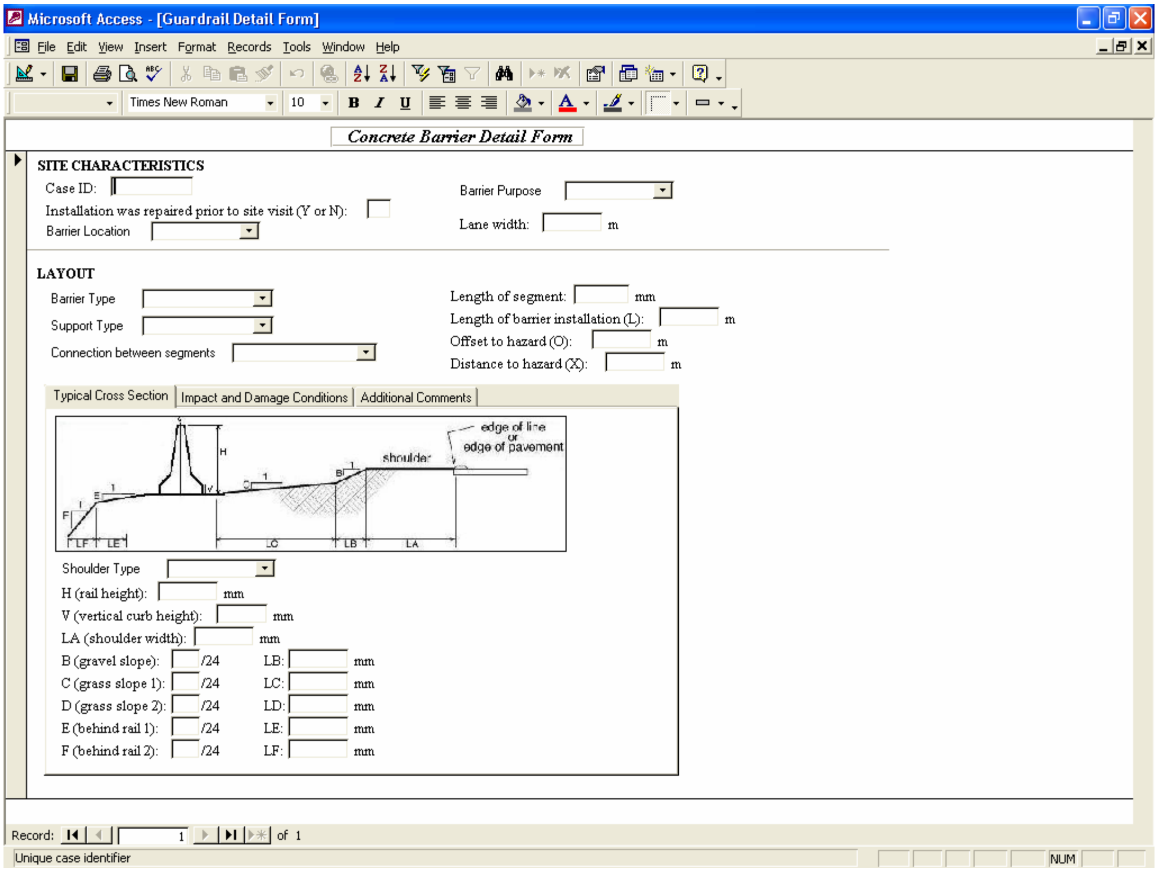


Figure D - 11. Concrete Barrier Form: Cross Section

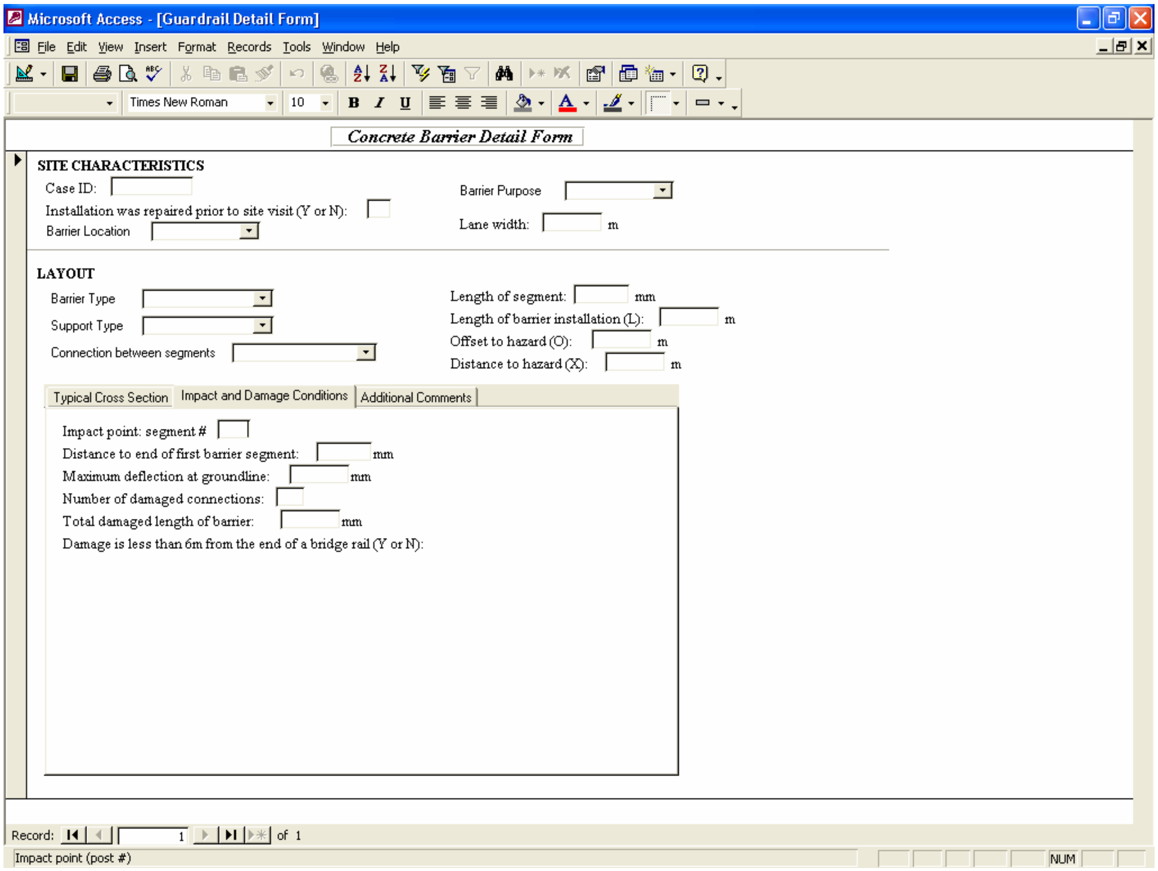


Figure D - 12. Concrete Barrier Form: Impact Damage

Appendix E – Field Accident Reports

The following table summarizes the investigated accidents on both pilot barrier sites. Each investigation date has a corresponding investigation report. Note an asterisk (*) indicates that there was not significant enough damage the pilot barrier to warrant a full investigation.

