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CABLE MEDIAN BARRIER FAILURE ANALYSIS AND REMEDIATION PHASE II

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16. Abstract (Limit: 200 words)

On divided roadways, cross-median fatalities are disproportionately overrepresented in fatal and serious injury crashes. Many state DOTs sought to mitigate cross-median crash risk by installing cable median barriers. Despite increased crash rates, studies evaluating crash rates before and after cable median barriers were installed indicated excellent improvement in overall safety. Nonetheless, cable barriers can also contribute to serious injury and fatality crashes which would not have otherwise occurred, including penetration and rollover crashes.

A study was conducted to evaluate the conditions associated with severe cable median barrier crashes. While average penetration and rollover rates were 9.3 and 5.1%, respectively, penetration rates for passenger cars exceeded 15%, while rollover rates for pickups and SUVs was approximately 13%. Generally, vehicles with low bumper heights, high CG heights, and higher masses were involved in statistically significantly more cable median barrier penetrations. CG trajectory angles leading up to impact with the barriers were analyzed, and the 85th percentile trajectory angle associated with severe cable median barrier crashes was 39 degrees. Additional factors contributing to cable median barrier penetrations and rollovers were identified and summarized, and updates to cable barrier crash tests were recommended to improve system performance.

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1 EXECUTIVE SUMMARY

Cable median barrier crashes from a total of 12 states were analyzed. Crash data included scene diagrams, photographs, and field measurements, crash narratives, although the availability of data in each crash varied.

Major contributors to penetration crash propensity were identified: diving underride, in which the front end of the vehicle dropped below the bottom cable; prying, in which the vehicle profile caused cable separation or lifting; override; bouncing override, in which the vehicle rebounded after contact with the back slope and bounced over the top of the barrier; system failure, in which one component failure or design failure prevented the cables from adequately engaging the vehicle; and large vehicle crashes, such as tractor trailers, buses, and single-unit trucks into TL-3 systems.

Major contributors to rollover were identified: steep median slopes, in which the slope caused unstable bouncing or abrupt changes in slope profiles acted as trip points for the tires; broadside skid, in which the vehicle was skidding with a sideslip angle of nearly 90 degrees prior to contact with the barrier; contact with post, in which the post acted as a trip point; and other factors such as towing trailer units, median anomalies, or with large vehicles such as tractor-trailers, buses, or motor homes.

Recommended improvements to cable median barrier systems included: minimum top cable height of 35 in. (890 mm); maximum top cable height of 15 in. (381 mm); minimum of 4 cables supported by posts; higher lateral cable-to-post attachment strength at bottom and lower strength at top; low strong-axis strength post sections; and to eliminate cable entrapment in a vertical slot in the post when initial cable contact occurs at a post location.

A summary of factors and how they contributed to penetration, rollover, and severe crash probability is shown in Table 1.

Table 1. Major Conclusions, Cable Median Barrier Systems

Factor	Effect of Factor on Rate of		
	Penetration	**Rollover**	**Severe Crashes**
Weather/Road Conditions			
Clear, Dry	Increase	Increase	Increase
Rain/Snow	Decrease	Decrease	Decrease
System Type			
Generic 3-Cable	Lowest	Highest	Lowest
Brifen TL-3	Unk	Low	Moderate
CASS TL-3	High	High	Moderate
CASS TL-4*	Moderate	High	Moderate
Nucor TL-3 at 15' Post Spacing	High	Moderate	High
Nucor TL-4*	Moderate	Unk	Moderate
Safence*	Unk	High	Low
Gibraltar*	High	Unk	Low
Season			
Winter	Lowest	Lowest	Lowest
Summer	Highest	Highest	Highest
Wide Median Approach Slopes**			
Flatter than 10:1	High	Moderate	Unk
10:1-8:1	Low	Moderate	Unk
8:1-6:1	Lowest	Lowest	Unk
Steeper than 6:1	Higher at Steeper Slopes	Higher at Steeper Slopes	Unk
Barrier Placement			
Near Shoulder	High	Highest	Highest
On Approach Slope/Back Slope	Moderate	Moderate	Moderate
Center of Median	Highest	Lowest	Lowest
CG Velocity Vector			
Below 20 Degrees	Low	Moderate	Low
20-40 Degrees	Moderate	Moderate	Moderate
Above 40 Degrees	High	High	High
Orientation Angle			
Greater than Velocity Vector	Highest	Moderate	High
Similar to Velocity Vector	Moderate	Low	Moderate
Less than Velocity Vector*	Low	Moderate	Unk
Vehicle Type			
Small/Mid-Size Car	Moderate	Low	Low
Large Car	High	Lowest	Moderate
SUV	Moderate	Highest	Moderate
Pickup	Moderate	High	Low
Van	Moderate	High	High
Large Truck/Tractor Trailer	High	High	Very High
Vehicle Weight Relative to Type of Vehicle (i.e. cars, utility vehicles)			
Heavier than Average	High	Low	No Effect
Approximately Average	Moderate	Moderate	No Effect
Lighter than Average	Low	High	No Effect
Vehicle Roll and Yaw Moments of Inertia Relative to Type of Vehicle (i.e. cars, utility vehicles)			
Higher than Average	High	Low	Unk
Approximately Average	Moderate	Moderate	Unk
Lower than Average	Low	High	Unk

* Data not statistically significant. Actual average result may vary from what is shown.

** Data was collected relative to TL-3 Nucor NU-CABLE system with 15 ft post spacing.

2 INTRODUCTION

2.1 Problem Statement

A cross-median crash is the most severe type of run-off-road event in the United States. Cross-median crashes represent approximately 2% to 5% of all divided interstate crashes; yet fatalities and serious injuries occur in as much as 30% of these crashes. With the significantly disproportionate number of severe crashes occurring due to cross-median crash events, many states have turned to cable median barriers to reduce the risk of these types of severe crashes.

Cable median barriers have been extensively studied to determine the cost-effectiveness of installation, in-service performance, rates of severe injury and fatality reduction, and maintenance and post-impact performance evaluation. For examples of these studies, the reader is encouraged to review those references noted in Chapter 16.

However, cable median barriers are median obstacles as well. They can place occupants at increased risk of severe injury or fatality if the barriers fail to adequately contain and redirect errant vehicles, resulting in rollover or vehicular penetration through the barrier. Furthermore, these barriers are also involved in many non-rollover, non-penetration fatalities and serious injuries, though no concerted effort has yet been made to determine the causes of these serious and fatal injuries.

Many industry experts expect the total mileage of cable median barrier to double within the next 10 years. As total cable median barrier mileage continues to climb, there is an opportunity to prevent many penetration, rollover, and serious injury or fatality crashes by improving barrier design, installation guidelines, and crash-testing guidelines to mitigate crash concerns with these barrier types.

2.2 Research Objective

The objective of this study was to evaluate a significant number of cable median barrier crashes across a broad spectrum of states to determine containment failure causality, design improvements, placement guidelines, and improved full-scale testing procedures to improve motorist safety performance.

2.3 Scope

In order to accomplish the research objective, a series of tasks were undertaken, and are summarized as follows:

(1) Cable barrier crash data were requested from many states with prominent histories of studying cable median barrier;

(2) Crash data were analyzed and segregated by state, vehicle type, vehicle class, impact conditions, median geometry, barrier type, crash result, crash severity, and containment failure mechanism; and

(3) Containment failure mechanisms of cable barriers were evaluated extensively using a combination of scene diagrams, crash narratives, photographic evidence, site measurements, and crash reconstruction techniques.

Additional studies are planned in the future to address specific vehicle types in vehicle-to-barrier interactions which may aggravate penetration or rollover tendencies.

3 LITERATURE REVIEW

Much of the U.S. freeway system was designed and constructed in the 1950s and 1960s. During this time, it was common to build high-speed facilities with 30-ft (9-m) and 40-ft (12-m) wide medians. With the low traffic volumes found on those freeways during this period, the frequency of tragic cross median crashes was low. The California Department of Transportation (Caltrans) conducted a study to determine the benefits of using median barriers in these relatively narrow medians [1]. This study indicated that barriers could not be justified in medians wider than 50 ft (15 m). Caltrans repeated this study several times between 1967 and 1997. Each time, the authors arrived at the same conclusion; barriers were not cost-effective when installed in medians wider than 50 ft (15.2 m), despite rising traffic volumes. However, findings from the 1997 version of this study were quite different and recommended that barriers be placed in medians as wide as 75 ft (22 m) [2]. The primary change between the 1997 report and earlier reports reflected the method of measuring real roadway departure data and travel speeds. Despite a mandated maximum speed of 55 mph through 1994 due to the National Maximum Speed Limit (NMSL) Law, actual travel speeds were between 15 to 20 mph higher (24 to 32 km/h). Following the repeal of this law, travel speeds in California were largely unchanged. This magnitude of speed increase observed between the 1968 and 1997 studies could easily explain the large increase in cross-median crashes and the differences in the benefits of using median barriers.

Following a trend of a high rate of cross-median crashes and associated fatalities, the North Carolina Department of Transportation (DOT) investigated the use of median barriers between 1997 and 2004, to mitigate the severity of median crashes and to reduce the frequency of cross-median crash events [3-4]. This pilot study analyzed 400 miles (644 km) of interstate with barrier, which included 175 miles (282 km) of cable barrier and an additional 44 miles (71 km) of cable barrier and W-beam combinations. Researchers observed a 71% drop in the number of cross-median crashes and associated fatalities or serious injuries due to the introduction of these cable median barriers. The total drop in severe and fatal injuries was 35% over this same period, while moderate injuries increased by 26%. The reason for the disparity between the drops in cross-median crash rates and severe crash rates is that any barrier system which can be struck by an errant motorist is a roadside obstacle. Every roadside obstacle can contribute to the number and frequency of severe crashes. Researchers postulated that by installing cable median barriers, 95 cross-median crashes were prevented and more than 100 lives were saved annually. The barriers prevented a large number of cross-median crashes and were ultimately successful in significantly reducing cumulative severe injury or fatality (A+K) crash frequency.

A similar study was conducted at Rowan University in 2005, identifying types of median barriers and crash histories for New Jersey Department of Transportation [5]. Although a net safety improvement was noted after median barrier installations, the crash frequency increased. Also, researchers noted that after cable barrier hits, maintenance personnel were slow to repair barriers often allowing the cables to sag to the ground in impact regions for up to several weeks.

The Wisconsin DOT investigated the correlation between cross-median crashes on the number of cross-median fatalities [6]. Researchers observed that between 2001 and 2003, Wisconsin roads and highways experienced 53 fatalities and more than 600 injuries in 631 cross-median crashes. Although most divided roadways were consistent with Wisconsin and American Association of State Highway and Transportation Officials (AASHTO) design standards, cross-median crashes were observed to be relatively independent of median width, average daily traffic (ADT), and lane width. The study was further expanded to determine median barrier warrants based on median widths [7]. Results were similar to the studies in North Carolina and California, in which many roadways with medians as wide as 70 ft (21 m) were applicable for median barrier installation.

A statistical analysis was conducted on cross-median crashes in the state of Minnesota between 2005 and 2008 to determine effectiveness of countermeasures as well as to validate or change the recommendations provided by AASHTO in the 2002 and 2006 Roadside Design Guides. Cross-median events were tabulated based on site statistics and used to generate statistical models of median encroachment frequencies [8]. The encroachment frequencies were then applied to models of freeway and rural expressway roads in the Roadside Safety Analysis Program (RSAP), and used in a benefit-to-cost analysis of median barrier types. Because Minnesota did not tabulate cross-median events directly on crash report forms, statistical data selection methods were used to determine frequency of cross-median encroachments based on subsamples. Based on the data analysis, cross-median events were most common during the period between December and February, when snowfall and ice formation was prevalent on Minnesota roads and medians. By reducing friction, vehicles that departed the roadway were unable to come to a stop before entering opposing travel lanes, despite typically lower travel speeds. Probabilities of vehicle collision, median encroachment, cross-median encroachment, and ADT were factored into a simulation using the Monte Carlo technique, and the model was recommended for evaluation against existing crash studies.

Cable barriers have long been recognized as an effective way of preventing vehicles from encountering side slopes which increase the risk of serious crashes as well as embankments and separating traffic on high-speed facilities. Crash data analysis has indicated that cable barriers provide the highest overall level of safety when compared to concrete safety shapes and steel beam guardrails [9-10]. Further, study of guardrail performance on slopes indicated that cable barriers can perform effectively when installed on slopes as steep as 5:1 [11], while metal beam guardrails did not demonstrate crashworthy performance on 6:1 slopes. Finally, cable barriers were the least expensive barrier option for use in medians of high-speed freeways. In view of the positive safety performance, capability of performing when installed on sloping medians, and low construction costs, it was not surprising that many highway agencies in the U.S. have decided to implement cable barriers whenever it was necessary to prevent cross-median crashes through depressed median ditches. As of today, the DOTs in more than 40 states have adopted this policy, and many of them have installed more than 100 miles of barrier. Industry experts have begun to predict that the installed base of cable median barrier in the U.S. will more than double over the next 7 to 10 years.

Even though cable median barrier has garnered a positive performance record, the high number of crashes that occur in narrow medians on high-speed, high-volume freeways still produces significant numbers of serious injury and fatal crashes involving cable barrier. A study of more than 5,000 cable barrier crashes over a two-year period found 12 fatal and 25 serious injury crashes [12]. Surprisingly, only half of the fatal crashes involved vehicles penetrating through the barrier and entering opposing traffic lanes. The remaining fatalities appeared to be related to impact with the cable barrier itself. Although the rate of six fatal crashes per year represented a 90% reduction in fatal crash rates when compared to the time prior to installation of cable barrier, these six fatal crashes per year would indicate that as many as 250 fatal crashes occur annually when extrapolated to data nationwide. Furthermore, crashes into the barriers indicated in this study had a lower-than-average rate of severe and fatal crashes compared to the national average of states surveyed in this study.

Further, if industry experts are correct and the installed base of cable barrier doubles over the next decade, up to 500 motorists could die annually during cable median barrier crashes within 10 short years. If this situation is to be avoided, improved cable barrier designs and deployment guidelines must be developed while construction of the barriers is still ongoing. The first step in developing better barrier designs and placement guidelines is to discover the primary causes associated with cable barrier crashes that produce fatalities and serious injuries.

In recognition of the critical need for a better understanding of the causes of cable barrier penetrations and serious injury and fatal crashes, the Mid-America Transportation Center (MATC) funded the study described herein. The goal of this study was to take the first step toward improving cable median barrier performance by determining the factors, such as impact conditions, vehicle type, median slope, and barrier placement, which tend to produce cable barrier penetrations and serious injury and fatal crashes. The Mid-America Transportation Center and the Midwest Roadside Safety Facility expect to utilize the findings from this study to develop better barrier designs and prepare guidelines for barrier implementation that can significantly reduce serious injury and fatal crash rates involving cable median barrier.

4 STATE BARRIER INSTALLATION GUIDELINES

4.1 Summary of Barrier Installation Practice by State

Each state surveyed in this study indicated guidelines by which cable median barriers were to be installed in the states. While all current state design standards are reflective of the state-of-the-art with respect to cable median barrier placement in divided medians to mitigate barrier underride, override, and rollover frequency, some historical systems were constructed prior to this important guidance. Those systems may not reflect the standards identified in this chapter.

The information presented in this report is accurate and current to the best knowledge of the reporting authors. However, state design and installation guidelines are available from state DOTs and should be consulted for the most up-to-date, accurate, and detailed design standards available. This guide is not intended for use as a reference manual. It is intended to summarize the current practices of states for overall comparison.

Iowa DOT currently requires cable median barriers to be placed 12 ft (3.7 m) from the edge of the travel way. Iowa requires that on narrow ditches approximately 30 ft (9.1 m) or less, that ditches be filled and slopes graded to 8:1 in front of the cable median barrier. The barrier is then installed adjacent to the median centerline. On wider medians, Iowa DOT requires that the approach slope to the barrier from the adjacent travel lanes be graded to 8:1, and the slope behind the barrier be tapered to match the existing slope with a slope shallower than or equal to 4:1. The grading in front of the cable median barrier is 10 ft (3.0 m) or wider.

Missouri DOT permits the use of high-tension cable median barriers on 4:1 slopes when those systems were eligible for installation based on acceptable crash testing results. Low-tension cable median barriers on steep slopes are eligible for replacement, and new or existing low-tension, 3-cable median barriers may only be installed on 6:1 or flatter slopes. Barriers are installed on slopes based on median widths. For medians greater than 30 ft (9.1 m) wide, barriers could be installed at least 8 ft (2.4 m) from the edge of the travel way and up to 4 ft (1.2 m) down the approach slope. For medians less than 30 ft (9.1 m) wide, median barriers are placed within 1 ft (0.3 m) of the center of the ditch. Vegetative barriers are located up to 2 ft (0.6 m) behind the barrier system.

Ohio DOT requires barrier installation a minimum of 12 ft (3.7 m) from the travel way and 8 ft (2.4 m) from the center of the ditch, on 6:1 or flatter V-ditches. Cable median barrier could also be placed adjacent to the shoulder if the shoulder was sufficiently wide. Shoulder placement is required on slopes steeper than 4:1. The maximum slope behind the barrier relative to adjacent travel lanes is 4:1. The maximum post spacing permitted is 15 ft (4.6 m).

Oklahoma DOT permits cable median barrier installation on 6:1 V-ditches or flatter. Generally, cable median barriers are only placed on medians which permitted at least 8 ft (2.4 m) on both sides of the median barrier without encroaching into adjacent travel lanes, but there is consideration for narrower medians on the grounds that small encroachments into opposing travel lanes are more desirable than cross-median crashes. Barriers are not permitted between 1 ft (0.3 m) and 8 ft (2.4 m) of the center of the ditch.

Oregon DOT permits limited installations in 4:1 V-ditches where crash testing indicated acceptable performance. Oregon DOT prohibited the use of cable median barriers in median V-ditches between 1 and 8 ft (0.3 and 2.4 m) from the center of the ditch. Barriers are always recommended to be placed as far from the travel was as could be practically installed. Median slopes are generally clear of debris, smooth, and frequently seeded with grass.

Texas DOT recommends barrier placement as far from the roadway as practical. Barriers may be placed within 1 ft (0.3 m) of the center of the median, or more than 8 ft (2.4 m) from the center of the median. Barriers are not permitted for installation in medians less than 24 ft (7.3 m) wide. Also, slopes in front of and behind the barrier are not permitted to be steeper than 6:1. On tight curves with radii of 650 to 2,500 ft (198 to 762 m), post spacing is required to be 6 ft – 8 in. (2.0 m) on center. For radii between 2,501 and 5,500 ft (762 to 1,676 m), cable barrier post spacing is 10 ft (3.0 m) on center, and for larger radii standard post spacing was utilized.

Utah DOT requires that cable median barriers be placed 1 ft (0.3 m) from the ditch center, 8 ft (2.4 m) from the ditch center, or between 8 and 16 ft (2.4 and 4.9 m) from one edge of the travel way. Utah DOT complies with recommendations from studies which indicated that the best capture behavior and rollover management indicated that the optimum placement was between 8 and 15 ft (2.4 and 4.6 m) from the edge of the road. In stepped medians, offsets are usually made with respect to the higher-elevated roadway. Cable median barriers are not used on medians with slopes steeper than 6:1.

Washington DOT required that cable median barriers be located 0 to 1 ft (0 to 0.3 m) of the center of the ditch, beyond 8 ft (2.4 m) from the center of the ditch, or near roadway shoulders. Barriers located at ditch shoulders are required to have a minimum clearance of 8 ft (2.4 m) from the roadway, and barriers were not permitted between 1 ft and 8 ft (0.3 m and 2.4 m) of the center of the ditch for slopes between 10:1 and 6:1. Cable median barriers could be installed on approach slopes of 6:1 or flatter, but required a minimum of 1 ft (0.3 m) lateral offset from the slope break point of a slope steeper than 6:1. Cable median barriers are also required to have a minimum top cable height of 35 in. (889 mm) and a bottom cable height not greater than 19 in. (483 mm). In general, cable barriers are always recommended to be located as far from the roadway as practicable.

Wisconsin DOT required that cable median barrier be placed 4 ft (1.2 m) from the slope break point in 4:1 V-ditches, although frequently cable median barrier is not selected for such steep terrain. Currently, cable median barrier is limited to installations on 6:1 V-ditches, and when cable median barrier is necessary on roadways with 4:1 V-ditches, typically two installations of cable median barrier are used adjacent to each shoulder. On 6:1 V-ditches, cable median barriers are located a minimum of 8 ft (2.4 m) from the center of the ditch, due to drainage and erosion concerns and to reduce risk of underride or override from vehicles traversing through the center of the median.

4.2 Reference Definitions

Unless defined explicitly, the following definitions were utilized:

1. Shoulder

The shoulder was defined as relatively flat extension of the roadway outside of the travel lanes in which no hazards were located. Shoulders could be paved or unpaved. The edge of the shoulder was defined as a transition in slopes from the roadway to the median. If no transition was present, the median was described as “flat” and the entire median was treated as if the two roadway shoulders intersected.

2. Approach Slope

Approach slopes were defined as the first slopes encountered by errant vehicles departing the roadway into the median after traversing the shoulder. In stepped medians in which there was only one median slope, the entire slope was considered an approach slope. Vehicle travel direction was always consulted in crash data analysis to determine the correct approach slope and vertical grade encountered. The barrier was considered to be on the approach slope if the barrier was more than 3 ft (0.9 m) from the edge of the shoulder.

3. Center of Ditch

The center of ditch referred to the area of the ditch spanning between 4 ft (1.2 m) on either side of the ditch slope transition between approach and back slopes. This definition does not necessarily refer to the physical centerline of the V-ditch. For ditches with flat centers more than 4 ft (1.2 m) wide and less than 15% of the ditch width, the entire flat center of the ditch was considered the ditch center.

4. Back Slope

The back slope, if present, was the slope encountered by a vehicle after crossing the center of the V-ditch. Back slopes were not relevant on all crashes involving cable median barrier redirection if the barriers were installed on traffic-side shoulders, approach slopes, or near the center of the ditch. In sawtooth medians in which back slopes had different slope rates than the approach slope, distinctions were made between each slope rate. As with approach slopes, travel direction of the errant vehicle was consulted when identifying which slope was an approach slope and which slope was a back slope. A barrier was considered to be on the back slope if the barrier was more than 3 ft (0.9 m) from the opposite-side shoulder.

5. Penetration

A barrier penetration was defined as a crash in which the impacting vehicle traversed completely from one side of the barrier to the other side, such that no cables were in advantageous positions to redirect the vehicle if it continued to move toward opposite travel lanes. A potential penetration was similar, except that the vehicle came to a stop before completely passing from one side of the cable median barrier to the other; nonetheless, no cables were in advantageous positions to redirect the vehicle.

6. Rollover

A rollover was defined as a crash in which the impacting vehicle made a minimum of one quarter-revolution about the longitudinal axis. In addition, to be considered a rollover, the vehicle must have had at least one side or the top/roof contact the ground to be considered a rollover.

7. Failure

Cable median barriers are generally designed to safely redirect or capture vehicles with controlled lateral displacement of the barrier. As such, barrier failures were defined as crashes in which any of the following events occurred: penetration, rollover, or serious injury or fatality of an occupant in a vehicle striking the cable median barrier.

However, a barrier failure does not necessarily indicate a poor crash result. For example, a barrier containment failure consisting of a penetration may result in property damage only to the impacting vehicle and potentially one or two cable median barrier posts. If the occupant of the impacting vehicle is unharmed, the barrier containment failure would not be considered hazardous. Furthermore, if the vehicle which was involved in a penetration event did not traverse into opposing travel lanes and the crash injury level was not severe, the barrier may have satisfactorily prevented a cross-median crash; in this instance, the barrier containment failure still resulted in acceptable overall performance and the crash outcome was positive.

Though the nature of cross-median crash prevention can be speculative, history has shown that even with penetration rates as high as 10% and rollover frequency as high as 8% of all crashes, overall median severity on many roadways improved after cable median barrier was installed. This was particularly true if a relatively high rate of fatalities was already present due to cross-median crashes. Neither penetration nor rollover containment failures indicate that the barrier is unsafe, but instead refer only to the breach in containment experienced by the impacting vehicle.

Barrier systems were located consistent with the state design standards. The only exceptions to this identification were with respect to systems installed before newer design guidelines became available between 2004 and 2007. Such barrier systems were analyzed and included in the results because of potential significance to the outcome of this report.

5 SUMMARY OF CABLE BARRIER CRASHES

5.1 Description of Study

A total of 12 states responded to a survey request for crash data regarding cable median barrier crashes. A total of more than 25,000 crashes were received which documented periods between 1996 and 2010. In addition, approximately 6,000 crashes with sufficient information were extracted for further evaluation. The state DOTs which provided data for this study were: Missouri, North Carolina, Ohio, Oklahoma, Washington, Iowa, Illinois, Texas, Oregon, Utah, Kentucky, and Wisconsin.

Between 2007 and 2009, 7,093 cable median barrier crashes were reported in Missouri, and of those crashes, 174 involved serious injuries or fatalities. Hence, the combined serious injury and fatal crash rate for cable barrier in Missouri was found to be 2.5%. This finding was consistent with prior crash studies of cable barriers that indicated low crash severities for cable barriers when compared to other types of barriers. For example, the combined serious and fatal injury rates for guardrail and bridge rail crashes in Kansas were 4.9% and 3.6% respectively [13].

Crash reports were obtained for all 174 crashes involving serious or fatal injuries in the Missouri database, of which 169 of the crash reports contained detailed drawings of the crash scene, including measurements of vehicle position near points of departure and impact and vehicle tire marks laid down as the vehicle approached the barrier. A careful examination of these crashes revealed that the cable barrier significantly contributed to occupant injury in 128 of the crashes. The remaining 46 crashes involved other mechanisms for occupant injury, including vehicle rollover prior to the barrier impact, impacts with another vehicle before leaving the travelway or after coming to rest, and acute health problems of the driver and occupants unrelated to the crash. In addition, some crashes were misreported as cable barrier crashes when other barriers, such as W-beam or concrete barriers, were actually involved. After eliminating cases which were unrelated to cable barrier performance, the combined serious and fatal injury crash rate was reduced to 1.8%.

Using reported lengths and widths measured by investigating officers at points of vehicle departure from the road and at the point of impact with the cable median barrier, crash scene diagrams were scaled to account for varying longitudinal and lateral compression to fit the boundaries of the scene diagram, which generated approximate, dimensionally representative crash scene drawings. Then, approximate scaled crash scenes were used to generate vehicle trajectory information up to the point of impact with the barrier system. Trajectory data included the vehicle CG trajectory angle, sideslip angle, and the angle between the vehicle's longitudinal axis and the barrier. This information was used to build a database of crash impact conditions to evaluate vehicle/barrier interaction.

A set of 22 crashes in North Carolina were provided and had exact scene measurements, photographs of the vehicle and system, median slope measurements, median widths, and vehicle information. The CG trajectory and orientation angles were also recorded for these crashes. The 22 crashes consisted only of penetrations; this dataset was not a random sample.

An additional 890 cases were extracted from a crash database in the state of Ohio, whose locations were observable using the Google Street View application. Slope data digitized from topographical surveying were used to obtain median geometries at each crash location, which was located using a combination of mile markers, latitudes and longitudes, feature references, and information from indicative scene diagram representations. As with the Missouri database, unrelated crashes were excluded from the analysis. Photographs of the crash scene and vehicle were requested for all crashes in which photographs were taken of the scene, and those photos were released through the Ohio Department of Public Safety, with additional cooperation from the Ohio State Patrol.

A tabulated database of crashes was obtained from the Oklahoma DOT, including crash results, roadway locations, and barrier types that were struck. Crash reports were not available for the crashes listed, and vehicle year, make, and model were not available for release under Oklahoma law. Due to limited funding, the purchase of crash report copies was not pursued.

A tabulated database of cable median barrier crashes was received from the State of Washington and covering a period between 1996 and 2008, with an additional tabulated list of model, make, and year of the vehicles involved in cable barrier crashes. Crash reports for serious injury and fatal crashes in the state were also provided. The database included information regarding the crash result and the manner of collision, along with an extensive investigation of injury tabulation. As with Oklahoma, the majority of crashes did not have a scene diagram or a narrative available to definitively identify crash injury causation, mechanisms of barrier containment failures, and potential data overlap. Nonetheless the database was useful for evaluating crash statistics, overall barrier performance, and installation practices.

The Iowa DOT provided a tabulated database of cable median barrier crashes and results between 2006 and 2009, along with scene diagrams and crash narratives. Although precise scene diagram measurements were not available, make, model, and year of vehicles striking the cable median barrier were provided. Precise geographical locational measurements were provided for each crash to identify the exact location of the crash site for further investigation.

The Illinois DOT provided a crash database to evaluate propensities for cross-median collisions, as well as a tabulated list of cable barrier crashes between 2005 and 2008 in the state of Illinois. Scene diagrams and narratives were not provided, and no median information was available. However, precise geographical location measurements were also available and the crash sites were located, allowing precise determination of barrier usage at each site.

The Texas DOT provided a large block of crash data regarding all crashes, not only cable median barrier crashes on divided median roadways between 2003 and 2009. Unfortunately Texas law, which is similar to Oklahoma, does not permit the free exchange of sensitive crash data such as scene diagrams, crash narratives, and occupant information. Because the crash data could not be used to determine crash causation or object struck, the Texas data were limited in scope to crash statistics for only broad evaluations.

The Oregon DOT provided a crash summary database for cable median barrier crashes in Oregon through 2007. This information included crash severity and relative risk based on the total number of crashes, as well as crash statistics measured by DOT researchers.

Similarly, the Kentucky Department of Public Safety (DPS) provided lists of crash reports available for sorting. However, since this information was received later in the analysis, the crash results were only used for generating statistical comparisons.

The Utah DOT provided a database of scene diagrams, crash narratives, impacting vehicle makes, models, and years, road segment traffic volumes, and crash statistics. Photos and annotated scene diagrams with survey measurements were available for purchase through the Department of Public Safety, but the available funding for the project prohibited this extra expense. Utah also provided information regarding barrier type for installations throughout the state.

The Wisconsin DOT provided crash reports, scene diagrams, and a webcam video of a single cable barrier penetration event in the state of Wisconsin. Each cable barrier crash was located using a geographical state surveying tool, and locations of each crash were identified. Included in the crash reports were vehicle make, model, and year.

It is possible that a number of critical injury and fatal crashes involving cable median barriers were incorrectly coded and therefore excluded from the database. However, prior experience with crash reports associated with barrier crashes would indicate that it is not common that a police officer fails to indicate the barrier was struck for a crash involving serious injuries and fatalities. Therefore, it was assumed that the number of crashes missing from the database was relatively low. Further, even if a significant number of unreported severe crashes do occur, there is no reason to believe that omitted cases would have a bias in any characteristic other than injury severity. Because police officers are likely to spend more time investigating serious injury and fatal crashes, the bias would reduce the risk of case omission as the severity increased.

5.2 Cable Barrier Impacts

In each state, cable barrier crashes were examined to determine if the barrier failed to adequately capture or redirect the vehicle without subjecting occupants to serious injury or fatality. For the purpose of analysis, three categories were created: penetration crashes, rollover crashes, and severe injury or fatality (A+K) crashes.

Severe A+K crashes were defined as crashes when at least one occupant of the vehicle impacting the cable barrier experienced a severe or disabling injury or fatality. An effort was made to exclude crashes in which the fatality or severe injury was not caused at least in part by the reaction of the cable barrier. Cable barrier crashes in which the vehicle was not redirected and passed from the impact side to non-impact side of the barrier were classified as penetration crashes. Crashes in which the vehicle either protruded under, between, or over the top of the barrier but came to rest before all four tires passed to the non-impact side were classified as potential penetrations, which displayed the propensity for a penetration to occur. Rollover crashes were defined as those in which impacting vehicles experienced at least a one-quarter revolution about the longitudinal axis before coming to rest. Rollover crashes in which the vehicle tripped before impacting the barrier or in which the rollover was unrelated to cable barrier performance were excluded.

The crash set was further segregated in the event that a rollover occurred contingently with a penetration. The overlapping data set was segregated into mutually exclusive causative factors, using scene diagrams, crash narratives, vehicles, and median information to determine which factor was the predominant or causative factor in penetration and rollover crashes. If a vehicle penetrated through the barrier before rolling over on the median back slope, opposing travel lanes, or other post-penetration impact location, the major causative factor was determined to be a penetration. However, if it was determined that the vehicle overturning caused or contributed to the vehicle penetrating through or over the top of the barrier, the major causative factor was identified to be a rollover. Separate efforts were made to determine the injury causes of A+K crashes due to contact with a barrier element, rollover, ejection, or other factors.

5.2.1 Weather and Road Conditions

Cable barrier crashes tabulated from each state DOT were investigated to evaluate the frequency of weather-related crashes compared to annual numbers of days with rainfall and snowfall in each state. The frequency of adverse weather effects in surveyed states are shown in Tables 2 and 3. Some states were characterized by a wide variation in regional annual snowfall and rainfall, based on data by NOAA National Climate Data Center for annual precipitation.

The standard deviations in average days with snowfall were as large as the average number of days with snowfall for some states. In some locations, the number of days with snow or rain could vary from one region to another by a factor of 10 [14]. Conversely, states in the lower Midwest and coastal regions did not have large variations in days with rainfall or snowfall, such as Missouri, North Carolina, and Washington.

Oklahoma averaged only 61 days with minimum rainfall of 0.01 in. (0.25 mm) and three days with minimum snowfall of 0.1 in. (2.5 mm). States with the lowest relative deviation based on the norm were located in the Midwest, including Ohio, Illinois, Missouri, and Iowa, with the one notable exception of Washington.

Table 2. Average Number of Days with Rainfall in Select Surveyed States

State	Average Number of Days with Minimum Rainfall of			Frequency of Days with Minimum Rainfall of			Average Deviation
	0.01 in. (0.3 mm)	0.1 in. (3 mm)	0.5 in. (13 mm)	0.01 in. (2.5 mm)	0.1 in. (2.5 mm)	0.5 in. (2.5 mm)	
Illinois	94.5	64.1	26.2	25.9%	17.5%	7.2%	10.2%
Iowa	82.2	53.1	21.4	22.5%	14.5%	5.9%	11.1%
Missouri	89.6	63.8	28.5	24.6%	17.5%	7.8%	10.4%
North Carolina	115.5	79.1	33.1	31.6%	21.7%	9.1%	11.9%
Ohio	118.7	75.4	25.5	32.5%	20.6%	7.0%	10.4%
Oklahoma	61.4	44.6	24.2	16.8%	12.2%	6.6%	21.6%
Utah	55.0	25.1	4.9	15.1%	6.9%	1.3%	57.7%
Washington	104.9	62.1	19.9	28.7%	17.0%	5.5%	8.9%
Wisconsin	123.3	75.4	23.3	33.8%	20.7%	6.4%	66.0%

Table 3. Average Number of Days with Snowfall in Select Surveyed States

State	Average Number of Days with Minimum Snowfall of			Frequency of Days with Minimum Snowfall of			Average Deviation
	0.1 in. (3 mm)	1.0 in. (25 mm)	5.0 in. (127 mm)	0.01 in. (2.5 mm)	0.1 in. (2.5 mm)	0.5 in. (2.5 mm)	
Illinois	11.9	6.9	0.8	3.3%	1.9%	0.2%	47.6%
Iowa	16.9	11.0	1.3	4.6%	3.0%	0.4%	22.6%
Missouri	6.5	4.2	0.5	1.8%	1.2%	0.1%	42.5%
North Carolina	2.7	1.9	0.4	0.7%	0.5%	0.1%	172.2%
Ohio	17.9	9.4	0.8	4.9%	2.6%	0.2%	68.9%
Oklahoma	3.0	2.1	0.3	0.8%	0.6%	0.1%	75.2%
Utah	19.2	15.5	3.0	5.3%	4.3%	0.8%	113.6%
Washington	27.2	17.2	2.1	7.5%	4.7%	0.6%	39.3%
Wisconsin	11.8	8.4	1.9	3.2%	2.3%	0.5%	195.0%

Monthly and annual precipitation totals of each participating state were also recorded, as shown in Tables 4 and 5. Since most states surveyed were in the central plains to Midwest region, the annual yearly precipitation is similar for Iowa, Illinois, Missouri, and Wisconsin, though Wisconsin had locally larger rain and snow accumulation due to proximity to Lakes Superior and Michigan. However, because Wisconsin is west and south of the Great Lakes, the additional precipitation is highly localized, with as much as 140 in. (3,556 mm) of snow falling annually at the southern-central portion of Lake Superior and 40 to 50 in. (1,016 to 1,270 mm) falling in most of the remainder of the state. Most cable median barrier crash data available from Wisconsin occurred in close proximity to Fon du Lac, Wisconsin.

Table 4. Average Monthly Precipitation in Select Surveyed States

State	Average Monthly Precipitation, 50th Percentile (in.)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Illinois	1.8	1.9	2.6	3.4	4.4	3.8	3.6	3.2	2.7	2.7	3.2	2.3	35.7
Iowa	0.9	1.0	1.8	3.2	4.3	4.5	3.9	3.6	3.0	2.2	1.8	1.2	31.3
Missouri	1.8	2.0	2.9	3.8	4.8	4.2	3.7	3.3	3.3	3.1	3.2	2.4	38.7
North Carolina	3.8	3.5	4.1	3.4	3.6	4.1	4.7	4.6	3.9	3.2	3.4	3.6	45.8
Ohio	2.3	2.1	2.9	3.5	4.3	3.9	3.8	3.2	2.8	2.6	3.0	2.8	37.1
Oklahoma	1.5	1.6	2.8	3.1	4.6	4.2	2.6	2.6	3.2	2.9	2.2	1.8	33.0
Utah	1.0	1.1	1.3	1.2	1.1	0.6	0.7	0.9	1.0	1.3	1.0	1.0	12.2
Washington	5.9	3.7	3.9	2.9	2.3	1.8	0.7	0.7	1.5	3.6	6.2	5.6	38.9
Wisconsin	1.0	1.0	1.7	2.8	3.4	3.8	3.7	3.7	3.3	2.6	1.9	1.3	30.1

Table 5. Average Monthly Snowfall in Select Surveyed States

State	Average Monthly Snowfall, 50th Percentile (in.)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Illinois	5.1	3.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	3.8	13.1
Iowa	6.7	5.6	3.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3	6.5	23.7
Missouri	2.3	2.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	6.2
North Carolina	0.7	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	2.0
Ohio	7.0	4.3	2.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.5	4.3	19.1
Oklahoma	0.8	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.7
Utah	9.1	8.2	5.8	2.8	0.5	0.0	0.0	0.0	0.0	0.7	4.5	9.0	40.5
Washington	5.6	2.9	1.5	0.7	0.2	0.0	0.0	0.0	0.0	0.2	2.4	6.9	20.4
Wisconsin	10.6	8.7	7.0	1.3	0.0	0.0	0.0	0.0	0.0	0.1	3.0	9.8	40.6

Whereas the average precipitation in Oklahoma varied from moderate annual rainfall to relatively arid conditions, most of the cable median barrier was located around the Norman and Oklahoma City areas. Rainfall in these regions is less frequent and with lower accumulation compared to the eastern parts of the state.

The approximate geographical distribution of cable median barrier locations with surveyed crash data were located on a NOAA precipitation map and is shown in Figure 1. Ohio's annual precipitation was higher because of close proximity to Lake Erie, which occasionally resulted in more than 5 in. (127 mm) of rain or 12 in. (305 mm) of snow within a span of a few days in some cable median barrier locations. In general, southern parts of the state recorded higher precipitation totals, due to contributions from gulf and coastal storm systems.

Precipitation: Annual Climatology (1981-2010)

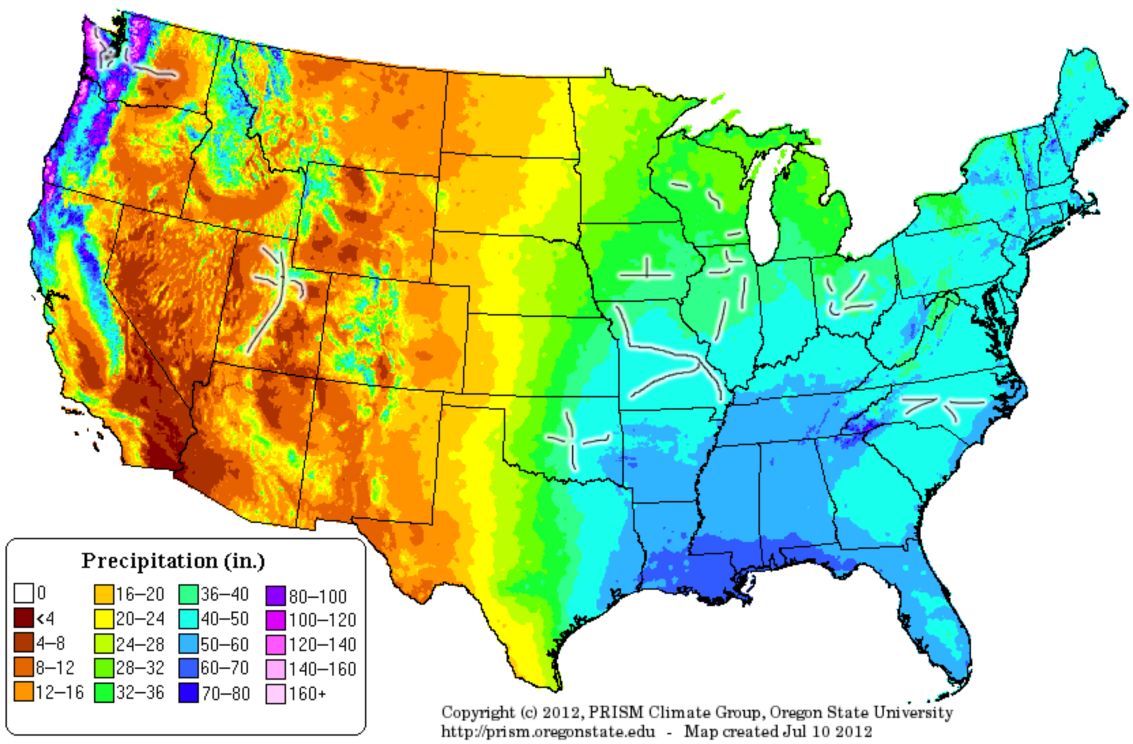


Figure 1. Selected Approximate Barrier Locations with Annual Precipitation Estimates [15]

Besides Ohio, both Washington and North Carolina experienced higher cumulative precipitation than other states in this survey. Both Washington and North Carolina are coastal states which experience significant rainfall, without much snowfall in the areas around cable barrier locations. In contrast, Utah was largely dry, except for the I-15 corridor. However, the I-15 corridor was also the site of much of the cable median barrier installed in Utah.

Barrier performance was tabulated for each impact in the available database of crashes; however, crashes in which a penetration or rollover occurred were subjected to additional scrutiny to identify the cause of the poor barrier performance. The process of selection and causality used in this study is described in greater detail in Chapters 8 and 11.

Results of each state were segregated by weather conditions (i.e., snowing, raining), road conditions at the time of the crash (i.e., wet, snow-covered, slush), crash severity, type of cable barrier system that was struck, the date of crash, and the barrier's performance. The results are tabulated in Tables 6 through 11. Primary barrier containment failures were identified and segregated by predominant weather and road conditions. By considering only primary barrier failures, secondary events such as penetration following rollover were excluded from the analysis. Primary barrier failure segregation also served the purpose of establishing mutually exclusive categories of penetration or rollover crashes; this was useful in determining what driving conditions were associated with the predominant cause of barrier containment failures.