Pilot Section	Location (MP)	Damaged Posts	Police Reported?	Investigation Date
I-78 Three Strand Cable Barrier	24.2	9	No	3/2/04
	23.8	3	No	3/2/04
	23.8	5	No	3/2/04
	24.4	1	No	3/2/04
	24.2	2	No	3/2/04
	23.8	1	No	3/2/04
	23.8	1	No	3/2/04
	23.9	19	Yes	4/19/04
	24.4	16	No	8/6/04
	23.3*	1	No	11/11/04
I-80 Thrie Beam	27.8*	-	No	3/2/04
	27.5*	-	No	11/11/04

NJDOT Project 2003-35
Evaluation of Cross-Median Crashes

Site Inspection Report
I-78 Median Barrier Pilot Site
03-02-04

Rowan University
Department of Mechanical Engineering
Glassboro, NJ

Summary

On February 26th, 2004, NJDOT-Region Central Maintenance notified Rowan University of impact damage to the I-78 median barrier pilot site. On March 2nd, Rowan University inspected the I-78 site to determine the barrier crash performance. Seven separate sections of the barrier where identified, 3 sections are described as major strikes and 4 sections as minor strikes. The barrier appeared to successfully redirect the vehicles. The accidents were apparently of low enough severity that they were not police reported.

Methodology

Each damaged section was identified and located on the site plan. Photos and measurements were taken at each damaged post. Additional measurements were taken to calculate vehicle impact angles at each strike location. These photographs and measurements are included in the pages that follow.

Notification and Inspection

Initial notification occurred on February 26th, 10:00AM. Bill Picatagi of Region Central Maintenance called David Bowen. David Bowen was informed of 2 areas of significant damage. The inspection was scheduled for March 2nd. The inspection was performed on March 2nd, between 11:30AM and 1:00PM. David Bowen and Douglas Gabauer performed the inspection.

Site Description

The following performance inspection was performed on the I-78 3-Strand Cable Median site that stretches from approximately MP23.3 to MP24.48. The site consists of two separately anchored 3-Strand Cable installations, each about 6/10 of a mile long. The installations overlap each other for about 40 feet in the center of the site (within a few feet of MP24).

The median at the site is a constant 50 feet wide with a slightly depressed cross section (slope approximately 10:1). The barrier is installed about 14 feet from the westbound edge of the median. The soil at the site was very firm; generally allow the damaged posts to move 0.5 to 1.0 inches in the ground. Some of these posts were bent to the ground and others had a partially sheared cross section.

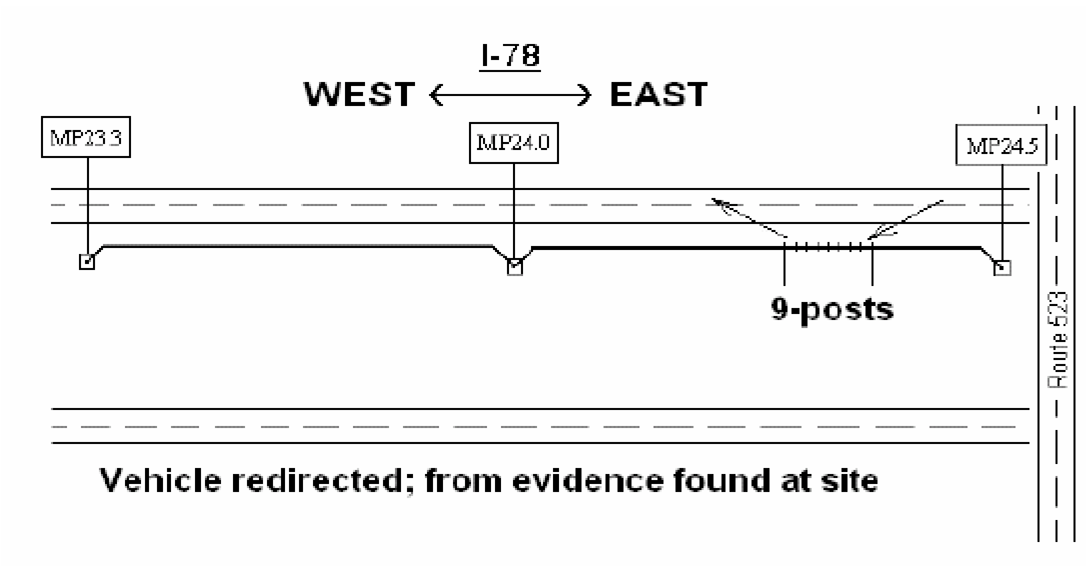
Summary of Barrier Performance

It appeared that the vehicles impacting the barrier were successfully redirected at each of the three major strike sections with no penetration of the barrier. The maximum deflection of the three major strike sections was only 2.5 feet. The 7 sections mentioned above represent 22 damaged posts or about 5.5% of the entire barrier. To our knowledge, no police reports were filed for these strikes.

IMPACT SITE OVERVIEW

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A 9-post section of barrier was damaged. This damage was most likely due to a strike from a vehicle moving in the westbound direction that ran off the road. The vehicle was redirected with no barrier penetration.		
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 52 meters (170 feet) eastbound from MP24.2, the last post (#9) is located 12 meters (40 feet) eastbound from MP24.2.		
Location of Impact:	3.5 meters (12 feet) westbound from the reference post (post #1).		
Angle of Impact:	9º from the westbound lanes.		
Number of Posts in Damaged Section:	9	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



SUPPLEMENTAL PHOTOS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Auxiliary Photographic Information

TOPLEFT: Front view of the damaged section of barrier, facing West. TOPRIGHT: Front view of the damaged section of barrier, facing East. RIGHT: Extra photo of post #4, completely separated from the barrier.

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	1		
Forward Displacement at Post End (mm):	None.	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	None.	**Angle Between Post and Ground:**	90°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): The center cable was unhooked from the post, but the post was otherwise undamaged.			

Post Number:	2		
Forward Displacement at Post End (mm):	740	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. All cables were unhooked from the post.			