Since some states had significant volumes of data and others had smaller data sets, a crash volume weighting factor was used to bias results toward states with more crashes when each state's crash results were averaged together. Weighting factors applied to determine the approximate average rate of cable barrier containment failures consisted of an average of the individual percentage of failures occurring in each state with the total percentage of failures of all states based on all crash data. This process weighted data from states with large volumes of crash data, but still incorporated data from states with limited available crash databases to draw from. The average rate of vehicular penetration through the barrier was approximately 9.3% when penetrations were the primary barrier containment failure. In contrast, the composite average rate of vehicle rollover as a primary containment failure mechanism was approximately 5.1%. When considering the rates of actual vehicle rollover and penetration over the barrier and relaxing the mutually-exclusive primary failure mechanism restriction, the composite rate of penetrations and rollovers rose to approximately 9.9% and 8.1%, respectively.

Table 6. Crash Result in States by Predominant Weather Condition

Weather Condition	Illinois			Iowa			Ohio			Oklahoma			Utah			Washington			Wisconsin		
at Time of Crash	Crashes	Penetration[1]	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover	Crashes	Cross-Median[2]	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover
No Adverse Effects	150	-	8	60	4	1	404	46	30	1147	26	48	479	26	42	1105	139	94	44	7	4
Rain	48	-	0	10	1	0	164	10	3	415	7	6	43	2	1	290	45	7	3	0	0
Snow or Sleet	100	-	3	52	4	1	274	18	1	190	1	4	397	10	8	225	24	11	49	5	2
Fog or Mist	4	-	0	1	0	0	7	2	1	13	0	1	3	0	0	20	2	3	0	0	0
Strong Crosswind	2	-	0	3	0	0	0	0	0	4	0	1	3	0	0	1	0	0	0	0	0
Unknown or Other	1	-	0	0	0	0	9	2	2	11	0	0	2	0	0	6	0	0	1	0	0
Total	**305**	**-**	**11**	**126**	**9**	**2**	**858**	**78**	**37**	**1780**	**34**	**60**	**927**	**38**	**51**	**1647**	**210**	**115**	**97**	**12**	**6**

Weather Condition	Illinois			Iowa			Ohio			Oklahoma			Utah			Washington			Wisconsin		
at Time of Crash	Crashes	Penetration[1]	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover	Crashes	Cross-Median[2]	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover	Crashes	Penetration	Rollover
No Adverse Effects	150	-	5.3%	60	6.7%	1.7%	404	11.4%	7.4%	1147	2.3%	4.2%	479	5.4%	8.8%	1105	12.6%	8.5%	44	15.9%	9.1%
Rain	48	-	0.0%	10	10.0%	0.0%	164	6.1%	1.8%	415	1.7%	1.4%	43	4.7%	2.3%	290	15.5%	2.4%	3	0.0%	0.0%
Snow or Sleet	100	-	3.0%	52	7.7%	1.9%	274	6.6%	0.4%	190	0.5%	2.1%	397	2.5%	2.0%	225	10.7%	4.9%	49	10.2%	4.1%
Fog or Mist	4	-	-	1	-	-	7	28.6%	14.3%	13	-	7.7%	3	-	-	20	10.0%	15.0%	0	-	-
Strong Crosswind	2	-	-	3	-	-	0	-	-	4	-	25.0%	3	-	-	1	-	-	0	-	-
Unknown or Other	1	-	-	0	-	-	9	22.2%	22.2%	11	-	-	2	-	-	6	-	-	1	-	-
Total	**305**	**-**	**3.6%**	**126**	**7.1%**	**1.6%**	**858**	**9.1%**	**4.3%**	**1780**	**1.9%**	**3.4%**	**927**	**4.1%**	**5.5%**	**1647**	**12.8%**	**7.0%**	**97**	**12.4%**	**6.2%**

Table 7. Crash Result in States with Complete Data Sets by Predominant Weather Condition

Iowa			Ohio			Utah			Wisconsin			Total		
Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
60	4	1	404	46	30	479	26	42	44	7	4	987	83	77
10	1	0	164	10	3	43	2	1	3	0	0	220	13	4
52	4	1	274	18	1	397	10	8	49	5	2	772	37	12
1	0	0	7	2	1	3	0	0	0	0	0	11	2	1
3	0	0	0	0	0	3	0	0	0	0	0	6	0	0
0	0	0	9	2	2	2	0	0	1	0	0	12	2	2
126	**9**	**2**	**858**	**78**	**37**	**927**	**38**	**51**	**97**	**12**	**6**	**2008**	**137**	**96**

Iowa			Ohio			Utah			Wisconsin			Total		
Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
60	6.7%	1.7%	404	11.4%	7.4%	479	5.4%	8.8%	44	15.9%	9.1%	987	8.4%	7.8%
10	10.0%	-	164	6.1%	1.8%	43	4.7%	2.3%	3	-	-	220	5.9%	1.8%
52	7.7%	1.9%	274	6.6%	0.4%	397	2.5%	2.0%	49	10.2%	4.1%	772	4.8%	1.6%
1	0.0%	-	7	28.6%	14.3%	3	-	-	0	-	-	11	18.2%	9.1%
3	0.0%	-	0	-	-	3	-	-	0	-	-	6	-	-
0	-	-	9	22.2%	22.2%	2	-	-	1	-	-	12	16.7%	16.7%
126	**7.1%**	**1.6%**	**858**	**9.1%**	**4.3%**	**927**	**4.1%**	**5.5%**	**97**	**12.4%**	**6.2%**	**2008**	**6.8%**	**4.8%**

Table 8. Crash Result in States by Predominant Road Condition

Illinois			Iowa			Ohio			Oklahoma			Utah			Washington			Wisconsin		
Crashes	Penetrations[1]	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Cross-Median[2]	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
127	-	8	44	4	2	333	40	30	1575	24	56	364	21	35	888	115	79	26	5	1
63	-	1	15	2	0	260	18	5	39	9	0	99	5	3	398	57	12	7	1	0
113	-	2	67	3	0	261	20	2	164	1	4	457	12	13	344	38	23	63	6	5
2	-	0	0	0	0	4	0	0	2	0	0	7	0	0	17	0	1	1	0	0
305	**0**	**11**	**126**	**9**	**2**	**858**	**78**	**37**	**1780**	**34**	**60**	**927**	**38**	**51**	**1647**	**210**	**115**	**97**	**12**	**6**

Illinois			Iowa			Ohio			Oklahoma			Utah			Washington			Wisconsin		
Crashes	Penetrations[1]	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Cross-Median[2]	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
127	-	6.3%	44	9.1%	4.5%	333	12.0%	9.0%	1575	1.5%	3.6%	364	5.8%	9.6%	888	13.0%	8.9%	26	19.2%	3.8%
63	-	1.6%	15	13.3%	-	260	6.9%	1.9%	39	23.1%	-	99	5.1%	3.0%	398	14.3%	3.0%	7	14.3%	-
113	-	1.8%	67	4.5%	-	261	7.7%	0.8%	164	0.6%	2.4%	457	2.6%	2.8%	344	11.0%	6.7%	63	9.5%	7.9%
2	-	-	0	-	-	4	-	-	2	-	-	7	-	-	17	-	-	1	-	-
305	**0.0%**	**3.6%**	**126**	**7.1%**	**1.6%**	**858**	**9.1%**	**4.3%**	**1780**	**1.9%**	**3.4%**	**927**	**4.1%**	**5.5%**	**1647**	**12.8%**	**7.0%**	**97**	**12.4%**	**6.2%**

Table 9. Crash Result in States with Complete Data Sets by Predominant Road Condition

Road Conditions at Time of Crash	Iowa			Ohio			Utah			Wisconsin			**Total**		
	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
No Adverse Effects	44	4	2	333	40	30	364	21	35	26	5	1	767	70	68
Wet or Pooling Water	15	2	0	260	18	5	99	5	3	7	1	0	381	26	8
Snow, Slush, or Ice	67	3	0	261	20	2	457	12	13	63	6	5	848	41	20
Unknown or Other	0	0	0	4	0	0	7	0	0	1	0	0	12	0	0
Total	**126**	**9**	**2**	**858**	**78**	**37**	**927**	**38**	**51**	**97**	**12**	**6**	**2008**	**137**	**96**

Road Conditions at Time of Crash	Iowa			Ohio			Utah			Wisconsin			**Total**		
	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers	Crashes	Penetrations	Rollovers
No Adverse Effects	44	9.1%	4.5%	333	12.0%	9.0%	364	5.8%	9.6%	26	19.2%	3.8%	767	9.1%	8.9%
Wet or Pooling Water	15	13.3%	-	260	6.9%	1.9%	99	5.1%	3.0%	7	14.3%	-	381	6.8%	2.1%
Snow, Slush, or Ice	67	4.5%	-	261	7.7%	0.8%	457	2.6%	2.8%	63	9.5%	7.9%	848	4.8%	2.4%
Unknown or Other	0	-	-	4	-	-	7	-	-	1	-	-	12	-	-
Total	**126**	**7.1%**	**1.6%**	**858**	**9.1%**	**4.3%**	**927**	**4.1%**	**5.5%**	**97**	**12.4%**	**6.2%**	**2008**	**6.8%**	**4.8%**

Table 10. Average Rates of Barrier Containment Failure by Predominant Weather Condition

Weather Condition	Penetration	Rollover
No Adverse Effects	9.8%	6.7%
Rain	6.9%	2.1%
Snow or Sleet	6.7%	2.1%
Average Failure Rate	**9.3%**	**5.1%**

Table 11. Average Rates of Barrier Containment Failure by Predominant Road Condition

Road Condition	Penetration	Rollover
No Adverse Effects	11.5%	6.8%
Wet or Pooling Water	9.9%	2.5%
Snow, Slush, or Ice	6.1%	3.8%
Average Failure Rate	**9.3%**	**5.1%**

Three key conclusions were drawn from the data:

(1) Dry, clear conditions were associated with the highest rates of penetration or rollover. Travel speeds and vehicle-to-ground friction values were the highest during dry, clear weather and road conditions. The increased travel speeds and greater friction generally contributed to more energetic impacts with cable median barrier systems due to a combination of high speed and high CG trajectory and orientation angles at impact.

(2) Reduced tire ground friction, which is the reason for lower travel speeds during inclement weather, also affected barrier interaction by influencing impact CG trajectory and orientation angles. When contact friction was decreased, the roll moment applied to the vehicle in sliding conditions was significantly reduced, which largely explains the reduction in rollover occurrences. The largest rate of reduction of penetration crashes related to adverse weather events is due to reduced travel speeds and a reduction in the CG trajectory angle present at the time of the crash, which is caused by less tire-ground friction. However, after storms struck and the roadsides were snowy or wet but road conditions improved, travel speeds were typically increased. Errant vehicles departing the road during these conditions were unable to slow down as quickly before impacting the barrier, which could explain the discrepancy observed between road and predominant weather condition data relevant to penetration rates.

(3) Although states with higher annual precipitation experienced higher annual rates of vehicle penetration through the barrier systems, the locations of the cable median barriers in wetter states affected crash likelihood. States with significant rainfall or snowfall and with relatively narrow medians frequently installed cable median barriers at or near roadside shoulders to accommodate generally steeper median

slopes. Cable median barrier installations near shoulders had higher rates of penetration and rollover than barrier installations placed on approach or back slopes.

5.2.2 Weather Conditions and Barrier Type

Rates of barrier containment failures by type of barrier were also investigated to evaluate the effect of weather on vehicle redirection by system type. A comparison of crash results by barrier make and weather condition is shown in Table 12. Additionally, a comparison of crash result by barrier make and road condition is shown in Table 13. Since rollovers were frequently coded with crash results in DPS reports, rollover characteristics were available even when no scene diagrams were provided in some states. However, penetrations are not currently tabulated explicitly by most responding officers or DOTs, and thus a scene diagram was required to make the proper crash result determination. As a result, the total number of applicable crashes in the penetration database was substantially lower than the number of crashes in the rollover database.

It was observed that various proprietary barrier systems had markedly different rates of penetration and rollover. Although its database was limited in scope, the Brifen Wire Rope Safety Fence (WRSF) had the lowest rate of penetration when compared to other high-tension systems. Conversely, Nucor Marion Steel's NU-CABLE system with three cables had a large database of hits and a considerable number of penetrations, with a penetration frequency of 9.7%. Additionally, the CASS and generic systems had intensive crash histories covering a broad geographical area, whereas the Nucor, Brifen, and Gibraltar systems were largely restricted to narrow geographical regions which affected distributions of weather patterns. Although Gibraltar's penetration frequency was higher than the Nucor system, the Gibraltar database too small in size to concretely determine penetration frequency and thus potential "outlier" cases contributed significant uncertainty. Other recent studies involving individual state data indicated penetration rates for Gibraltar and CASS systems as high as 16% [30].

Unfortunately, it was misleading to separate barrier statistics by manufacturer without a more intensive investigation into site details and state crash histories. Some states primarily use one type of barrier system. Since impact conditions and vehicle type can vary widely, these factors can lead to different propensities for penetration or rollover due to median geometries, traffic volumes, weather patterns, and barrier placement.

Table 12. Crash Result per System in States with Complete Data Sets by Predominant Weather Condition

Weather Conditions at Time of Crash	Low-Tension 3-Cable			Brifen WRSF			Nucor NU-CABLE			Trinity CASS		
	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency
No Adverse Effects	3020	224	7.4%	56	3	5.4%	333	40	12.0%	1134	112	9.9%
Rain	969	59	6.1%	29	2	6.9%	131	8	6.1%	189	26	13.8%
Snow or Sleet	243	13	5.3%	33	3	9.1%	213	15	7.0%	652	33	5.1%
Fog or Mist	28	6	21.4%	0	0	-	7	2	28.6%	16	2	12.5%
Strong Crosswind	0	0	-	1	0	-	0	0	-	6	0	-
Unknown or Other	8	0	-	0	0	-	8	2	25.0%	5	0	-
Total	**4268**	**302**	**7.1%**	**119**	**8**	**6.7%**	**692**	**67**	**9.7%**	**2002**	**173**	**8.6%**

Weather Conditions at Time of Crash	Low-Tension 3-Cable			Brifen WRSF			Nucor NU-CABLE			Trinity CASS		
	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency
No Adverse Effects	542	53	9.8%	991	39	3.9%	446	29	6.5%	1183	94	7.9%
Rain	159	7	4.4%	338	3	0.9%	168	3	1.8%	209	1	0.5%
Snow or Sleet	81	3	3.7%	194	4	2.1%	288	2	0.7%	661	18	2.7%
Fog or Mist	8	2	25.0%	9	1	11.1%	11	1	9.1%	17	1	5.9%
Strong Crosswind	0	0	-	3	1	33.3%	3	0	-	6	0	-
Unknown or Other	5	0	-	9	0	-	9	2	22.2%	5	0	-
Total	**795**	**65**	**8.2%**	**1544**	**48**	**3.1%**	**925**	**37**	**4.0%**	**2081**	**114**	**5.5%**

Table 13. Crash Result per System in States with Complete Data Sets by Predominant Road Condition

Road Conditions at Time of Crash	Low-Tension 3-Cable			Brifen WRSF			Nucor NU-CABLE			Trinity CASS		
	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency	Crashes	Penetrations	Frequency
No Adverse Effects	437	53	12.1%	37	3	8.1%	278	34	12.2%	879	93	10.6%
Wet or Pooling Water	214	28	13.1%	36	2	5.6%	212	15	7.1%	313	37	11.8%
Snow, Slush, or Ice	135	14	10.4%	46	3	6.5%	199	18	9.0%	793	43	5.4%
Unknown or Other	9	0	-	0	0	-	3	0	-	17	0	-
Total	**795**	**95**	**11.9%**	**119**	**8**	**6.7%**	**692**	**67**	**9.7%**	**2002**	**173**	**8.6%**

Road Conditions at Time of Crash	Low-Tension 3-Cable			Brifen WRSF			Nucor NU-CABLE			Trinity CASS		
	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency	Crashes	Rollovers	Frequency
No Adverse Effects	437	45	10.3%	1269	45	3.5%	374	30	8.0%	951	76	8.0%
Wet or Pooling Water	214	9	4.2%	80	1	1.3%	262	4	1.5%	313	7	2.2%
Snow, Slush, or Ice	135	10	7.4%	193	2	1.0%	284	3	1.1%	800	31	3.9%
Unknown or Other	9	1	-	2	0	-	5	0	-	17	0	-
Total	**795**	**65**	**8.2%**	**1544**	**48**	**3.1%**	**925**	**37**	**4.0%**	**2081**	**114**	**5.5%**

5.2.3 Weather and Time of Year

The number of crashes into cable barriers was plotted with severity against week number of each crash to determine if there was any additional adverse effect from the time of year, and by extension specific weather patterns, on crash severity and frequency. The result is shown in Figure 2. A significant spike in crashes was noted between December (beginning in week 47) and February (ending week 9), which was likely related to an increase in low-severity crashes during snowy or icy conditions. Crash frequency was also largely related to cultural patterns as well. For example, the spike in crashes during week 12 corresponds to the approximate time frame for collegiate spring breaks. Between weeks 13 and 47 during the year, crash rates were relatively constant and crash frequency distributions were random. However, no distinct pattern of fatalities could be discerned except for a rise during the middle of the year, which may be due to an increased number of vehicle miles traveled.

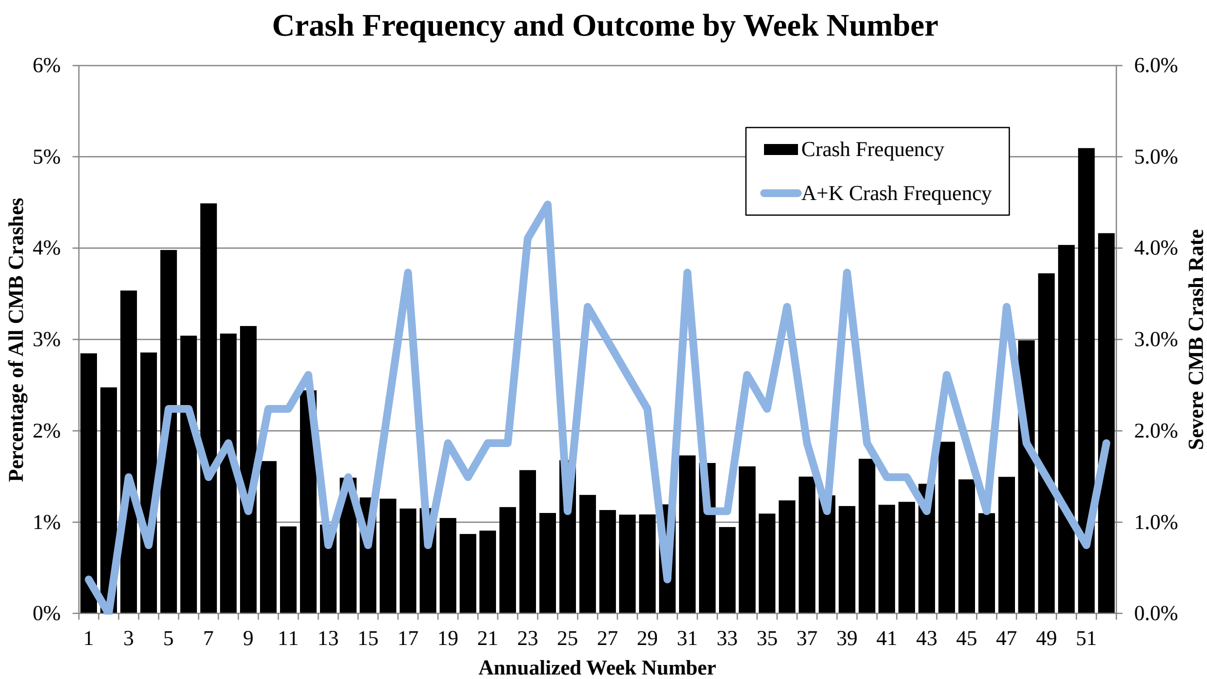


Figure 2. Crash Frequency and Severity by Week Number

For a different perspective, crash severity was also plotted by month, as shown in Figure 3. The number of crashes was significantly higher in the winter months, especially in December, when the first snows of each winter season usually fell. Monthly averages of fatalities rose slightly between January and April, with large increases in fatalities during June, July, and September. This is likely the result of summer vacations and travel which is more common in the summer. The analogous drop in fatalities and crashes in August is likely due to the end of summer travel and vacations and correspond to the impending start of the school year.

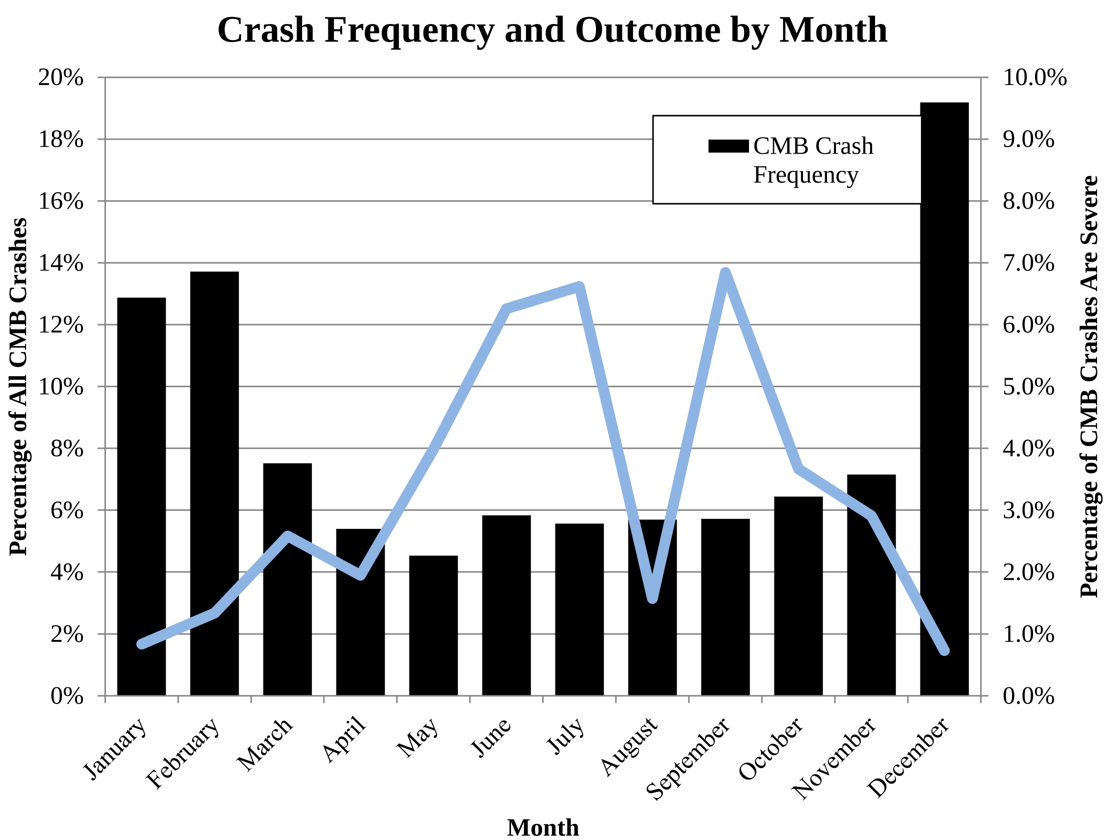


Figure 3. Crash Frequency and Severity by Month

5.2.4 Slope Characteristics

A frequently-cited parameter for the likely cause of barrier containment failures was related to median slopes and barrier placement within medians. Median slopes were investigated in several different states to determine the relative contribution to the crash result. Whenever it was possible, median geometries were obtained exactly using site details collected by DOT personnel or using geotechnical surveying equipment. Ohio DOT was able to provide geodetic survey information for all roadways with cable median barrier installed. In other states, selected site tours and investigation using barrier geometries, photogrammetry, and reference configurations were applied to photographs of cable barriers at crash sites observable using the Google Maps street view application.

The 857 cable median barrier crash records between 2007 and 2010 from Ohio were tabulated to determine the relative frequency of penetration and rollover crash events by median geometry. Crash results were tabulated by median geometries at the crash sites and are shown in Tables 14 through 16. Higher slope rates tended to increase penetration propensity, but there was a large number of penetrations which occurred on flat slopes or near roadway shoulders. Crashes into cable median barriers located on the back-side median ditch resulted in fewer penetrations than when the barrier was installed in either the ditch center or on the approach slope of the median. However, independent of barrier placement in the median, barriers placed in medians with flat approach slopes always had an equal or higher rate of penetration than barriers located on an approach slopes with slope rates between 6:1 and 8:1. Since FHWA currently permits barriers to be placed on 6:1 or shallower approach slopes, these findings suggest that sloped median crashes occurring in medians wider than 40 ft (12 m) may not be as critical as was first estimated.

Very few rollovers occurred on moderately steep slopes between 6:1 and 8:1. Rollovers were more frequent on the shallower slopes. More than 71% of the rollovers occurred on approach slopes of 8:1 or flatter. Alternatively, 13% of rollovers occurred on medians with approach slopes steeper than 6:1. However, 56.7% of all crashes on Ohio roadways occurred on roads with slopes of 8:1 or flatter, and steep median crashes constituted 13.9% of all crashes.

Table 14. Crash Results for Flat or V-Ditch Medians with Barriers on Traffic-Side Slopes

Barrier on Traffic-Side Shoulder or Slope					
Approach Slope	Crashes	Penetrations	% Penetrations	Rollovers	% Rollovers
Steeper than 6:1	74	11	14.9%	4	5.4%
6:1-8:1	128	8	6.3%	2	1.6%
8:1-10:1	118	6	5.1%	7	5.9%
Flatter than 10:1	174	18	10.3%	9	5.2%
All Crashes	**494**	**43**	**8.7%**	**22**	**4.5%**

Table 15. Crash Results with Barriers Located Less than 4 ft (1.2 m) from Bottom of V-Ditch

Barrier within 4 ft (1.2 m) of Ditch Bottom						
Approach Slope	Backside Slope	Crashes	Penetrations	Penetrations	Rollovers	Rollovers
Steeper than 6:1	Steeper than 6:1	1	1	100.0%	0	-
	6:1-8:1	5	0	-	0	-
	8:1-10:1	6	2	33.3%	0	-
	Flatter than 10:1	3	0	-	0	-
Total		***15***	***3***	***20.0%***	***0***	-
6:1-8:1	Steeper than 6:1	7	1	14.3%	0	-
	6:1-8:1	20	1	5.0%	0	-
	8:1-10:1	11	1	9.1%	0	-
	Flatter than 10:1	7	2	28.6%	0	-
Total		***45***	***5***	***11.1%***	***0***	-
8:1-10:1	Steeper than 6:1	6	0	-	0	-
	6:1-8:1	14	1	7.1%	0	-
	8:1-10:1	10	2	20.0%	0	-
	Flatter than 10:1	10	3	30.0%	0	-
Total		***40***	***6***	***15.0%***	***0***	-
Flatter than 10:1	Steeper than 6:1	2	0	-	0	-
	6:1-8:1	2	0	-	0	-
	8:1-10:1	19	3	15.8%	3	15.8%
Total		***23***	***3***	***13.0%***	***3***	***13.0%***
All Crashes		**123**	**17**	**13.8%**	**3**	**2.4%**

Table 16. Crash Results for V-Ditch Medians with Barriers Installed on Back Slope

Barrier on Opposite Slope of V-Ditch						
Approach Slope	Backside Slope	Crashes	Penetrations	Penetrations	Rollovers	Rollovers
Steeper than 6:1	Steeper than 6:1	12	0	-	0	-
	6:1-8:1	9	1	11.1%	0	-
	8:1-10:1	4	2	50.0%	0	-
	Flatter than 10:1	5	2	40.0%	1	20.0%
Total		***30***	***5***	***16.7%***	***1***	***3.3%***
6:1-8:1	Steeper than 6:1	7	0	-	0	-
	6:1-8:1	31	1	3.2%	0	-
	8:1-10:1	14	2	14.3%	0	-
	Flatter than 10:1	14	2	14.3%	1	7.1%
Total		***66***	***5***	***7.6%***	***1***	***1.5%***
8:1-10:1	Steeper than 6:1	11	0	-	0	-
	6:1-8:1	19	2	10.5%	0	-
	8:1-10:1	24	4	16.7%	4	16.7%
	Flatter than 10:1	15	1	6.7%	1	6.7%
Total		***69***	***7***	***10.1%***	***5***	***7.2%***
Flatter than 10:1	Steeper than 6:1	3	0	-	0	-
	6:1-8:1	14	0	-	1	7.1%
	8:1-10:1	58	7	12.1%	2	3.4%
Total		***75***	***7***	***9.3%***	***3***	***4.0%***
All Crashes		**240**	**24**	**10.0%**	**10**	**4.2%**

For moderately steep slopes of 6:1 to 8:1, the vehicle tended to travel toward the center of the ditch (i.e. to the lowest point), since that is an energetically favorable position due to minimization of gravitational potential energy. Barriers installed on these slopes applied redirective forces which were largely parallel with the slope because of the orientation of the vehicle at impact. Whereas the initial applied load on the vehicle due to cable barrier systems was large, if the vehicle's orientation angle was not excessive, the slope tended to counteract the roll moment applied by the barrier on the vehicle. This was historically evident in most full-scale crash tests conducted on level and sloped terrain. Following redirection, vehicles departing cable barrier systems tended to redirect at very low angles [17-19]. Low-angle redirection on a 6:1 slope caused a subsequent continued engagement between the vehicle and the barrier, and the reactive force from the cable barrier largely balanced the overturning moment from the slope, improving vehicle stability. The competing roll influences are explained in greater detail in Chapter 11.

Occasionally, based on orientation angle, the vehicle yawed counterclockwise toward higher orientation angles (i.e., yawing with the left-front and right-rear corners leading) near a post location. When the yaw occurred on a slope, the vehicle pitched forward to allow the rear wheels to rise consistent with the slope, which increased local front tire-ground friction. On shallower slopes, the resistance was decreased, and on steeper slopes, resistance increased significantly. For moderate slopes such as 6:1 to 8:1 slopes, the increase in resistance due to yaw motion on the slope was not trivial but frequently did not contribute to rollover; instead, these slope rates tended to resist yaw rotations to 90 degree orientation angles, then increased yaw tendency thereafter. If the vehicle did not trip as the vehicle orientation approached 90 degrees to the barrier, the vehicle stabilized and the trailing end of the vehicle rotated into the barrier and became the leading end. On flat or nearly flat slopes, there was no re-stabilizing slope which could shift the vehicle toward tracking in either frontal or rear directions. Instead, the increase in trailing-end tire friction due to tire slip tended to arrest the yaw motion of the vehicle near an orientation angle of 90 or 270 degrees and initiate rollover.

A statistical analysis was conducted on the slope data to determine how crash outcome depended on median approach slope rate. A chi-squared test on crashes in Ohio indicated that occupants of vehicles involved in penetration or rollover crashes were 5 times more likely to be seriously injured or killed than occupants involved in non-penetration or non-rollover crashes. Further segregation of the crash data and additional statistical tests indicated that penetration crashes were 3-times more likely to produce serious injury or fatality, and rollover crashes were 10-times more likely to involve A+K injuries, than non-penetration or non-rollover crashes.

Other chi-squared tests for independence were performed on the penetration and rollover frequency as a function of slope steepness. The chi-squared test for independence indicated that penetration frequency was not independent of slope steepness at the 10% confidence level, and rollover frequency was not independent of slope steepness at the 4% confidence level. An analogous but equally true statement would be that the risk of penetration would be correlated to slope steepness in no less than 90% of the cable median barrier crashes, and the risk of rollover would be correlated to slope steepness in no less than 96% of the crashes. However, the functional nature of the correlation was not a factor in this test.

Further investigation of the correlation demonstrated two trends which were supported by crash data in all of the participating states. In general, the highest risk of barrier penetration and rollover risk either occurred on slopes steeper than 6:1 or slopes flatter than 10:1. When the relative risk of rollover in each category was plotted against slope steepness, an asymptotic-like relationship was obtained in both system failure types. The penetration and rollover risk plots and interpolated risk curves obtained from this effort are shown in Figures 4 through 6. The lowest risk for both penetration and rollover combined occurred on median slopes between 7:1 and 6:1, and the risk increased for both steeper and flatter slopes. Rollovers were more frequent on level ground than on steep slopes in this study, although there were a limited number of very steep slopes in this database. Penetrations were much more frequent on steeper slope rates; this was expected and was consistent with the current state-of-knowledge of cable barrier design with respect to vehicle motion on slopes. Median slope crash data is summarized in Tables 17 and 18.

However, divided medians in Ohio were frequently wider than 50 ft (15 m). As a result, the bouncing and underride tendencies aggravated in narrow medians less than 40 ft (12 m) wide were not present in this database. Caution should be used when applying these results to narrow median applications.

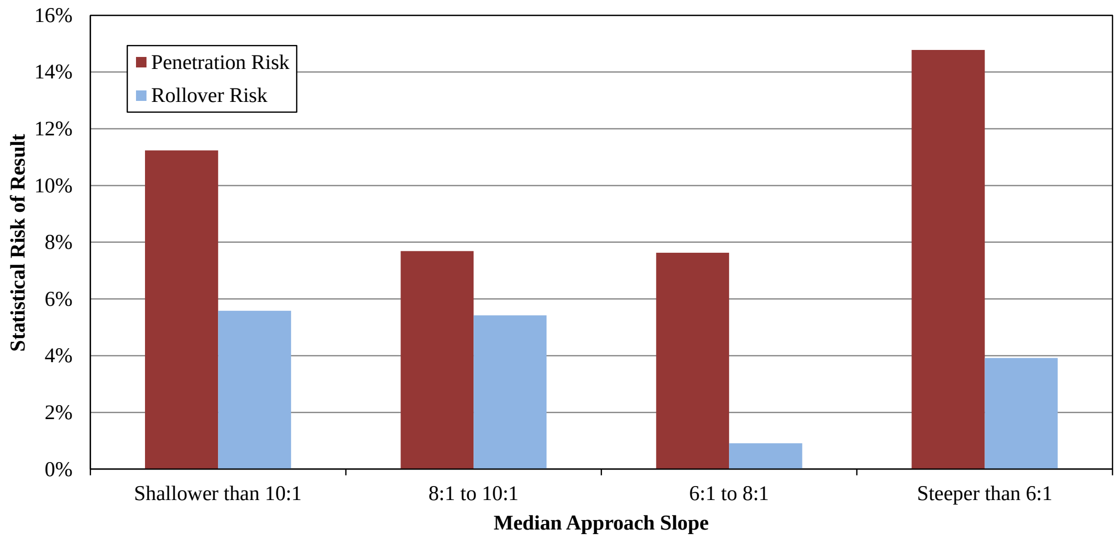


Figure 4. Statistical Analysis of Penetration and Rollover Risk by Median Slope

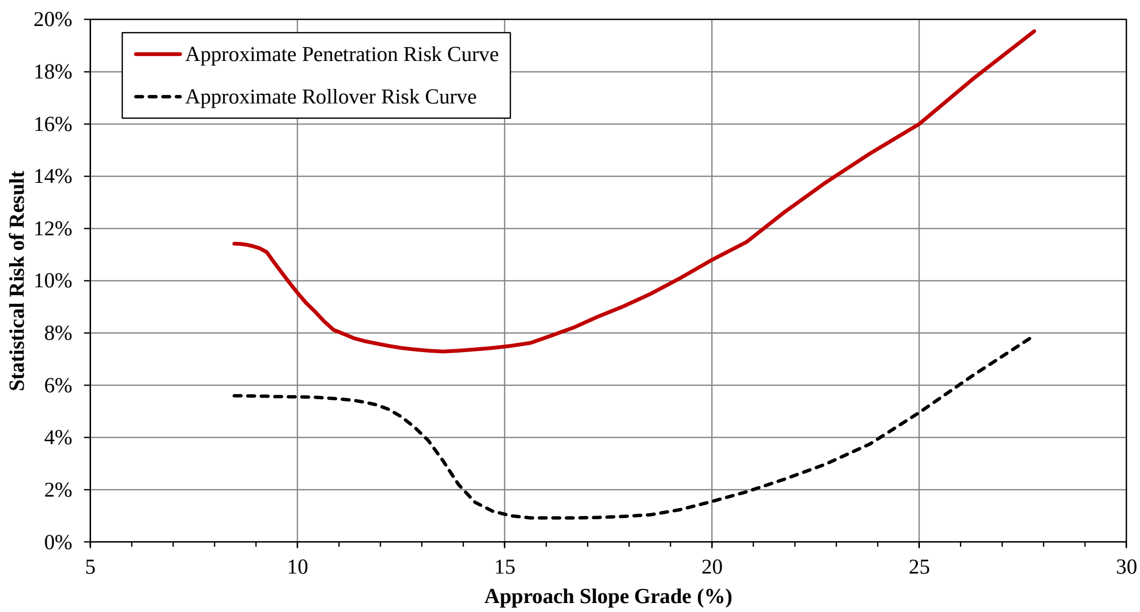


Figure 5. Estimated Ohio Median Approach Slope Risk Curves by Approach Slope Grade (Relative to Nucor Systems)

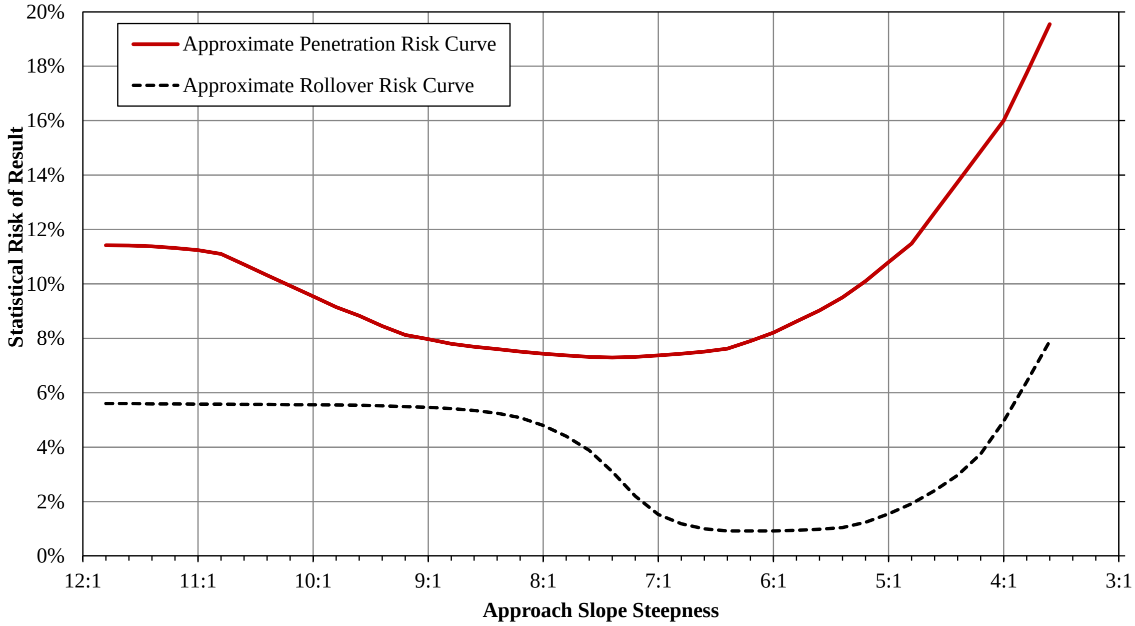


Figure 6. Estimated Ohio Median Approach Slope Risk Curves by Approach Slope Steepness (Relative to Nucor Systems)

Table 17. Crash Result and Median Slope Summary

Summary of Median Slope Results							
Barrier Position	Approach Slope	Crashes	Penetrations	% Penetrations	Rollovers	% Rollovers
Traffic-Side Approach Slope	Steeper than 6:1	74	11	14.9%	4	5.4%
	6:1-8:1	128	8	6.3%	2	1.6%
	8:1-10:1	118	6	5.1%	7	5.9%
	Flatter than 10:1	174	18	10.3%	9	5.2%
	TOTAL	***494***	***43***	***8.7%***	***22***	***4.5%***
< 4 ft from Ditch Bottom	Steeper than 6:1	15	3	20.0%	0	-
	6:1-8:1	45	5	11.1%	0	-
	8:1-10:1	40	6	15.0%	0	-
	Flatter than 10:1	23	3	13.0%	3	13.0%
	TOTAL	***123***	***17***	***13.8%***	***3***	***2.4%***
Opposite-Side Back Slope	Steeper than 6:1	30	5	16.7%	1	3.3%
	6:1-8:1	66	5	7.6%	1	1.5%
	8:1-10:1	69	7	10.1%	5	7.2%
	Flatter than 10:1	75	7	9.3%	3	4.0%
	TOTAL	***240***	***24***	***10.0%***	***10***	***4.2%***
All Crashes		***857***	***84***	***9.8%***	***35***	***4.1%***

Table 18. Summary of Crash Result and Severity by Barrier Location and Median Slope

Barrier Location	Crashes	Penetrations	Rollovers	A+K Injuries
Shoulders (Either Side)	20	20.0%	5.0%	15.0%
Traffic-Side Slope	485	8.5%	4.3%	4.5%
Within 4 ft of Ditch Bottom	*123*	*13.8%*	*2.4%*	*0.8%*
Opposite-Side Slope	229	8.3%	4.4%	3.5%
All Traffic-Side Crashes	494	8.7%	4.5%	4.9%
All Opposite-Side Crashes	240	8.8%	4.2%	3.8%
All Crashes Not in Ditch Center	734	8.7%	4.4%	4.5%
All Crashes	857	9.5%	4.1%	4.0%

Approximately 80% of the crashes in the Ohio database occurred on Nucor NU-CABLE barrier systems. Precise slope data were not available at the time of this study from most of the other states and barrier systems involved in this research effort. Nonetheless, a concerted effort was made to tabulate approximate median conditions in other states with different barrier systems.

A database of Missouri median conditions available at all sites was beyond the scope of this study, but median geometries for serious crashes involving penetrations or rollovers were tabulated. The Missouri DOT had approximately 950 miles of low-tension, 3-cable median barrier installed on interstate roadways. Even though the vast majority of Missouri's interstate system has V-ditches with slopes as steep as 4:1, many severe penetration and rollover crashes occurred on shallower slopes. Missouri's severe crash data is shown in Tables 19 and 20. Unlike Ohio, many Missouri medians were relatively narrow, with widths of 40 ft (12 m) or less.

Table 19. Missouri's Severe Penetration Crash Median Slope Summary

<table>
<tr><th colspan="7">Severe Penetration Crashes</th></tr>
<tr><th rowspan="2">Approach Slope</th><th colspan="4">Barrier Installed On</th><th colspan="2" rowspan="2">All Severe Penetrations</th></tr>
<tr><th>Shoulders (Both)</th><th>Approach Slope</th><th>Center</th><th>Opposite Slope</th></tr>
<tr><td>4:1-6:1</td><td>1</td><td>4</td><td>5</td><td>1</td><td>11</td><td>26%</td></tr>
<tr><td>6:1-8:1</td><td>1</td><td>5</td><td>9</td><td>1</td><td>16</td><td>38%</td></tr>
<tr><td>8:1-10:1</td><td>0</td><td>2</td><td>6</td><td>1</td><td>9</td><td>21%</td></tr>
<tr><td>Flatter than 10:1</td><td>1</td><td>2</td><td>2</td><td>1</td><td>6</td><td>14%</td></tr>
<tr><td rowspan="2">All Severe Penetrations</td><td>3</td><td>13</td><td>22</td><td>4</td><td></td><td></td></tr>
<tr><td>7%</td><td>31%</td><td>52%</td><td>10%</td><td></td><td></td></tr>
</table>

Table 20. Missouri's Severe Rollover Crash Median Slope Summary

Severe Rollover Crashes						
Approach Slope	Barrier Installed On				**All Severe Rollovers**	
	Shoulders (Both)	Approach Slope	Center	Opposite Slope		
4:1-6:1	1	0	3	0	**4**	**14%**
6:1-8:1	2	1	6	0	**9**	**32%**
8:1-10:1	0	3	3	4	**10**	**36%**
Flatter than 10:1	0	2	3	0	**5**	**18%**
All Severe	**3**	**6**	**15**	**4**		
Rollovers	**11%**	**21%**	**54%**	**14%**		

Despite the limited data set, some tendencies were clear. Barriers installed on approach slopes relative to traffic flow of encroaching vehicles in Missouri were more frequently involved in penetration crashes, and the most common location for penetration was when the median barrier was located near the center of the slope. This is not surprising, and the same effect was observed in the Ohio median slopes database. Barriers installed on approach slopes, back slopes, and the center of the V-ditch were subject to the greatest variation in front-end height and impact orientation angles of the impacting vehicle [20]. Since a large number of low-tension, 3-cable median barrier installations in Missouri were located near the center of relatively steep, narrow V-ditches, it was not surprising that center impacts were most common in both the severe penetration and severe rollover crashes. However, a proportionate distribution of crashes on each slope type was not available, so estimates of the rates of penetrations or rollovers based on slope steepness were not applicable.

Approximately 46% of all severe rollover crashes and 64% of all severe penetration crashes occurred on slope steeper than 8:1; this indicates that rollovers were less frequent on the steeper slopes than penetrations were. The slopes flatter than 8:1 were relatively infrequent in Missouri where cable median barriers were installed, but still accounted for 54% of all severe rollover crashes. General observations about median slope performance were not applicable in Missouri, since the database did not incorporate non-severe crashes. However, variations in the results of the Ohio and Missouri databases were likely due to four reasons: (1) Missouri used a standard low-tension, 3-cable median barrier with S3x5.7 (S76x8.5) steel posts, which are stronger in weak-axis and strong-axis bending than most proprietary system posts; (2) the Missouri database was limited to only severe crashes; (3) slopes flatter than 6:1 were infrequent; and (4) medians were typically narrower in Missouri than in Ohio.

5.2.5 Impact Conditions

Vehicular impact conditions were investigated by performing crash reconstructions with available scene diagrams and photographic evidence, when available. A total of 110 severe crashes with enough information to reconstruct the crash were analyzed in the State of Missouri. Vehicle CG trajectory, orientation, and sideslip angles were calculated. Unfortunately, roadway curvature data were not available, which would allow for comparison of expected and actual CG trajectory angles; however, most roadways were straight in this study.

The CG trajectory angle was defined as the angle formed between the vehicle CG path and a tangent line to the barrier at the point of impact (POI). Vehicle orientation angle was defined as the angle formed by a driver's line of sight (LOS) and a tangent line to the barrier at the POI or equivalently, the angle between the vehicle's centerline and the barrier tangent. The sideslip angle represented the degree to which a vehicle was "tracking," a condition in which the rear tires follow the tracks of the front tires. Sideslip angles were measured between the CG trajectory angle and the orientation angle of the vehicle at the POI. For both trajectory and orientation angles, vehicle heading toward the median was positive ranging between 0 and 180 degrees; heading angles directed away from the median ranged between 180 and 360 degrees.

Trajectory angles were plotted by orientation angle and sideslip angle, and are shown in Figures 7 and 8. Although sideslip angles between the path of the vehicle and heading can exceed 90 deg, high sideslip angles were generated by non-zero yaw rates; this is assumed to be an effectively non-tracking impact condition. Moreover, if the driver was conscious and aware to steer the vehicle in avoidance maneuvers, a large number of drivers will also instinctively apply the brakes and attempt to stop an errant vehicle, which further contributes to non-tracking behavior. The threshold between when a vehicle was considered tracking and non-tracking was determined to be approximately 20 degrees based on analysis of non-tracking behavior on crash results [21].

The trajectory angle distribution was very high relative to other studies conducted on severe crash results. The severe CMB crash results were compared to the distribution of severe crash results in the 2010 NCHRP Report No. 665 database [22]. The 50th, 75th, 85th, and 95th percentiles of the severe CMB crash distributions corresponded to 18, 30, 38, and 53 degrees, respectively. By contrast, the 50th, 75th, 85th, and 95th percentile departure angles measured from the database of severe crashes in NCHRP Report No. 665, which was used to determine the test speed and angles for full-scale test criteria for assessing safety hardware, corresponded to 15, 22, 26, and 36 degrees, respectively.

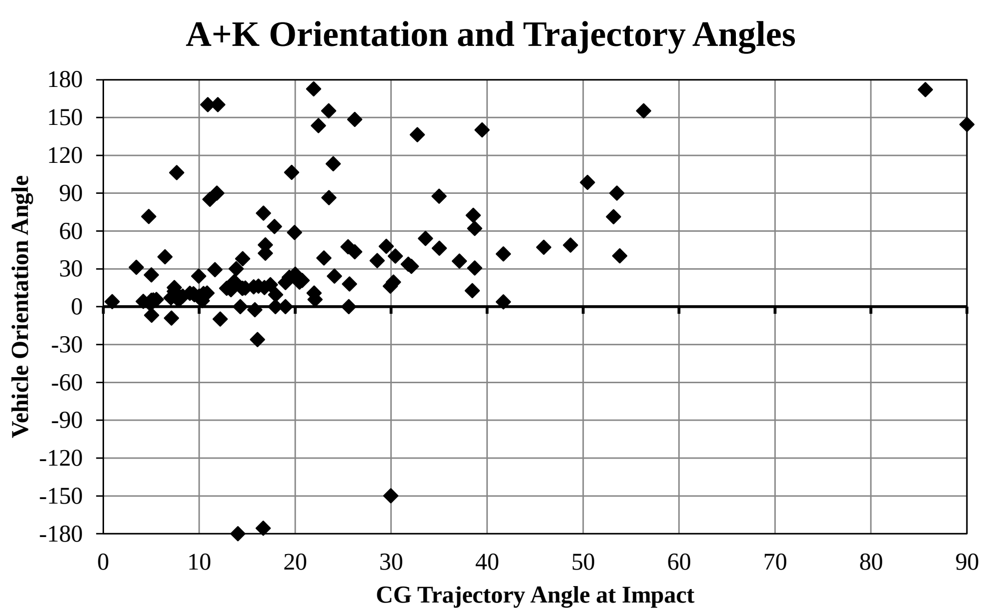


Figure 7. CG Trajectory and Orientation Angles in Severe Cable Median Barrier Crashes

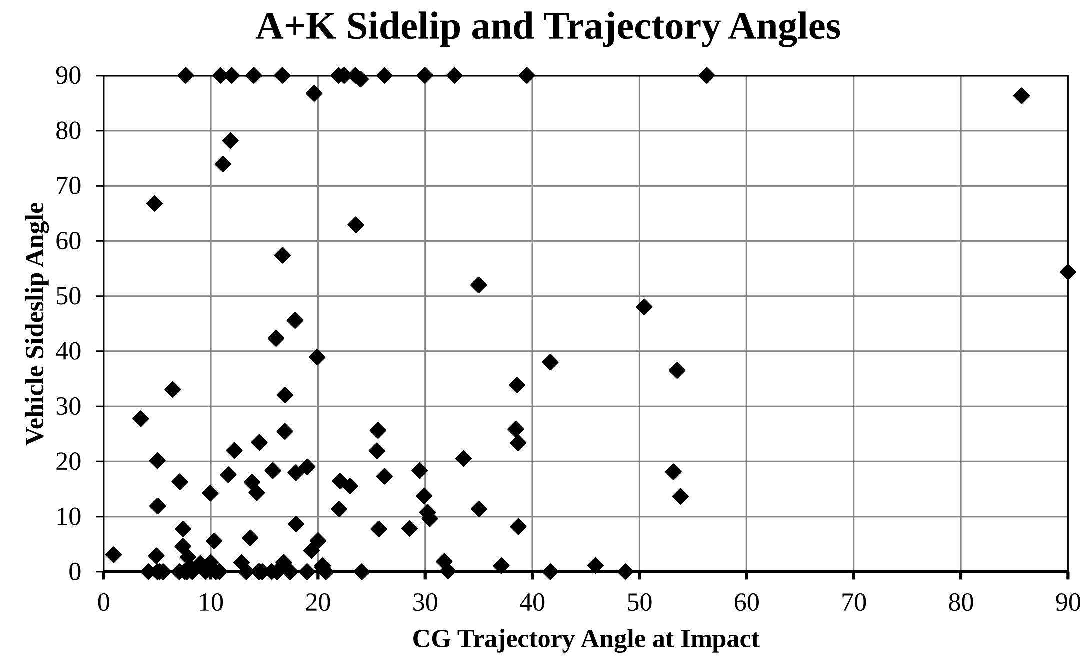


Figure 8. CG Trajectory and Sideslip Angles in Severe Cable Median Barrier Crashes

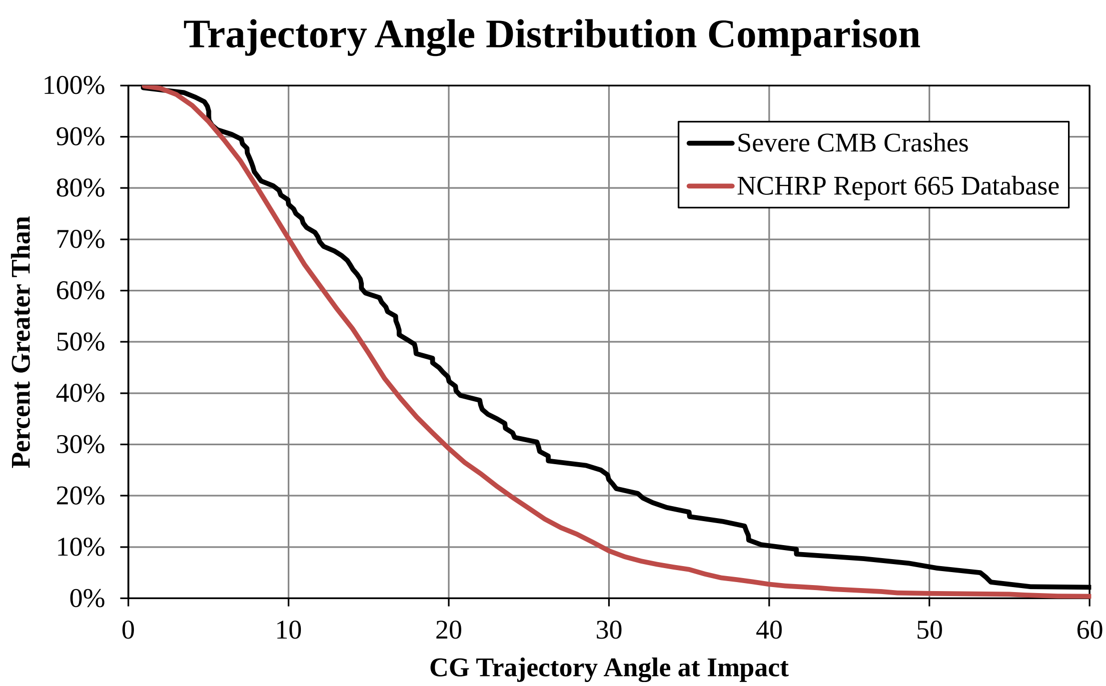


Figure 9. Comparison of Trajectory Angle Distributions

Historically, the roadside safety community collectively agreed that the 85th percentile impact condition for both speeds and angles could be regarded as a practical worst-case impact scenario to evaluate roadside hardware. As has been discussed in depth, selection of practical impact conditions should not be subjective and should evaluate a system's capacity to capture, contain, or redirect the majority of impacting vehicles [23]. Although the 25 degree impact angle previously used for crash tests using 4,400-lb (2,000-kg) pickup trucks was approximately 0.6 degrees lower than the 85th percentile roadside departure condition identified in NCHRP Report No. 665, the small difference between testing and actual impact conditions suggested that the historical impact angle was sufficiently accurate for continued evaluation of roadside features. The departure angle was selected in lieu of the impact angle when determining appropriate testing conditions. This angle was selected for many reasons, including:

(1) Initial impact location was affected by proximity of the struck object to the sides of the road. Impacts far from the road permit the vehicle to slow down to low speeds, reducing the crash severity that would normally occur with a barrier or roadside feature at much closer proximity. Because there are currently no required crash tests to evaluate vehicular braking in advance of a barrier system, impact conditions currently do not accommodate driver inputs prior to impact.

(2) In many multiple-impact events, selection would have to be applied to determine which event was most significant, which introduces both subjectivity and error. Crush energy contributions were frequently very difficult to partition to individual impacts.

(3) Barrier crashes were undersampled in the NCHRP Report No. 665 database. The small barrier crash data set prohibited meaningful statistical analysis out of barrier crash results. Furthermore, the majority of the barrier impact events were at much higher speeds than occurred in non-barrier crashes.

(4) Some roadside departures resulting in disabling vehicle damage, such as rollovers, did not have a clearly defined orientation angle prior to impact. Interpretations of the effective location of impact varied widely, and vehicle orientation during these types of crashes was frequently difficult to determine. Orientation and departure angles were not only easier to measure at departure, they were often more meaningful, since crash testing has historically been conducted with fully-tracking vehicles.

CG trajectory and orientation angles measured at the first recorded location of impact obtained from the NCHRP 665 database were much closer to the corresponding angles at impact measured in the severe cable median barrier crashes in Missouri. If current MASH [24] crash tests were conducted at the same speed but the angle was increased from 25 degrees to 39 degrees, the impact severity (IS) of the crash would increase by 120%. Few barriers have ever been subject to this level of scrutiny.

The CG trajectory and orientation angle plot was segregated by crash result into "Penetration", "Rollover", or "Other" categories. The segregated database is shown in Figure 10, and a detail view for vehicle orientation angles greater than -10 degrees is shown in Figure 11.

Of all the severe cable median barrier crashes, 43% occurred with sideslip angles in excess of 20 degrees. Approximately 40% of penetration crashes were non-tracking at impact with the barrier. Severe penetrations occurred more commonly at higher CG trajectory angles than severe rollovers. The median CG trajectory angle in severe penetration crashes in Missouri was 24 degrees, and the 85th percentile angle was 46 degrees.

In Missouri, 63% of the severe rollover crashes that were caused by the cable median barrier occurred with CG trajectory angles less than 20 degrees. The median CG trajectory angle for the severe rollover crashes was 16 degrees, and the 85th percentile CG trajectory angle was 35 degrees.

Very few crashes occurred with “overcorrecting” and non-tracking impact conditions in which the driver of the vehicle was attempting to steer the vehicle away from the barrier. This type of orientation tended to promote a more “broadside” impact condition, where the side of the vehicle makes first contact with the barrier instead of the front end. This was likely a product of the generally steep terrain found in Missouri’s medians, and relatively narrow medians typically measuring 40 ft (12.2 m) wide. Drivers who steered into the median would then find it very difficult to steer away from the barrier and back up the approach slope, which could have contributed to fewer “overcorrecting” impacts.

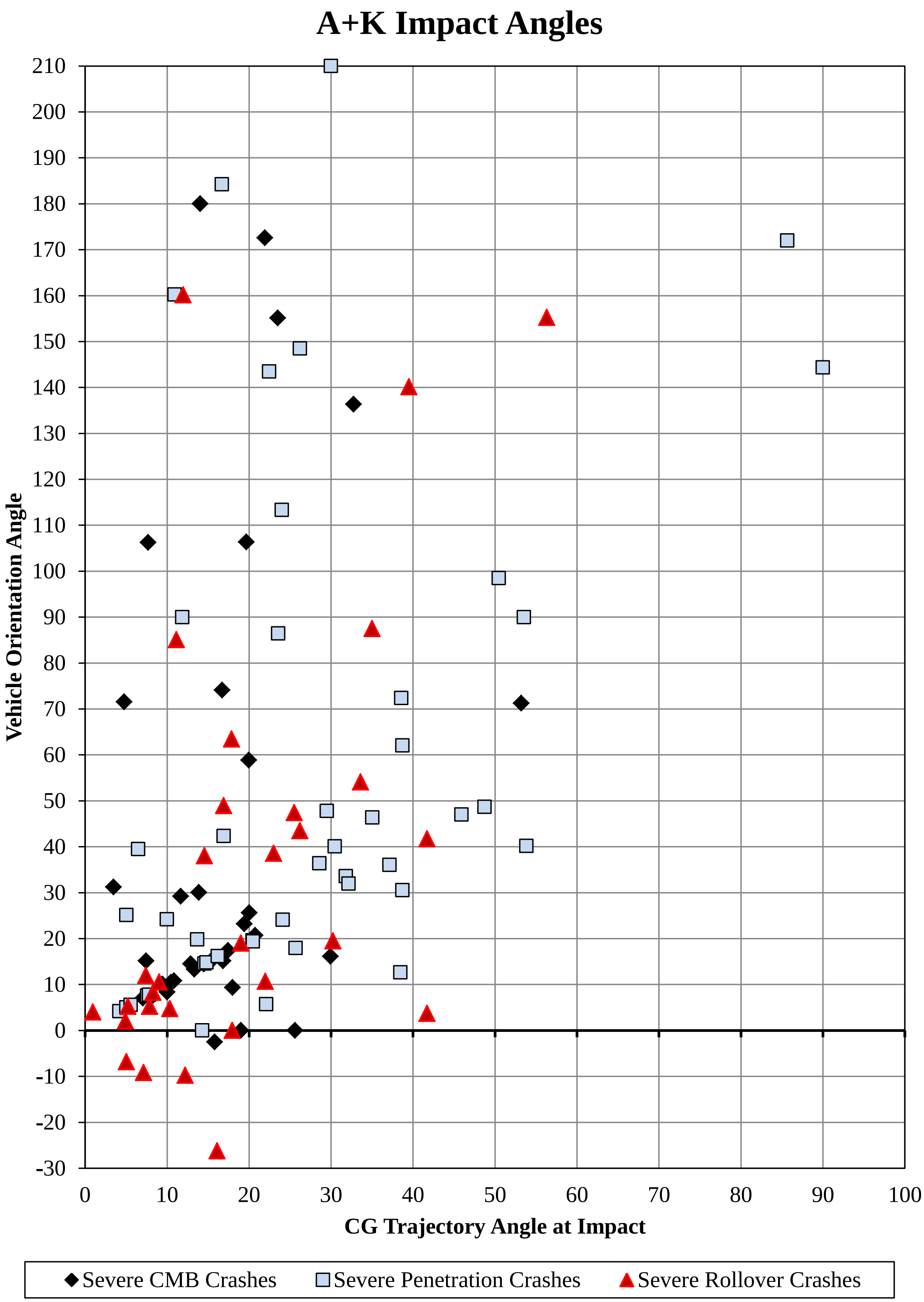


Figure 10. CG Trajectory and Orientation Angles by Crash Result

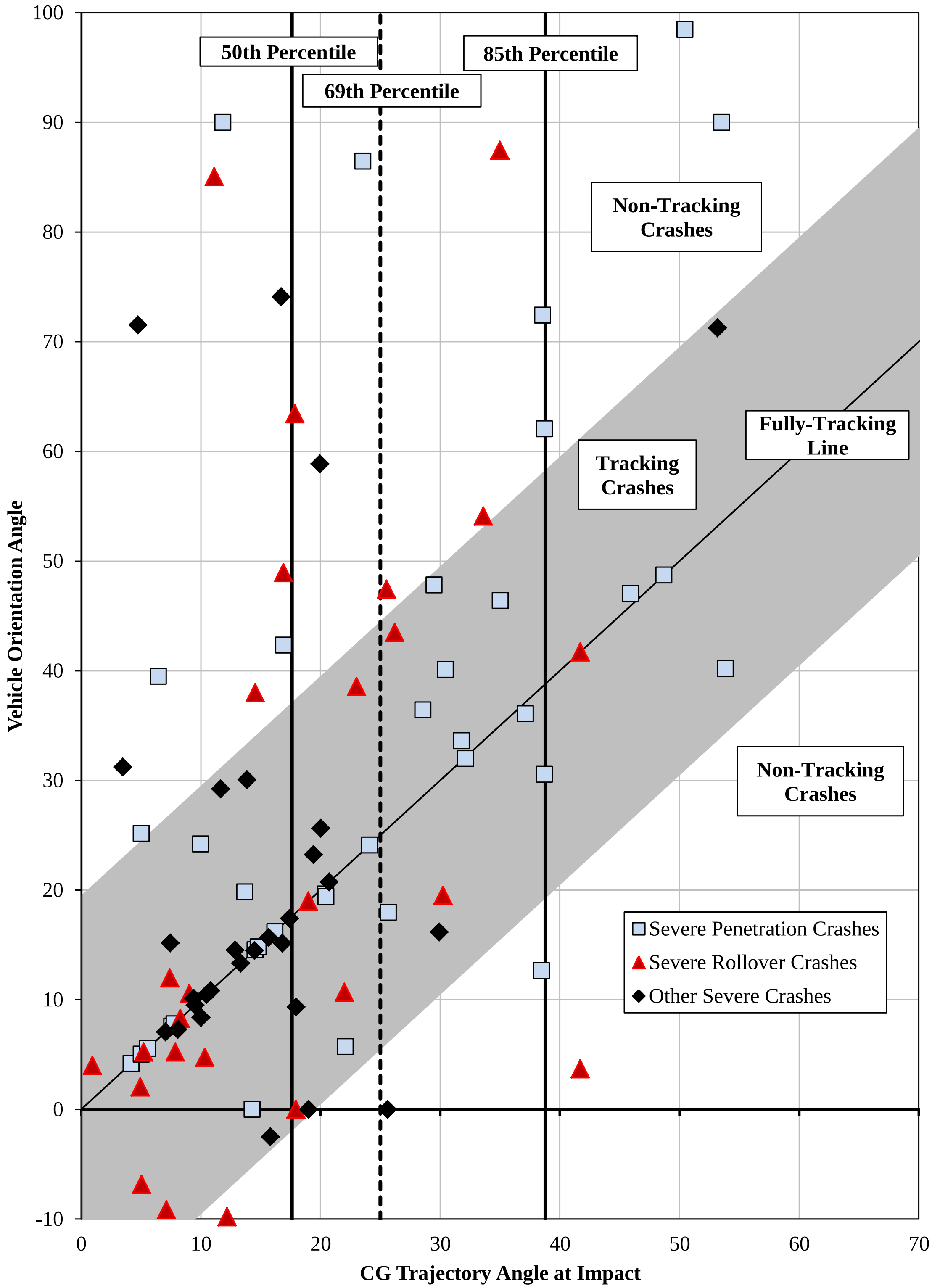


Figure 11. Detail View of Severe Crash CG Trajectory and Orientation Angles in Missouri

Alternatively, "oversteering" impacts, in which the orientation angle of the vehicle was larger than the CG trajectory angle, were very common. Approximately 51% of severe penetration crashes, 53% of severe rollover crashes, and 49% of all severe crashes had "oversteering" conditions. Comparatively, 83% of severe penetrations, 85% of severe rollovers, and 82% of severe non-penetration, non- rollover crashes with non-tracking impact conditions were "oversteering" crashes. The high number of oversteering crashes in the median was a reflection of median geometry and roadway conditions. Vehicles which strike a cable median barrier located near the center of a V-ditch have a minimum lateral offset that must be traversed before impact, which tends to bias crash results toward higher CG trajectory angles. This crash condition was reflected in real-world crash results, but suggests that future testing of cable median barriers should be conducted for both tracking and non-tracking impact conditions.

The crash set was further evaluated by considering the relationship between CG trajectory angle and containment rate for severe crashes. A cumulative distribution plot of CG trajectory angle for severe penetration and rollover crashes as well as severe non-penetration, non-rollover crashes is shown in Figure 12. A statistical analysis was conducted on the CG trajectory angle distributions, and a probability curve for likelihood of penetration or rollover crash results in severe cable median barrier crashes is shown in Figure 13.

In all severe crashes, there was a minimum of a 49% risk of penetration or rollover at very small CG trajectory angles to a high risk of penetration or rollover at large CG trajectory angles. As the CG trajectory angle approached 90 degrees, the risk of penetration or rollover crash results in severe cable median barrier crashes approached 100%, indicating that with a 90 degree CG trajectory angle and a severe crash result, every crash would be expected to be either a penetration or rollover.

Cumulative CG Trajectory Angle Distribution

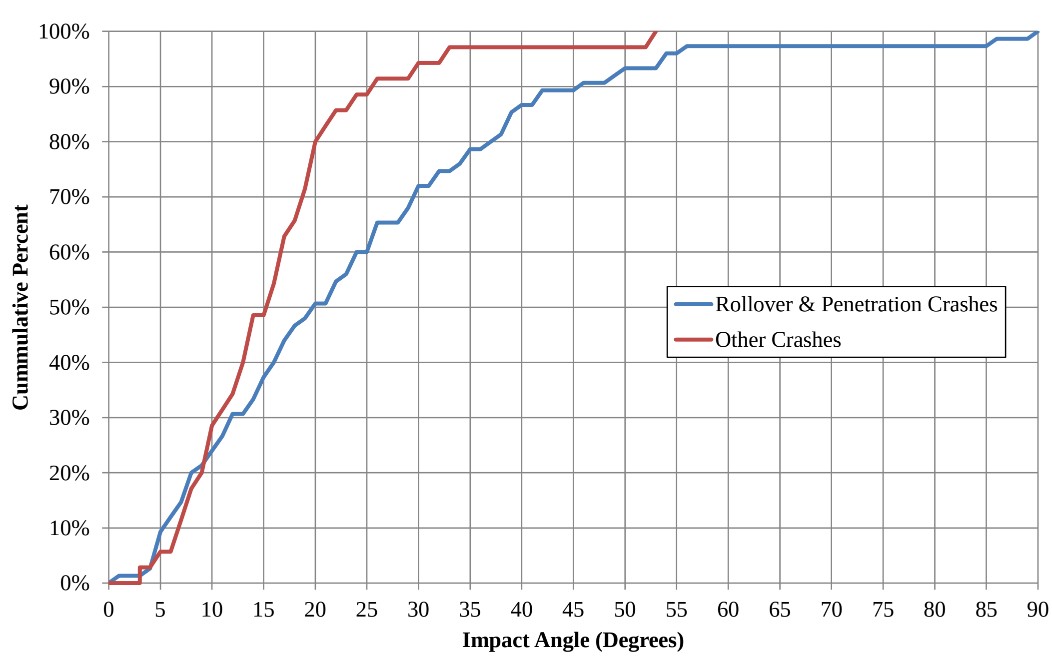


Figure 12. Cumulative Distribution of CG Trajectory Angles by Severe Crash Result

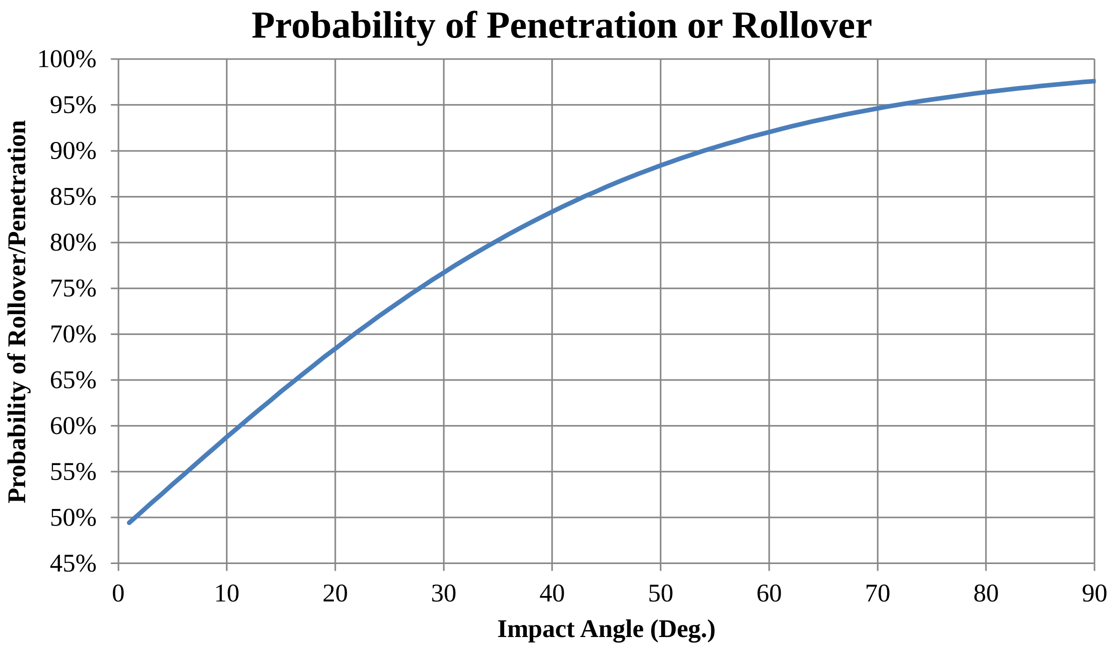


Figure 13. Probability Distribution of Containment Failure in Severe Crashes

5.2.6 Comparison of Missouri and North Carolina

Additionally, a subset of crashes in North Carolina was analyzed, consisting of entirely penetration-related crashes. The penetration crashes were not randomly selected, but typically were investigated in greater detail either when DOT staff saw crash results on newscasts or when crashes were spotted by a field observation team. The investigative teams typically measured median profiles, center-of-cable heights, which side of the low-tension 3-cable median barrier was struck (i.e., side with one or with two cables), tire trajectory marks, and the number of posts damaged. Researchers were then able to determine departure and impact CG trajectory and orientation angles, and observed a higher number of "backside" penetration crashes, in which the barrier was penetrated more often when struck on the side of the barrier with one supported cable. Photographs were taken of both the vehicle and barrier system involved in the crash.

The subset of crashes investigated, totaling 22 in all, were plotted in a distribution and compared with the severe crashes in Missouri, as shown in Figure 14. The North Carolina sample also tended toward higher angles than the NCHRP 665 crashes, but the sample size was too small to make judgments about the distribution. Preliminary attempts to determine correlations using chi-squared tests were not statistically significant (i.e., p values between 0.4 to 0.7), but it is likely that the distributions would be similar if additional data were obtained.

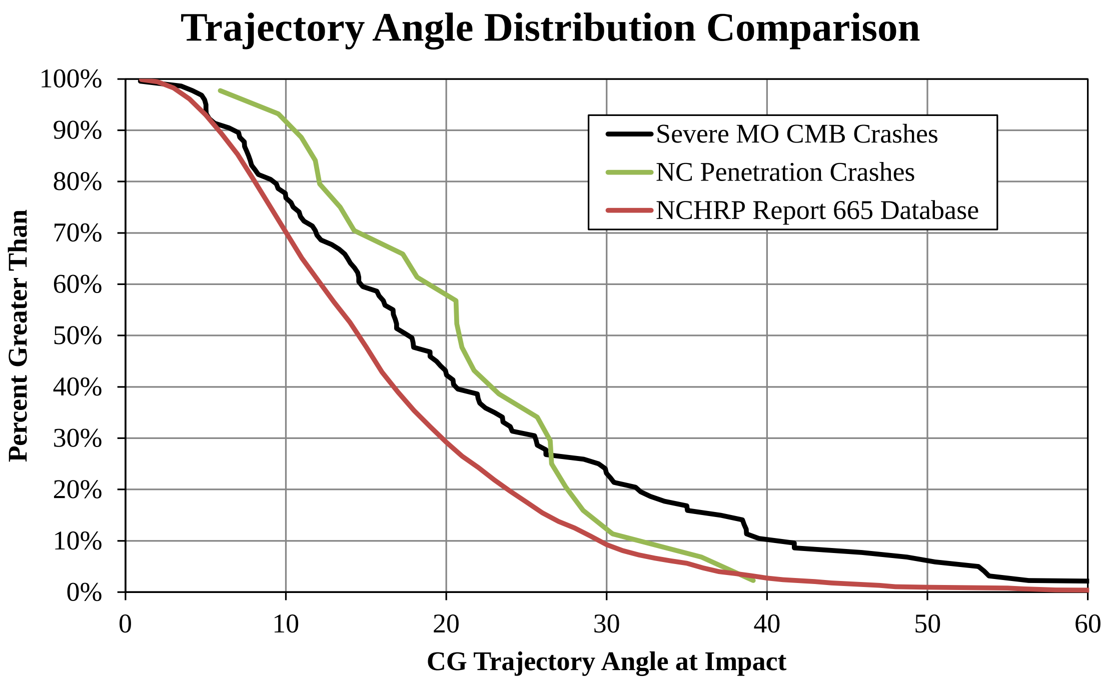


Figure 14. Comparison of North Carolina, Missouri, and NCHRP Crashes

5.2.7 Crash Severity

The relative severity of crashes on each barrier type is shown in Tables 21 through 23. Penetration Severe Crash Contributions (PSCC) and Rollover Severe Crash Contribution (RSCC), along with Penetration Severity Increase Factors (PSIF) and Rollover Severity Increase Factors (RSIF) metrics, were created to evaluate the relative severity risk of each type of crash outcome based on the barrier system. PSIF, PSCC, RSIF, and RSCC metrics are explained on page 43.

The severe crash contribution factors represent the total contribution of penetration and rollover crashes to all severe crash outcomes. Both PSCC and RSCC were summed to analyze relative severities. If the sum of PSCC and RSCC approach 100%, it would correspond to a situation in which every severe crash outcome was determined solely by penetration or rollover crash occurrence. If the sum of PSCC and RSCC was low, it would indicate little correlation between crash outcome and crash severity, instead suggesting other factors were more significant to severe crash outcome.

The PSIF was calculated from the ratio of the frequency of severe penetration crashes to the frequency of severe non-penetration crashes. Likewise, the RSIF was calculated from the ratio of the frequency of severe rollover crashes to the frequency of severe non-rollover crashes. In this way, the ratio of the severities of penetration and rollover crashes were determined. As a result, a PSIF of 1.0 corresponded to a case in which the penetration crash had an equivalent risk of severe injury or fatality as a non-penetration crash. The highest average PSIF was 13.2 for low-tension, 3-cable median barrier, and the highest RSIF was 12.0 for the Brifen Wire Rope Safety Fence (WRSF). In general, higher PSIF and RSIF corresponded to lower average severity non-penetration and non-rollover crashes. The aggregate A+K crash severities for each system were reported, even when PSCC, RSCC, PSIF, and RSIF were not available.

When data were not available for either rollover or penetration data sets, data subsets were created for each group and the results were compared to the composite totals. For every barrier except the low-tension cable median barrier, the subset distributions were nearly identical to the aggregate. Subsets of the low-tension cable median barrier crash results are compared in Tables 21 through 23.

Although Gibraltar barrier systems were represented in the database, less than 100 total crashes and less than 15 total penetration crashes were available for analysis on the Gibraltar data. The Safence database was at the level of statistical significance (295 crashes); however, the number of penetrations was unknown and the tolerance on the number of A+K crashes in the rollover database was significant; the variation in a single crash at the A+K level would produce 0.4% difference in net A+K rate. Therefore, PSCC, RSCC, PSIF, and RSIF were not calculated for these systems. Additionally, very few Brifen crashes were available for examination with respect to penetration frequencies, which rendered the PSCC and PSIF less useful.

The "effective" A+K rate was a obtained by averaging the A+K ratios in the datasets, if average state-level data were available; otherwise it was equal to the sum of severe crashes divided by the total number of crashes. Since Missouri's A+K ratio was known, it was included when calculating the effective A+K ratio, even though all cable median barrier crashes were not included in the data set.

Based on the metrics created to analyze the crash results, several important but surprising conclusions were made. First, the barrier system with the lowest average severity was the low-tension, 3-cable median barrier system. The maximum state-reported frequency of severe crashes on the low-tension, 3-cable median barrier was 2.0%. Even this maximum number was lower than every other barrier type analyzed in every other state.

Second, rollover severity was higher on high-tension systems than on the low-tension, 3-cable median barrier, on average. This was unexpected since the low-tension, 3-cable median barriers have the highest rates of rollover of all barrier systems. Although the proportionate number of rollovers was high, these crashes included "tip-overs" in which vehicles made less than 3 quarter-turns. When rollover crashes involved less than 3 quarter-turns, the rollovers were generally low-speed, and as such had a significantly lower risk of severe injury than higher-speed rollovers. The rollover mechanism most commonly associated with low-speed rollovers was contact with post members. Since the low-tension cable median barrier uses the stiffest post in weak-axis bending, it is not surprising that rollovers occurred more frequently, but with lower average severity, than high-tension systems. A more complete discussion of rollover crashes is provided in Chapter 11.

Third, severe penetration and rollover crashes had the highest representation of all severe crashes on low-tension cable median barriers. This indicated that the number of non-rollover, non-penetration severe crashes on low-tension cable median barrier was the lowest of all barrier types evaluated. Alternatively, this statistic indicated that uncontrolled or unknown types of serious injury mechanisms, such as occupant contact with system components or high-exit angle redirection crashes, were minimal.

Table 21. Crash Severities by System Type and Penetration Crash Outcome

Injury Severity	Low-Tension 3-Cable Set 1				Low-Tension 3-Cable Set 2				Brifen WRSF TL-3				Nucor NU-CABLE TL-3				Trinity CASS 3-Cable			
	Crashes	Freq	Penetrations	Freq	Crashes	Freq	Penetrations	Freq	Crashes	Freq	Penetrations	Freq	Crashes	Freq	Penetrations	Freq	Crashes	Freq	Penetrations	Freq
Killed (K)	3	0.4%	3	100.0%	19	0.6%	10	52.6%	6	0.4%	-	-	3	0.4%	0	-	19	1.0%	7	36.8%
Disabling Injury (A)	13	1.6%	7	53.8%	25	0.7%	9	36.0%	34	2.2%	-	-	26	3.7%	7	26.9%	33	1.7%	5	15.2%
Moderate Injury (B)	59	7.4%	12	20.3%	164	4.9%	33	20.1%	109	7.0%	-	-	81	11.4%	10	12.3%	125	6.4%	13	10.4%
Slight Injury (C)	76	9.6%	12	15.8%	462	13.8%	37	8.0%	139	9.0%	-	-	58	8.2%	5	8.6%	173	8.9%	19	11.0%
Property Damage Only (O)	644	81.0%	63	9.8%	2688	80.0%	110	4.1%	1263	81.4%	-	-	543	76.4%	43	7.9%	1593	82.0%	129	8.1%
Severe Crashes (A+K)	**16**	**2.0%**	**10**	**10.3%**	**44**	**1.3%**	**19**	**9.5%**	**40**	**2.6%**	**-**	**-**	**29**	**4.1%**	**7**	**10.8%**	**52**	**2.7%**	**12**	**6.9%**
Total Applicable Crashes	**795**	**-**	**97**	**12.2%**	**3358**	**-**	**199**	**5.9%**	**1551**		**-**	**-**	**711**	**-**	**65**	**9.1%**	**1943**	**-**	**173**	**8.9%**
CONTRIBUTION	***62.5% PSCC***				***43.2% PSCC***				***-***				***24.1% PSCC***				***23.1% PSCC***			
PENETRATION FACTOR	***13.7 PSIF***				***12.8 PSIF***				***-***				***3.5 PSIF***				***2.6 PSIF***			

Table 22. Crash Severities by System Type and Rollover Crash Outcome

Injury Severity	Low-Tension 3-Cable Set 1				Low-Tension 3-Cable Set 2				Brifen WRSF TL-3				Nucor NU-CABLE TL-3				Trinity CASS 3-Cable			
	Crashes	Freq	Rollovers	Freq	Crashes	Freq	Rollovers	Freq	Crashes	Freq	Rollovers	Freq	Crashes	Freq	Rollovers	Freq	Crashes	Freq	Rollovers	Freq
Killed (K)	3	0.4%	0	-	19	0.6%	-	-	6	0.4%	1	16.7%	3	0.3%	1	33.3%	20	1.0%	6	30.0%
Disabling Injury (A)	13	1.6%	3	23.1%	25	0.7%	-	-	34	2.2%	10	29.4%	35	3.7%	7	20.0%	35	1.7%	9	25.7%
Moderate Injury (B)	59	7.4%	22	37.3%	164	4.9%	-	-	109	7.0%	13	11.9%	93	9.9%	12	12.9%	130	6.4%	26	20.0%
Slight Injury (C)	76	9.6%	10	13.2%	462	13.8%	-	-	139	9.0%	7	5.0%	64	6.8%	7	10.9%	176	8.7%	13	7.4%
Property Damage Only (O)	644	81.0%	27	4.2%	2688	80.0%	-	-	1263	81.4%	18	1.4%	749	79.3%	7	0.9%	1661	82.1%	44	2.6%
Severe Crashes (A+K)	**16**	**2.0%**	**3**	**4.8%**	**44**	**1.3%**	**-**	**-**	**40**	**2.6%**	**11**	**22.4%**	**38**	**4.0%**	**8**	**23.5%**	**55**	**2.7%**	**15**	**15.3%**
Total Applicable Crashes	**795**	**-**	**62**	**7.8%**	**3358**	**-**	**-**	**-**	**1551**		**49**	**3.2%**	**944**	**-**	**34**	**3.6%**	**2022**	**-**	**98**	**4.8%**
CONTRIBUTION	***18.8% RSCC***				***-***				***27.5% RSCC***				***21.1% RSCC***				***27.3% RSCC***			
ROLLOVER FACTOR	***3.0 RSIF***				***-***				***12.0 RSIF***				***7.4 RSIF***				***7.7 RSIF***			

PSCC = Penetration Severe Crash Contribution; ratio of number of severe penetration crashes to number of all severe crashes
PSIF = Penetration Severity Increase Factor; ratio of percent risk of A+K crash in penetration crashes to non-penetration crashes
RSCC = Rollover Severe Crash Contribution; ratio of number of severe rollover crashes to number of all severe crashes
RSIF = Rollover Severity Increase Factor; ratio of percent risk of A+K in rollover crashes to non-rollover crashes

Table 23. Risk Factor Summary for Barrier Systems

	Low-Tension 3-Cable	Brifen WRSF	Nucor NU-CABLE	Trinity CASS	Gibraltar	Safence (4-Cable)
PSCC	48.1%	-	24.1%	23.1%	-	-
RSCC	22.8%	27.5%	21.1%	27.3%	-	-
TOTAL	**70.8%**	**-**	**45.2%**	**50.3%**	**-**	**-**
PSIF	13.2	-	3.5	2.6	-	-
RSIF	3.0	12.0	7.4	7.7	-	-
AVERAGE	**8.1**	**-**	**5.4**	**5.2**	**-**	**-**
EFFECTIVE A+K	***1.8%***	***2.6%***	***4.1%***	***2.7%***	***2.9%***	***2.2%***

A closer examination of the non-penetration and non-rollover severe crashes with cable median barriers frequently incorporated occupant contact with posts supporting cables, unbelted occupant ejection, occupant compartment intrusion not caused by penetration or rollover events, and high lateral or longitudinal accelerations due to cable tension. All of these factors were more pronounced in the high-tension cable barrier system crashes than in low-tension system crashes, indicating that increased cable tension may have led to an increase in A+K crashes.

Consideration of barrier placement may explain some of the differences in barrier performance. An analysis on the severity of crashes based on barrier location was conducted in Ohio. Crashes were tabulated based on barrier location in the median as Traffic Side, Center, or Opposite Side positions. Crashes with barriers included in the Center category were within 4 ft (1.2 m) of the center of the median. All installations further than 4 ft (1.2 m) from the median were either classified as Traffic Side or Opposite Side installations, depending on the vehicle's direction of travel. A summary of the performance evaluation of crashes in Ohio is shown in Table 24.

Table 24. Crash Severity by Barrier Location

Barrier Location	Crashes	Penetrations	Rollovers	A+K Injuries
Traffic-Side	235	8.7%	4.5%	4.9%
Center	128	14.1%	3.1%	1.6%
Opposite-Side	494	7.7%	3.8%	3.4%
Traffic- and Opposite-Sides	729	8.4%	4.3%	4.4%

It was determined that the highest crash severity occurred with traffic-side installations, with an effective A+K rate of 4.9%. Barriers installed in the median center had an effective A+K rate of 1.6%, whereas barriers installed on the opposite side had an effective A+K rate of 3.4%. Chi-squared tests conducted comparing the Traffic and Opposite Side crashes to Center crashes were on the bounds of significance. The p-value of the severe crash comparison was 0.118, which was significant at the 12% confidence level. Comparison of the distribution of penetration and rollover crashes was much more significant, with a p-value of 0.002; this is very statistically significant. Likewise, if the injury distributions were shifted, and A, B, and K injuries were compared, the distributions were statistically different with p-value 0.020, and was statistically significant at the 2% level. Therefore, it can be conclusively determined that the distributions of crashes are not similar, and it is very likely that barriers placed in the center of medians are associated with fewer severe crashes than installations on the traffic- or opposite sides of the roadway. Although it was beyond the level of statistical significance, the analysis also suggested a higher rate of severe crash outcomes with installations placed near either shoulder.