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	3		
Forward Displacement at Post End (mm):	810	**Lateral Displacement at Post End (mm) (away from vehicle):**	75
Forward Displacement at Ground Surface (mm):	150	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. All cables were unhooked from the post.

Post Number:	4		
Forward Displacement at Post End (mm):	N/A	**Lateral Displacement at Post End (mm) (away from vehicle):**	N/A
Forward Displacement at Ground Surface (mm):	N/A	**Angle Between Post and Ground:**	N/A

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Completely out of the ground. Post was bent and all three cables were unhooked. Post was completely separated from the barrier.

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	5		
Forward Displacement at Post End (mm):	790	**Lateral Displacement at Post End (mm) (away from vehicle):**	50
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. All cables were unhooked from the post.			

Post Number:	6		
Forward Displacement at Post End (mm):	740	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. Partially sheared at ground level. All cables were unhooked from the post.			

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	7		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	100
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	10°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. The top and middle cables were unhooked from the post. The bottom cable was still in its hook.

Post Number:	8		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	280
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. All cables were unhooked from the post.

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

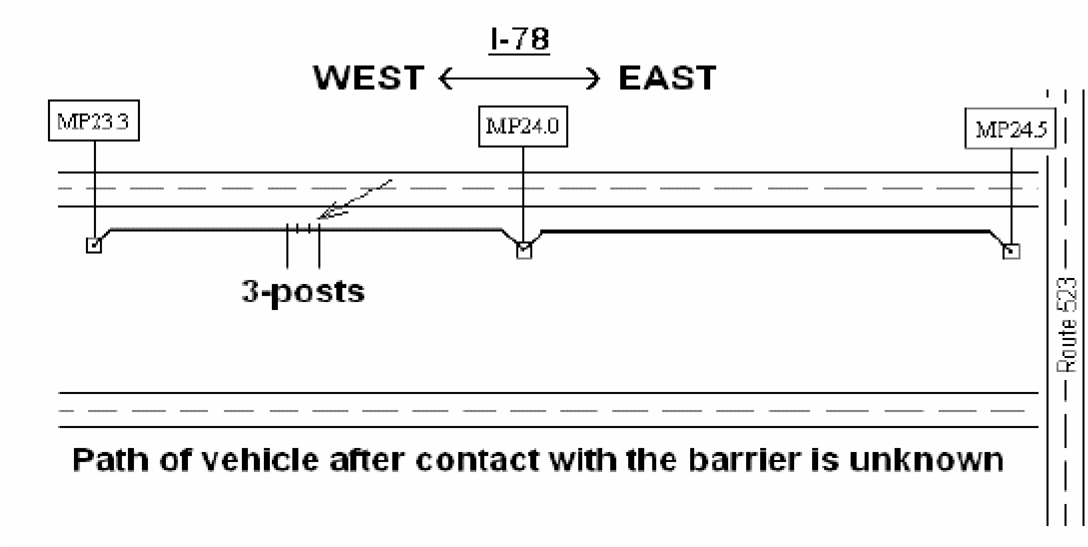
Post Number:	9		
Forward Displacement at Post End (mm):	None.	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	None.	**Angle Between Post and Ground:**	90°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): The bottom cable was unhooked from the post, but the post was otherwise undamaged.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

IMPACT SITE OVERVIEW

Section Designation:	Major Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A 3-post section of barrier was damaged. This damage was most likely due to a strike from a vehicle moving in the westbound direction that ran off the road. The vehicle was redirected with no barrier penetration. The median has a significant downward slope towards the barrier and there are 2 undamaged posts between Major Strikes 1 and 2. It is possible that the same vehicle was involved in both events, or that the events happened at the same time.		
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 56 meters (185 feet) westbound from MP23.8, the last post (#3) is located 67 meters (220 feet) westbound from MP23.8.		
Location of Impact:	Approximately 0 to 5 meters (0 to 16 feet) westbound from the reference post (#1).		
Angle of Impact:	Unknown		
Number of Posts in Damaged Section:	3	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



SUPPLEMENTAL PHOTOS

Section Designation:	Major Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Auxiliary Photographic Information

TOPLEFT: Front view of the damaged section of barrier, facing East.

COMPONENT DETAILS

Section Designation:	Major Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	1		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	80
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. The top and bottom cables were unhooked from the post. The middle cable was still in its hook.

Post Number:	2		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	50
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. The top and bottom cables were unhooked from the post. The middle cable was still in its hook.

COMPONENT DETAILS

Section Designation:	Major Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	3		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	180
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. Partially sheared at ground. All three cables were unhooked from the post.			

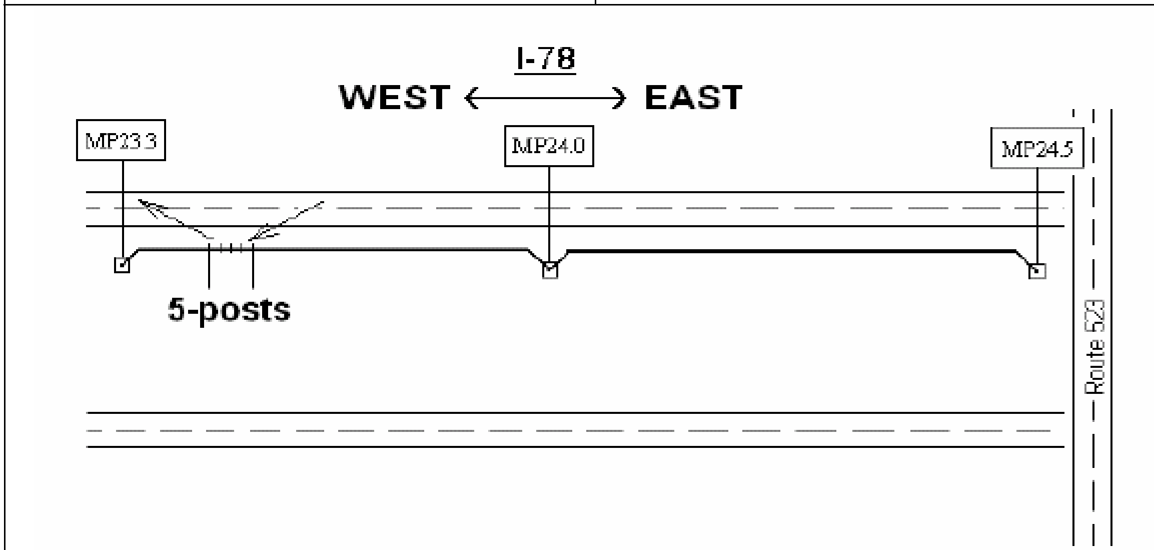
Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

IMPACT SITE OVERVIEW

Section Designation:	Major Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A 5-post section of barrier was damaged. This damage was most likely due to a strike from a vehicle moving in the westbound direction that ran off the road. The vehicle was redirected with no barrier penetration. The median has a significant downward slope towards the barrier and there are 2 undamaged posts between Major Strikes 1 and 2. It is possible that the same vehicle was involved in both events, or that the events happened at the same time.
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 76 meters (250 feet) westbound from MP23.8, the last post (#5) is located 97.5 meters (320 feet) westbound from MP23.8.
Location of Impact:	3.5 meters (12 feet) westbound from the reference post (#1).
Angle of Impact:	3.5° from the westbound lanes.