5.3 Discussion

Results from this study were groundbreaking in several facets. To date, few studies were available which have applied a broad cross-section evaluation of any barrier type to determine weaknesses, barrier containment failures, and potential improvements which could be made on the barrier systems. As such, there was little precedent on which to build in this crash study, and many recommendations made previously were determined to be less advantageous than originally believed.

With the lack of precedent, surveyed state DOTs could not supply all of the information desired by researchers. No single state could supply a comprehensive data set with crash reports filed by responding emergency personnel and DOT staff, photos of crash scenes, measurements from crash sites, vehicle information, and slope geometries. Most states dedicated effort to assist with individual portions of the data requested even at cost to the state DOTs. The information presented in this report represents the best-effort and broad cooperation of state DOTs pooling information together to solve problems and improve cable barrier safety performance. As a result, some interpolation and extrapolation was necessary, which introduced uncertainty in the analysis.

One element of cable barrier serious crash risk included risk due to motorcyclist travel. Motorcyclist impacts with cable median barriers have historically caused concern. A study completed in 2011 determined that although motorcyclist traffic accounted for approximately 2% of all cable median barrier crashes, over 40% of those crashes were severe [25]. Out of states with complete data sets in this study, 13 motorcyclists were involved in crashes with cable median barriers, and 10 of those crashes were severe, with 4 fatalities. In Missouri, out of 127 severe crashes, motorcyclists accounted for 3 crashes, or 2.4% of all serious and fatal crash events. Motorcyclist safety will continue to be a concern for roadside safety engineers.

Lastly, it should be noted that high-severity crashes which occurred with barrier systems installed on roadway shoulders were not caused by problems with construction. No cable median barrier installation observed was found to be deficient with respect to manufacturer’s installation recommendations. However, site-specific analysis was limited to detailed narrative, site drawing, photographic, and scene diagram evidence. Future improvements to cable median barrier designs must be accomplished to realize the maximum safety improvement potential.

6 CASE STUDY

One distinctive discrepancy in the data set in particular was centered around the Trinity Cable Safety System (CASS) performance in Utah versus Washington. Both states had a significant number of miles of CASS system installed yet the rates of penetration on this system were markedly different between the states. In fact, the average rate of penetration due to the combined effects of vehicle underride, override, and rollover on CASS systems in Utah was only 6.1% on a per-crash basis. However, in Washington, the rate of penetration was much higher, with a possible net frequency of 14.5%. Cross-median events in which the vehicle entered opposing lanes totaled 4.6% of all cable median barrier crashes in Washington, and CMCs resulting from cable median barrier penetrations occurred in 2.0% of all CMB crashes. Yet, based on images of barrier installations along Washington and Utah roadways using Google Street View, there were no apparent differences between the states with respect to barrier construction using the C-channel post, and both states rigorously maintained recommended barrier placement guidelines provided by FHWA and research reports. An analysis of the differences between Utah and Washington results is provided below.

6.1 Weather Conditions

Along the I-15 corridor in Utah, annual snowfall totals can exceed 200 in. (5,080 mm) per year, more than 10 times greater than the state average. The precipitation totals along I-15 are much higher than the remainder of the state, as shown in Figure 1. More than 50% of all crashes reported in Utah involved snowfall. This was more than twice as large as the snow representation in Washington. Although some locations in Washington received high snow totals, particularly at higher-elevation locations near the mountains, the majority of the crashes into cable median barrier occurred in coastal regions where snowfall was infrequent. Snowfall tended to decrease both penetration and rollover propensity, whereas frequent rain near cable barrier locations could contribute to weak post-soil interaction in Washington, increasing penetration propensity.

6.2 Traffic Volumes

Typical ADT counts in Washington on roadways with cable median barriers varied between 20,000 vehicles per day to over 100,000 vehicles per day throughout the state. In Utah, traffic volumes ranged from less than 10,000 vehicles per day to over 100,000 vehicles per day on similar roadways with cable median barrier. More crashes in Utah occurred on roadways with lower traffic volumes than in Washington. The average difference in traffic volumes between crashes in Utah and Washington was over 20%. Furthermore, a larger percentage of heavy trucks were present in Washington relative to Utah. Thus, cross-median and penetration crash events which were not within the design limits of the barrier occurred. Although these crashes were not part of the failure analysis study since these barriers were not designed to withstand impact from larger trucks, these crashes nonetheless contributed to some severe injuries.

6.3 Avoidance Maneuvers

In Utah, most cable barrier crashes were caused by vehicles losing control due to wet, snow-covered, or icy road conditions. Crashes in which the vehicle striking the cable median barrier encountered dry roads and clear weather conditions in addition to being involved in avoidance maneuvers, were relatively sparse. For example, the frequency of avoidance-related crashes in Utah was approximately 9.0%, and at least one additional vehicle contributed to the crash sequence in 19.8% of the cable barrier crashes. Although avoidance maneuver statistics could not be obtained for Washington crashes, approximately 37.2% of crashes involved more than one vehicle, which was nearly twice the rate of Utah. This suggests that due to large traffic volumes, avoidance maneuvers occurred more frequently in Washington than in Utah, and fewer severe crashes occurred in Utah as a result.

Avoidance maneuvers generally resulted in higher CG trajectory and orientation angles because of highly-dynamic, large steering angle motions. These motions can alter a vehicle's travel path and cause a non-tracking skid engagement. As was observed in the Missouri cable median barrier impact angle analysis, high CG trajectory and orientation angles frequently led to severe penetration crash events. The lower number of avoidance-related crashes in Utah indicated that many cable barrier crashes were likely low-angle events caused by loss of control, not avoidance from an adjacent or encroaching vehicle.

6.4 Median Geometries

Medians on Washington roadways frequently ranged between 35 and 50 ft (10 and 15 m) wide. Over 63% of the crashes in Washington occurred with maximum median widths less than 45 ft (13.7 m). In Utah, however, average median widths exceeded 50 ft (15 m) in many sample sites measured from satellite images with map scaling using CAD programs. Some median widths on roadways with cable median barrier installed approached 80 ft (24.3 m).

Cross-median crashes occurred on roads with median widths exceeding 70 ft (21 m), as recorded in the California, Wisconsin, Minnesota, and Missouri studies mentioned previously [2,6,8,12]. By placing a barrier in the median, the barrier impact absorbs some energy from a crash even if a penetration occurs. By decreasing vehicle energy and providing some lateral resistance during impact, the tendency for cross-median crashes to occur on roads with wide medians drops significantly. With this reduction in CMCs, severe crash risks are also reduced.

In Utah, with larger medians and relatively flat slopes (most slopes were between 6:1 and 10:1), a higher proportion of impacts occurred on the median slopes with lowest risk of penetration than in Washington, based on the median slope results shown in Figure 6. Site-specific estimates in Washington indicated that the roads with the highest rates of penetration were sites with either fairly flat (i.e., flatter than 8:1) or steep (i.e., greater than 6:1) median slopes. The two roads with the lowest rates of penetration had estimated slope rates of between 6:1 and 8:1 over much of the protected length, and much of that roadway was at 8:1.

6.5 Barrier Placement

Cable median barriers were also frequently placed near the edge of median shoulders in Washington, adjacent to the travel lanes. In Utah, many cable median barrier installations were located in the median, either 1 ft (0.3 m) or 8 ft (2.4 m) from the ditch centerline, or up to 16 ft (4.9 m) from the road. Barrier installations near the ditch center can reduce the number of nuisance hits by allowing an opportunity for vehicles to correct from errant maneuvers. When vehicles are engaged in avoidance maneuvers, CG trajectory angles tend to increase relative to the barrier proportionately with the distance between the travel lanes and the barrier installation.

During loss of control, however, vehicle speeds at impact were typically lower when barriers were far from the roadway due to heavy braking and skidding.

Swerving, avoidance, or over-correcting maneuvers in Washington caused more vehicles to strike the barrier at higher orientation angles and CG trajectory angles. Barriers located on the shoulder permitted the vehicle striking the barrier from adjacent travel lanes to pry under or override the cables, and vehicles impacting from the opposite direction to pry underneath or launch over the barrier. Crash outcomes depended on the impact angles, impact speeds, slope rates, and vehicle profiles.

6.6 Conclusions

As a result, it was reasonable to assume that average impact CG trajectory angles and speeds during cable barrier impacts in Washington were higher than the average impact CG trajectory angles and speeds in Utah. This determination was based on the frequencies in snow-related crashes, as well as differences in median widths, traffic volumes, and the number of lanes on each roadway where crashes occurred. Similar arguments can also be provided for many of the states participating in this study.

However, Washington provided a tabulated list of only whether or not a rollover occurred, as well as the maximum injury level sustained in a crash, in lieu of which vehicle rolled and which vehicle had the highest severity. Rollovers occurred in 12% of all crashes involving more than one vehicle in Washington, and data from other states suggested that in at least 15% of multi-vehicle crashes involving cable median barrier, and possibly up to 30%, the vehicle which does not strike the cable median barrier was involved in the rollover. This could reduce the actual rate of rollover on Washington systems by 1.8% to 3.6%. Similarly, multiple vehicles were involved in most of the severe crashes in Washington. Approximately 1.5% of all Washington crashes were A+K crashes not involving head-on collisions with vehicles in opposing travel lanes. Approximately 20% of the non-cross-median serious crashes in which multiple vehicles were involved should not have been classified as serious crashes due to higher injury severity to an occupant in the vehicle which did not strike the barrier than in the vehicle which did. Accounting for this adjustment, the average rate of severe crashes caused by the cable median barrier would be reduced to 2.1% in Washington, which compares favorably with all other states in this study. Unfortunately, these adjustments cannot be made on the individual case level, which could affect one installed system to a greater degree than another.

However, none of the aforementioned factors should increase liability to any state participating in this study. As stated, this study was both groundbreaking and unique, and the recommendations provided in this research establish a precedent for future research and consideration. Barrier installations already constructed or in construction prior to the publication of this report cannot be treated with the same scrutiny as future barrier installations. Benefit-to-cost analyses are required to provide improved guidance in the future changes to policy and construction. Furthermore, all states participating in this study indicated that the findings would be helpful to guide future policy and construction, as part of a very active attempt to improve roadside safety. For this reason, states participating in this study should be lauded for their enduring commitments to safety.

For example, expanding median widths and regrading medians of established roadways can be often impossible due to constraints on the right-of-way, drainage, and prohibitively large construction costs in these locations. The benefit-to-cost ratios of many of these efforts are often much less than 1. Future construction projects may not have a sufficient budget to address these needs as well. Furthermore, no median slope was “immune” to either penetration or rollover crashes; only a minimization was observed. Instead, it is generally desirable that modifications can be made to existing cable median barrier systems to improve performance regardless of placement or median slope rate, since this generally has a lower net cost to the state and a higher propensity for better overall barrier performance. However, such developments require extensive crash-testing, design and validation work, marketing, and production, and it will require time for manufacturers to develop products to address these newly-identified needs.

In every state, significant effort was expended to adhere to the current state of knowledge of cable median barrier construction and recommendations at the time of barrier installation [26-28]. It has been frequently re-iterated in roadside safety conversations that barrier installations at or near the shoulder should decrease impact severity; the opposite effect was observed. Most cable median barrier placement guidelines have been developed based on case studies and simulations of cable median barrier impacts, and have led to some important and meaningful conclusions about improper placement and practices. However, in nearly every design simulation utilized by roadside safety research organizations, modeled cable properties were not reflective of actual cable material and physical properties [29]. However, since replacing systems installed on the shoulder could also be cost-prohibitive compared to the safety benefit realized; a better solution would be to improve barrier design for systems installed on shoulders.

Every cable median barrier system evaluated in this study has passed NCHRP Report No. 350 crash test standards at the TL-3 impact conditions. Currently, there are no standards or requirements for agencies or states to test barriers to non-standard impact conditions, and systems are currently in testing according to MASH standards. However, impact conditions which led to an increased propensity for penetration through the barrier or rollover were not consistent with NCHRP Report 350 or MASH crash-testing standards. Oversteering crashes dominated the database, occurring more frequently than even low-sideslip crashes. Since no cable median barrier has been tested with these impact conditions to date, and these impact conditions are not required for a barrier system to be installed in the median of a roadway in the National Highway System (NHS), there is no meaningful argument that states or barrier manufacturers have acted negligently with respect to any existing barrier installation or barriers currently under construction.

7 VEHICLE ANALYSIS

7.1 Introduction

Vehicle profiles have often been cited as critical factors in the performance of cable median barrier systems. Unfortunately, a comprehensive cross-sectional analysis of cable median barrier crashes and vehicle profiles has not been available. It was frequently cited in publications and re-iterated in conversations with DOT representatives that cable median barriers are less capable of safely containing larger, taller vehicles such as trucks, as well as to low-profile, narrow-front-end vehicles such as roadster or sport car vehicles. Furthermore, many experts believed some vehicles were uniquely susceptible to penetration or rollover compared to other vehicles, due to inertial, suspension, and front profile differences [e.g. 10, 20, 27]. As a result, it was uncertain whether the roadside safety community was conducting crash tests with representative practical worst-case vehicles, or if more critical vehicles should be used.

Based on vehicle makes, models, and years involved in cable median barrier crashes, a database was constructed relating vehicle dimensions and properties to crash results. Data from states not providing vehicle year, make, and model were excluded from the analysis.

Two different reference databases of vehicle dimensions were consulted to identify critical features of vehicles involved in roadside safety crashes. The first reference was the National Highway Transportation Safety Administration (NHTSA) crash testing vehicle data spreadsheet, which tabulated vehicle dimensions and weights of vehicles used in various crash testing programs including the New Car Assessment Program (NCAP) [30]. The second resource consulted included dimensions of various vehicles tabulated by make, model, and year. The data were assembled by expert crash reconstructionists into the program Expert AutoStats, produced by 4N6XPRT Systems.

Vehicle dimensions and inertial properties of both databases were compared. In general, less information was available from the NHTSA dataset, since data tabulation in the NHTSA set supported frontal crash testing programs. Discrepancies between the databases were typically minimal, with the exception of weights. The differences are believed to be the result of the inclusion of dummies in NCAP testing.

7.2 Vehicle Types

Vehicle types were classified using a simple heuristic combination of Highway Loss Data Institute (HLDI) classifications of passenger cars, and segregation of utility vehicles into van, SUV, and light truck profiles. HLDI classifications segregated passenger cars by wheelbase and overall length. Small cars were defined to be cars with total lengths less than 180 in. (4,572 mm) and wheelbases less than 105 in. (2,667 mm). Mid-size cars were defined as vehicles with wheelbases between 105 and 110 in. (2,667 and 2,794 mm) and overall lengths between 180 and 195 in. (4,572 and 4,953 mm), and large cars were taken to be the remainder of the passenger cars. Tractor-trailer, large truck, and commercial or mass transit vehicles were categorized as “Large Vehicles,” but due to the relatively low frequency of impacts at only 1.9% of all crashes, a detailed analysis of tractor-trailer and large vehicle crashes was not conducted.

The impact distribution by vehicle type is shown in Figure 15. Each distribution was plotted as a percentage with the type of crash noted. Small cars were involved in the highest number of crashes and penetrations, but were involved in fewer rollovers than SUVs. Likewise, mid-size cars were involved in the second highest number of crashes and penetrations, but were involved in fewer rollovers than small cars, SUVs, and pickups, in terms of total crashes.

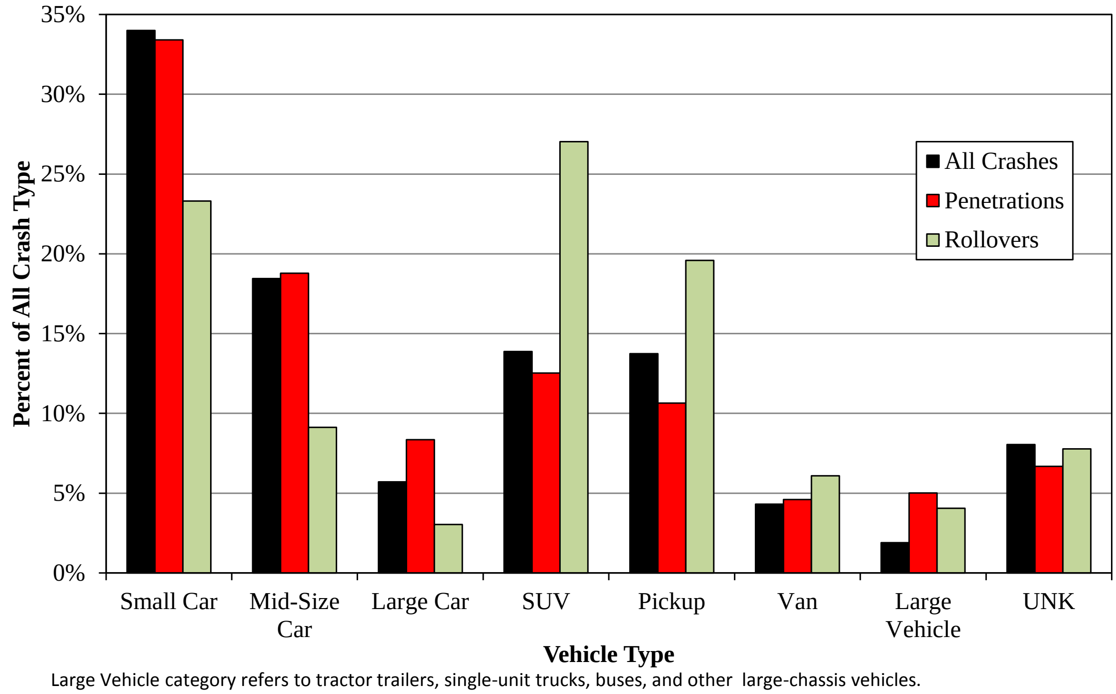


Figure 15. Vehicle Types Involved in Cable Barrier Crashes

By comparison, rates of vehicle penetration and rollover on a per-crash basis are shown in Figure 16. Large cars were involved in the highest frequency of penetration crashes, followed by vans, mid-size cars, and small cars. Surprisingly, pickups had the lowest rates of penetration of any vehicle type. Although some pickup models were identified which had a higher susceptibility to penetration crashes, as discussed later, generally pickups were not prone to penetrating through cable median barriers. Rollovers were infrequent with all passenger car types, but were common for larger vehicles, averaging more than 10% of all pickup, SUV, and van crashes combined.

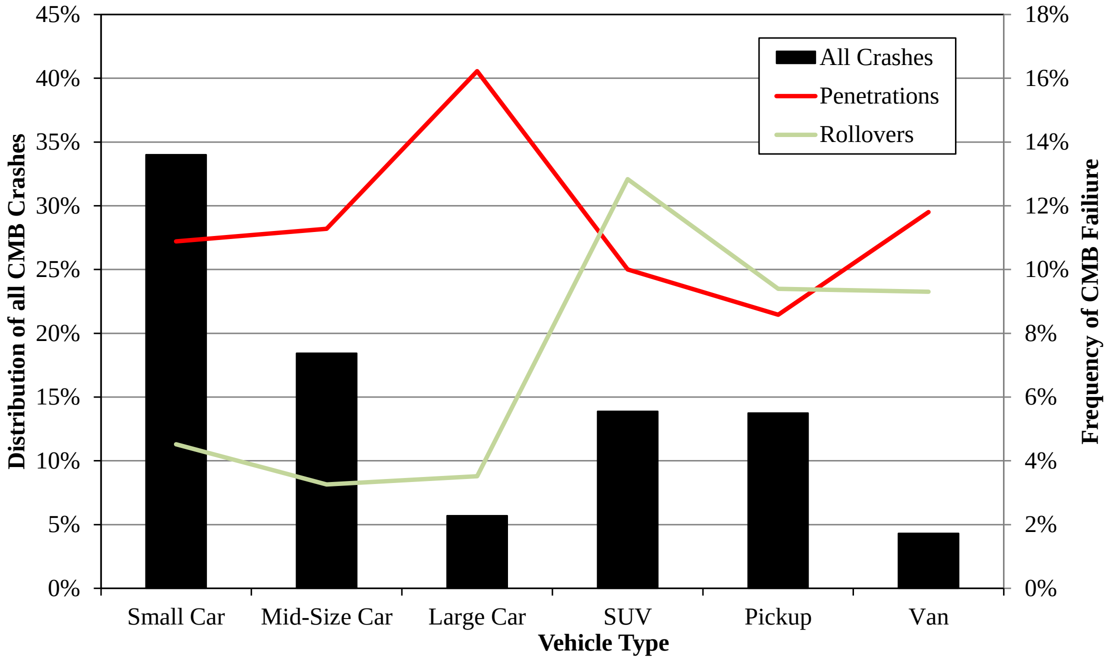


Figure 16. Frequency of Barrier Failure by Vehicle Type

Serious injury and fatal crashes were distributed between all vehicle classes, as shown in Figures 17 and 18. Large car and SUV crashes were more severe in general than small car, mid-size car, or pickups. Vans had the highest rate of severe crashes. A high number of severe crashes occurred involving vans. Tractor-trailer crashes involved a high number of cross-median crashes and rollovers which contributed to the increased average crash severity.

SUVs and large cars were involved in a disproportionately high number of severe crashes. The high rate of severe crashes with these vehicle classes correlated with the high rollover and penetration rates. Likewise, despite a high rate of rollovers, pickup trucks were involved in a significantly lower number of penetration crashes than other vehicle types, which contributed to a comparable rate of severe crashes as small and mid-size cars.

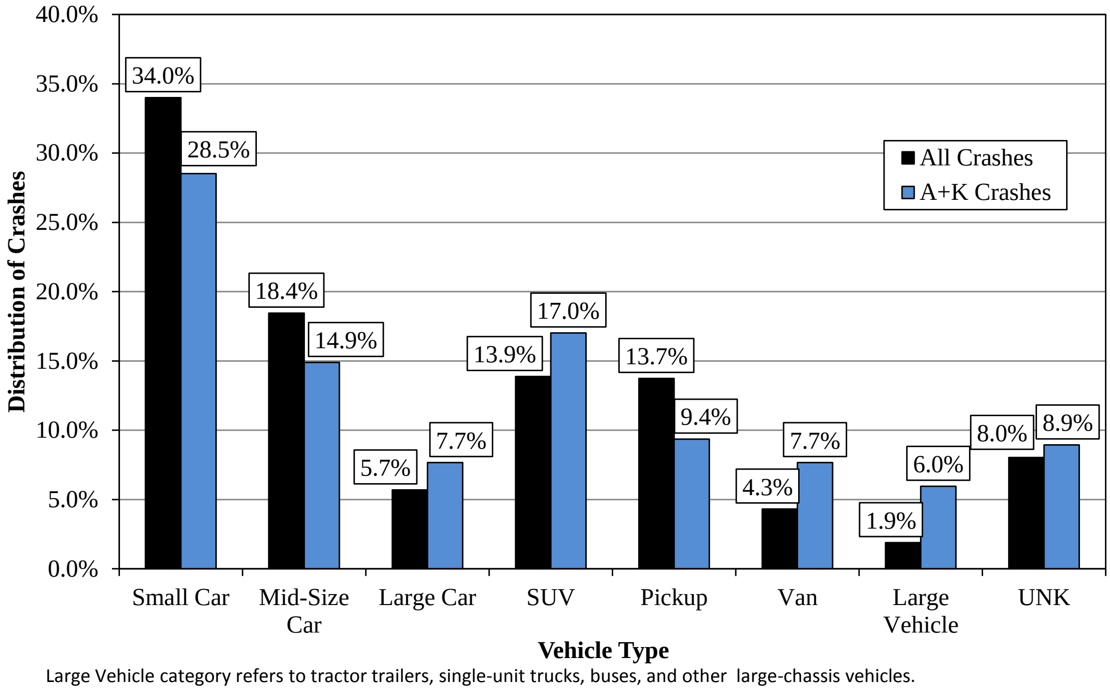


Figure 17. Risk of A+K Crash by Vehicle Type

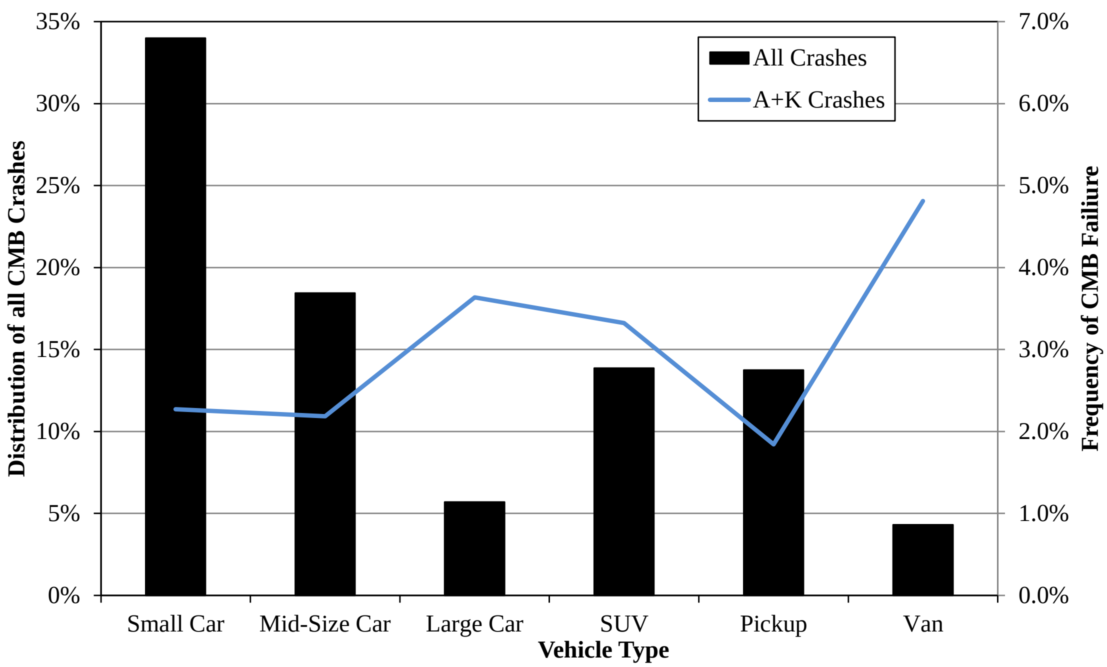


Figure 18. Frequency of Severe Injury by Crash Result and Vehicle Type

An analysis of severe crashes based on barrier containment rates indicated that the majority of severe crashes were associated with barrier containment failures, as shown in Figure

19. The highest frequencies of severe crashes based on containment failures occurred with large cars, SUVs, and pickups. Not surprisingly, vans had the lowest rate of severe injuries related to barrier containment failures, since the penetration and rollover rates for vans were not extremely high while the severe crash rate was conversely very high. Also, mid-size cars were involved in more crashes in which the vehicle became entrapped in the cables and cables crushed the hood, roof, or windshield, or penetrated into the occupant compartment of convertibles. As a result, more non-containment failure related crashes were severe involving mid-size cars than other vehicle types.

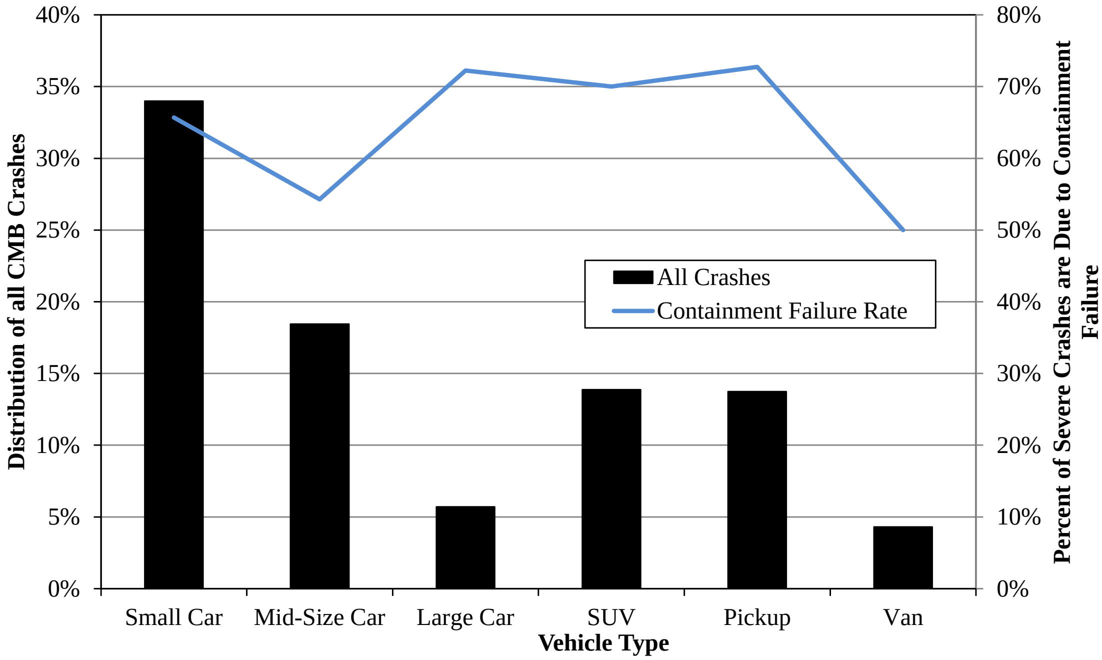


Figure 19. Percentage of Severe Crashes Related to Containment Failures

7.3 Vehicle Factor Analysis

In order to evaluate the statistical relationships between vehicle parameters and CMB containment failures, chi-squared tests were performed to evaluate the similarity between vehicle parameters and the global distribution related to that parameter. The statistical weighting scale used to evaluate statistical significance is shown in Table 25.

Table 25. Scales Used to Evaluate Statistical Significance of Chi-Squared Tests

Lower Limit p-value	Upper Limit p-value	Interpretation
0	0.15	Statistically Independent
0.15	0.25	Likely Independent
0.25	0.4	Possibly Independent
0.4	0.6	No Conclusion
0.6	0.75	Possibly Similar
0.75	0.85	Likely Similar
0.85	1	Statistically Similar

7.3.1 Summary of Important Findings

A summary of critical results pertaining to penetration and rollover crashes is shown in Table 26. It was obvious that the distribution of vehicles involved in rollover events varied considerably from the composite distribution. The composite distribution was defined as the database of all crashes.

Containment failure causes were not known for many of the penetration and rollover crashes in which vehicle year, make, and model were known. As a result, penetration and rollover rates could not be segregated for every vehicle. If crashes without containment failure causes were excluded, the dataset was too small to make critical analysis of the features which contributed to penetration or rollover. Thus, all containment failures were included and analyzed in this dataset. In addition, containment failure data from Missouri and North Carolina, which oversampled severe and penetration crashes, respectively, were included. Overall penetration, rollover, and severe crash rates were used to scale the resultant frequencies of penetration and rollover to the calculated national average.

Table 26. Chi-Squared Tests for Independence of Tested Vehicle Factors

Distributions Evaluated for Independence using Chi-Squared Tests	Penetration Subset p-value	Rollover Subset p-value	Comparison of Subset to Global Set	
			Penetration	Rollover
Weight	**0.7972**	**0.0000**	**Likely Similar**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.0758	0.2870	Statistically Independent	Possibly Independent
SUVs, Pickups, and Vans	0.1415	0.1914	Statistically Independent	Likely Independent
Wheelbase	**0.4496**	**0.0005**	**No Conclusion**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.0582	0.6882	Statistically Independent	Possibly Similar
SUVs, Pickups, and Vans	0.2674	0.8409	Possibly Independent	Likely Similar
Track Width	**0.5099**	**0.0187**	**No Conclusion**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.0320	0.6503	Statistically Independent	Possibly Similar
SUVs, Pickups, and Vans	0.3922	0.3348	Possibly Independent	Possibly Independent
Bumper Height	**0.5732**	**0.0000**	**No Conclusion**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.8591	0.4536	Statistically Similar	No Conclusion
SUVs, Pickups, and Vans	0.5924	0.2010	No Conclusion	Likely Independent
Center of Headlight Height	**0.2634**	**0.0000**	**Possibly Independent**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.5394	0.7157	No Conclusion	Possibly Similar
SUVs, Pickups, and Vans	0.5454	0.4408	No Conclusion	No Conclusion
Front Hood Height	**0.6267**	**0.0000**	**Possibly Similar**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.0320	0.6503	Statistically Independent	Possibly Similar
SUVs, Pickups, and Vans	0.3922	0.3348	Possibly Independent	Possibly Independent
Rear Bumper Height	**0.0615**	**0.0853**	**Statistically Independent**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.2890	0.8065	Possibly Independent	Likely Similar
SUVs, Pickups, and Vans	0.3338	0.3627	Possibly Independent	Possibly Independent
Top of Trunk Height	**0.4531**	**0.0000**	**No Conclusion**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.5263	0.6545	No Conclusion	Possibly Similar
SUVs, Pickups, and Vans	0.7745	0.9159	Likely Similar	Statistically Similar
CG Height	**0.1691**	**0.0000**	**Likely Independent**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.2053	0.1585	Likely Independent	Likely Independent
SUVs, Pickups, and Vans	0.2089	0.5335	Likely Independent	No Conclusion
CG from Front Axle	**0.6634**	**0.0000**	**Possibly Similar**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.9015	0.1211	Statistically Similar	Statistically Independent
SUVs, Pickups, and Vans	0.4500	0.9136	No Conclusion	Statistically Similar
Turning Circle Diameter	**0.1363**	**0.0340**	**Statistically Independent**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.1950	0.8586	Likely Independent	Statistically Similar
SUVs, Pickups, and Vans	0.7420	0.8660	Possibly Similar	Statistically Similar
Max Turning Angle	**0.3267**	**0.4031**	**Possibly Independent**	**No Conclusion**
Small, Mid-Size, and Large Cars	0.3354	0.7174	Possibly Independent	Possibly Similar
SUVs, Pickups, and Vans	0.7855	0.5520	Likely Similar	No Conclusion
Roll Moment-of-Inertia	**0.9626**	**0.0000**	**Statistically Similar**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.0497	0.1406	Statistically Independent	Statistically Independent
SUVs, Pickups, and Vans	0.4665	0.2802	No Conclusion	Possibly Independent
Yaw Moment-of-Inertia	**0.4904**	**0.0008**	**No Conclusion**	**Statistically Independent**
Small, Mid-Size, and Large Cars	0.6047	0.1987	Possibly Similar	Likely Independent
SUVs, Pickups, and Vans	0.1170	0.9384	Statistically Independent	Statistically Similar

As shown in Figure 16, SUVs were involved in rollovers in approximately 13% of all crashes. Likewise, rollovers occurred in 9.4% and 9.3% of all pickup and van crashes, respectively. With such a significant frequency of rollovers occurring with larger vehicles, the combined distribution of vehicle dimensions, weights, and inertial properties varied at an overwhelmingly statistically significant level from the distribution of all crashes, which was much more balanced in terms of vehicle representation.

By contrast the penetration subset was largely inconclusive with respect to the composite dataset. While penetration crash frequency was the highest with large cars, penetrations varied between 9% and 11% of all crashes for four of the vehicle body types. Thus, penetration crashes did not vary widely from the global composite distribution. The large similarity between the penetration rates suggests that other factors than the vehicle type, including impact conditions, median barrier placement, and median slopes have a stronger correlation with penetration propensity than the vehicle type. Certain features on impacting vehicles, such as sharp front nose profiles, rear bumper heights, turning circle diameters, and CG heights, serve to accentuate the risk of penetration.

Vehicle dimensions tabulated from both the NHTSA database and 4N6XPRT Expert AutoStats program were plotted and compared. Some discrepancies were observed in the distributions of vehicle wheelbase, weight, and CG heights using both methods, but most of the variations were within 5% difference. The only statistically significant difference occurred with large vehicle wheelbases and weights. For example, the Chi-squared error, calculated using the formula

$$Error = \frac{(Observed\ Num\ Crashes - Expected\ Num\ Crashes)^2}{Expected\ Num\ Crashes}$$

was 52.5 for wheelbases between 115 and 120 in. (2,921 and 3,048 mm), heavily oversampling larger vehicles in the NHTSA database. As a result, overall p-values of the distributions were less than 0.001.

7.3.2 Vehicle Curb Properties

Weight distributions varied widely between the NHTSA and AutoStats databases, and are shown in Figure 20. The discrepancies in weights were likely the result of added weight which could be attributable of dummies, ballast, and instrumentation used in NCAP testing. Additionally, the Expert AutoStats program tabulated the vehicle curb weights, whereas the NHTSA database tabulated gross weight prior to testing. The resultant difference in weights was approximately 500 lb (227 kg) for the composite distributions.

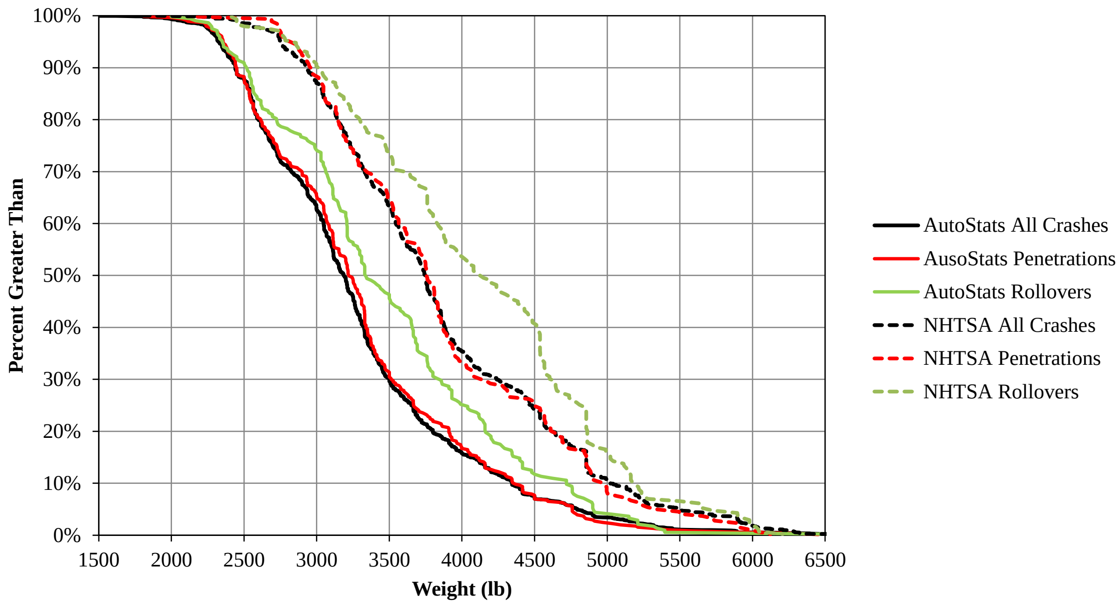


Figure 20. Distribution of Vehicle Weight in Severe CMB Impacts by Crash Result

Differences in the database were also related to the information constraints available in the NHTSA database. When certain years or models of vehicle were not available, the database was cross-referenced using knowledge of the structural frames used in each model year. For example, the Ford Taurus and the Mercury Sable were geometrically similar and built on the same frames through 2006. When one vehicle type was involved in a crash and information on that year or model could not be found, a search was made for an analogous vehicle platform and shape from the same year. Also, vehicles from the same production generation years were examined and occasionally data from older or newer vehicles of the same model were used. As a result, dimensions and properties obtained from the NHTSA database were extrapolated to the available vehicles, and were therefore an approximation. This approximation was excellent for small, mid-size, and full-size cars and SUVs, but was poor for pickups and vans.

Comparisons of the curb weights and exterior dimensions of vehicles in the Expert AutoStats programs matched manufacturer-provided data in discrete tests. In light of the differences between the databases, unrealistically high weights, the need for approximations to associate dimensions in the NHSTA database, and the greater volume of data available using the Autostats database, the Expert AutoStats data results were concluded to be more accurate and thus are exclusively shown from this point forward.

The distribution of vehicle weights plotted by crash result and vehicle body type is shown in Figure 21. The global vehicle weights were poor estimates for the independent effects observed in the databases. In particular, the global rollover distribution suggests that heavier vehicles, as a whole, are more likely to be involved in rollover crashes than lighter vehicles. However, a comparison by vehicle types indicate the opposite effect is likely true – lighter cars are more commonly involved in rollovers than heavier cars, and there does not appear to be a causal relationship between SUV, pickup, and van rollovers and vehicle weights. Passenger car rollover relationships were not statistically significant because there were few passenger car rollovers, but it is believed that the relationship would be significant with additional data. By contrast, heavier passenger cars were statistically significantly more likely to be involved in penetrations than lighter vehicles. Heavier SUV, van, and pickup vehicles also were involved in more penetrations than lighter vehicles. Individual plots of the relationships between vehicle weights and penetration and rollover propensities are shown in Figures 22 and 23.