Number of Posts in Damaged Section:	5	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



SUPPLEMENTAL PHOTOS

Section Designation:	Major Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Auxiliary Photographic Information

TOPLEFT: Front view of the damaged section of barrier, facing West.

COMPONENT DETAILS

Section Designation:	Major Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	1		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	180
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. All three cables were unhooked from the post.			

Post Number:	2		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. Partial sheared at ground. All three cables were unhooked from the post.			

COMPONENT DETAILS

Section Designation:	Major Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	3		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	-50
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. All three cables were unhooked from the post. Post was actually bent laterally towards the westbound lanes.

Post Number:	4		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	50
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Almost completely bent over to the ground. All three cables were unhooked from the post.

COMPONENT DETAILS

Section Designation:	Major Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

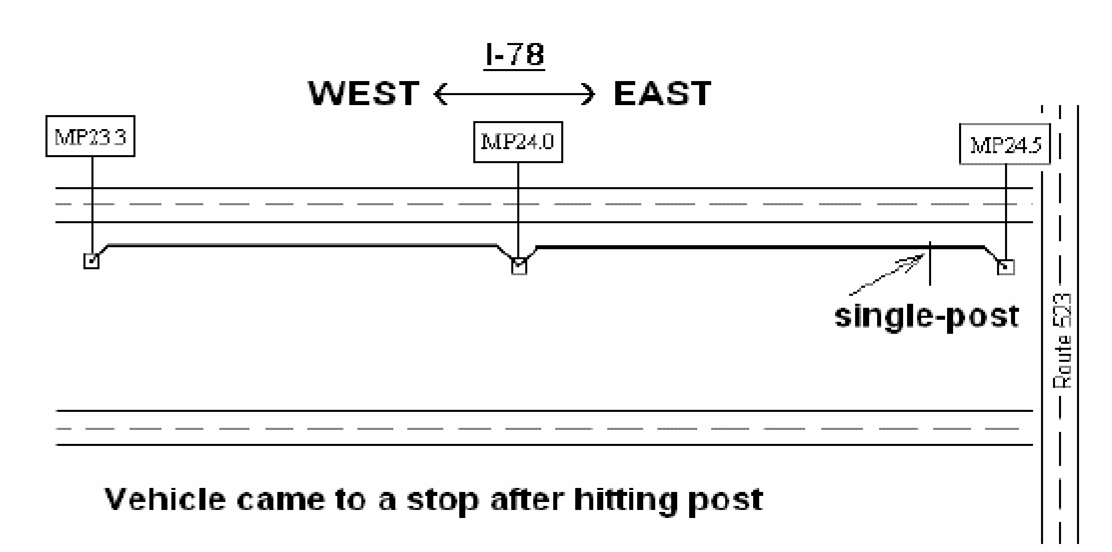
Post Number:	5		
Forward Displacement at Post End (mm):	940	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	100	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. All three cables were unhooked from the post. Post was slightly ripped out of the ground, its soil plate was visible.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

IMPACT SITE OVERVIEW

Section Designation:	Minor Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A single post was damaged. This damage was most likely due to a strike from a vehicle moving in the eastbound direction that ran off the road. The vehicle probably hit the barrier with minimal speed and stopped after hitting the post.		
Location of Reference Post (with respect to milepost):	The post is the 10th post from the East end of the East barrier section, counting the special end post as the 1st post.		
Location of Impact:	Less than 1 meter (3 feet) west of the damaged post.		
Angle of Impact:	15° from the eastbound lanes.		
Number of Posts in Damaged Section:	1	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



COMPONENT DETAILS

Section Designation:	Minor Strike 1		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

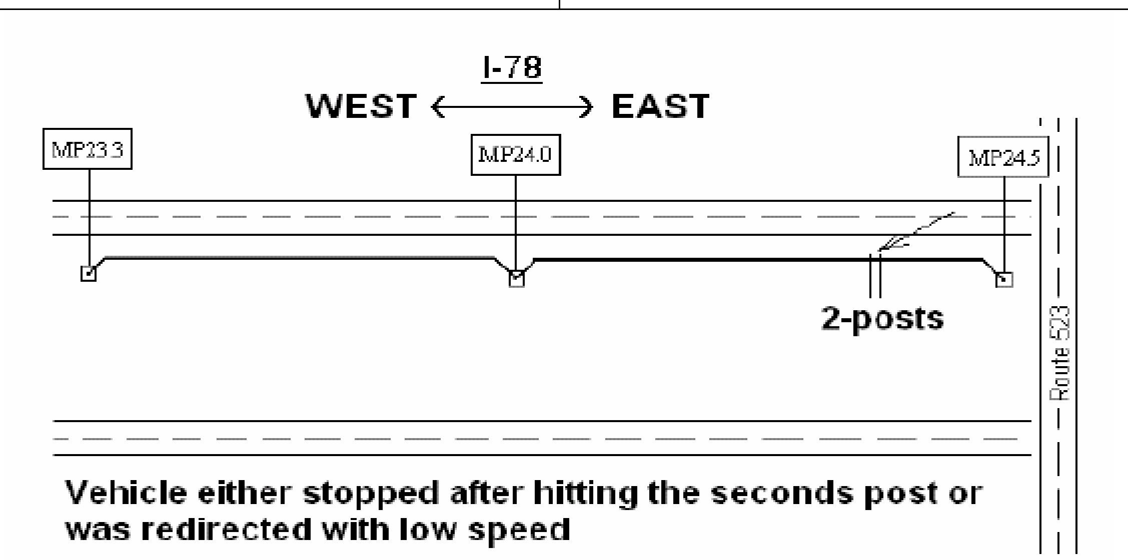
Post Number:	1		
Forward Displacement at Post End (mm):	810	**Lateral Displacement at Post End (mm) (away from vehicle):**	65
Forward Displacement at Ground Surface (mm):	150	**Angle Between Post and Ground:**	35°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): All three cables were unhooked from the post, but the post was otherwise undamaged.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