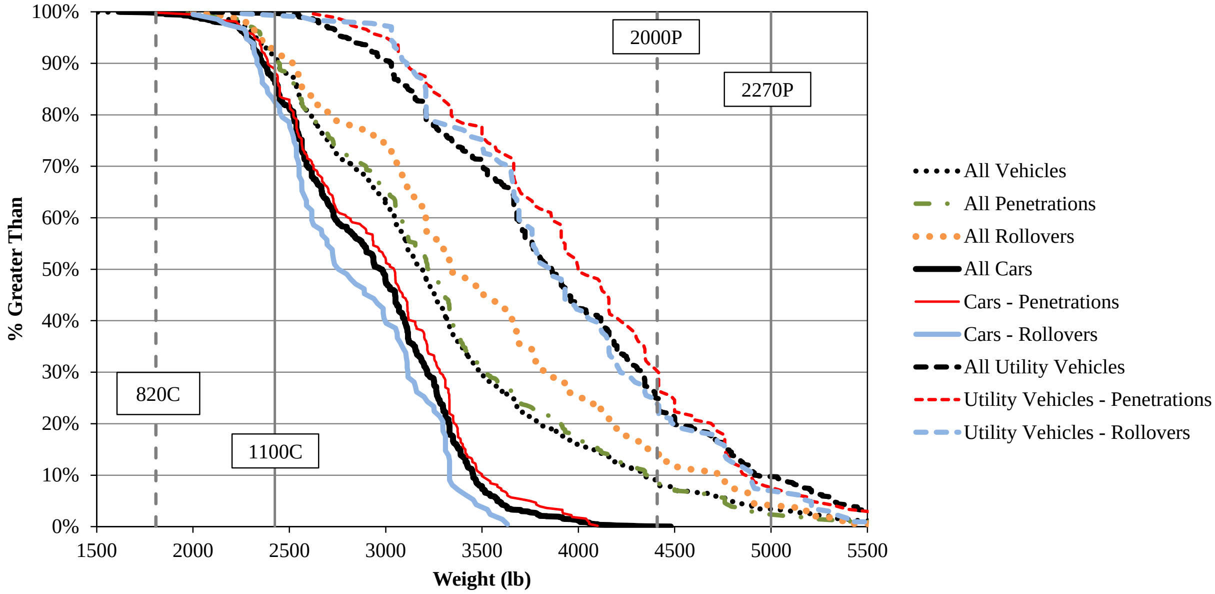


Figure 21. Distribution of Vehicle Weights by Crash Result and Vehicle Type

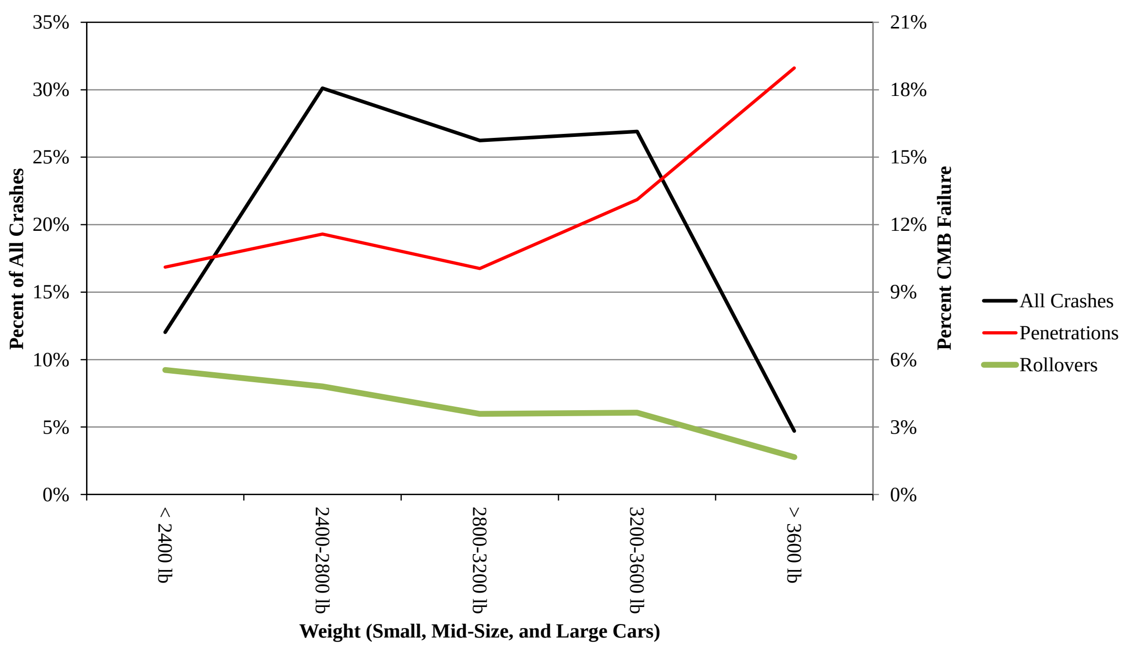


Figure 22. Crash Result by Vehicle Weight, Small, Mid-Size, and Large Cars

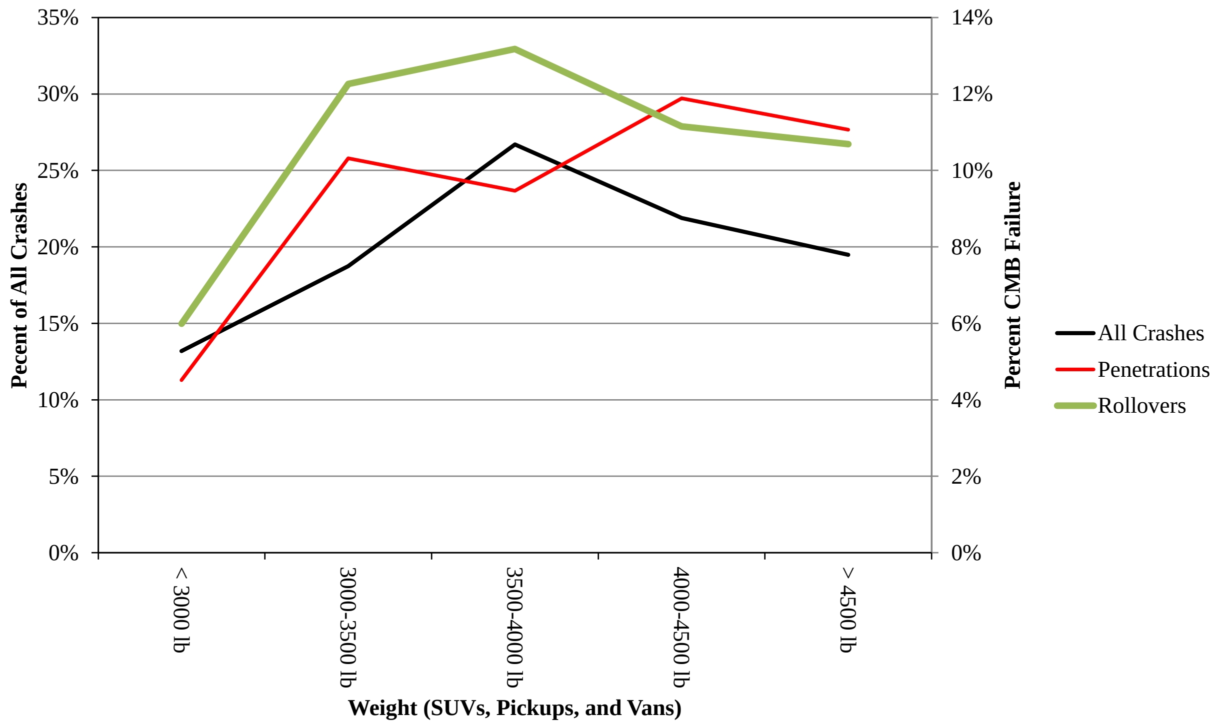


Figure 23. Crash Result by Vehicle Weight, SUVs, Pickups, and Vans

Cable barrier failure propensity based on wheelbase is shown in Figure 24. The distribution of vehicles was plotted with the frequency of penetration or rollover in each category. Rollovers were more frequent with increasing wheelbase. Recall that small car classes according to HLDI classifications had wheelbases less than 105 in. (2,667 mm) and total lengths less than 185 in. (4,699 mm), and mid-size cars had wheelbases between 105 and 110 in. (2,667 and 2,794 mm) and overall lengths between 180 and 195 in. (4,572 and 4,953 mm). Because mid-size cars had such a low rate of rollovers, the rollover curve reached a minimum in the mid-size car wheelbase range of 4.7% of crashes.

Approximately 57% of all crashes into cable median barrier involved vehicles with wheelbases ranging between 100 and 110 in. (8 ft-4 in. and 9 ft-2 in., or 2,540 and 2,794 mm). Of all vehicles with wheelbases exceeding 130 in. (3,302 mm), 106 vehicles were pickup trucks, 6 were SUVs, and 16 were vans. The high contribution of pickups in this large wheelbase category likely contributed to the increase in rollover frequency.

The wheelbase distribution was further segregated by vehicle type. Small car, mid-size car, and full-size car classes were segregated into one group, and SUVs, vans, and pickups were segregated into a second group. Plots of the two groupings are shown in Figures 25 and 26. Rollover rates were relatively flat when segregated by vehicle type, which indicated that wheelbase alone was not a causative factor in rollover crashes. Vehicle type was a controlling factor. Alternatively, mid-length SUVs, pickups, and vans had high penetration rates, whereas mid-length cars had the lowest penetration rates.

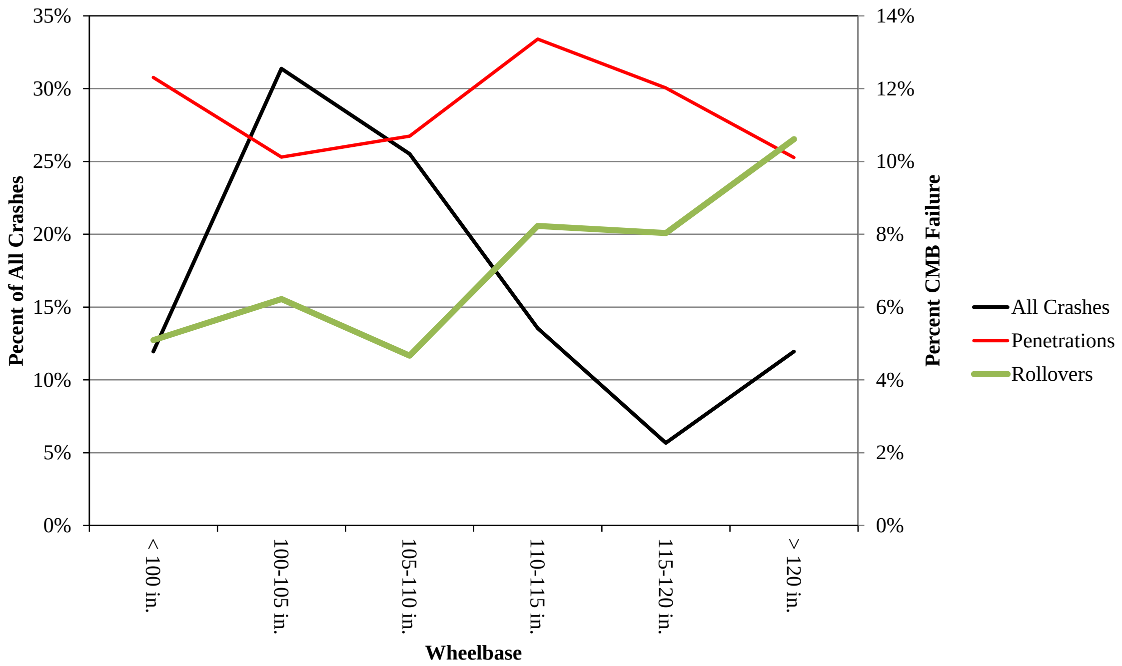


Figure 24. Crash Result Based on Wheelbase

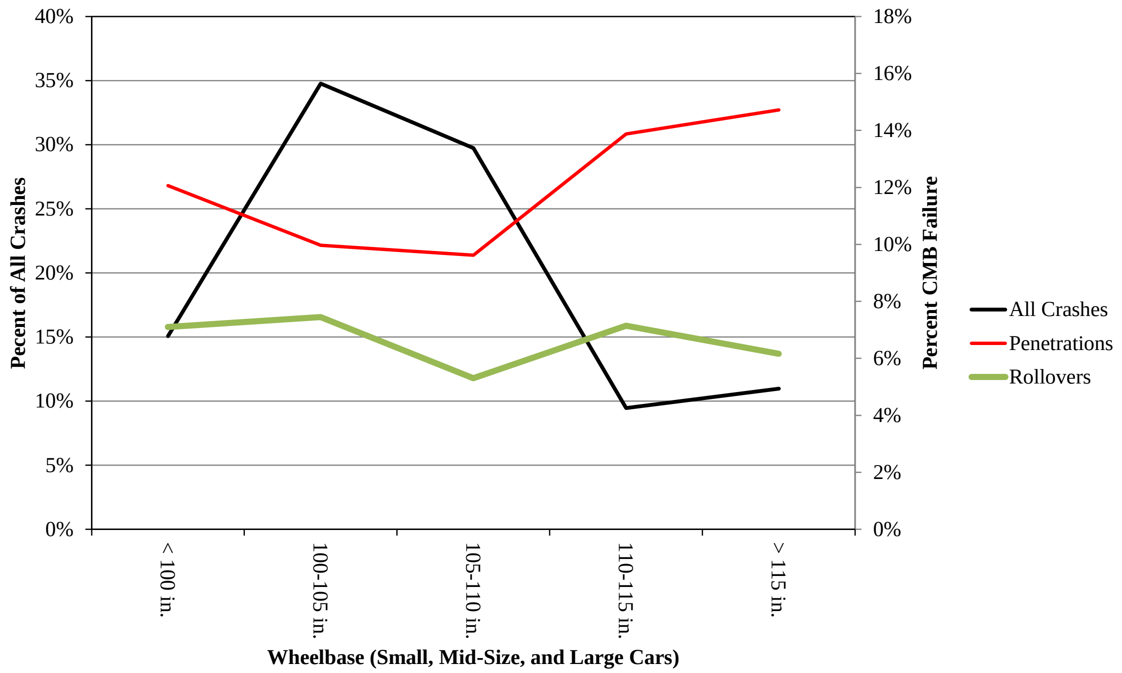


Figure 25. Crash Result Based on Wheelbase, Small, Mid-Size, and Large Cars

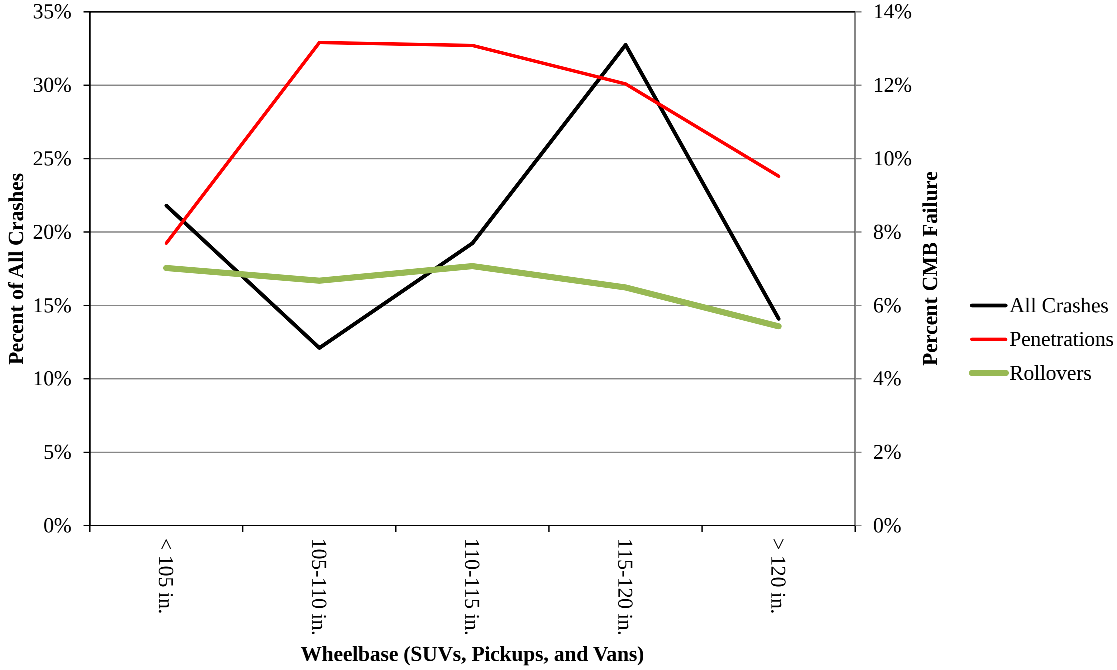


Figure 26. Crash Result Based on Wheelbase, SUVs, Pickups, and Vans

The distribution of wheelbase lengths is shown in Figure 27. The distribution was stepped, because wheelbase numbers were tabulated by whole inches in the AutoStats program. An attempt was made to smooth the distributions by capturing the median percentile for each wheelbase increment. The smoothed plot of the distribution is shown in Figure 28.

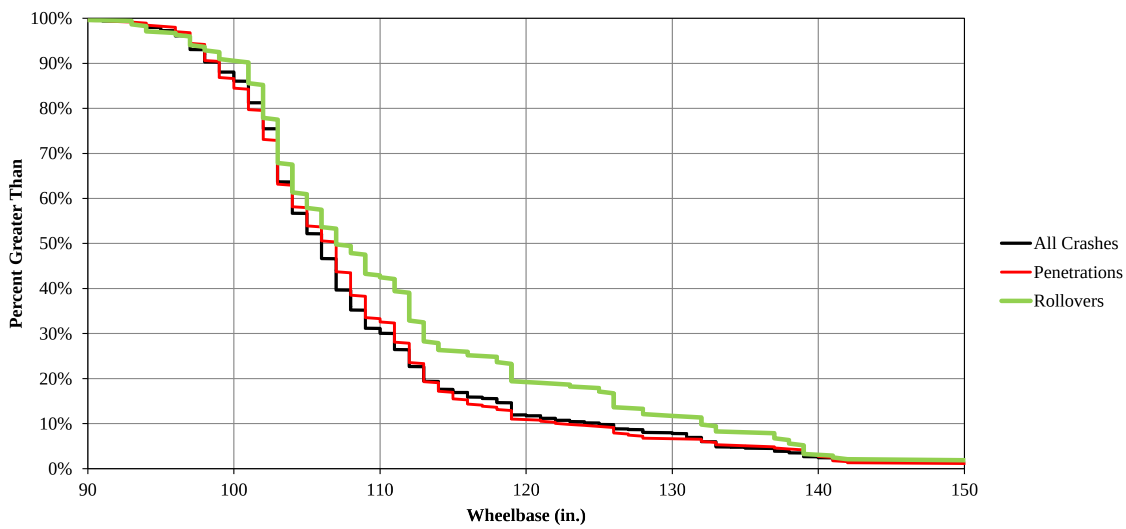


Figure 27. Distribution of Vehicle Wheelbase in Cable Median Barrier Crashes

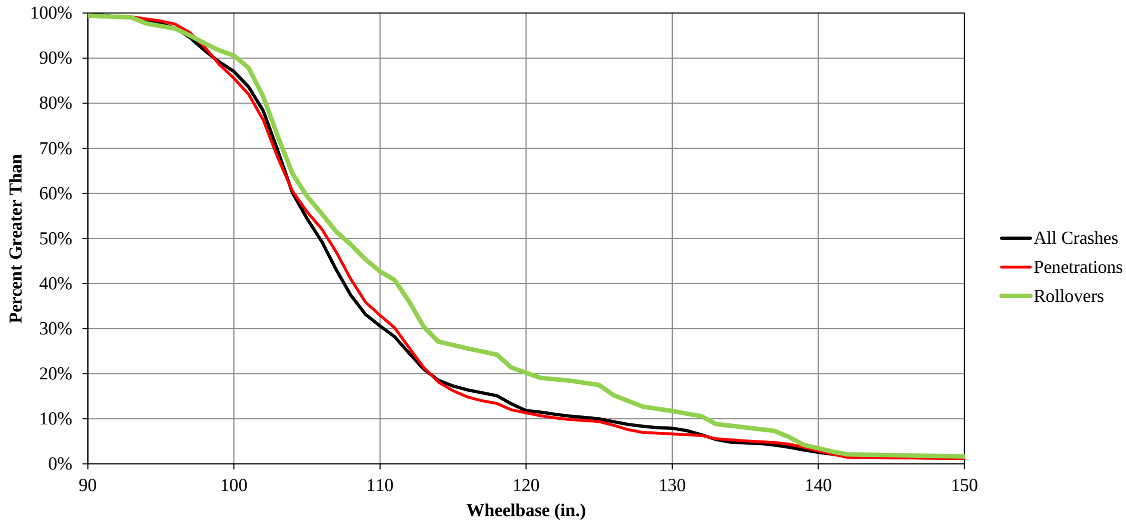


Figure 28. Smoothed Distribution of Vehicle Wheelbase in Cable Median Barrier Crashes

The distribution of wheelbase by crash result for all vehicles suggested that large wheelbase vehicles were involved in more rollovers than small-wheelbase vehicles. This was confirmed in Figure 24. There were no obvious differences between the penetration and composite distributions.

Distributions based on vehicle segregation into passenger car vs. SUV, van, and pickup classes are shown in Figure 29. Unlike in the composite distributions, this sub-divided distribution indicated a typically slightly larger wheelbase involved in passenger car and SUV, pickup, or van penetrations. Alternatively, the rollover distribution was virtually indistinguishable from the composite distributions for both vehicle classes.

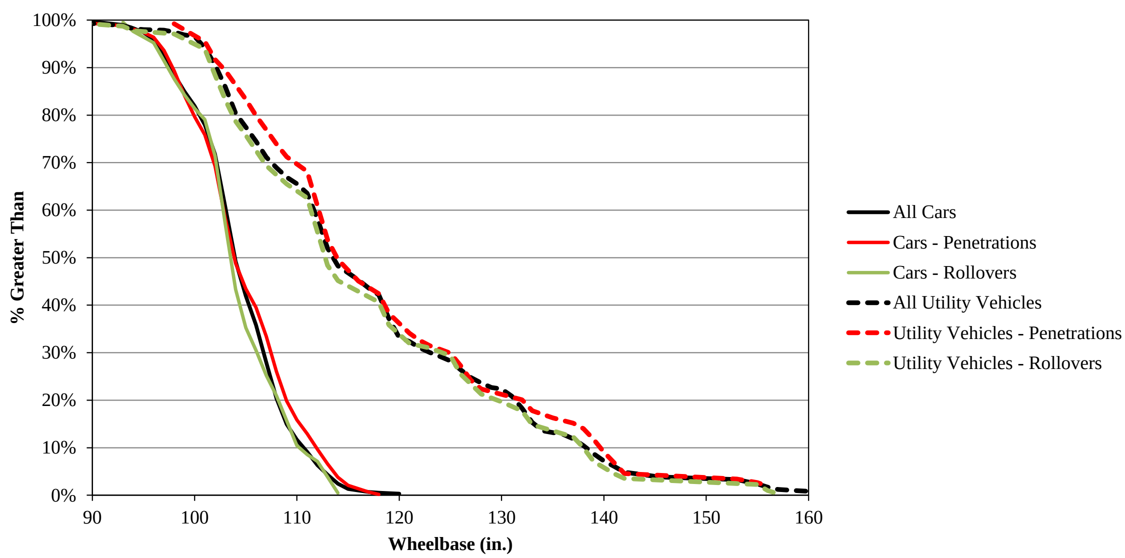


Figure 29. Smoothed Distribution of Vehicle Wheelbase by Vehicle Type and Crash Result

Track widths were also plotted to identify potential relationships, as shown in Figure 30. Generally, rollovers were more prevalent with larger track widths. This was expected, because SUVs, pickups, and vans, which are involved in more rollovers than cars, also typically have larger track widths.

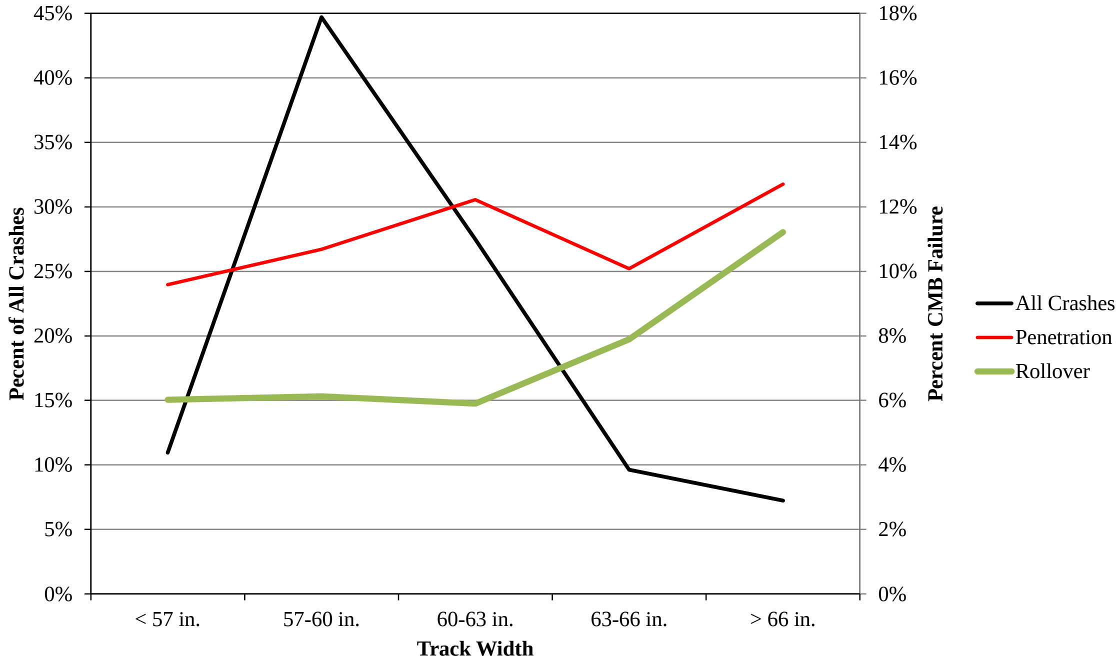


Figure 30. Crash Result Based on Track Width

Track widths were segregated by vehicle type as shown in Figures 31 and 32. The distributions were compared by crash outcome. Segregation by vehicle type indicated a strong relationship between track width and penetration rates for passenger cars, whereas statistically significant differences in penetration rate were not observed for SUVs, pickups, and vans. Penetrations were infrequent with small track with utility vehicles, but remained relatively constant for vehicles with track widths greater than 60 in. (1,524 mm). Rollover rates were not strongly related to track width in either vehicle grouping. Further analysis of track width with respect to CG height is discussed in Section 7.3.4.

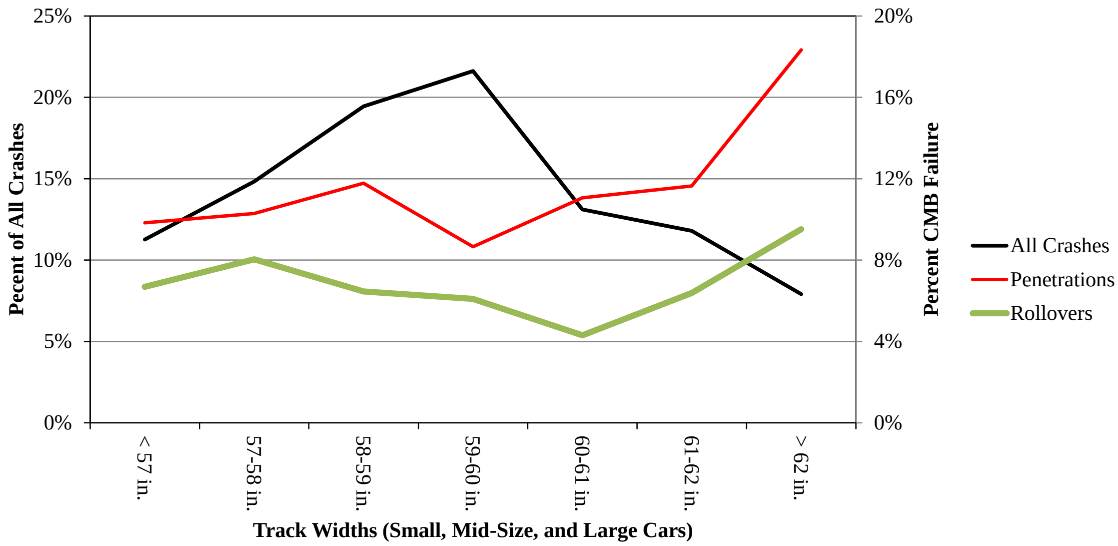


Figure 31. Crash Result Based on Track Width, Small, Mid-Size, and Large Cars

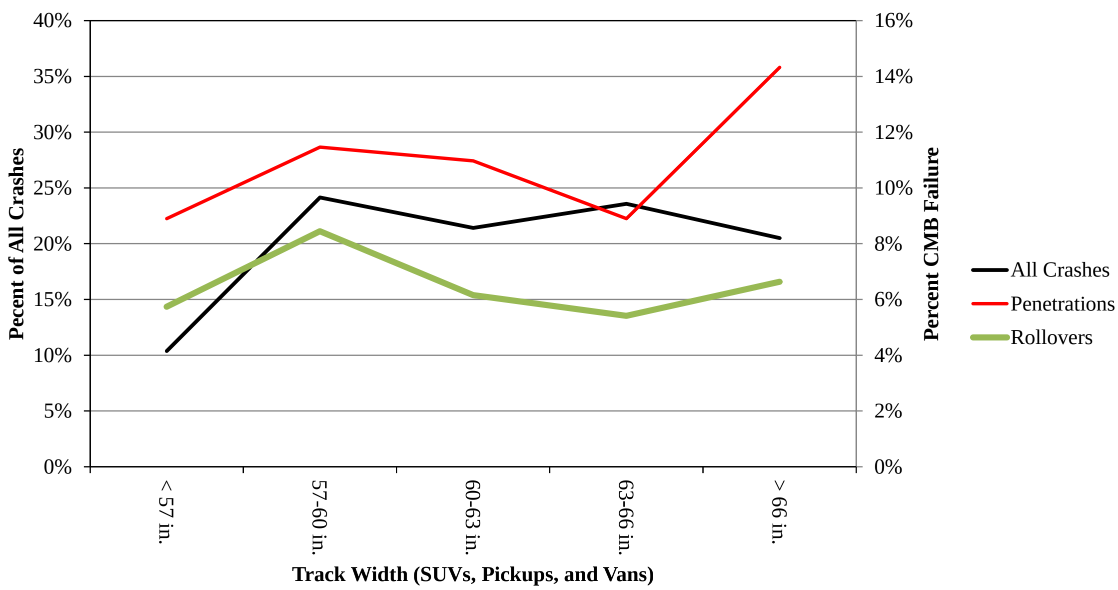


Figure 32. Crash Result Based on Track Width, SUVs, Pickups, and Vans

A smoothed distribution of crash result by track width is shown in Figure 33. The penetration distribution was dominated by larger-track width passenger cars. The 85th percentile track width in all car crashes was 63.3 in. (1,608 mm), whereas the 85th percentile track width for cars involved in penetration crashes was 63.8 in. (1,621 mm). By contrast, rollovers frequently occurred with greater frequency at smaller track widths, which would contradict the conclusions made by solely evaluating the results shown in Figure 30.

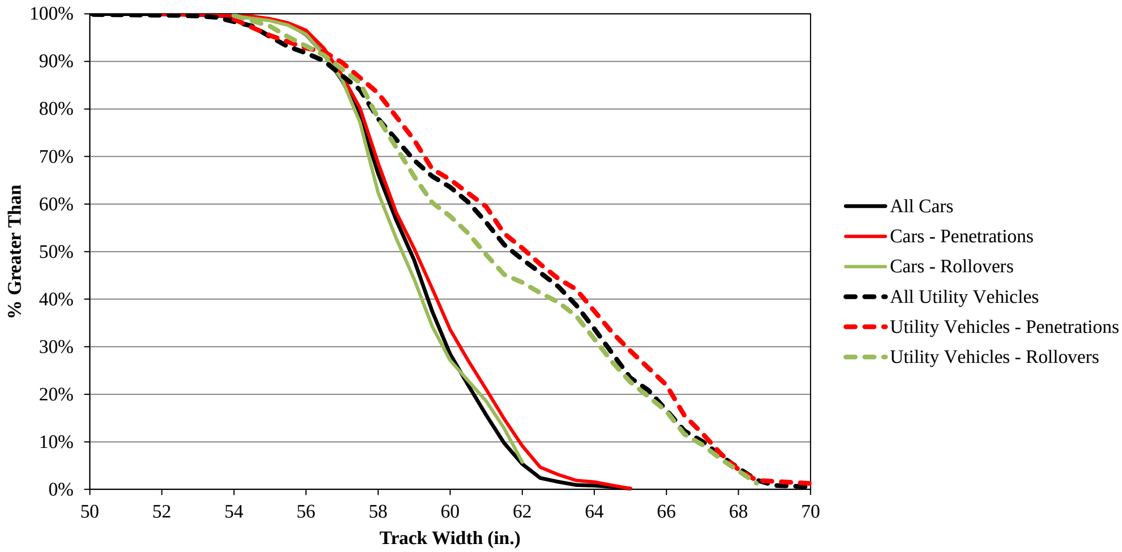


Figure 33. Smoothed Distribution of Track Width by Vehicle Type and Crash Result

7.3.3 Vehicle Profile Dimensions

Crash results based on front bumper height were plotted and are shown in Figure 34. There was an unmistakable increasing trend toward higher rollover rates with increasing bumper height. Surprisingly, this correlation appeared nearly linear with bumper height. A similar relationship could not be determined for penetration crashes. The overall distribution of vehicles involved in the crashes had no discernible trend in penetration rates.

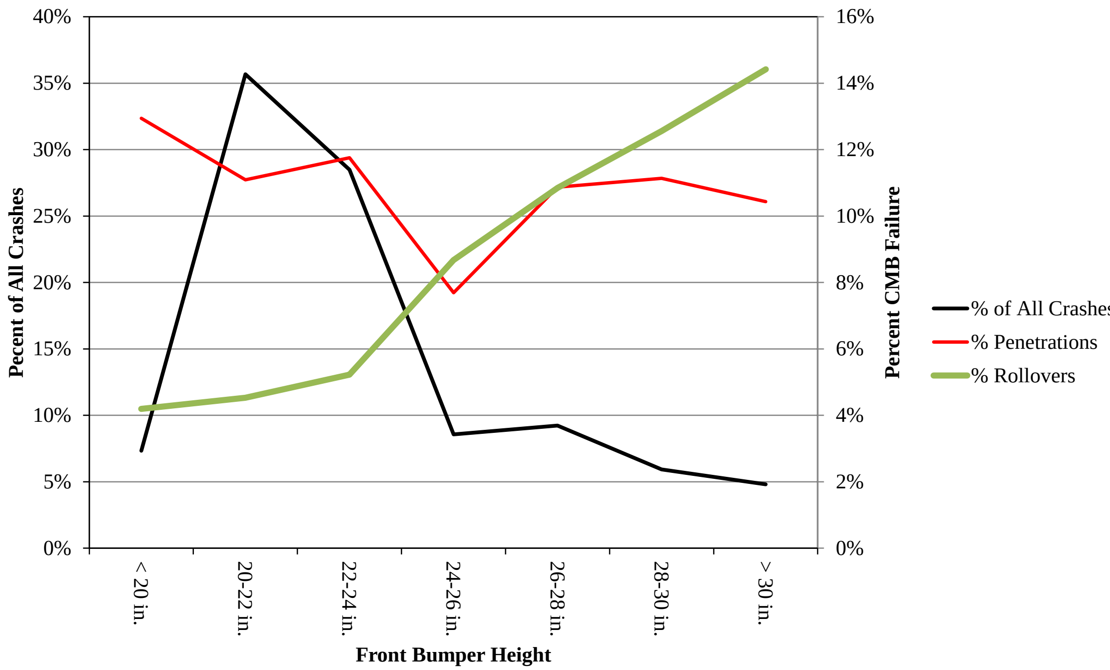


Figure 34. Crash Result Based on Top of Front Bumper Height

As with wheelbase and track widths, the crash results were segregated by vehicle type and plotted separately. The plots are shown in Figures 35 and 36. Although rollover rates were very strongly related to front bumper heights when all vehicles were compared together, comparisons by classes revealed mixed results. Passenger cars had no strong correlation between rollover rates and front bumper heights. A strong correlation was observed between SUV, pickup, and van rollover rates and front bumper heights.

The penetration distributions were not independent from the composite distributions of each vehicle type when compared by bumper height; in fact, the passenger car penetration distribution was statistically similar to the distribution of all passenger car crashes. This result was surprising, since it is widely known that lower bumper heights can contribute to higher penetration rates for low-profile cars. This likely indicates that median terrain and impact conditions have a far stronger effect on penetration than top-of-bumper height.

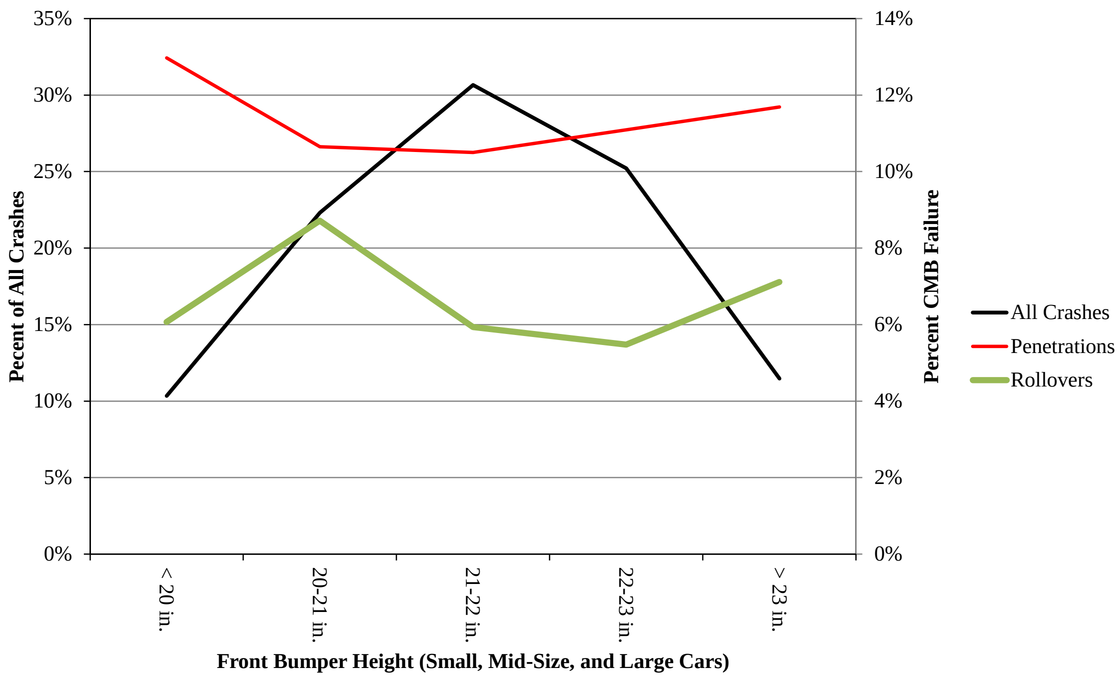


Figure 35. Crash Results by Front Bumper Height, Small, Mid-Size, and Large Cars

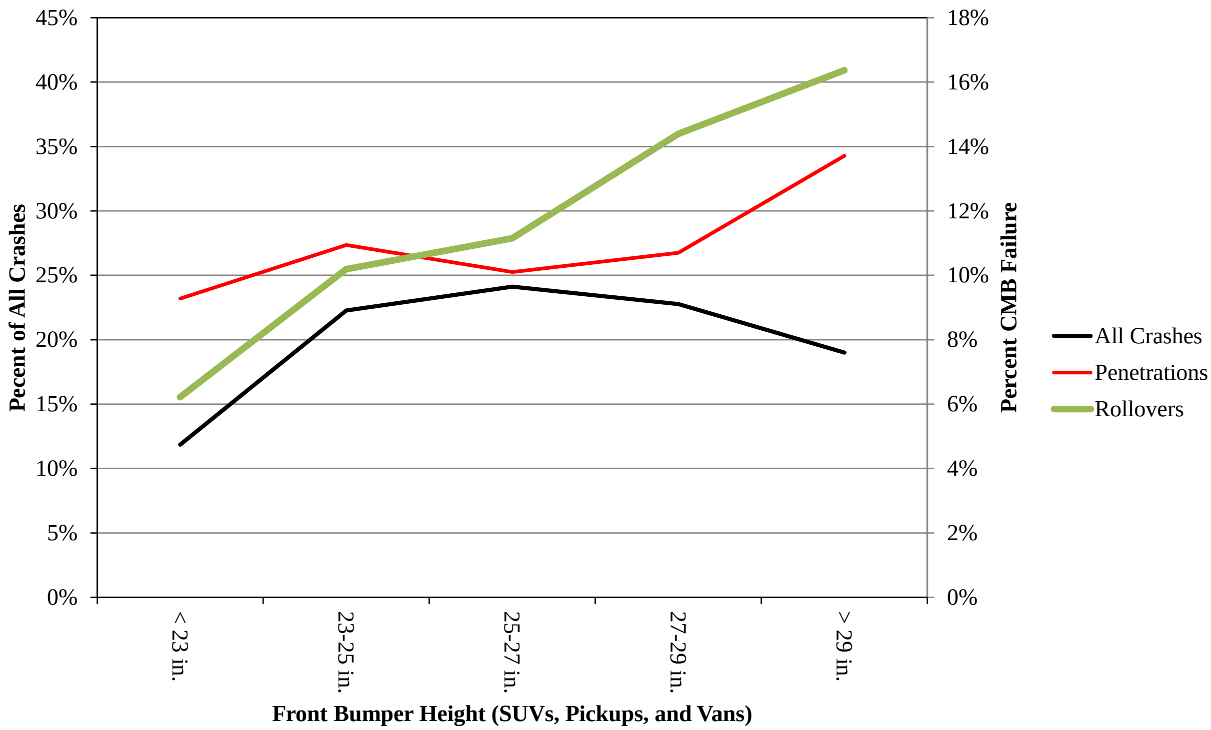


Figure 36. Crash Result by Front Bumper Height, SUVs, Pickups, and Vans

A smoothed distribution of bumper heights by vehicle class and crash result is shown in Figure 37. The distributions of bumper heights indicated significant differences between car and utility vehicle bumper heights. Differences in bumper heights between car penetrations and rollovers compared to the composite were negligible. The distribution of passenger car bumper heights strongly supports the presumption that the differences in suspension characteristics, such as stiffness and travel, were more significant than differences in bumper heights for these cars, since 85% of all passenger car bumper heights were between 19 and 23 in. (483 and 584 mm). This also further supported the conclusion that impact conditions may be more important than bumper heights for passenger car impacts in relationship to penetration frequency.

In addition to the top of the front bumper, crash results were analyzed by center-of-headlight heights, as shown in Figure 38. As before, a strong relationship between the center-of-headlight height and rollover frequency was observed. Higher center-of-headlight heights were associated with higher rates of rollover. However, this was expected because higher rollover rates were associated with pickups, vans, and SUVs, all of which had higher average center-of-headlight heights than passenger cars.

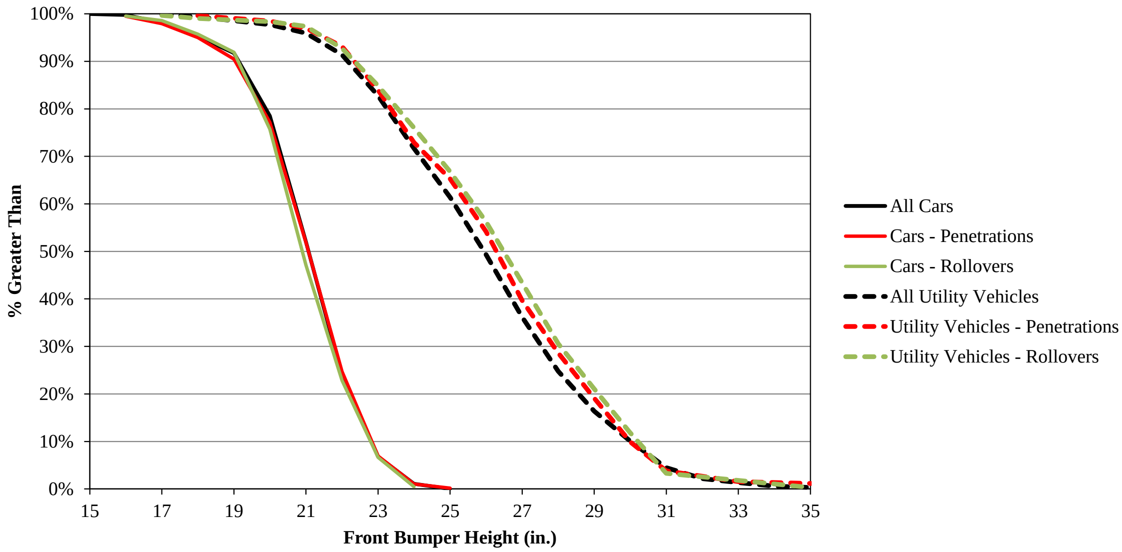


Figure 37. Smoothed Distribution of Bumper Height by Crash Result and Vehicle Type

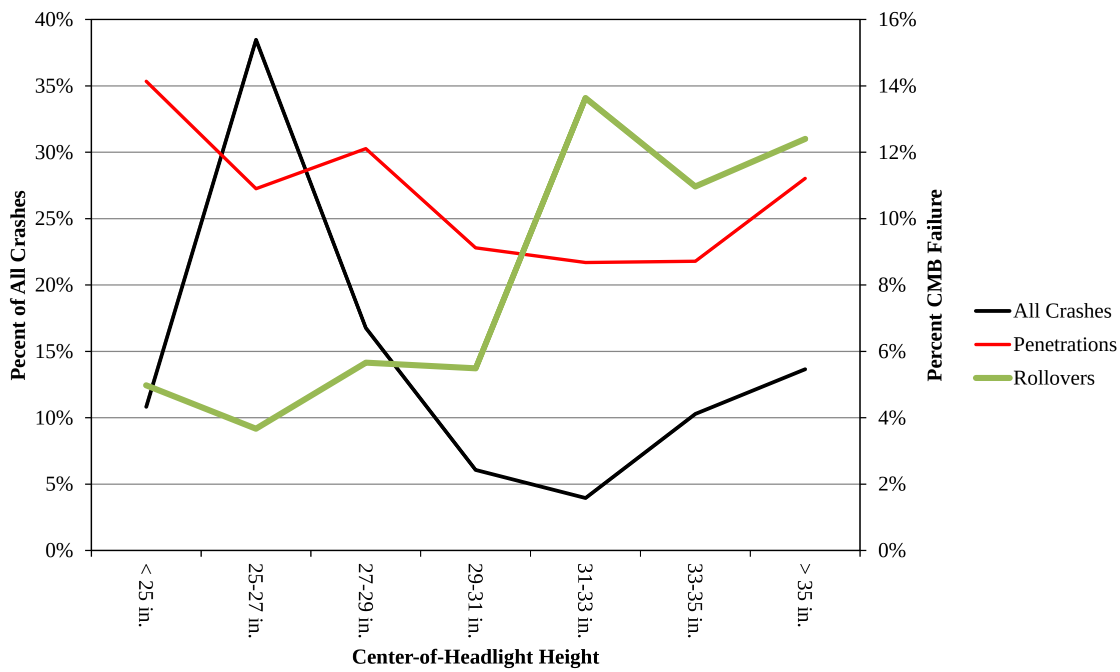


Figure 38. Crash Result by Center-of-Headlight Height

When compared by vehicle types, rates of penetration and rollover due to variations in center-of-headlight height were less significant, as shown in Figures 39 and 40. However, a generally decreasing trend in penetration rates for increasing center-of-headlight heights was observed for passenger cars, as shown in Figure 39. This was intuitive; very low front bumper height vehicles were involved in more penetration crashes than other passenger cars due to an increased propensity to underride. No significant correlations were observed with respect to SUVs, pickups, and vans.

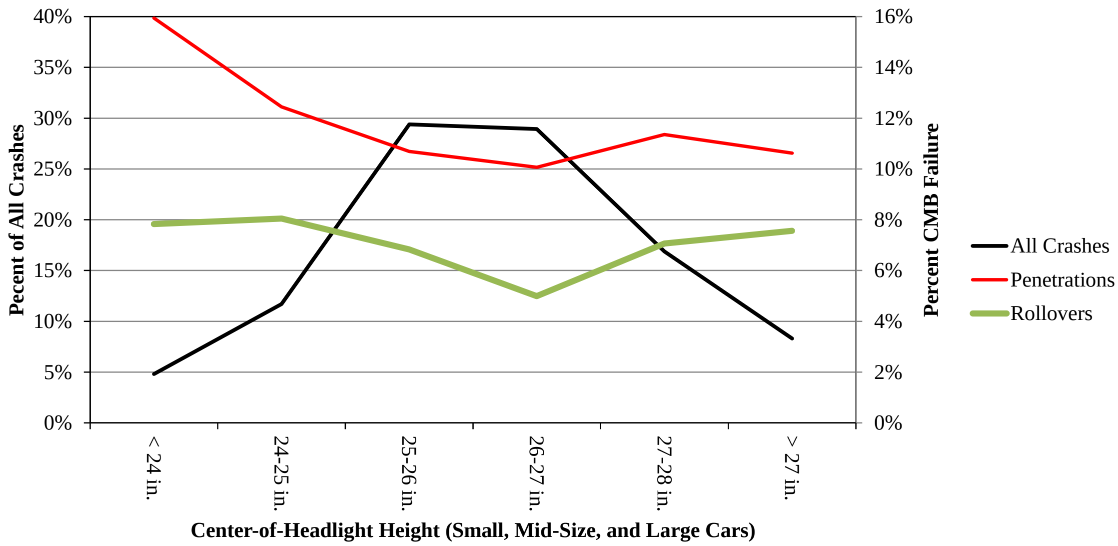


Figure 39. Crash Result by Center-of-Headlight Height, Small, Mid-Size, and Large Cars

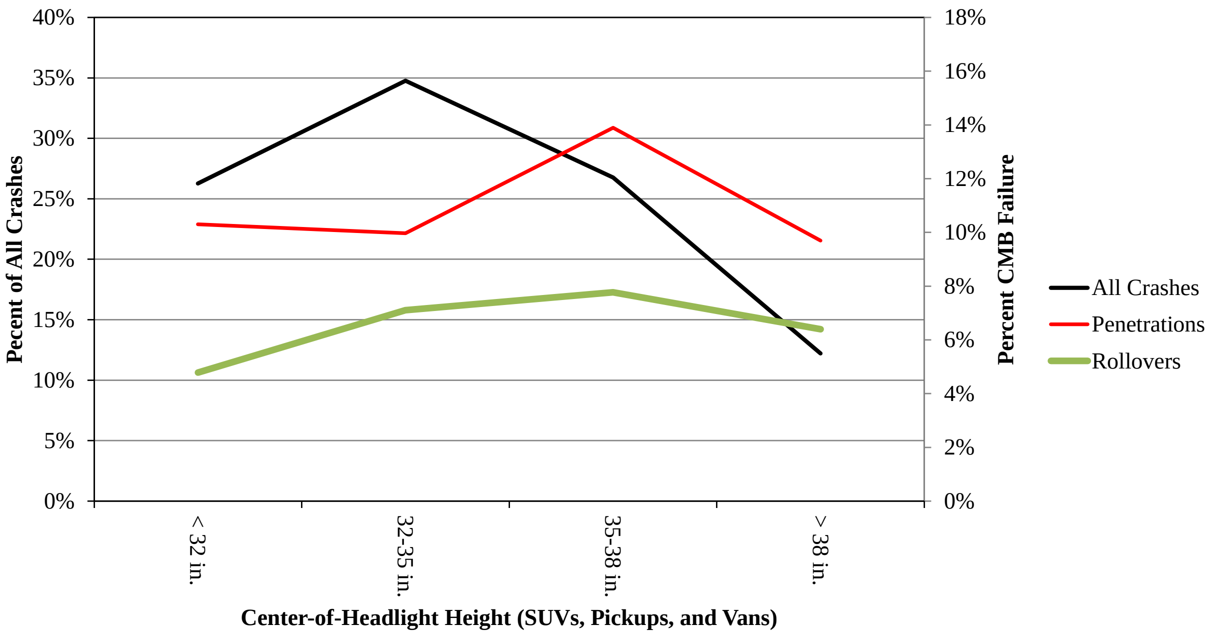


Figure 40. Crash Result by Center-of-Headlight Height, SUVs, Pickups, and Vans

The distributions of center-of-headlight heights were plotted and are shown in Figure 41. The deviation of the rollover dataset of SUVs, pickups, and vans was clearly visible. The correlation between larger center-of-headlight height and rollover frequency was clearly visible for SUVs, pickups, and vans.

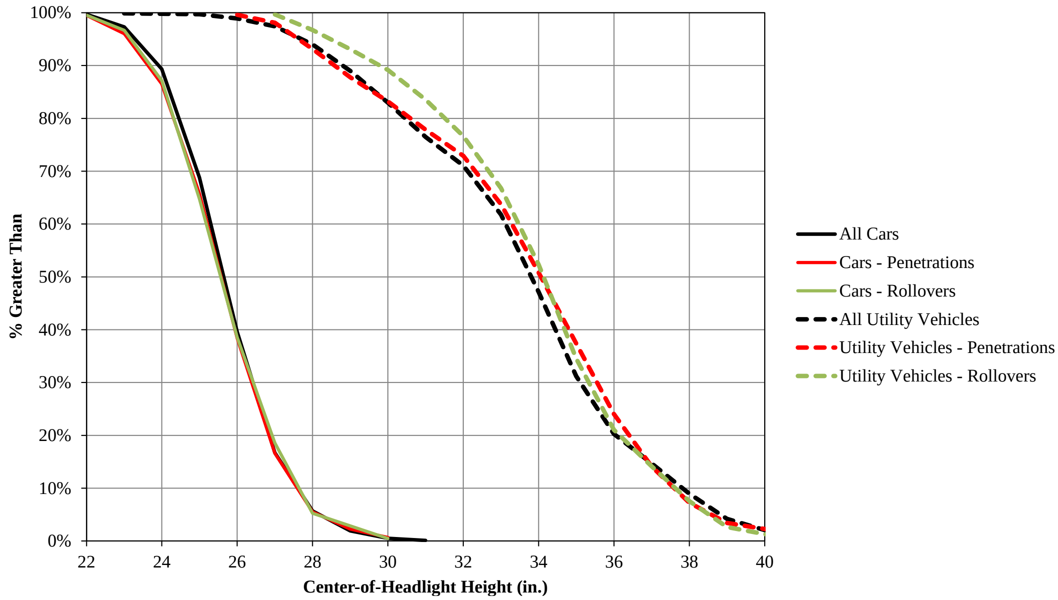


Figure 41. Smoothed Distribution of Center-of-Headlight Heights by Crash Result and Vehicle Type

The front-of-hood height was also plotted, and is shown in Figure 42. As with the bumper and center-of-headlight heights, the rollover distribution was statistically significantly different from the composite dataset. The increase in rollover rates occurred at front hood heights exceeding 33 in. (838 mm). This is significant since the top cable heights on most TL-3 high-tension and low-tension cable median barrier systems is 35 in. (889 mm) or less. The penetration rates did not appear to be strongly influenced by front-of-hood height.

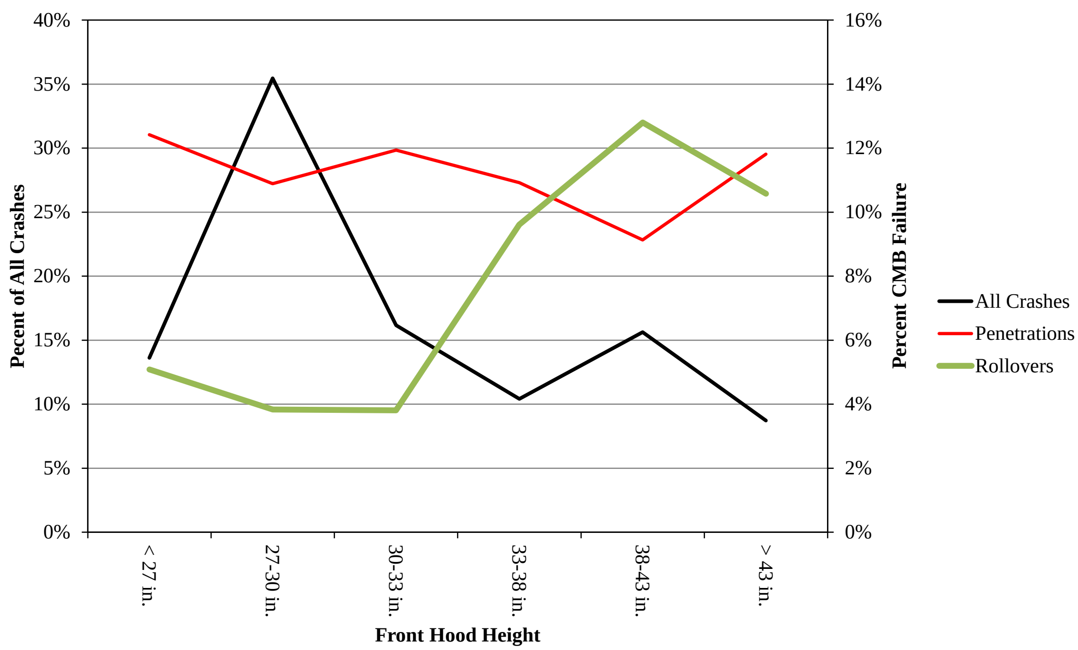


Figure 42. Crash Result by Leading Edge of Hood Height

When compared by vehicle types, results were mixed. Comparisons of crash results by vehicle type and hood heights are shown in Figures 43 and 44.The passenger car distribution of front hood heights involved in penetrations was statistically independent of the composite. Likewise, the distribution of front hood heights for SUVs, pickups, and rollovers approached statistical independence. However, the relationships were opposite. In general, cars had lower rollover rates with increasing hood heights, except for hood heights in excess of 31 in. (787 mm). By contrast, SUVs, pickups, and vans were involved in more rollovers with increasing hood height, with the exception of vehicles with hood heights greater than 44 in. (1,118 mm).

In both classes, the median front hood heights had the lowest rates of penetration. Higher rates were observed at both lower and higher hood heights. Also, the highest front hood heights for both cars and utility vehicles had the highest rates of rollover.

The smoothed distribution of front hood heights of all vehicles is shown in Figure 45. The difference between the composite and rollover datasets is clearly visible, particularly with hood heights between 30 and 40 in. (762 and 1,016 mm). A surprising trend was observed that very few rollover crashes involved vehicles with front hood heights between 30 and 35 in. (762 and 889 mm). Over 65% of all cable median barrier crashes occurred involving vehicles with front hood heights less than 32 in. (813 mm), whereas 55% of all rollovers involved vehicles with front hood heights greater than 35 in. (889 mm). The distribution of front hood height by crash result and vehicle group were virtually indistinguishable for both vehicle groups, and was not shown.

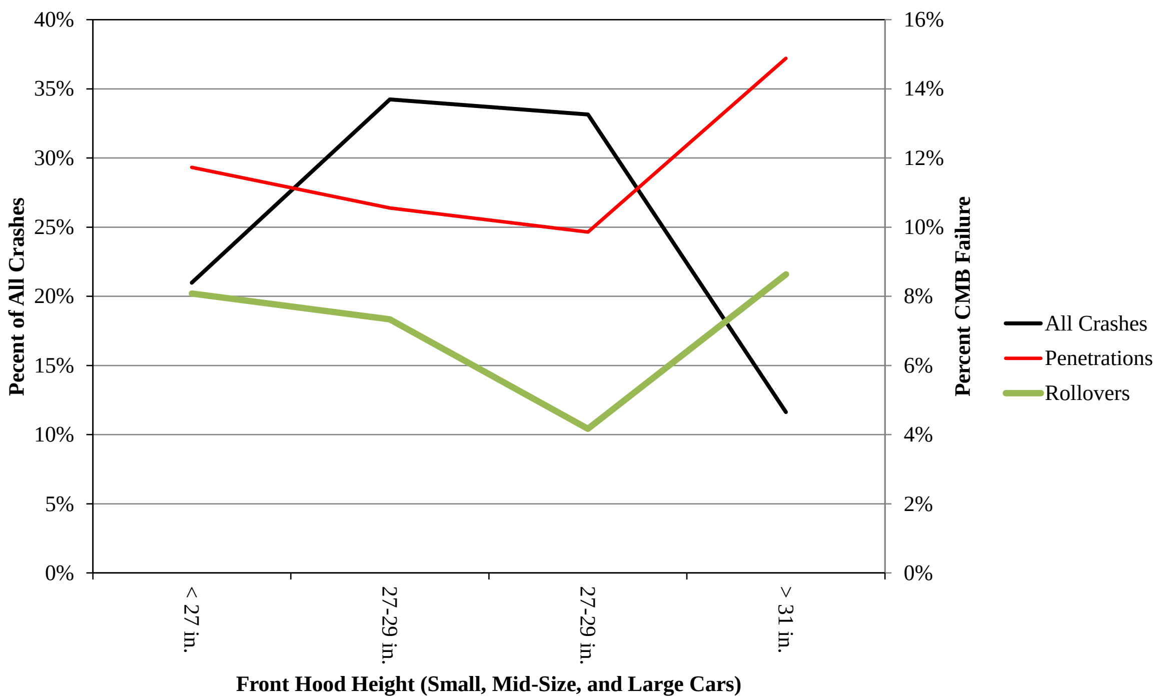


Figure 43. Crash Result by Front Hood Height, Small, Mid-Size, and Large Cars

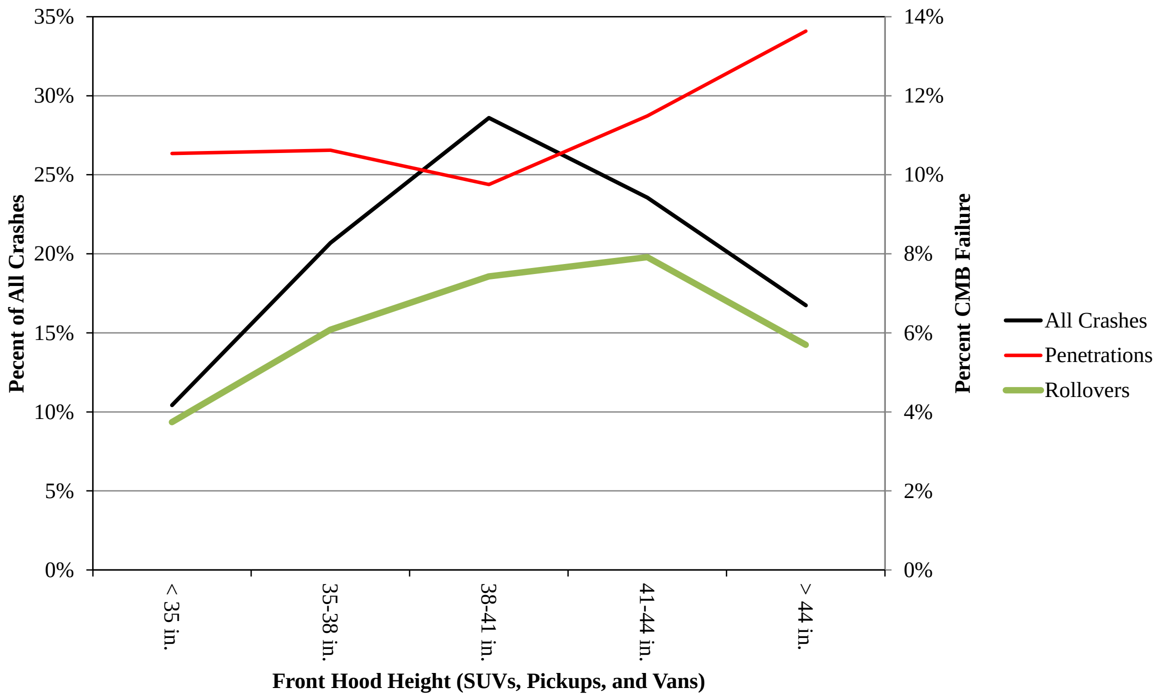


Figure 44. Crash Result by Front Hood Height, SUVs, Pickups, and Vans

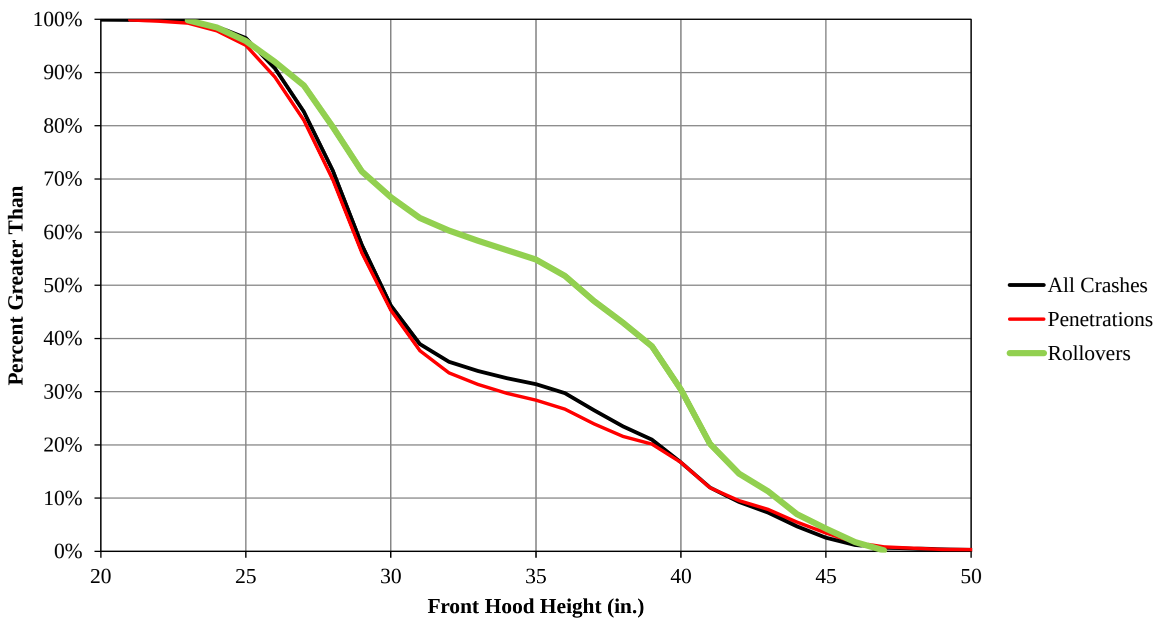


Figure 45. Distribution of Front Hood Heights in CMB Crashes

The top of bumper to front of hood height separation distances were plotted against crash result, but results were not statistically significant when plotted by vehicle grouping. Although statistical significance was observed with respect to the rollover database when all vehicle types were plotted together, the differences were strongly related to the types of vehicle involved in rollover crashes, and were not caused by the bumper-to-hood separation distance. Furthermore, statistical tests evaluating bumper-to-hood separation distances of passenger cars indicated a very strong statistical similarity between bumper-to-hood separation distances in rollovers and all crashes; stated differently, the two distributions were virtually indistinguishable. If there is a relationship between bumper-to-hood separation distance and penetration rates for passenger cars or utility vehicles, it was not obvious in the available database of 3,804 crashes with known vehicle types and crash outcomes, as shown in Figure 46.

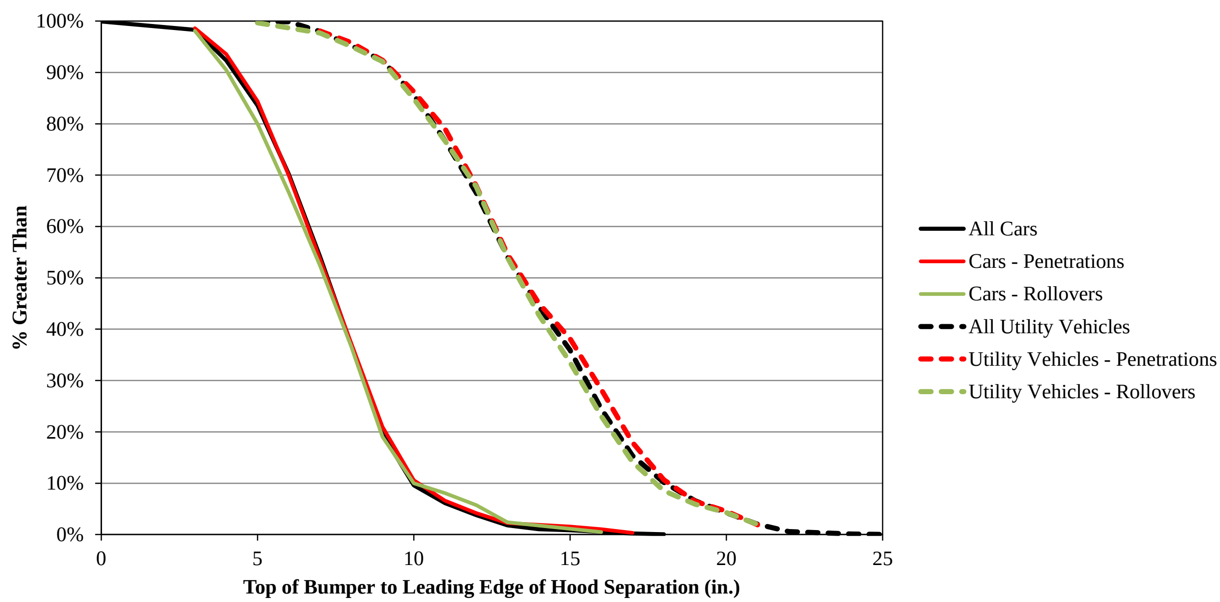


Figure 46. Smoothed Distribution of Separation Between Leading Edge of Hood and Top of Bumper by Crash Result and Vehicle Type

Rear bumper heights were compared to the composite and plotted, as shown in Figure 47. The penetration frequencies peaked between 24 and 28 in. (610 and 711 mm), and was reduced at both lower and higher rear bumper heights. Rollovers reached a minimum between 22 and 24 in. (559 and 610 mm) rear bumper height. Both distributions were statistically independent of the composite distribution.

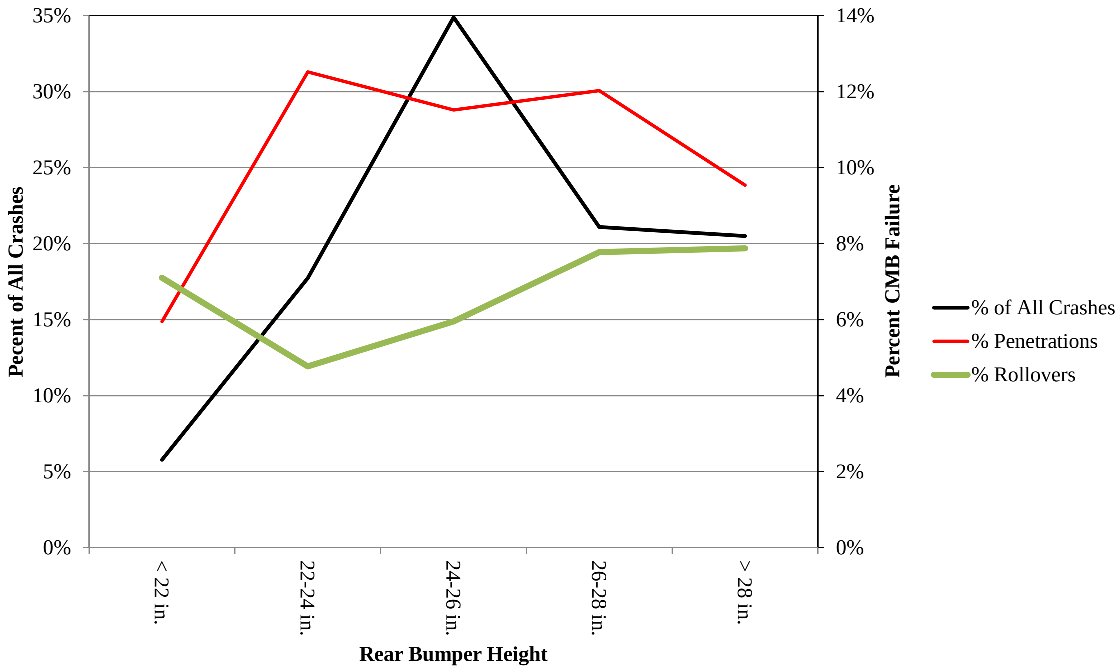


Figure 47. Crash Results by Rear Bumper Height

Rear bumper heights were plotted by crash result and vehicle class, and are shown in Figures 48 and 49. Although results were not statistically independent for either rollover or penetration crashes for either dataset, the penetration dataset for passenger cars approached statistical independence from the composite distribution. The penetration rates varied significantly between bumper heights of 25 and 27 in. (635 and 686 mm). However, penetration rates for rear-leading impacts, which were not distinguished in this data analysis, were higher for both lower and higher bumper heights. Although evidence of this claim is currently limited to anecdotal observations, further evidence is being explored.

Top-of-trunk heights were related to both penetration and rollover rates. The top-of-trunk height plots for all vehicles are shown in Figure 50. Penetration rates generally declined with increasing rear trunk heights. This was intuitive: higher rear trunk heights were associated with greater vertical capture area and higher energetic requirements to underride the barrier, particularly in rear-leading impacts. As the trunk or hatch height increased, underride penetrations were virtually eliminated, which decreased the overall penetration rate. However, a competing effect due to increased CG and bumper heights tended to increase the rate of override for higher trunk or hatch heights as well, though this effect was less pronounced.

In addition, rollover rates increased with increasing trunk or hatch height, but this was expected based on vehicle dimensions of the typical vehicles involved in rollover crashes. Trunk or hatch heights were determined to not be causatively linked to rollover frequency.

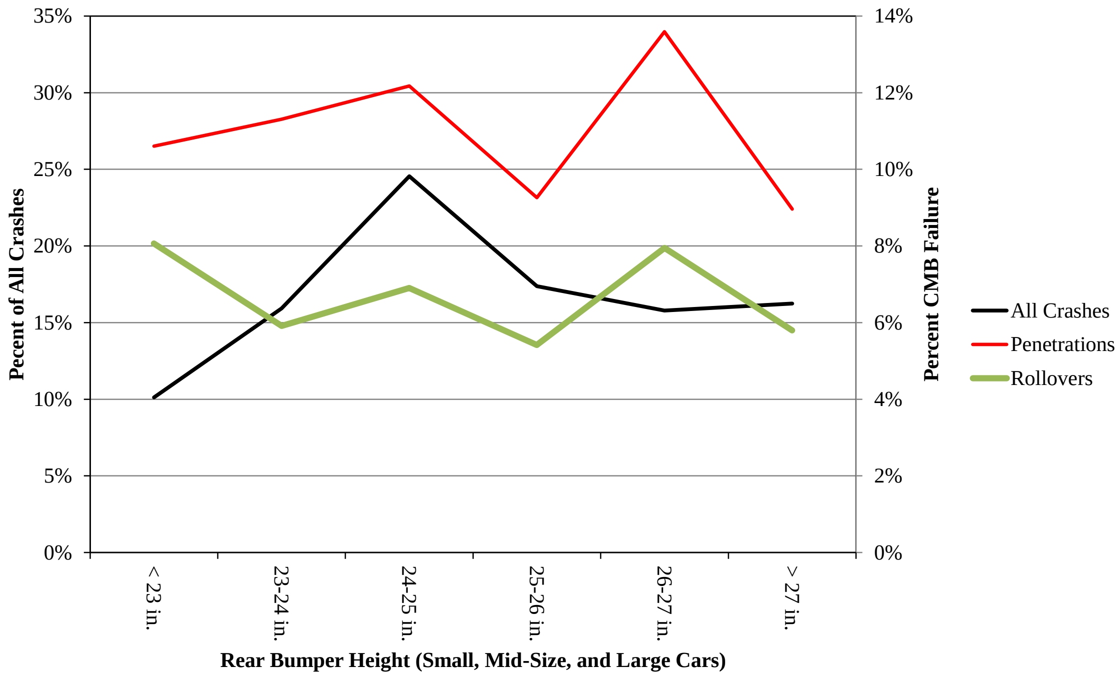


Figure 48. Crash Result by Rear Bumper Height, Small, Mid-Size, and Large Cars

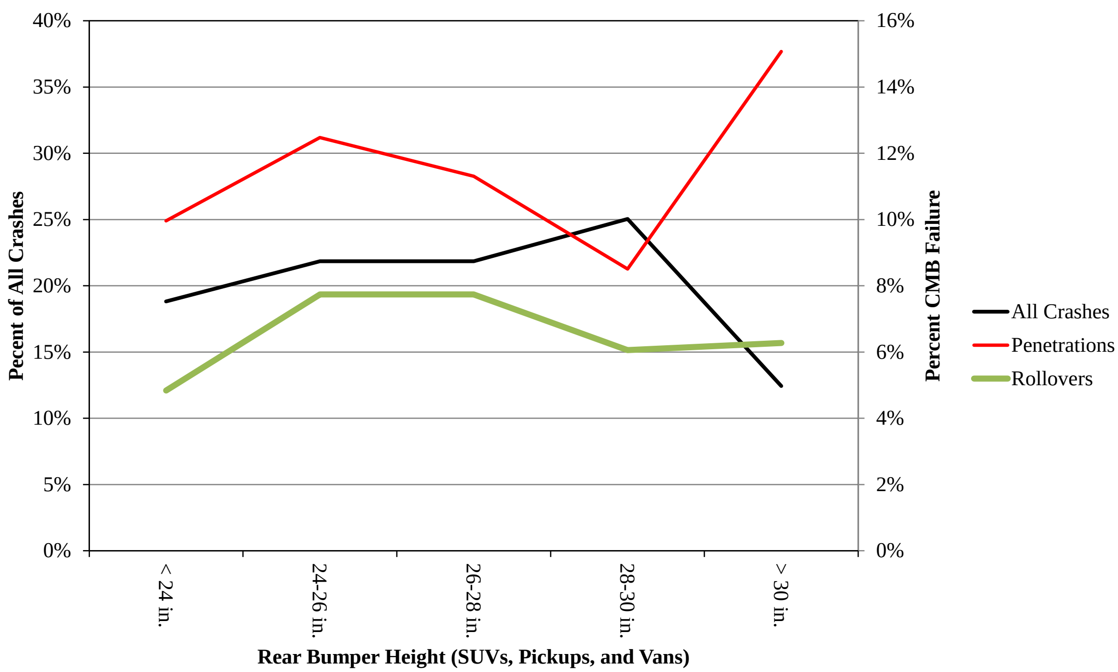


Figure 49. Crash Result by Rear Bumper Height, SUVs, Vans, and Pickups

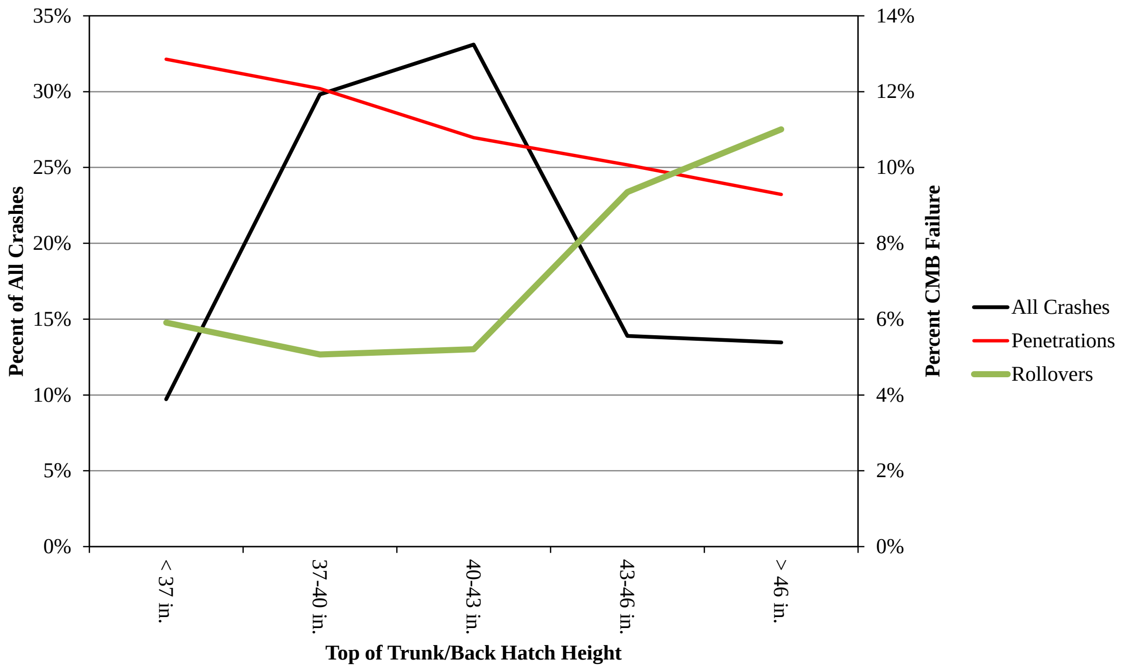


Figure 50. Crash Result by Top of Trunk/Rear Hatch Height

A smoothed distribution of trunk and hatch heights based on crash results and vehicle groups is shown in Figure 51. The distributions were each virtually identical to the composite for each respective vehicle group.

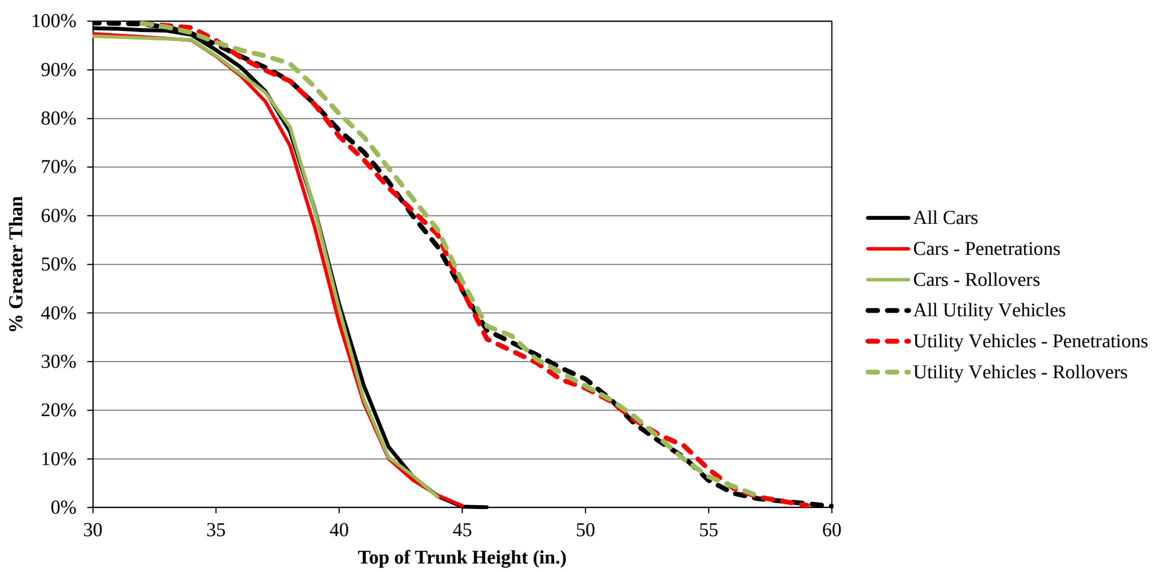


Figure 51. Smoothed Distribution of Top of Trunk/Rear Hatch Heights

7.3.4 Center-of-Gravity Location

The position of the CG was a critical factor in the selection of crash testing vehicles for standardized testing according to NCHRP Report No. 350 and MASH [31, 24]. A comparison of CG heights by crash results was plotted and is shown in Figure 52. The rollover rate was intuitively related to CG height. Higher CG heights were generally associated with higher rollover rates. One unexpected relationship was that penetrations generally decreased with increasing CG height, through 28 in. (711 mm), then increased thereafter for passenger cars and utility vehicles.

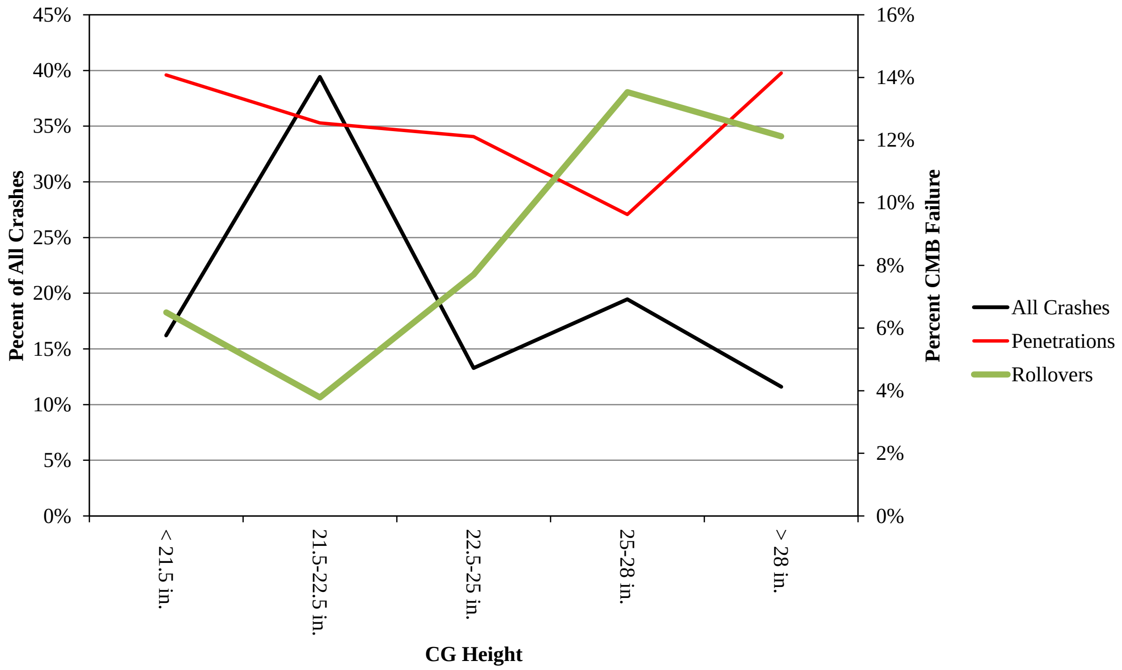


Figure 52. Crash Result by CG Heights

CG height distributions based on crash result and vehicle type indicated strong correlations between penetration and rollover rates based on vehicle CG. Plots of CG heights for passenger cars and SUVs, pickups, and vans are shown in Figures 53 and 54.

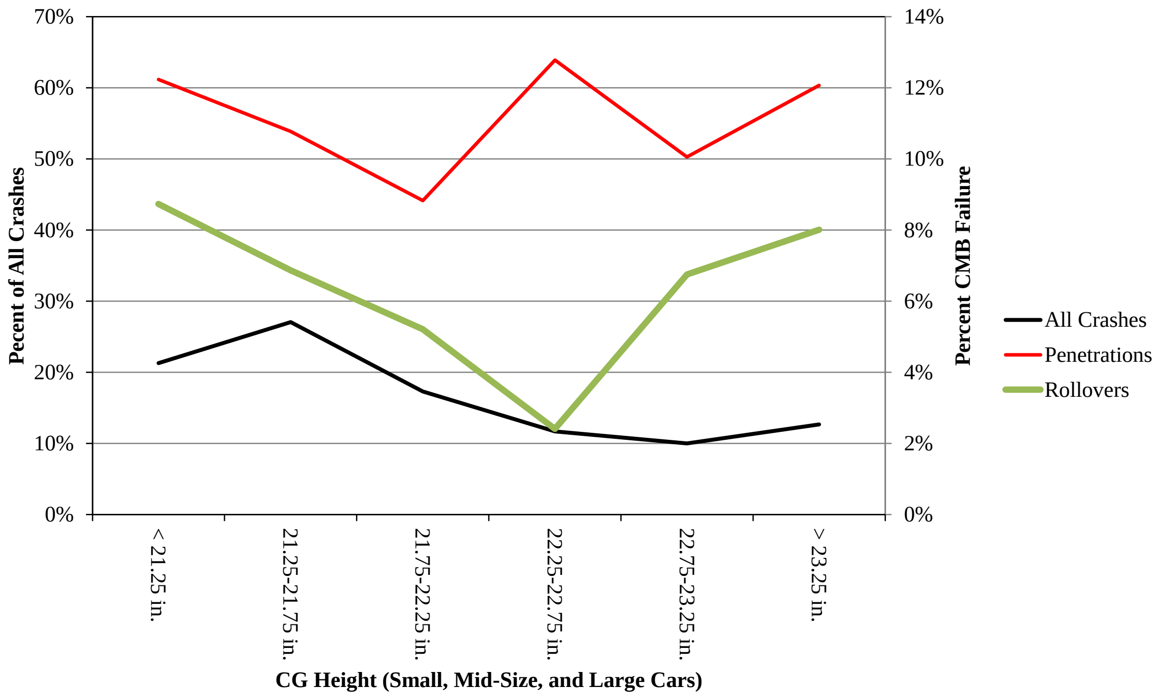


Figure 53. Crash Result by CG Height, Small, Mid-Size, and Large Cars

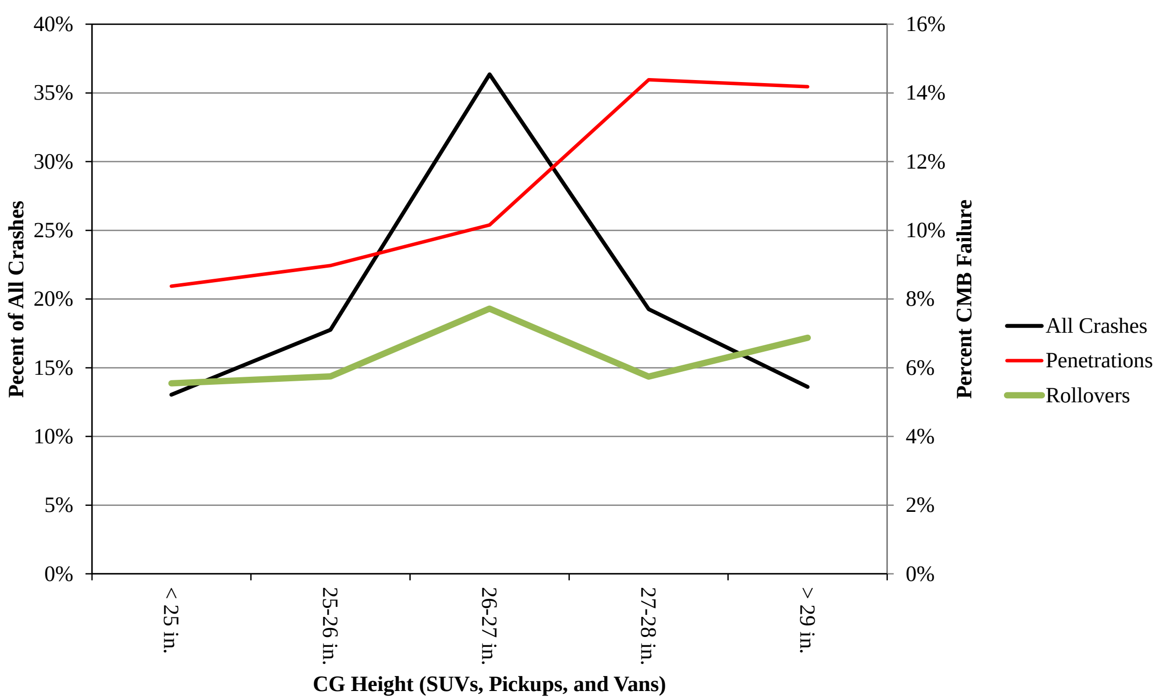


Figure 54. Crash Result by CG Height, SUVs, Pickups, and Vans

CG heights were not strongly correlated with rollover rates for SUVs, pickups, and vans. This result suggested that these types of vehicles were susceptible to rollover independent of the CG heights. However, penetration rates were strongly correlated with CG heights, as penetration rates increased with increasing CG height.