IMPACT SITE OVERVIEW

Section Designation:	Minor Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	Two posts were damaged. This damage was most likely due to a strike from a vehicle moving in the westbound direction that ran off the road. The vehicle probably hit the barrier at a low speed and angle and probably came to a stop after hitting post #2. This event is very close to Major Strike 1 and the two events may happened at the same time.		
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 220 feet eastbound from MP24.2.		
Location of Impact:	Approximately 0 to 3 meters (0 to 10 feet) east of the reference post.		
Angle of Impact:	Unknown		
Number of Posts in Damaged Section:	2	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



COMPONENT DETAILS

Section Designation:	Minor Strike 2		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	1		
Forward Displacement at Post End (mm):	915	**Lateral Displacement at Post End (mm) (away from vehicle):**	230
Forward Displacement at Ground Surface (mm):	75	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
All three cables were unhooked from the post, but the post was otherwise undamaged.

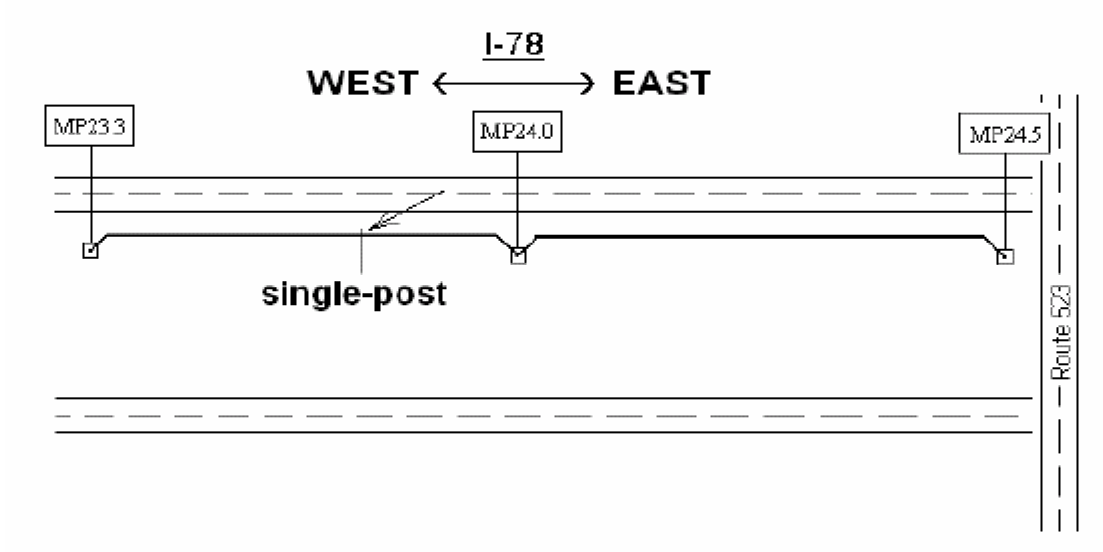
Post Number:	2		
Forward Displacement at Post End (mm):	430	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	10	**Angle Between Post and Ground:**	60°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Bent over slightly, towards the ground. The top and bottom cables were unhooked from the post. The middle cable was still in its hook.

IMPACT SITE OVERVIEW

Section Designation:	Minor Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A single post was damaged. It was unclear how this post was damaged.		
Location of Reference Post (with respect to milepost):	The post is located 40 meters (130 feet) East of milepost 23.8.		
Location of Impact:	Approximately 0 to 5 meters (0 to 16 feet) East of the damaged post.		
Angle of Impact:	Unknown		
Number of Posts in Damaged Section:	1	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



COMPONENT DETAILS

Section Designation:	Minor Strike 3		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

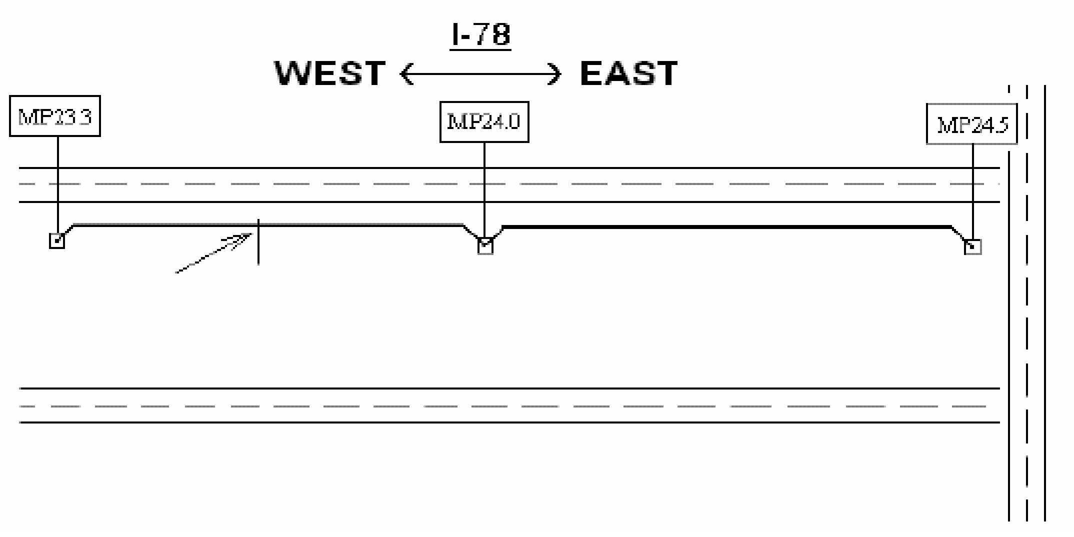
Post Number:	1		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	75	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. Partially sheared at ground. All cables were unhooked from the post.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

IMPACT SITE OVERVIEW

Section Designation:	Minor Strike 4		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Description of Damaged Area:	A single post was damaged. It was unclear how this post was damaged.		
Location of Reference Post (with respect to milepost):	The post is located 43 meters (140 feet) East of milepost 23.8.		
Location of Impact:	Approximately 0 to 3 meters (0 to 10 feet) Wast of the reference post.		
Angle of Impact:	Unknown		
Number of Posts in Damaged Section:	1	**Police Report:**	No.
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



COMPONENT DETAILS

Section Designation:	Minor Strike 4		
Location:	I-78	**Date:**	03-02-2004
Date of Impact:	Unknown	**Investigators:**	David Bowen Douglas Gabauer

Post Number:	1		
Forward Displacement at Post End (mm):	840	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	75	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Almost completely bent over to the ground. All cables were unhooked from the post.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

NJDOT Project 2003-35
Evaluation of Cross-Median Crashes

Site Inspection Report
I-78 Median Barrier Pilot Site
04-19-04

Rowan University
Department of Mechanical Engineering
Glassboro, NJ

Summary

On April 16, 2004, NJDOT notified Rowan University of impact damage to the I-78 median barrier pilot site. On April 19, Rowan University inspected the I-78 site to determine the barrier crash performance. A passenger vehicle impacted the barrier and was successfully contained. The accident was of mild severity, but it is unknown if it is police reported.