Passenger cars had a mixed rate of penetrations with CG height, with a maximum between 22.25 and 22.5 in. (565 and 572 mm). The minimum occurred between 21.75 and 22.25 in. (552 and 565 mm). Rollover rates demonstrated a much more linear relationship, generally declining with increasing CG height through 23 in. (584 mm). Results of all these factors were on the bounds of statistical significance, but the small differences between the passenger car CG height distribution would be erased if a vehicle entered a sloped median and struck the cable median barrier at any height other than nominal level. Thus, although CG height had an effect, particularly on stability, overall CG height did not have a causative relationship in cable median barrier containment performance within the indicated vehicle groupings.

Surprisingly, no passenger cars and only two SUVs in the entire database of 3,806 vehicles had recorded CG heights between 22.5 in. (572 mm) and 22.75 in. (578 mm). Between 22.25 in. (565 mm) and 22.5 in. (572 mm) a total of 282 vehicle crashes were recorded, and between 22.75 in. (578 mm) and 23.0 in. (584 mm), a total of 201 crashes were recorded. There were no obvious explanations for the apparent gap in vehicles with CG heights between 22.5 and 22.75 in. (572 and 578 mm).

The smoothed distribution of CG heights in cable barrier crashes is shown in Figure 55. Over 60% of all crashes occurred with CG heights less than 23 in. (584 mm), but approximately 9% of crashes and penetrations occurred with CG heights between 23 and 26 in. (584 and 660 mm). The 85^{th} percentile CG heights for the composite, penetration, and rollover data sets were 21.6, 20.7, and 25.8 in. (548, 525, and 654 mm), respectively.

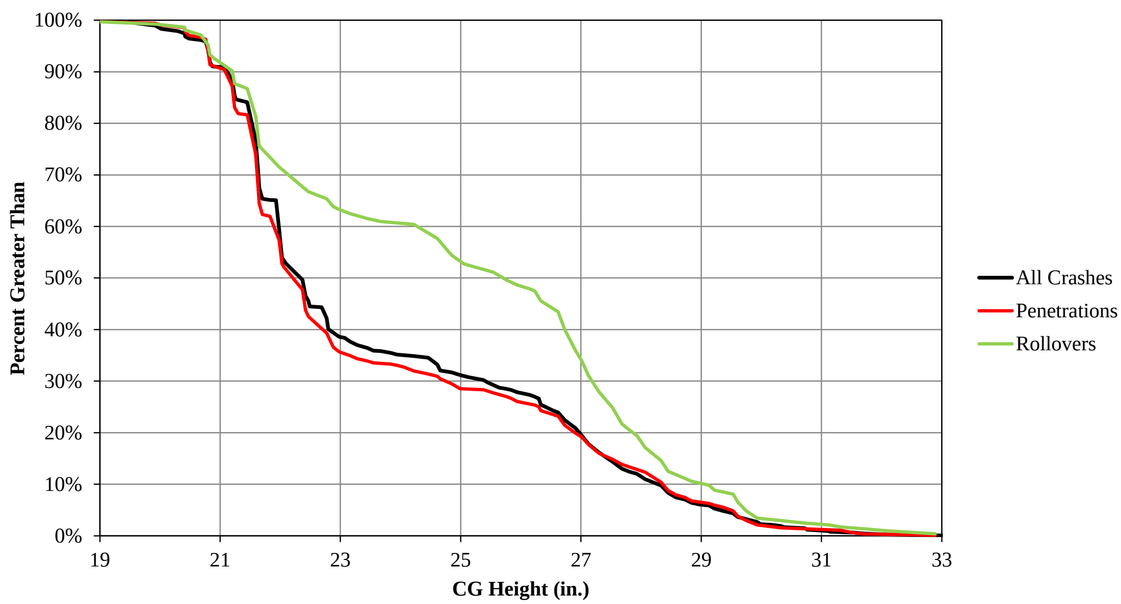


Figure 55. Smoothed Distribution of CG Heights in Cable Barrier Crashes

A comparison of the longitudinal CG location relative to the front axle was plotted and is shown in Figure 56. Penetration rates were relatively independent of the longitudinal distance between the CG and the front axle, but rollover rates tended to increase as the CG distance from the front axle increased. Historical tests with cable median barriers has indicated a higher proportion of large yaw displacements using rear engine mount cars with CGs located far from the front axle [32, 33]. The yaw displacement following redirection may contribute to vehicle instability.

The distribution of longitudinal CG locations is shown in Figure 57. The distribution of longitudinal CG location suggested that both penetration and rollover crashes tended to occur more frequently with vehicles with CGs located further from the front axle, but closely mimicked the distribution of all crashes for longitudinal distances less than 40 in. (1,016 mm). The 85th percentile longitudinal CG locations for the composite, penetration, and rollover databases were 51.7 in., 52.5 in., and 54.5 in. (1,313 mm, 1,333 mm, and 1,384 mm), respectively.

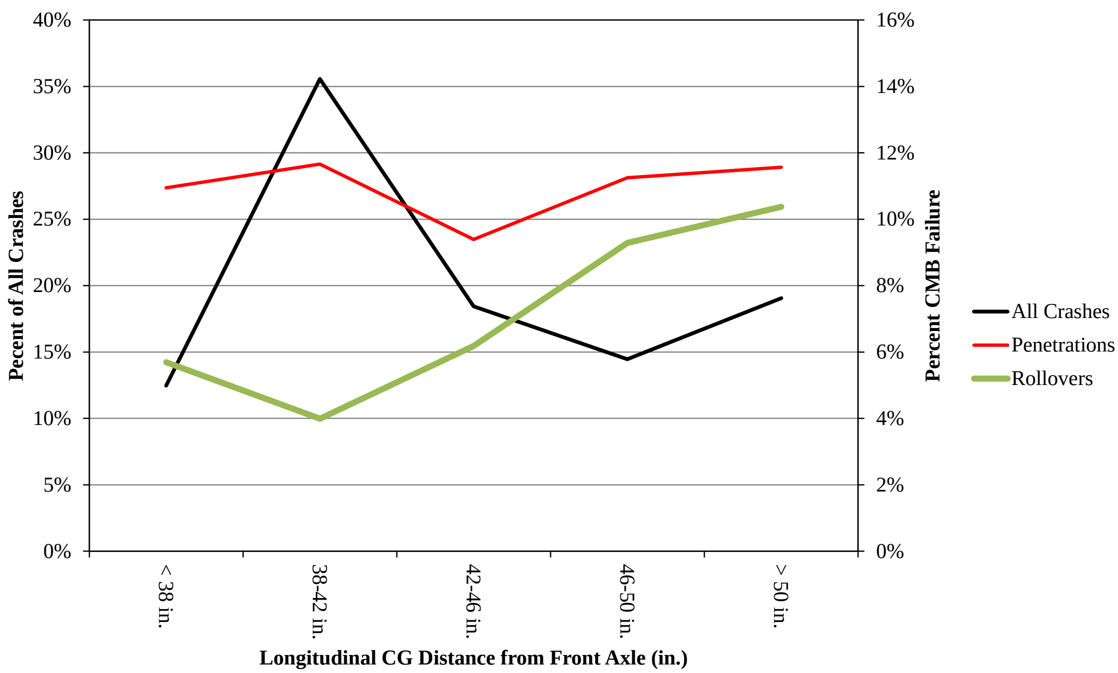


Figure 56. Longitudinal CG Distance from Front Axle by Crash Result

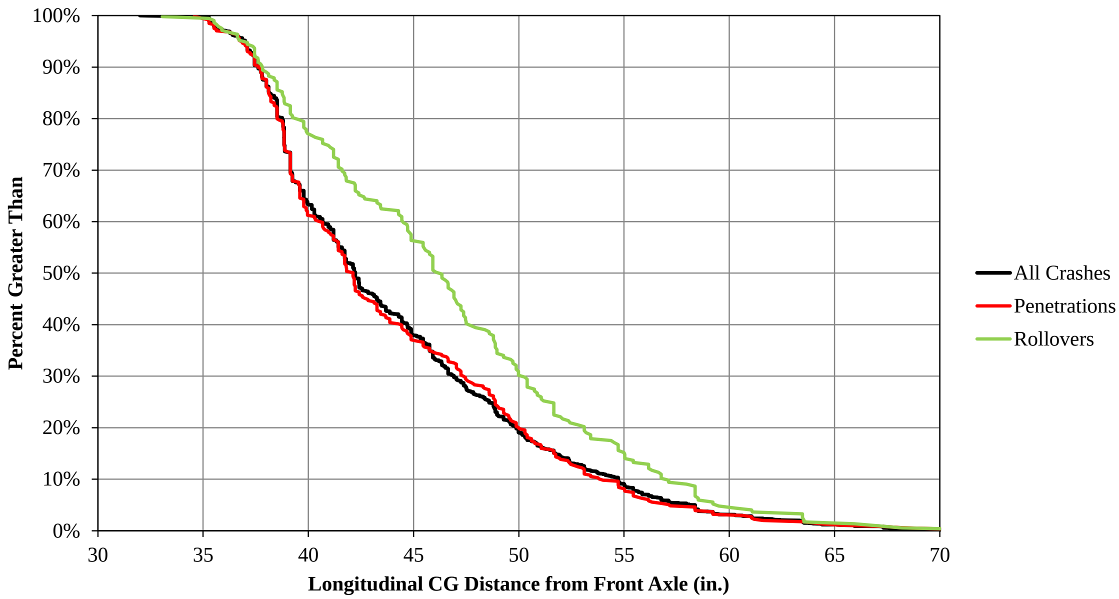


Figure 57. Distribution of Longitudinal CG Location Relative to Front Axle

The static stability factor (SSF) [34], which is calculated using the formula

$$SSF = \frac{Track\ Width}{2(CG\ Height)} \tag{1}$$

was used to segregate crash outcomes. Results are plotted in Figure 58. The SSF is a statistical measure of the likelihood of rollover, based on the slope angle that would cause a static vehicle to tip over. SSF star ratings and the probability function ranges of estimated rollover rates is shown in Table 27.

Table 27. NHTSA SSF Star Ratings and Probability Function Values [34]

NHTSA Star Rating	SSF Range	Rollover Probability Function Value Range
★	< 1.04	> 0.40
★★	1.04-1.12	0.30-0.40
★★★	1.12-1.24	0.20-0.30
★★★★	1.24-1.45	0.10-0.20
★★★★★	> 1.45	< 0.10

Although end effects were present at the 1- and 5-star ratings since less than 100 crashes involved either 1-star or 5-star rated vehicles, generally rollovers decreased with higher SSF ranking. These results are not surprising, but reinforce what is known about rollover stability with relation to CG position and track width.

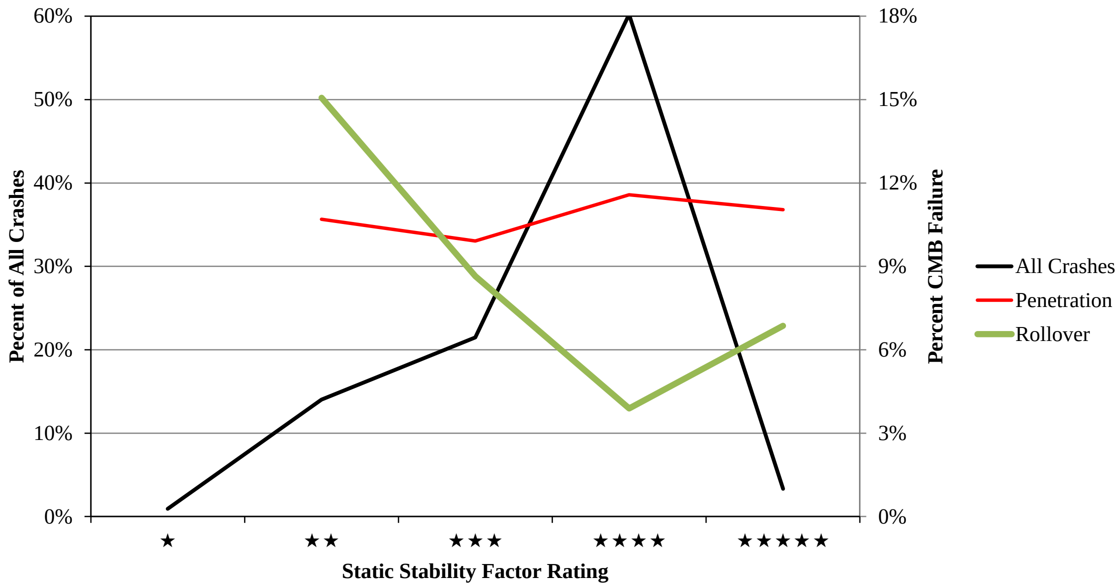


Figure 58. Crash Result Based on Track Width and CG Height (SSF)

Whereas a very strong relationship between rollover and SSF was observed with respect to all vehicles, when the data was segregated into subsets by vehicle types, variations were not as distinctive. However, it is worth noting that very few SUVs, pickups, or vans were rated with four-star SSF rating, whereas very few passenger cars had a three-star SSF rating or less. Distributions were statistically independent at the 5% confidence level but functionally distributions were not unique. Penetrations and rollovers were both more common with lower SSF values for SUVs, pickups, and vans, but were more common at higher SSF values for much of the passenger car distribution.

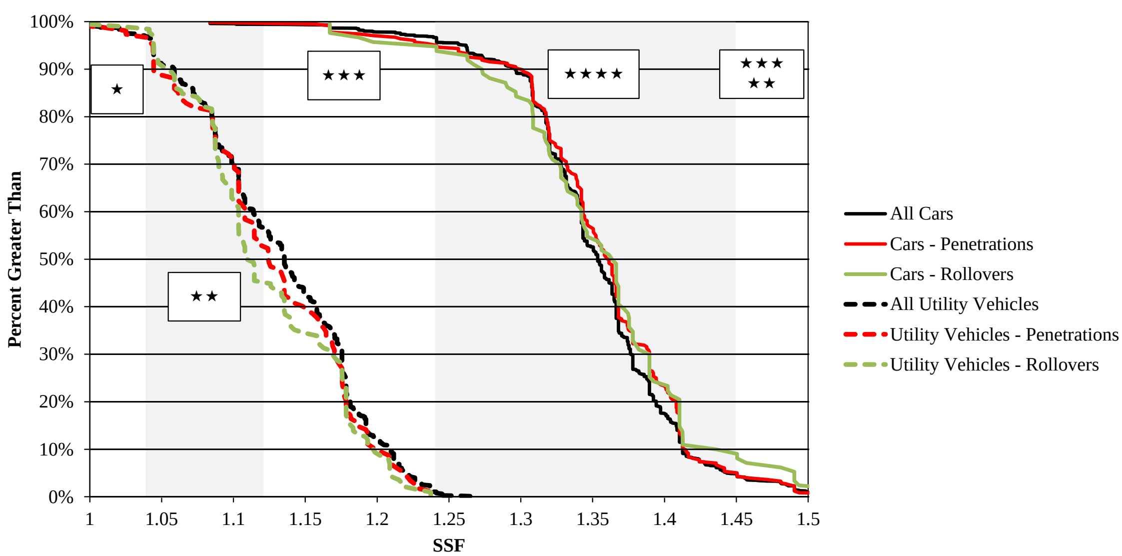


Figure 59. Distribution of Crash Result by SSF and Vehicle Type

7.3.5 Vehicle Cornering and Inertia

Crash results by minimum turning circle diameters were also plotted and evaluated. The plot is shown in Figure 51. The minimum turning circle is a measure of the maximum steering angle and reaction of the wheels and suspension to driver steering input. As a result, it was expected that smaller turning circles, corresponding to higher cornering rates and larger maximum steering angles, would be associated with more rollovers and penetrations due to a more rapid increase in CG trajectory angle.

In general, larger turning circles corresponded to higher rates of rollover. This was because SUVs, pickups, and vans had larger turning circle diameters than cars, on average. When distributions were plotted by vehicle type and crash results, the penetration and rollover rates were not clearly related to turning circle diameter, as shown in Figure 61. A large portion of car penetrations occurred with turning circle diameters between 38 and 45 in. (96 and 1,143 mm). This class of passenger car corresponded to sports-type cars, such as the Chevrolet Camaro, Dodge Charger, Pontiac Firebird/Trans Am, and Dodge Viper, in addition to imported sports cars.

Figure 60. Crash Result by Turning Circle Diameter

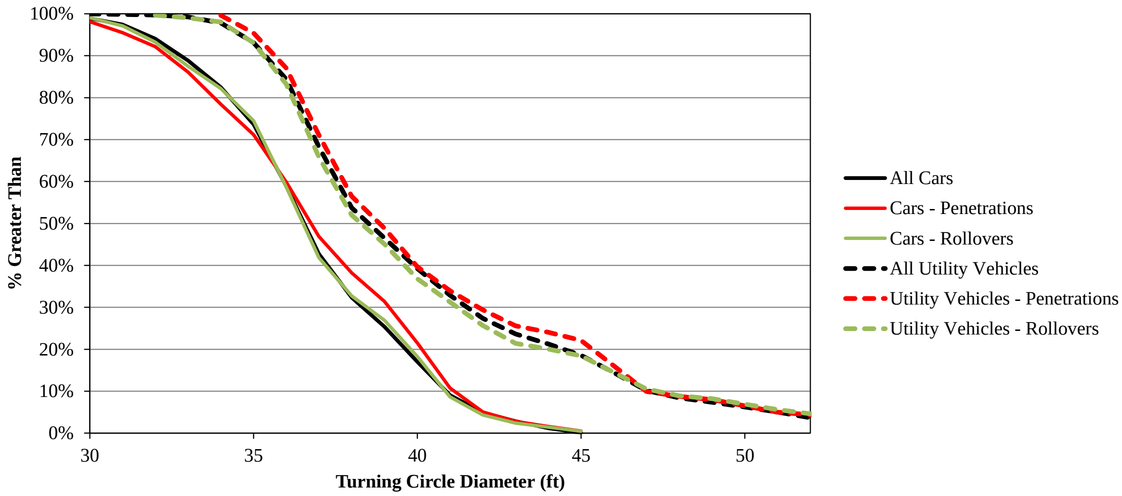


Figure 61. Smoothed Distribution of Turning Circle Diameter by Crash Result and Vehicle Type

The distribution of roll moments of inertia of vehicles involved in cable median barrier crashes is shown in Figure 62. For both passenger car and utility vehicles, penetrations occurred at larger roll moments of inertia than the composite distribution. However, rollover rates were mixed. For utility vehicles, higher roll moments corresponded to higher rollover rates for roll moments of inertia less than 600 lb-ft-s^2 (248 kg-m^2), but for larger roll moments of inertia the rollover distribution matched the composite. Alternatively, for the passenger car rollover distribution, rollovers generally occurred with lower roll moments of inertia. The passenger car distribution matched the intuitive expectation that lower roll moments of inertia were associated with higher rates of rollover. Penetrations were more common at higher roll moments of inertia for both vehicle types.

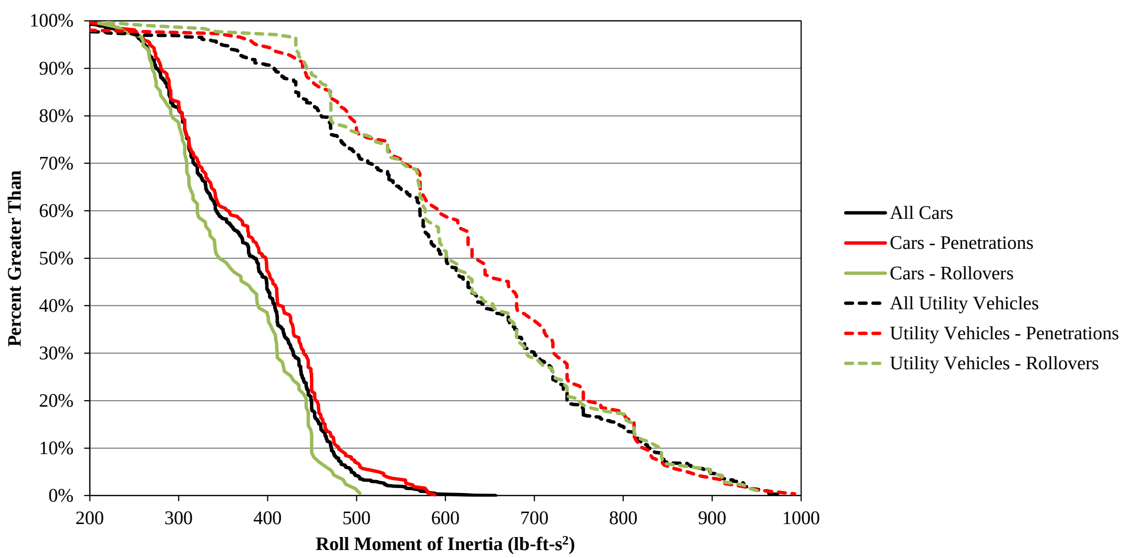


Figure 62. Distribution of Roll Moments of Inertia by Crash Result and Vehicle Type

Roll moments of inertia were non-dimensionalized by dividing by the mass and CG height squared. Results are plotted in Figure 63. By non-dimensionalizing the rollover distribution of SUVs, pickups, and vans, the rollover distribution was altered from approaching statistical independence to bordering statistical similarity, with a p-value of 0.83. None of the other distributions had statistically significant differences to the composite.

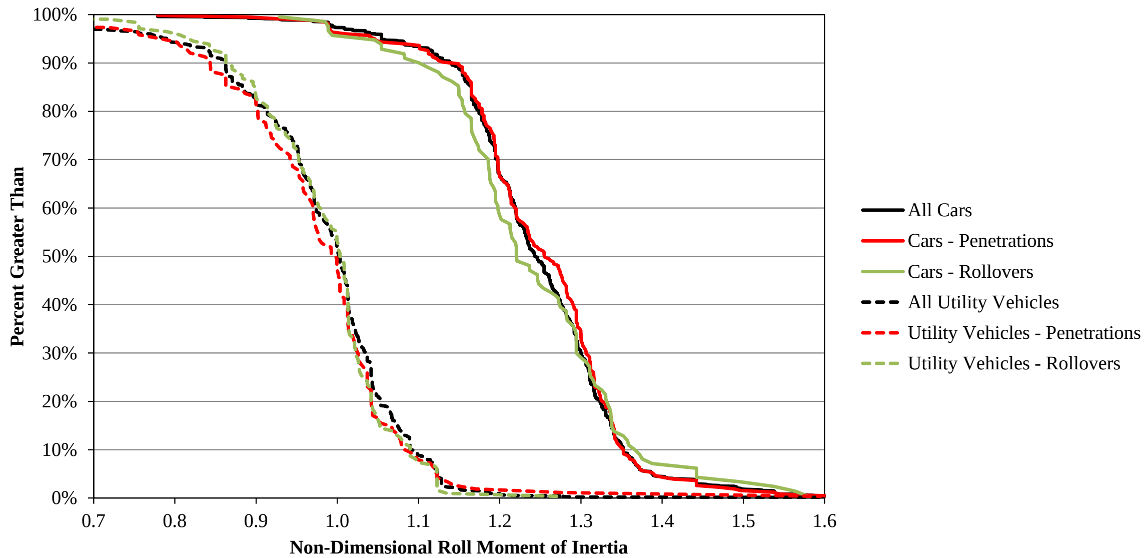


Figure 63. Distribution of Non-Dimensionalized Roll Moments of Inertia by Crash Result and Vehicle Type

Likewise, the distribution of the yaw moments of inertia of vehicles involved in cable barrier crashes is shown in Figure 64. As with roll moments of inertia, higher yaw moments of inertia were associated with higher rates of penetration. Higher yaw moments of inertia were correlated with higher rollover frequency for SUVs, pickups, and vans through 2,500 lb-ft-s^2 (1,033 kg-m^2), but converged to the composite distribution at higher yaw moments of inertia, similarly to the roll moments-of-inertia distribution. Additionally, lower yaw moments of inertia were associated with higher rollover rates for passenger cars.

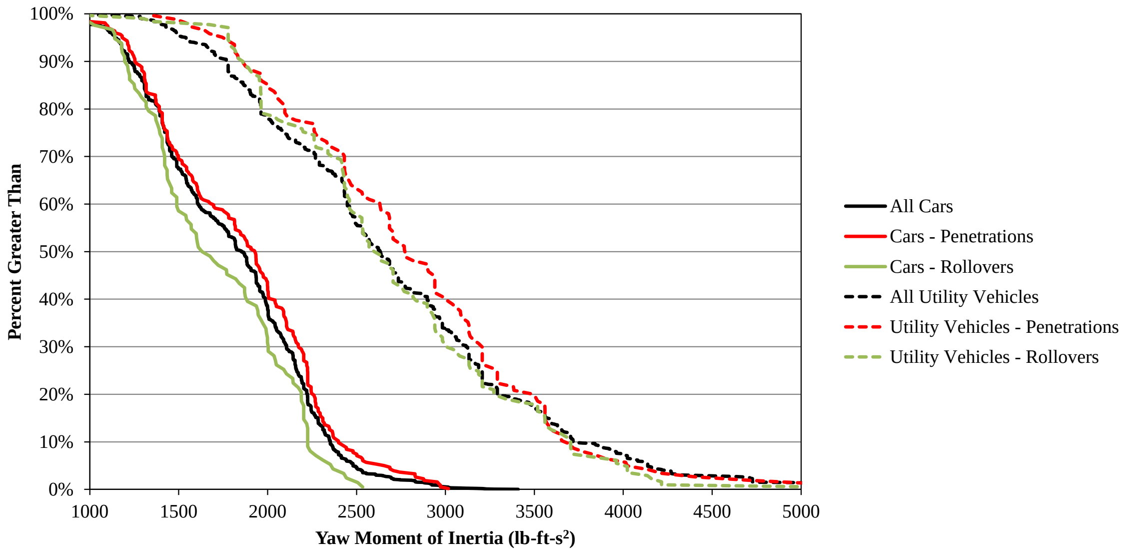


Figure 64. Distribution of Yaw Moments of Inertia by Crash Result and Vehicle Type

7.3.6 Conclusions

The vehicle dimension and performance analysis suggested that there is no “silver bullet” vehicle profile or set of dimensions which can functionally explain all of the penetration or rollover occurrences. Vehicles such as SUVs are involved in a disproportionately large number of rollover crashes resulting from vehicle instability. However, the high rate of rollovers was not indicative of a high rate of penetrations. Furthermore, pickup trucks had the *lowest* overall rate of penetrations, which may be related to years of cable median barrier full-scale testing with pickup trucks. Vehicles not commonly used in cable median barrier testing, including large cars, SUVs, and vans were involved in more penetrations than pickup trucks. Furthermore, vans were also involved in more rollovers and severe crashes than pickup trucks in general.

It may be necessary to adjust the vehicles used in crash testing to be more reflective of the actual fleet involved in penetration or rollover crashes. The historical perspective on vehicle selection can be improved using these results, because vehicle types and selection can be catered directly to those vehicles which were involved in containment failures or severe crashes.

7.4 Vehicle Make and Model Analysis

A summary of the vehicles most commonly involved in penetration and rollover crashes with cable median barriers is shown in Tables 28 and 29. Recall that both penetration and rollover rates for all vehicle types were scaled down to reflect calculated national overall penetration and rollover rates. Vehicles included in Tables 28 and 29 were in a minimum of 10% penetration or rollover crashes, respectively, and were typically involved in at least 15 crashes. Vehicles with the highest rates of penetration were the 1996-2007 Ford Taurus, which spanned two generations of the Taurus model, as well as the Subaru Impreza, Ford F250 and F350, and Chrysler PT Cruiser.

Vehicles involved in penetrations were largely either high-CG, stiff-body panel vehicles or large cars with narrow, sharp front profiles. Likewise, rollovers were most frequent with high-CG SUVs, pickups, and vans. However, in addition to notably high crash rates it is also constructive to consider vehicles which were involved in relatively few rollover or penetration crashes. A tabulated list of vehicles with relatively low risk of penetration or rollover are shown in Tables 30 and 31.

There has been a trend in recent years away from sharply-contoured front end profiles. Many of the vehicles involved in high penetration crash frequencies are no longer in production. This is an unfortunate consequence of having datasets which extend more than 10 years from the present. However, Subaru Imprezas and Chrysler PT Cruisers, for example, are relatively common, have models readily available, and had penetration rates above 20%.

Table 28. Vehicles Involved in Penetration Crashes at High Frequencies

PENETRATIONS					
Vehicle	Crashes	Penetrations	Rollovers	Scaled Penetration Rate	Scaled Rollover Rate
Honda Civic	130	18	5	12%	3%
Honda Accord	118	15	4	11%	3%
Ford Explorer	81	11	20	12%	21%
Ford Taurus (1996-2007)	48	10	6	18%	10%
Saturn SL/SL1/SL2	41	5	3	11%	6%
Nissan Sentra	40	8	2	17%	4%
Chevrolet Blazer	37	7	9	16%	20%
Pontiac Grand Am	37	5	2	12%	5%
Ford Escort	33	5	2	13%	5%
Volkswagen Jetta	33	5	0	13%	0%
Pontiac Grand Prix	33	4	1	11%	3%
Chevrolet Trailblazer	28	4	3	12%	9%
Toyota 4 Runner	25	5	6	17%	20%
Ford F250	24	6	5	22%	17%
Acura Integra	24	6	0	22%	0%
Chevrolet Impala	23	5	1	19%	4%
Chrysler Sebring	23	4	0	15%	0%
Dodge Durango	21	4	2	17%	8%
Jeep Liberty	21	3	3	12%	12%
Dodge Intrepid	19	4	3	18%	13%
Toyota Tundra	19	3	3	14%	13%
Chevrolet Cobalt	19	3	1	14%	4%
Chevrolet Lumina	18	4	0	19%	0%
Ford F350	17	4	2	20%	10%
Chevrolet Astro	16	3	2	16%	10%
Chevrolet Camaro	15	3	1	17%	6%
Chevrolet S10	15	3	0	17%	0%
Ford Crown Victoria	14	4	0	25%	0%
Buick Regal	14	3	1	19%	6%
Chrysler PT Cruiser	12	4	3	29%	21%
Oldsmobile Alero	12	3	0	22%	0%
Subaru Impreza	11	6	0	47%	0%
Ford Escape	11	3	0	24%	0%
Toyota Celica	10	3	2	26%	17%
Chrysler Concorde	7	3	2	37%	24%
Lincoln Town Car	7	3	0	37%	0%
Mercury Tracer	6	3	0	43%	0%
Mitsubishi Mirage	6	2	1	29%	14%
Chrysler Cirrus	6	2	0	29%	0%
Toyota Matrix	6	2	0	29%	0%
Ford Aerostar	5	2	0	35%	0%
Mercury Grand Marquis	4	2	0	43%	0%
Oldsmobile 88	4	2	0	43%	0%
Volkswagen Golf	4	2	0	43%	0%

Table 29. Vehicles Involved in Rollover Crashes at High Frequencies

ROLLOVERS					
Vehicle	**Crashes**	**Penetrations**	**Rollovers**	**Scaled Penetration Rate**	**Scaled Rollover Rate**
Ford Explorer	81	11	20	12%	21%
Ford Ranger	72	4	13	5%	15%
Chevrolet Blazer	37	14	8	16%	20%
Chevrolet C1500/2500/3500	32	7	9	5%	21%
Jeep Cherokee	30	2	8	9%	11%
Dodge Ram 1500	27	3	4	10%	19%
Toyota 4 Runner	25	3	6	17%	20%
Ford F250	24	5	6	22%	17%
Jeep Liberty	21	6	5	12%	12%
Dodge Intrepid	19	3	3	18%	13%
Toyota Tundra	19	4	3	14%	13%
Chrysler PT Cruiser	12	3	3	29%	21%
Isuzu Rodeo	11	4	3	16%	31%
Dodge Grand Caravan	11	2	4	16%	23%
Ford Econoline	11	2	3	8%	23%
Chrysler Concorde	7	1	3	37%	24%
Mazda Tribute	6	3	2	0%	28%
Mazda 323	5	0	2	17%	34%

Table 30. Vehicles Involved in Penetration Crashes at Low Frequencies

PENETRATIONS					
Vehicle	**Crashes**	**Penetrations**	**Rollovers**	**Scaled Penetration Rate**	**Scaled Rollover Rate**
Ford Ranger	72	4	13	5%	15%
Ford Focus	61	4	5	6%	7%
Chevrolet Malibu	32	2	1	5%	3%
Dodge Dakota	33	1	0	3%	0%
Toyota Tacoma	24	0	1	0%	3%
Dodge Caravan	23	0	2	0%	7%
Hyundai Accent	22	1	0	4%	0%
Mitsubishi Eclipse	21	1	2	4%	8%
Dodge Stratus	21	1	1	4%	4%
Jeep Grand Cherokee	20	1	2	4%	8%
Honda CRV	19	0	2	0%	9%
Ford Expedition	19	1	2	5%	9%
Nissan Pathfinder	18	0	2	0%	9%
Geo Metro/Prizm	17	1	1	5%	5%
Chevrolet Suburban	16	1	1	5%	5%
Pontiac Sunfire	16	1	0	5%	0%
Nissan Maxima	15	0	0	0%	0%
Chevrolet K2500	15	1	2	6%	11%
Jeep Wrangler	14	0	2	0%	12%
Mazda Protégé	14	1	1	6%	6%
Ford Contour	13	0	0	0%	0%

Table 31. Vehicles Involved in Rollover Crashes at Low Frequencies

ROLLOVERS					
Vehicle	**Crashes**	**Penetrations**	**Rollovers**	**Scaled Penetration Rate**	**Scaled Rollover Rate**
Ford Mustang	52	6	0	10%	0%
Chevrolet Malibu	32	2	1	5%	3%
Chevrolet Silverado	34	4	1	10%	2%
Pontiac Grand Prix	33	4	1	11%	3%
Dodge Dakota	33	1	0	3%	0%
Volkswagen Jetta	33	5	0	13%	0%
Chevrolet Malibu (2004-2008)	34	3	0	8%	0%
Toyota Camry (2001-Present)	26	2	1	7%	3%
Toyota Tacoma	24	0	1	0%	3%
Acura Integra	24	6	0	22%	0%
Chevrolet Impala	23	5	1	19%	4%
Buick Lesabre	23	2	0	8%	0%
Chrysler Sebring	23	4	0	15%	0%
Hyundai Accent	22	1	0	4%	0%
Dodge Stratus	21	1	1	4%	4%
Hyundai Elantra	21	2	1	8%	4%
Subaru Legacy	21	2	0	8%	0%
Chevrolet Cobalt	19	3	1	14%	4%
Mercury Sable	19	2	0	9%	0%
Chevrolet Tahoe	18	2	1	10%	5%
Mitsubishi Galant	18	2	1	10%	5%
Chevrolet Lumina	18	4	0	19%	0%
Pontiac Sunfire	16	1	0	5%	0%
Chevrolet Camaro	15	3	1	17%	6%
Buick Century	15	2	0	12%	0%
Chevrolet S10	15	3	0	17%	0%
Mazda 3	15	2	0	12%	0%
Nissan Maxima	15	0	0	0%	0%

Current- and previously-used small cars were not well-represented in terms of penetration crash frequency. The combined number of crashes involving Geo Metro/Geo Prizm, Volkswagon Golf, Suzuki Swift, and Hyundai Accent was 47 crashes, but only 4 penetrations and 1 rollover were recorded on these small cars. These cars were frequently used in NCHRP Report 350 crash testing. This is not surprising, since full-scale crash testing with these small cars under NCHRP Report No. 350 and MASH has only showed critical behavior when tested in a V-ditch [35]. Few crashes were tabulated with vehicles frequently used in MASH testing.

Vehicles demonstrating more frequent barrier failures should be considered in future crash testing efforts. Testing with vehicles which are susceptible to penetrations or rollovers should be conducted in order to maximize the resultant safety of all impacting vehicles. Results shown suggest that crash testing with new MASH trucks may not be sufficient to capture the extent of the penetration and rollover crash types observed in this study. Further analysis of the causes of penetration crashes is explored in Chapter 8.

8 CAUSES OF CABLE MEDIAN BARRIER PENETRATIONS

Cable median barrier penetrations were heavily dependent on which type of system was struck. Penetration mechanisms were heavily dependent on the mechanics of barrier deformation and cable release. In order to describe the mechanisms of penetration, system details for the Nucor NU-CABLE TL-3 3-Cable System, C-Shaped post and S-Shaped post Trinity Cable Safety System (CASS) TL-3 Systems, Brifen Wire Rope Safety Fence (WRSF) TL-3 4-Cable System, and the TL-3, low-tension, 3-cable median barrier system are described below.

8.1 System Design Details

8.1.1 Nucor NU-CABLE TL-3 3-Cable System

Nucor system details are shown in Figures 65 through 68. The cable-to-post attachment used by Nucor was very strong compared to all other barrier systems, and is shown in Figures 68 and 68. This cable-to-post attachment is also used in the Trinity CASS barrier near end anchorages and terminations. The details which follow were reflective of the systems available for analysis in the existing database; an alternative construction with the Nucor system utilizes cable hangars on the top of the post instead of the strong cable attachment shown in this report.

The clips were fastened to the post by inserting the bent upper leg into the appropriate hole on the flanged U-channel, and then were locked in place with a nut threaded onto the bottom clip threads. Holes in the flanges were spaced approximately 1 in. (25 mm) on center vertically through the centerline of the flange. Many posts were 4 lb/ft (6 kg/m) flanged U-channel with Rib-Bak construction, though some installations utilized the 5 lb/ft (7 kg/m) posts. The median barrier configuration for this post utilized two short clips, shown in Figure 68, for the top and bottom cables, and one long clip, shown in Figure 67, to support the middle cable.