Methodology

Each damaged section was identified and located on the site plan. Photos and measurements were taken at each damaged post. Additional measurements were taken to calculate vehicle impact angles at each strike location. These photographs and measurements are included in the pages that follow.

Notification and Inspection

Initial notification occurred on April 16 when Karen Minch of NJDOT contacted Dr. Clay Gabler. Dr. Gabler was informed of a significant strike to the I-78 barrier that occurred during that week. The inspection was scheduled for April 19 and performed between 11:30AM and 1:00PM. David Bowen and Jamie Smith performed the inspection.

Site Description

The following site inspection was performed on the I-78 3-Strand Cable Median site that stretches from approximately MP23.3 to MP24.48. The site consists of two separately anchored 3-Strand Cable installations, each about 6/10 of a mile long. The installations overlap each other for about 40 feet in the center of the site (within a few feet of MP24).

The median at the site is a constant 50 feet wide with a slightly depressed cross section (slope approximately 10:1). The barrier is installed about 14 feet from the westbound edge of the median. Some of the damaged posts were ripped partially or completely from the ground with little or no damage, indicating very wet or very soft soil. Most of the damaged posts were partially pressed into the ground.

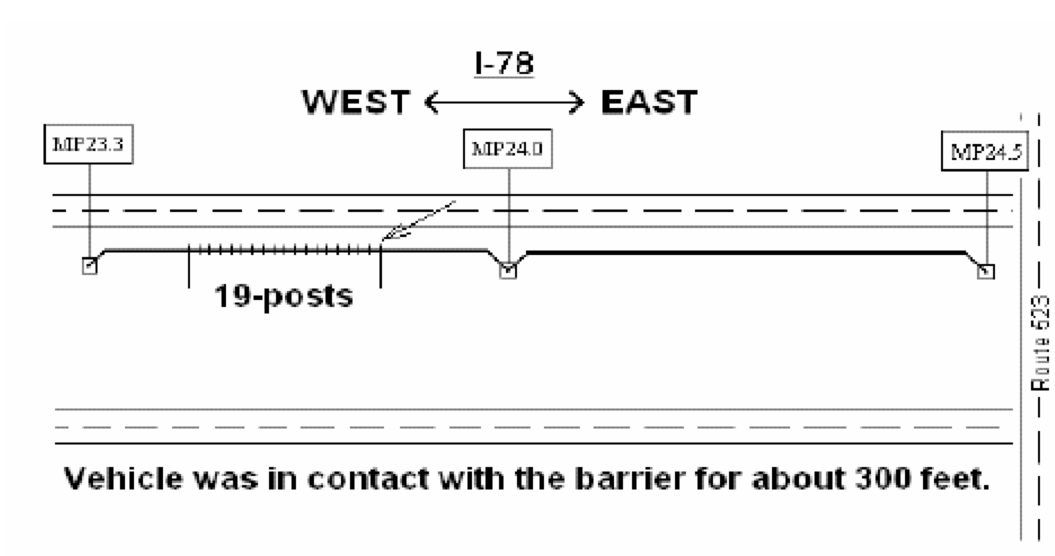
Summary of Barrier Performance

It appeared that the vehicle impacting the barrier was successfully redirected or stopped. The exact path of the vehicle is unclear, especially towards the end of the impact. The tracks indicated that the vehicle might have spun around 180 degrees at the end of the impact. To our knowledge, no police reports were filed for this strike.

IMPACT SITE OVERVIEW

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Description of Damaged Area:	A 19-post section of barrier was damaged. This damage was most likely due to a strike from a vehicle moving in the westbound direction that ran off the road. The vehicle was redirected with no barrier penetration.		
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 40 meters (130 feet) eastbound from MP23.9, the last post (#19) is located 50 meters (160 feet) westbound from MP23.9.		
Location of Impact:	Between post #1 and post #2.		
Angle of Impact:	Less than 5º from the westbound lanes.		
Number of Posts in Damaged Section:	19	**Police Report:**	No
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes.	**Barrier Penetration**	No.



SUPPLEMENTAL PHOTOS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Auxiliary Photographic Information

TOP: East views of the site showing damaged posts and vehicle tracks. LEFT: Post #9. The post was almost completely removed from the ground, yet completely undamaged. This indicates that the soil was very soft and wet at the time of the incident. BOTTOM: West views of the site showing damaged posts and vehicle tracks.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	1		
Forward Displacement at Post End (mm):	860	**Lateral Displacement at Post End (mm) (away from vehicle):**	230
Forward Displacement at Ground Surface (mm):	130	**Angle Between Post and Ground:**	29°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Post was mildly bent over and partially sheared below the ground level. The post's soil plate was visible and all three cables were unhooked from their cable hooks.

Post Number:	2		
Forward Displacement at Post End (mm):	N/A	**Lateral Displacement at Post End (mm) (away from vehicle):**	N/A
Forward Displacement at Ground Surface (mm):	N/A	**Angle Between Post and Ground:**	N/A

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
Post was completely removed from the ground. This post was found on top of post #5 and appears in the photo for post #5. It was unhooked from all three cable hooks and was only mildly bent.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	3		
Forward Displacement at Post End (mm):	1190	**Lateral Displacement at Post End (mm) (away from vehicle):**	None
Forward Displacement at Ground Surface (mm):	430	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): This post was bent over almost completely to the ground and partially sheared below the ground level. The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks.			

Post Number:	4		
Forward Displacement at Post End (mm):	1120	**Lateral Displacement at Post End (mm) (away from vehicle):**	None
Forward Displacement at Ground Surface (mm):	250	**Angle Between Post and Ground:**	Less than 5°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): This post was bent over almost completely to the ground and partially sheared below the ground level. The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks.			

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	5		
Forward Displacement at Post End (mm):	1170	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	560	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. This post was twisted around about 135°. Post #2 was found on top of this post. Post #5 is the post still in the ground. All three cables were unhooked from heir cable hooks.

Post Number:	6		
Forward Displacement at Post End (mm):	1120	**Lateral Displacement at Post End (mm) (away from vehicle):**	80
Forward Displacement at Ground Surface (mm):	230	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from heir cable hooks.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	7		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	150	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The post's soil plate was visible. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks.

Post Number:	8		
Forward Displacement at Post End (mm):	1220	**Lateral Displacement at Post End (mm) (away from vehicle):**	200
Forward Displacement at Ground Surface (mm):	410	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks. This post was otherwise undamaged and was still perfectly straight.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	9		
Forward Displacement at Post End (mm):	1170	**Lateral Displacement at Post End (mm) (away from vehicle):**	N/A
Forward Displacement at Ground Surface (mm):	580	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
The post's soil plate was visible and the post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks. This post was otherwise undamaged and was still perfectly straight.

Post Number:	10		
Forward Displacement at Post End (mm):	1120	**Lateral Displacement at Post End (mm) (away from vehicle):**	-100
Forward Displacement at Ground Surface (mm):	430	**Angle Between Post and Ground:**	13°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and the post's soil plate was visible. All three cables were unhooked from their cable hooks. This post was twisted around about 15°.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	11		
Forward Displacement at Post End (mm):	1170	**Lateral Displacement at Post End (mm) (away from vehicle):**	80
Forward Displacement at Ground Surface (mm):	510	**Angle Between Post and Ground:**	9°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The post was partially removed from the ground. The bottom portion of the post (the part in the ground) was substantially tilted, indicating very soft/wet soil at time of impact. All three cables were unhooked from their cable hooks.

Post Number:	12		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	80
Forward Displacement at Ground Surface (mm):	130	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground. All three cables were unhooked from their cable hooks.

COMPONENT DETAILS

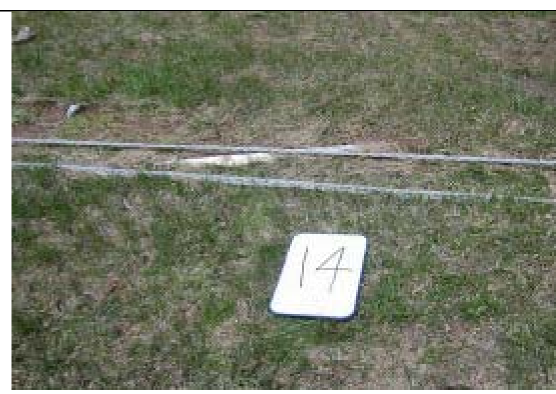
Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	13		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	150	**Angle Between Post and Ground:**	12°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The top and bottom cables were unhooked from their cable hooks. The middle cable was still in its cable hook.

Post Number:	14		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	Less than 25	**Angle Between Post and Ground:**	-2°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over back into the ground, creating a negative angle. It was partially sheared below the ground level. All three cables were unhooked from their cable hooks.

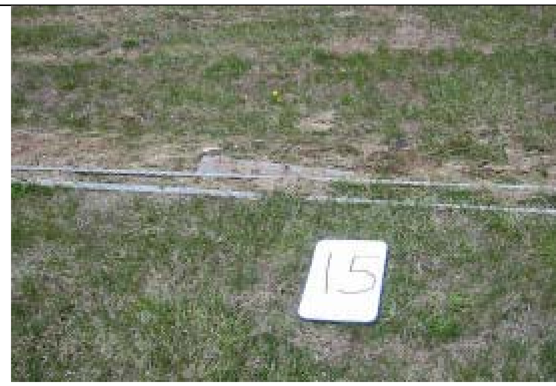


COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	15		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	100	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. All three cables were unhooked from their cable hooks.



Post Number:	16		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	None.
Forward Displacement at Ground Surface (mm):	80	**Angle Between Post and Ground:**	Less than 5°

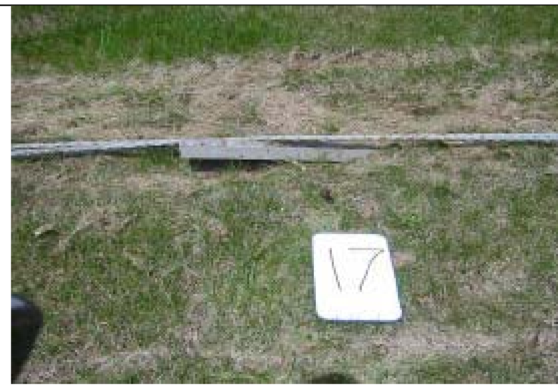
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The soil plate was visible. All three cables were unhooked from their cable hooks.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	17		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	80
Forward Displacement at Ground Surface (mm):	150	**Angle Between Post and Ground:**	Less than 5°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. The soil plate was visible. All three cables were unhooked from their cable hooks.



Post Number:	18		
Forward Displacement at Post End (mm):	910	**Lateral Displacement at Post End (mm) (away from vehicle):**	130
Forward Displacement at Ground Surface (mm):	230	**Angle Between Post and Ground:**	11°

Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):
This post was bent over almost completely to the ground and partially sheared below the ground level. All three cables were unhooked from their cable hooks.

COMPONENT DETAILS

Section Designation:	Major Strike 4		
Location:	I-78	**Date:**	04-19-04
Date of Impact:	Sometime during the week of April 12.	**Investigators:**	David Bowen Jamey Smith

Post Number:	19		
Forward Displacement at Post End (mm):	760	**Lateral Displacement at Post End (mm) (away from vehicle):**	150
Forward Displacement at Ground Surface (mm):	130	**Angle Between Post and Ground:**	32°
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): This post was mildly bent over and partially sheared below the ground level. All three cables were unhooked from their cable hooks.			

Post Number:	-		
Forward Displacement at Post End (mm):		**Lateral Displacement at Post End (mm) (away from vehicle):**	
Forward Displacement at Ground Surface (mm):		**Angle Between Post and Ground:**	
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity):		**PHOTO**	

NJDOT Project 2003-35
Evaluation of Cross-Median Crashes

Site Inspection Report
I-78 Median Barrier Pilot Site
08-06-04

Rowan University
Department of Mechanical Engineering
Glassboro, NJ

Summary

On August 8th, 2004, Rowan University made a periodic inspection of the I-78 median barrier pilot site to check for any unreported barrier damage. A vehicle impacted the barrier damaging a total of 16 posts. The barrier appeared to successfully redirect the vehicle.

Methodology

Each damaged section was identified and located on the site plan. Photos and measurements were taken at each damaged post. Additional measurements were taken to calculate vehicle impact angles at each strike location. These photographs and measurements are included in the pages that follow.

Notification and Inspection

As this incident was discovered during a periodic inspection of the pilot site, no notification occurred. The inspection was performed on August 6th, between 11:30AM and 12:30PM. Manning Smith and Peter Niehoff performed the inspection.

Site Description

The following performance inspection was performed on the I-78 3-Strand Cable Median site that stretches from approximately MP23.3 to MP24.48. The site consists of two separately anchored 3-Strand Cable installations, each about 6/10 of a mile long. The installations overlap each other for about 40 feet in the center of the site (within a few feet of MP24).

The median at the site is a constant 50 feet wide with a slightly depressed cross section (slope approximately 10:1). The barrier is installed about 14 feet from the westbound edge of the median. The soil at the site was very firm; generally allow the damaged posts to move 0.5 to 1.0 inches in the ground.

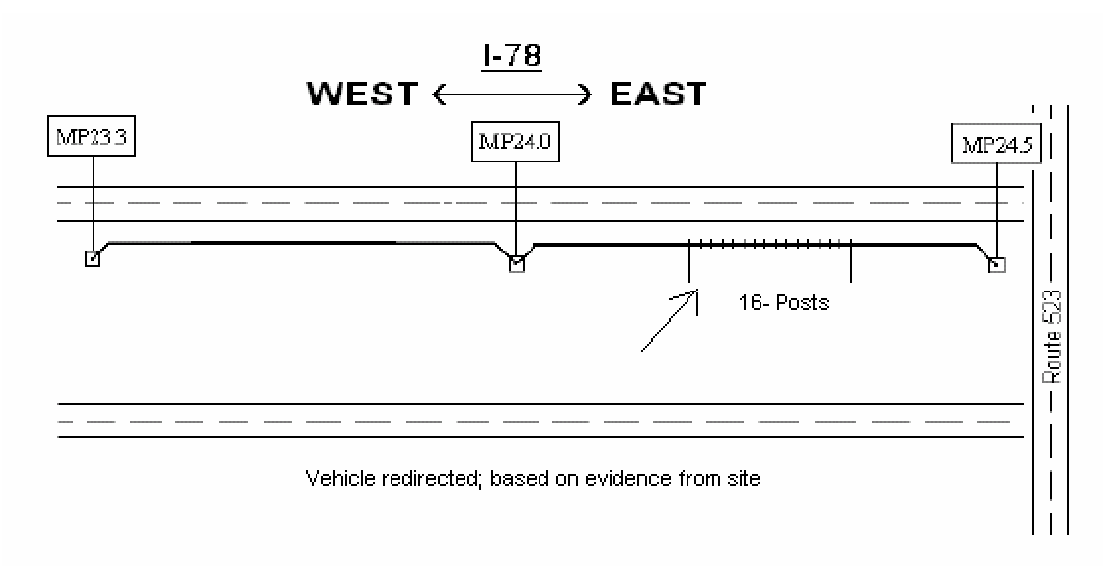
Summary of Barrier Performance

It appeared that the vehicle impacting the barrier was successfully redirected with no penetration of the barrier. The errant vehicle was traveling in the eastbound direction when it left the roadway and impacted the barrier at an angle of approximately 50º. A total of 16 posts sustained some form of damage. To our knowledge, no police report was filed for this strike.

IMPACT SITE OVERVIEW

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	08-06-2004
Date of Impact:	Unknown	**Investigators:**	Manning Smith Peter Niehoff

Description of Damaged Area:	A 16-post section of the barrier was damaged most likely due to an errant vehicle originally traveling eastbound. Although only 3 posts were damaged, the cable was detached from a total of 16 posts. The vehicle was redirected with no barrier penetration.		
Location of Reference Post (with respect to milepost):	The reference post (#1) is located 5 meters (16 feet) eastbound of MP 24.4.		
Location of Impact:	10 meters (33 feet) eastbound from the reference post (#1).		
Angle of Impact:	Approximately 50º		
Number of Posts in Damaged Section:	16	**Police Report:**	No
Rail Type/Block out Type:	3-Strand Cable Median	**Post Spacing (mm):**	5000
Rail Height (mm):	840	**Track Width (mm)**	Unknown
Post Type (include footing):	S3x5.7 weak post with soil plate. Soil footing.	**End Terminal Type:**	Tied & Anchored
Vehicle Redirection / Barrier Performance:	Yes	**Barrier Penetration**	No



SUPPLEMENTAL PHOTOS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	08-06-2004
Date of Impact:	Unknown	**Investigators:**	Manning Smith Peter Niehoff

Auxiliary Photographic Information

Post 3 bent, tire tracks visible

Tire tracks

Bent U-Bolts

View Approaching Site

COMPONENT DETAILS

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	08-06-2004
Date of Impact:	Unknown	**Investigators:**	Manning Smith Peter Niehoff

Post Number:	1		
Forward Displacement at Post End (mm):	0	**Lateral Displacement at Post End (mm) (away from vehicle):**	0
Forward Displacement at Ground Surface (mm):	0	**Angle Between Post and Ground:**	89
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): No physical damage to the post other than bending of the upper cable hook bolt. Upper cable detached from post.			

Post Number:	2		
Forward Displacement at Post End (mm):	100	**Lateral Displacement at Post End (mm) (away from vehicle):**	30
Forward Displacement at Ground Surface (mm):	0	**Angle Between Post and Ground:**	81
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Slight westbound bend in the post. All cable hook bolts bent outward; All cables detached from post.			

Section Designation:	Major Strike 1		
Location:	I-78	**Date:**	08-06-2004
Date of Impact:	Unknown	**Investigators:**	Manning Smith Peter Niehoff

Post Number:	3		
Forward Displacement at Post End (mm):	600	**Lateral Displacement at Post End (mm) (away from vehicle):**	75
Forward Displacement at Ground Surface (mm):	15	**Angle Between Post and Ground:**	30
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Bending of the post near the ground line. All cables detached from the post.			

Post Number:	4		
Forward Displacement at Post End (mm):	0	**Lateral Displacement at Post End (mm) (away from vehicle):**	15
Forward Displacement at Ground Surface (mm):	0	**Angle Between Post and Ground:**	87.7
Description of Damage to Post (Bending, Torsion, Shear, Rail Connectivity): Slight bend in the post toward the westbound lanes. Lower cable detached from post.			

Additional Information:	No other posts (of the 16 total) sustained any bending or torsion damage. Cable detachment is as follows: lower cable detached at 15 posts, middle cable detached at 4 posts, and upper cable at 3 posts.