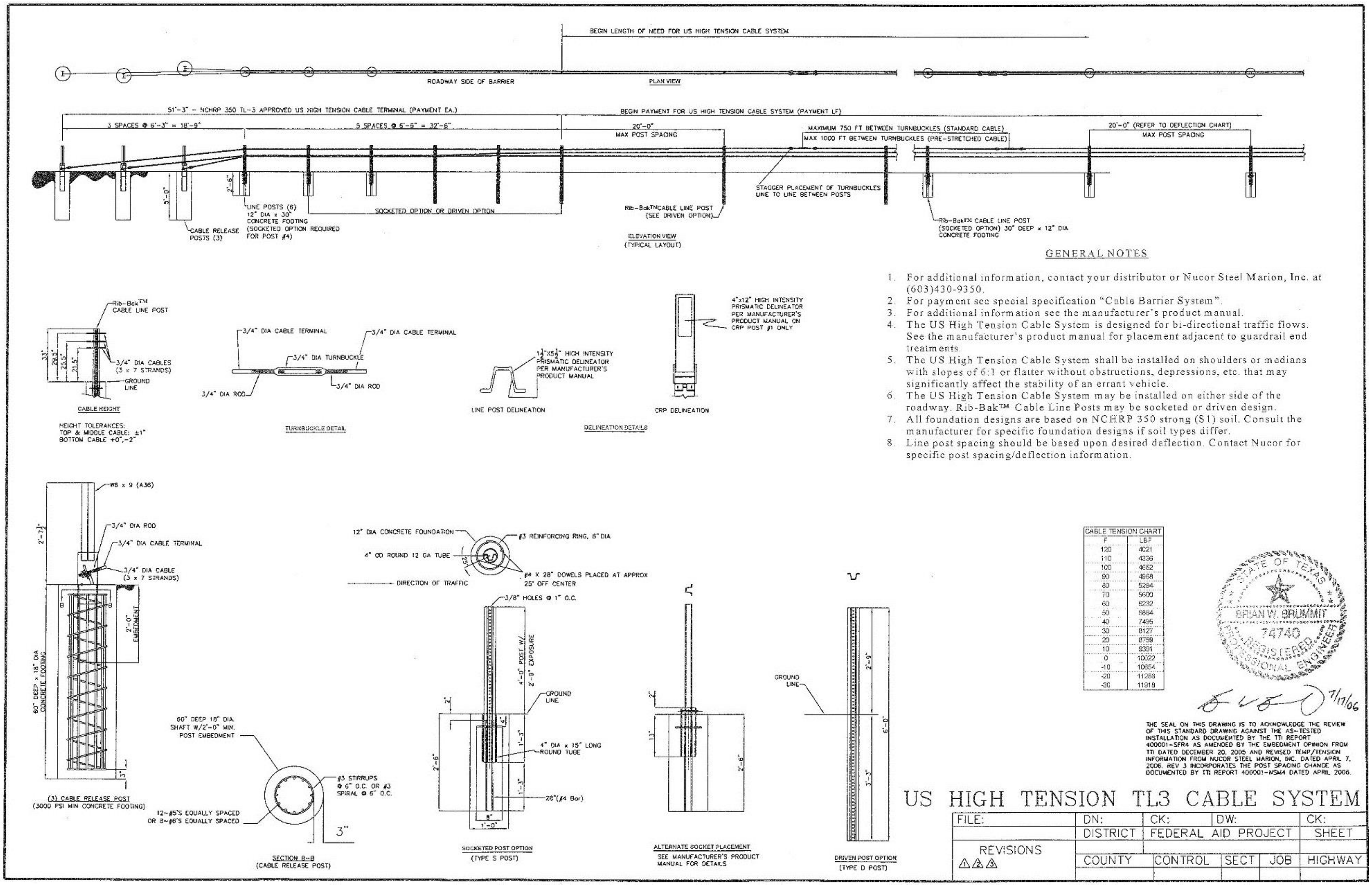


Figure 65. Nucor Cable Barrier Design Details [36]

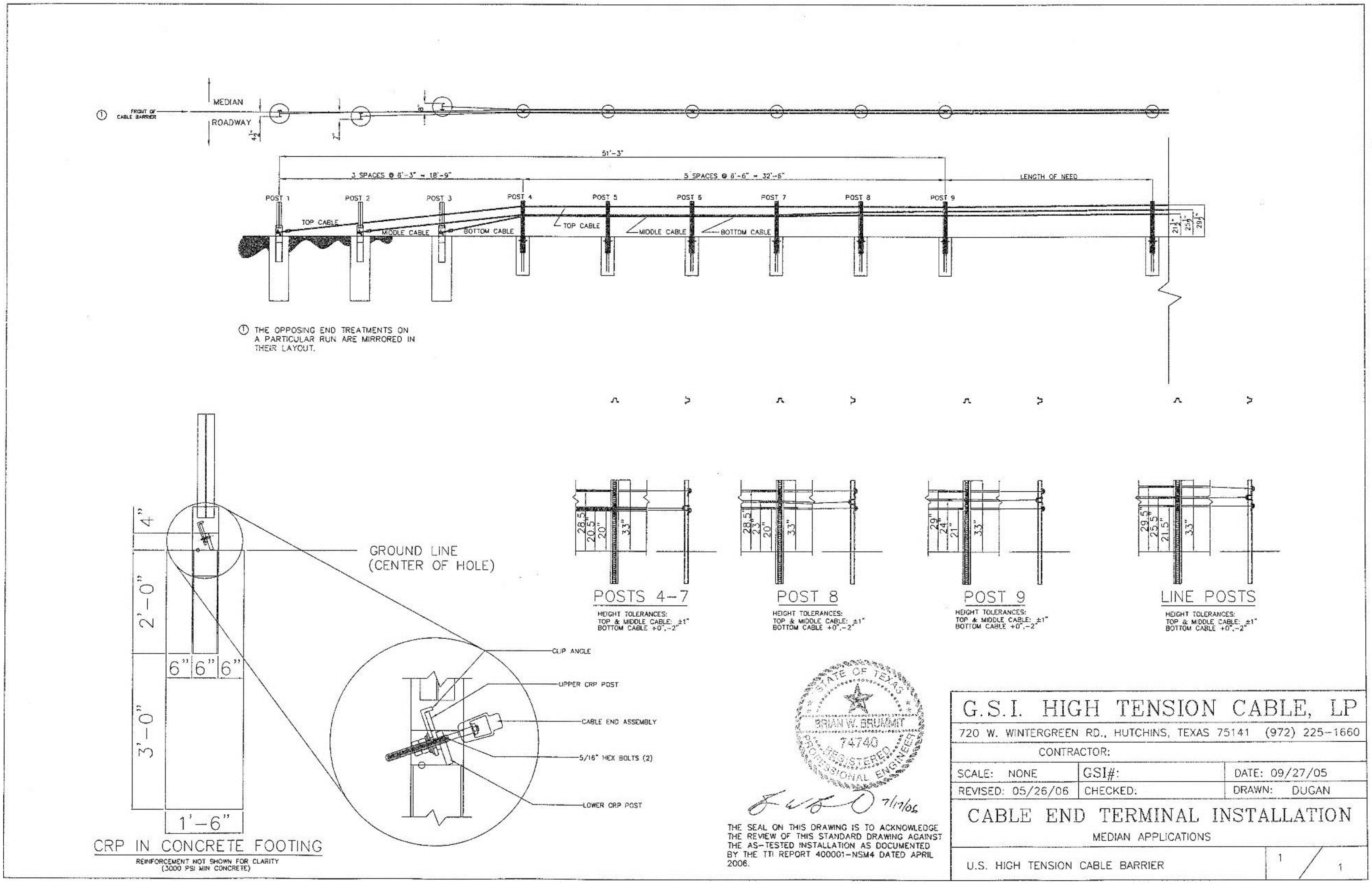


Figure 66. Nucor Cable Barrier Design Details [36]

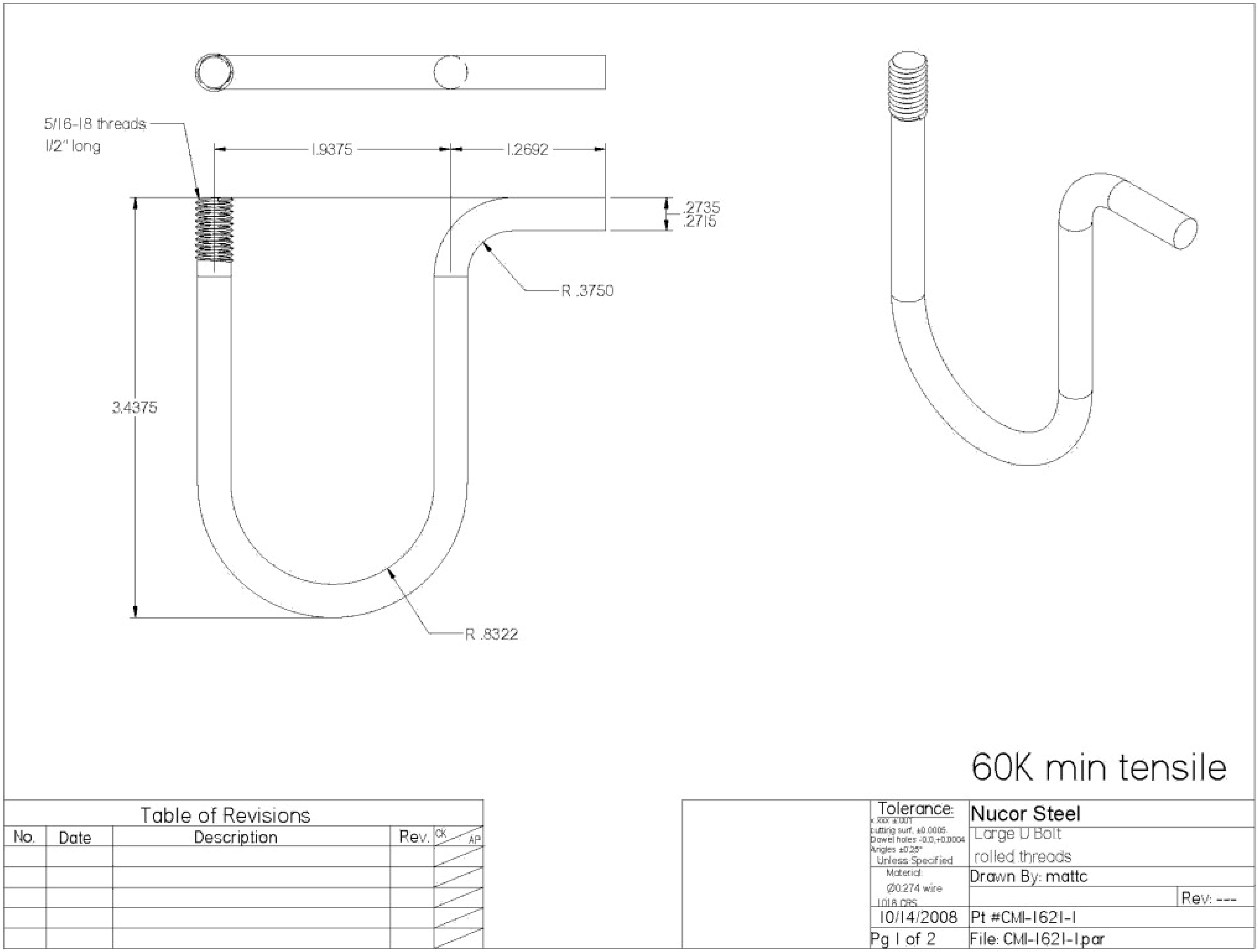


Figure 67. Nucor Cable Barrier Long Clip Design Details [37]

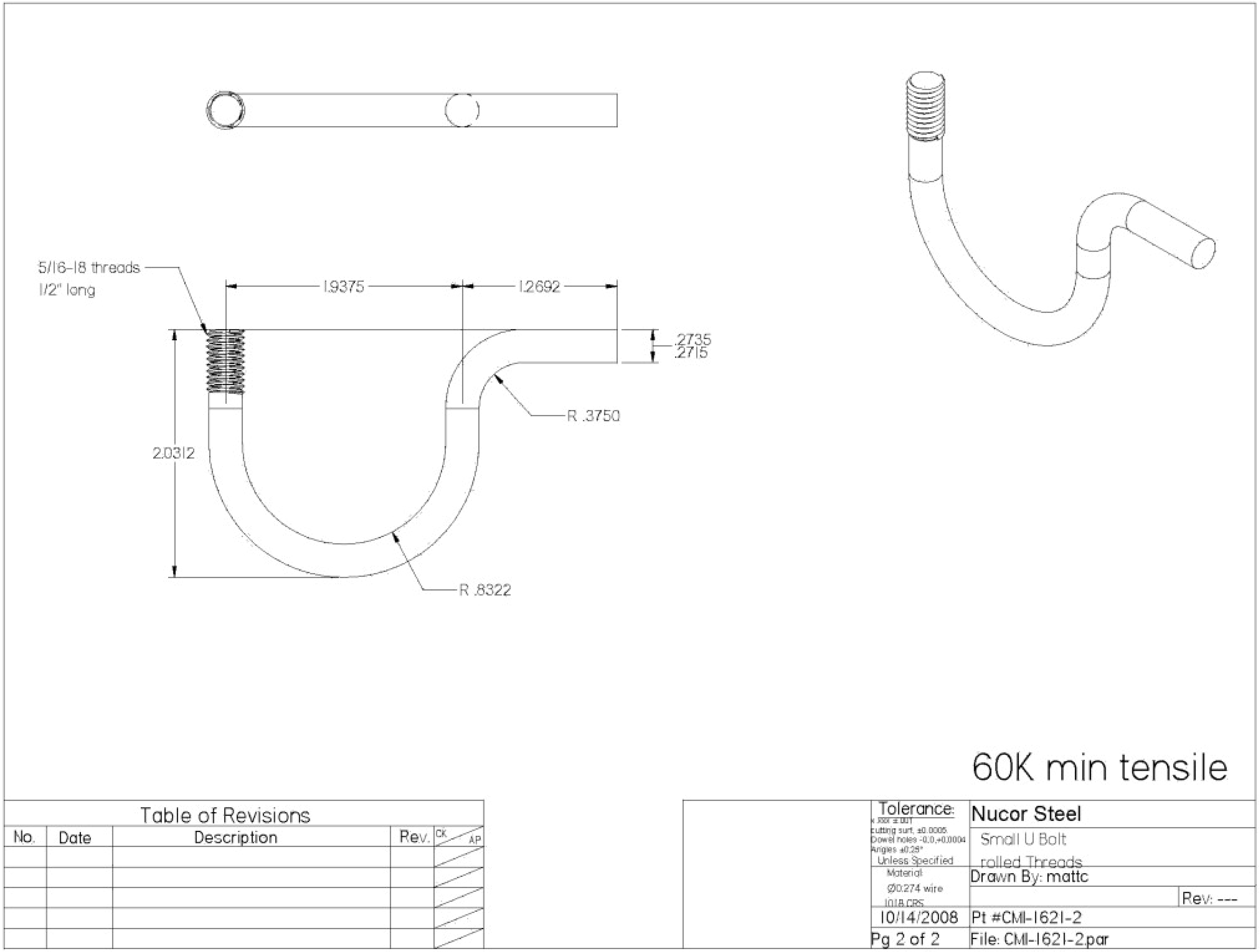


Figure 68. Nucor Cable Barrier Short Clip Design Details [37]

Since the attachment had a 60 ksi (414 MPa) minimum ultimate strength requirement, the resulting minimum tensile load required to cause rupture of the shank was 4.6 kip (20.5 kN) through a single leg. The clip appeared to be designed to dissipate energy through the bending deformation of the upper leg of the clip. During vertical pullout loading conditions, the curved clip construction contributed to friction wedge locking of the bent leg in the bottom hole. Due to vertical forces, the couple at the bottom of the clip tended to aggravate the locking tendency as the bottom leg interacted with the web. A schematic of the vertical release problems identified is shown in Figure 69. The friction lock resisted the lower leg bending and releasing from the post, frequently resulting in large applied tensile loads carried by both legs of the clip until the clip fractured, the post was pulled vertically out of the ground or post socket, or the post fractured. The vertical loading resulted in post pullout in most crashes.

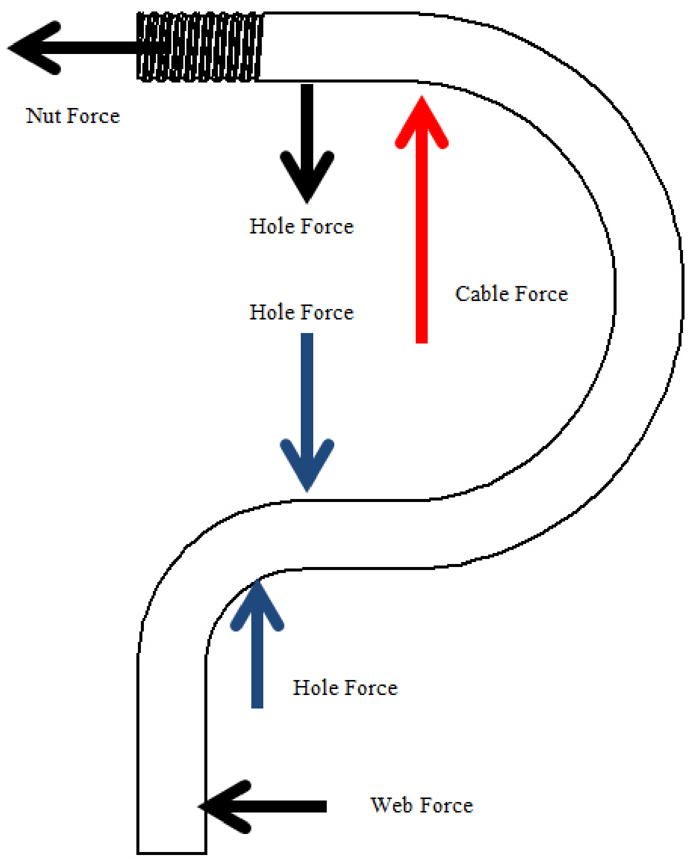


Figure 69. Vertical Pullout Moment Couple on Nucor Cable-To-Post Attachment

Although the clip would perform adequately in horizontal pullout with posts that are sufficiently stiff, the flange-channel U-post does not have the rigidity necessary to resist bending and buckling or fracture to permit the top cable to release. During horizontal pullout loading, the post deflected with the cable, and the horizontal load applied experienced a rotation to a mixed horizontal and vertical loading. As the loading transitioned to vertical pullout, the posts were pulled upward and out of the ground or fractured in many crashes. Relatively few crashes were observed in which the cable-to-post attachments released as intended.

8.1.2 Trinity Cable Safety System (CASS) 3-Cable Barrier

Like the Nucor TL-3 3-cable barrier on flange-channel posts, the Trinity CASS 3-cable barrier installed on C-shaped posts had a large installed base in the United States. CASS installations were present in such states as Iowa, Ohio, Oklahoma, Utah, and Washington, as well as many others. Details of the C-channel and S-post versions of the TL-3 CASS system are shown in Figures 70 through 73.

Most of the Trinity CASS system installed in the participating states utilized the TL-3 C-shape post sections. Installations of both the TL-4 and TL-3 structural S-type post section barrier designs were identified. However, relatively few crashes with the TL-4 design were available for analysis.

The direction of the channel in the C-shaped posts was alternated, per construction design. As a result, the radius of gyration to the weak axis was different when the posts were struck on the channel or continuous sides. Alternatively, the S-shape posts were comprised of S4x7.7 (S102x11.5) shape sections, with two $^{11}/_{16}$-in. (17-mm) holes in each flange. Researchers estimated that weakening holes decreased the strong-axis section modulus from 3.03 in.^{3} to 2.54 in.^{3} (49,652 mm^3 to 41,623 mm^3), and decreased the weak-axis section modulus from 0.562 in.^{3} to 0.368 in.^{3} (9,210 mm^3 to 6,030 mm^3). By comparison, a standard S3x5.7 post has a strong-axis bending modulus of 1.67 in.^{3} (27,366 mm^3), and a weak-axis bending modulus of 0.383 in.^{3} (6,276 mm^3).

All of the cables in the Trinity CASS systems were located in a slot in the top of the post. Cable spacers and retainers were used to prevent the cables from slipping out of the posts in nuisance impacts. A sleeve tie was also used to retain the lower cable with a higher vertical release load and to stiffen the flanges where the web was cut. Driven and socketed options were available. The S-post TL-3 system had cables mounted at 29½, 25$^3/_{16}$, and 20⅞ in. (749, 640, and 530 mm) and are shown in Figure 72. Cables in the TL-3 C-shape post system were $^1/_{16}$ in. (2 mm) lower than in the S-post system. The TL-4 system had cables mounted at 38⅛, 29½, and 20⅞ in. (968, 749, and 530 mm).

A common cause of penetration in the CASS database occurred when the vehicle struck a post before striking the cable barrier system. The posts then transmitted the impact load to the posts through the internal slot. Because the vehicle had little, if any, interaction with the cables prior to striking the post, lateral loads applied to the cables tended to engage the cables more deeply in the slot, preventing the cables from disengaging from the post to capture the vehicle. The slot engagement contributed to many override containment failures of vehicles, including passenger cars which are typically not prone to override. This type of cable entrapment can occur whenever cables are located within a post slot.

Because this mechanism of penetration was determined to occur frequently, this form of cable entrapment was referred to as a “ramp formation” override penetration. The Trinity CASS system may be intrinsically susceptible to cable entrapment and ramp formation override penetrations unless barrier modifications to prevent cable entrapment can be made. A schematic of the cable entrapment mechanism is shown in Figure 74.

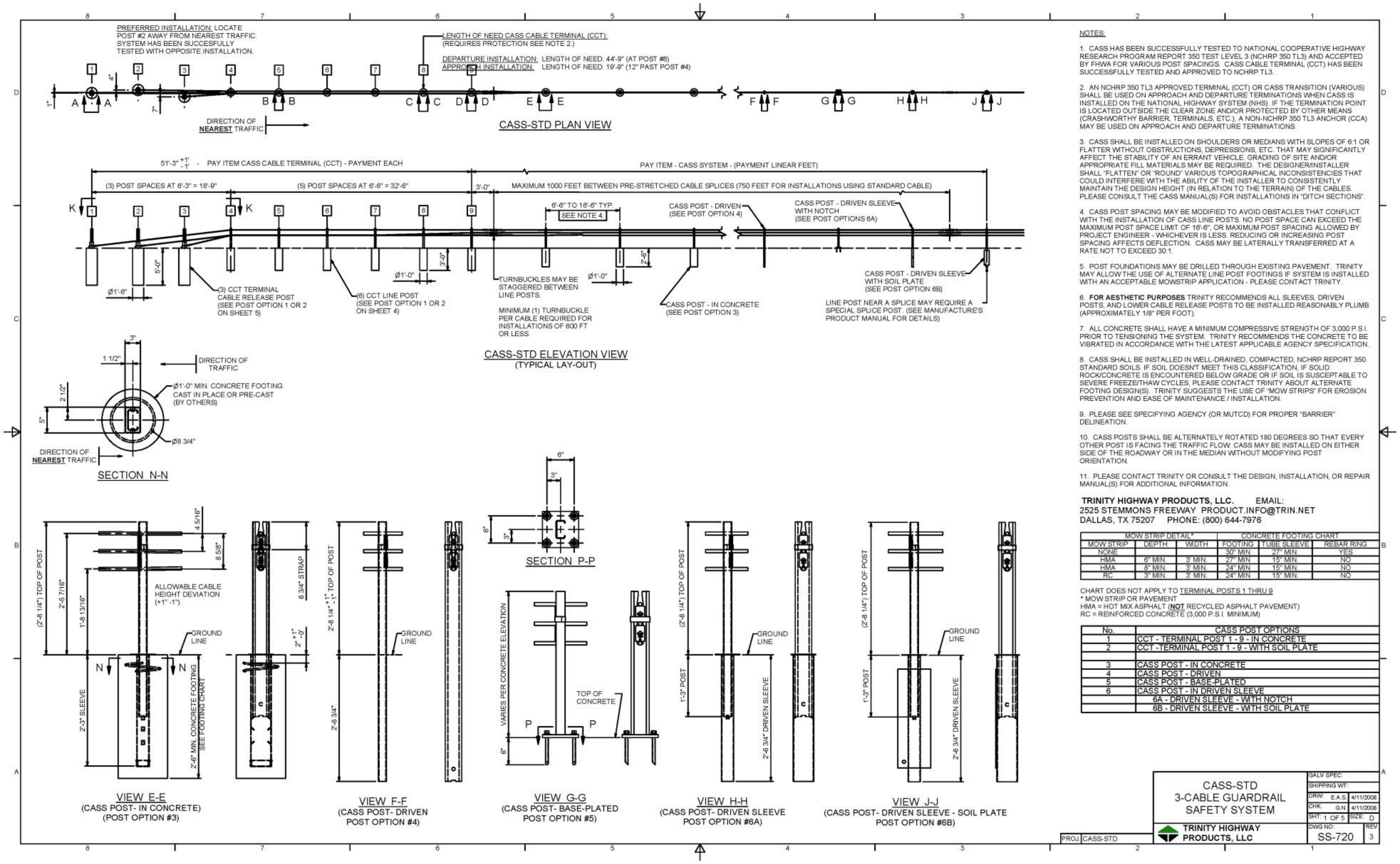
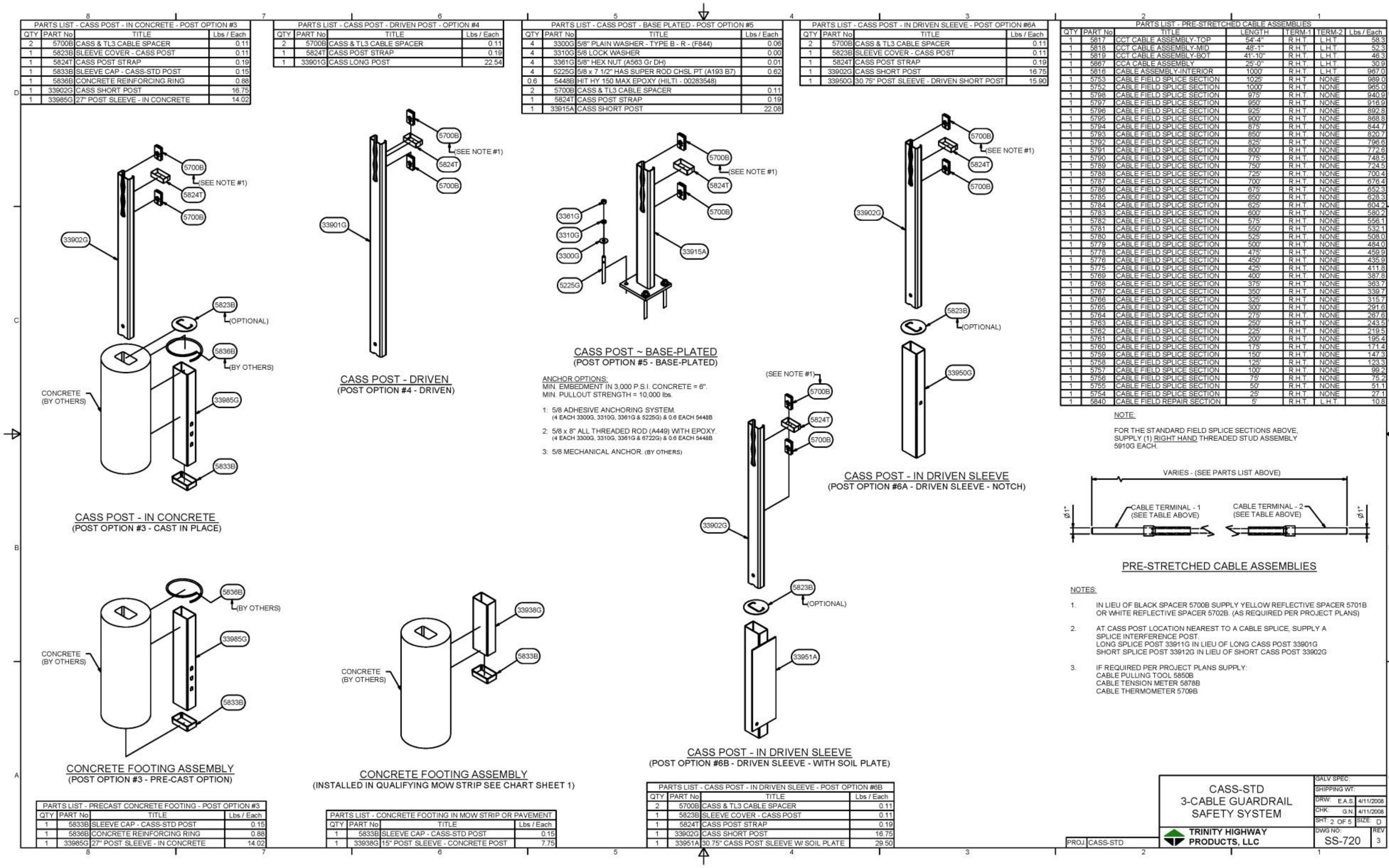


Figure 70. Trinity CASS C-Shape Post System Details [38]



PARTS LIST - CASS POST - IN CONCRETE - POST OPTION #3

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5823B	SLEEVE COVER - CASS POST	0.11
1	5824T	CASS POST STRAP	0.19
1	5833B	SLEEVE CAP - CASS-STD POST	0.15
1	5836B	CONCRETE REINFORCING RING	0.88
1	33902G	CASS SHORT POST	16.75
1	33985G	27" POST SLEEVE - IN CONCRETE	14.02

PARTS LIST - CASS POST - DRIVEN POST - OPTION #4

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5824T	CASS POST STRAP	0.19
1	33901G	CASS LONG POST	22.54

PARTS LIST - CASS POST - BASE PLATED - POST OPTION #5

QTY	PART No	TITLE	Lbs / Each
4	3300G	5/8" PLAIN WASHER - TYPE B - R - (F844)	0.06
4	3310G	5/8 LOCK WASHER	0.00
4	3361G	5/8" HEX NUT (A563 Gr DH)	0.01
4	5225G	5/8 x 7 1/2" HAS SUPER ROD CHSL PT (A193 B7)	0.62
0.6	5448B	HIT HY 150 MAX EPOXY (HILTI - 00283548)	
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5824T	CASS POST STRAP	0.19
1	33915A	CASS SHORT POST	22.08

PARTS LIST - CASS POST - IN DRIVEN SLEEVE - POST OPTION #6A

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5823B	SLEEVE COVER - CASS POST	0.11
1	5824T	CASS POST STRAP	0.19
1	33902G	CASS SHORT POST	16.75
1	33950G	30.75" POST SLEEVE - DRIVEN SHORT POST	15.90

PARTS LIST - PRE-STRETCHED CABLE ASSEMBLIES

QTY	PART No	TITLE	LENGTH	TERM-1	TERM-2	Lbs / Each
1	5817	CCT CABLE ASSEMBLY-TOP	54'-4"	R.H.T.	L.H.T.	58.3
1	5818	CCT CABLE ASSEMBLY-MID	48'-1"	R.H.T.	L.H.T.	52.3
1	5819	CCT CABLE ASSEMBLY-BOT	41'-10"	R.H.T.	L.H.T.	46.3
1	5867	CCA CABLE ASSEMBLY	25'-0"	R.H.T.	L.H.T.	30.9
1	5816	CABLE ASSEMBLY-INTERIOR	1000'	R.H.T.	L.H.T.	967.0
1	5753	CABLE FIELD SPLICE SECTION	1025'	R.H.T.	NONE	989.0
1	5752	CABLE FIELD SPLICE SECTION	1000'	R.H.T.	NONE	965.0
1	5798	CABLE FIELD SPLICE SECTION	975'	R.H.T.	NONE	940.9
1	5797	CABLE FIELD SPLICE SECTION	950'	R.H.T.	NONE	916.9
1	5796	CABLE FIELD SPLICE SECTION	925'	R.H.T.	NONE	892.8
1	5795	CABLE FIELD SPLICE SECTION	900'	R.H.T.	NONE	868.8
1	5794	CABLE FIELD SPLICE SECTION	875'	R.H.T.	NONE	844.7
1	5793	CABLE FIELD SPLICE SECTION	850'	R.H.T.	NONE	820.7
1	5792	CABLE FIELD SPLICE SECTION	825'	R.H.T.	NONE	796.6
1	5791	CABLE FIELD SPLICE SECTION	800'	R.H.T.	NONE	772.6
1	5790	CABLE FIELD SPLICE SECTION	775'	R.H.T.	NONE	748.5
1	5789	CABLE FIELD SPLICE SECTION	750'	R.H.T.	NONE	724.5
1	5788	CABLE FIELD SPLICE SECTION	725'	R.H.T.	NONE	700.4
1	5787	CABLE FIELD SPLICE SECTION	700'	R.H.T.	NONE	676.4
1	5786	CABLE FIELD SPLICE SECTION	675'	R.H.T.	NONE	652.3
1	5785	CABLE FIELD SPLICE SECTION	650'	R.H.T.	NONE	628.3
1	5784	CABLE FIELD SPLICE SECTION	625'	R.H.T.	NONE	604.2
1	5783	CABLE FIELD SPLICE SECTION	600'	R.H.T.	NONE	580.2
1	5782	CABLE FIELD SPLICE SECTION	575'	R.H.T.	NONE	556.1
1	5781	CABLE FIELD SPLICE SECTION	550'	R.H.T.	NONE	532.1
1	5780	CABLE FIELD SPLICE SECTION	525'	R.H.T.	NONE	508.0
1	5779	CABLE FIELD SPLICE SECTION	500'	R.H.T.	NONE	484.0
1	5778	CABLE FIELD SPLICE SECTION	475'	R.H.T.	NONE	459.9
1	5776	CABLE FIELD SPLICE SECTION	450'	R.H.T.	NONE	435.9
1	5775	CABLE FIELD SPLICE SECTION	425'	R.H.T.	NONE	411.8
1	5769	CABLE FIELD SPLICE SECTION	400'	R.H.T.	NONE	387.8
1	5768	CABLE FIELD SPLICE SECTION	375'	R.H.T.	NONE	363.7
1	5767	CABLE FIELD SPLICE SECTION	350'	R.H.T.	NONE	339.7
1	5766	CABLE FIELD SPLICE SECTION	325'	R.H.T.	NONE	315.7
1	5765	CABLE FIELD SPLICE SECTION	300'	R.H.T.	NONE	291.6
1	5764	CABLE FIELD SPLICE SECTION	275'	R.H.T.	NONE	267.6
1	5763	CABLE FIELD SPLICE SECTION	250'	R.H.T.	NONE	243.5
1	5762	CABLE FIELD SPLICE SECTION	225'	R.H.T.	NONE	219.5
1	5761	CABLE FIELD SPLICE SECTION	200'	R.H.T.	NONE	195.4
1	5760	CABLE FIELD SPLICE SECTION	175'	R.H.T.	NONE	171.4
1	5759	CABLE FIELD SPLICE SECTION	150'	R.H.T.	NONE	147.3
1	5758	CABLE FIELD SPLICE SECTION	125'	R.H.T.	NONE	123.3
1	5757	CABLE FIELD SPLICE SECTION	100'	R.H.T.	NONE	99.2
1	5756	CABLE FIELD SPLICE SECTION	75'	R.H.T.	NONE	75.2
1	5755	CABLE FIELD SPLICE SECTION	50'	R.H.T.	NONE	51.1
1	5754	CABLE FIELD SPLICE SECTION	25'	R.H.T.	NONE	27.1
1	5840	CABLE FIELD REPAIR SECTION	5'	R.H.T.	L.H.T.	10.8

PARTS LIST - PRECAST CONCRETE FOOTING - POST OPTION #3

QTY	PART No	TITLE	Lbs / Each
1	5833B	SLEEVE CAP - CASS-STD POST	0.15
1	5836B	CONCRETE REINFORCING RING	0.88
1	33985G	27" POST SLEEVE - IN CONCRETE	14.02

PARTS LIST - CONCRETE FOOTING IN MOW STRIP OR PAVEMENT

QTY	PART No	TITLE	Lbs / Each
1	5833B	SLEEVE CAP - CASS-STD POST	0.15
1	33938G	15" POST SLEEVE - CONCRETE POST	7.75

PARTS LIST - CASS POST - IN DRIVEN SLEEVE - POST OPTION #6B

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5823B	SLEEVE COVER - CASS POST	0.11
1	5824T	CASS POST STRAP	0.19
1	33902G	CASS SHORT POST	16.75
1	33951A	30.75" CASS POST SLEEVE W/ SOIL PLATE	29.50

Figure 71. Trinity CASS C-Shaped Post System Details [38]

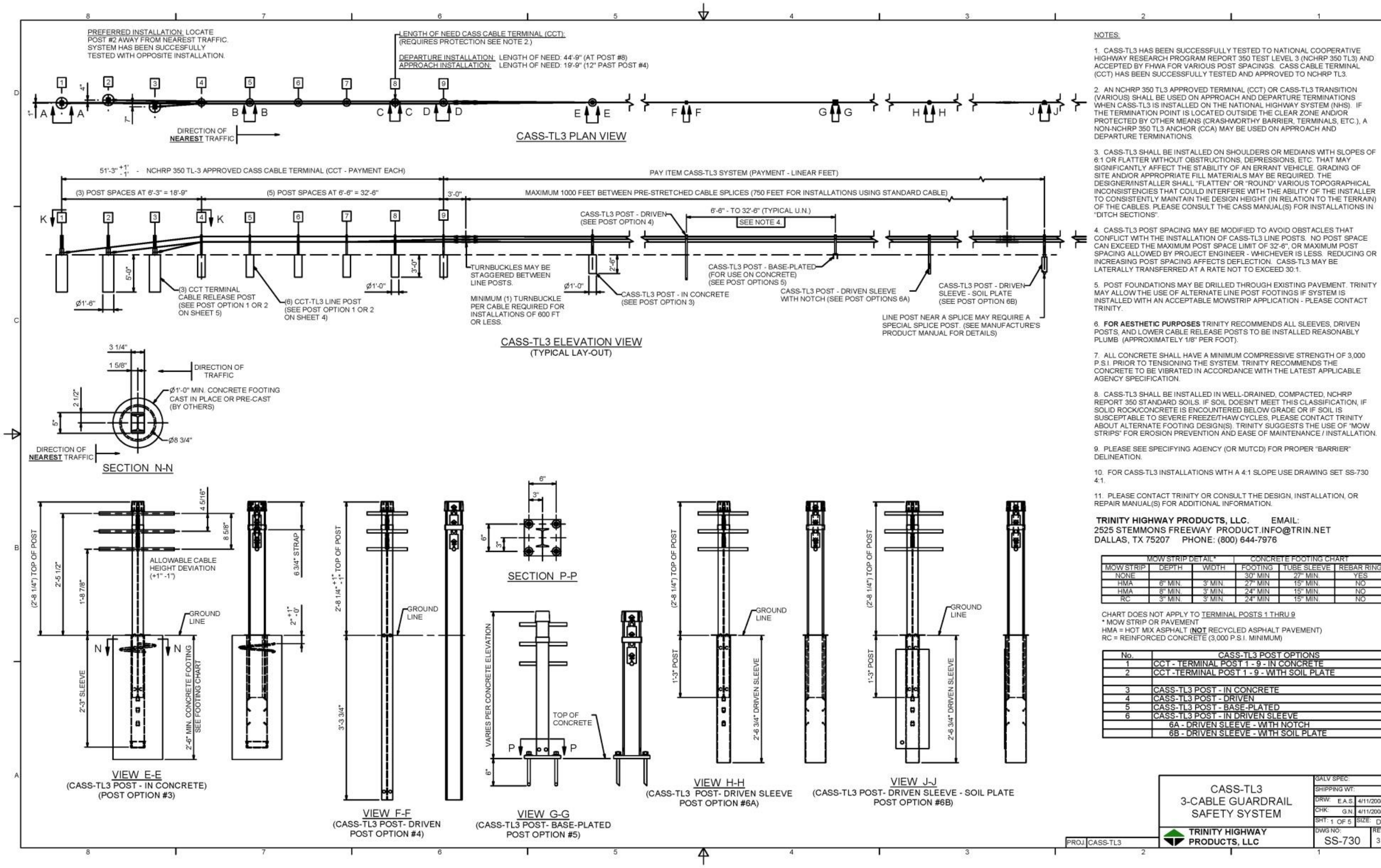
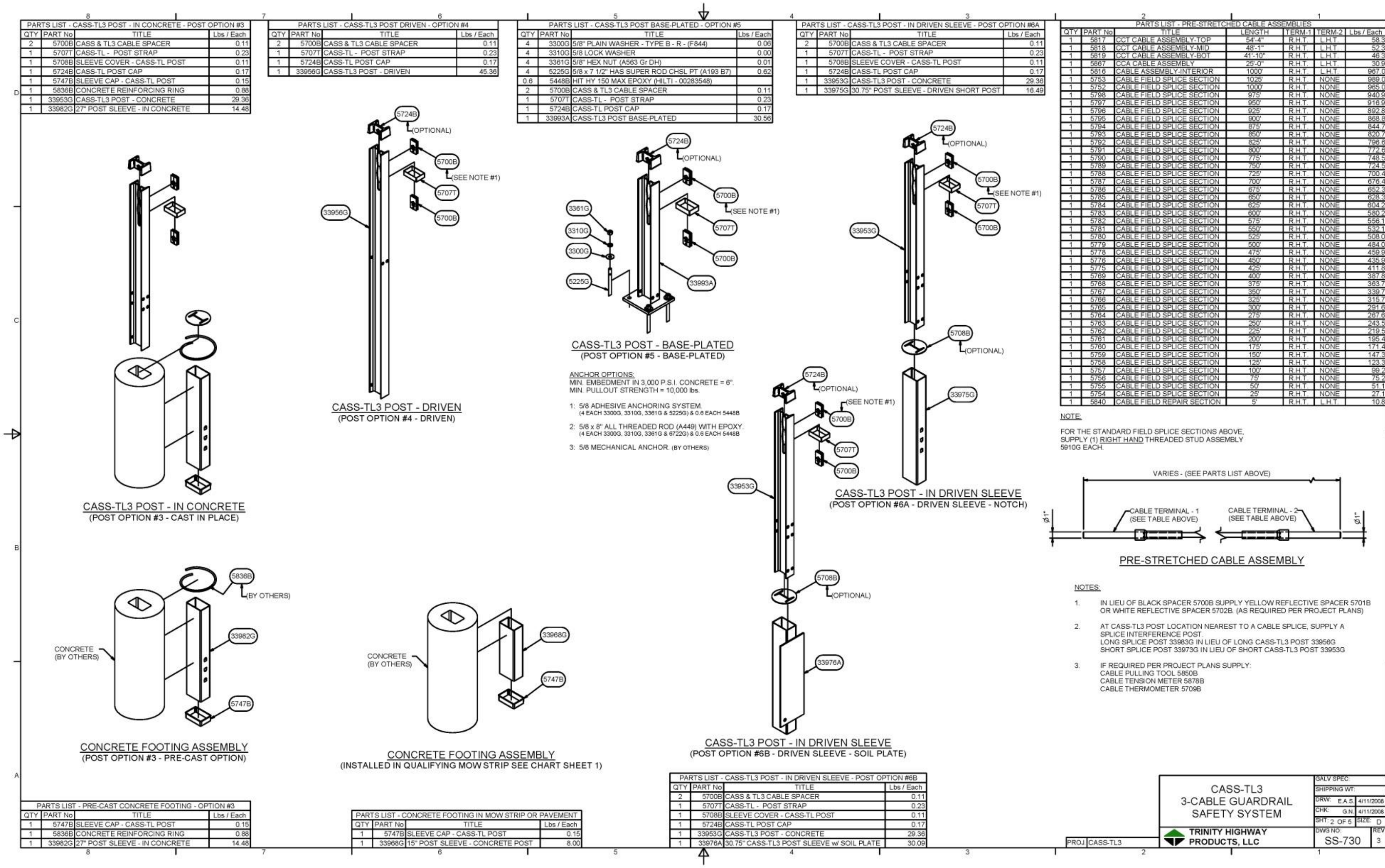


Figure 72. Trinity CASS TL-3 S-Post System Details [39]



PARTS LIST - CASS-TL3 POST - IN CONCRETE - POST OPTION #3

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5707T	CASS-TL - POST STRAP	0.23
1	5708B	SLEEVE COVER - CASS-TL POST	0.11
1	5724B	CASS-TL POST CAP	0.17
1	5747B	SLEEVE CAP - CASS-TL POST	0.15
1	5836B	CONCRETE REINFORCING RING	0.88
1	33953G	CASS-TL3 POST - CONCRETE	29.36
1	33982G	27" POST SLEEVE - IN CONCRETE	14.48

PARTS LIST - CASS-TL3 POST DRIVEN - OPTION #4

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5707T	CASS-TL - POST STRAP	0.23
1	5724B	CASS-TL POST CAP	0.17
1	33956G	CASS-TL3 POST - DRIVEN	45.36

PARTS LIST - CASS-TL3 POST BASE-PLATED - OPTION #5

QTY	PART No	TITLE	Lbs / Each
4	3300G	5/8" PLAIN WASHER - TYPE B - R - (F844)	0.06
4	3310G	5/8 LOCK WASHER	0.00
4	3361G	5/8" HEX NUT (A563 Gr DH)	0.01
4	5225G	5/8 x 7 1/2" HAS SUPER ROD CHSL PT (A193 B7)	0.62
0.6	5448B	HIT HY 150 MAX EPOXY (HILTI - 00283548)	
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5707T	CASS-TL - POST STRAP	0.23
1	5724B	CASS-TL POST CAP	0.17
1	33993A	CASS-TL3 POST BASE-PLATED	30.56

PARTS LIST - CASS-TL3 POST - IN DRIVEN SLEEVE - POST OPTION #6A

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5707T	CASS-TL - POST STRAP	0.23
1	5708B	SLEEVE COVER - CASS-TL POST	0.11
1	5724B	CASS-TL POST CAP	0.17
1	33953G	CASS-TL3 POST - CONCRETE	29.36
1	33975G	30.75" POST SLEEVE - DRIVEN SHORT POST	16.49

PARTS LIST - PRE-STRETCHED CABLE ASSEMBLIES

QTY	PART No	TITLE	LENGTH	TERM-1	TERM-2	Lbs / Each
1	5817	CCT CABLE ASSEMBLY-TOP	54'-4"	R.H.T.	L.H.T.	58.3
1	5818	CCT CABLE ASSEMBLY-MID	48'-1"	R.H.T.	L.H.T.	52.3
1	5819	CCT CABLE ASSEMBLY-BOT	41'-10"	R.H.T.	L.H.T.	46.3
1	5867	CCA CABLE ASSEMBLY	25'-0"	R.H.T.	L.H.T.	30.9
1	5816	CABLE ASSEMBLY-INTERIOR	1000'	R.H.T.	L.H.T.	967.0
1	5753	CABLE FIELD SPLICE SECTION	1025'	R.H.T.	NONE	989.0
1	5752	CABLE FIELD SPLICE SECTION	1000'	R.H.T.	NONE	965.0
1	5798	CABLE FIELD SPLICE SECTION	975'	R.H.T.	NONE	940.9
1	5797	CABLE FIELD SPLICE SECTION	950'	R.H.T.	NONE	916.9
1	5796	CABLE FIELD SPLICE SECTION	925'	R.H.T.	NONE	892.8
1	5795	CABLE FIELD SPLICE SECTION	900'	R.H.T.	NONE	868.8
1	5794	CABLE FIELD SPLICE SECTION	875'	R.H.T.	NONE	844.7
1	5793	CABLE FIELD SPLICE SECTION	850'	R.H.T.	NONE	820.7
1	5792	CABLE FIELD SPLICE SECTION	825'	R.H.T.	NONE	796.6
1	5791	CABLE FIELD SPLICE SECTION	800'	R.H.T.	NONE	772.6
1	5790	CABLE FIELD SPLICE SECTION	775'	R.H.T.	NONE	748.5
1	5789	CABLE FIELD SPLICE SECTION	750'	R.H.T.	NONE	724.5
1	5788	CABLE FIELD SPLICE SECTION	725'	R.H.T.	NONE	700.4
1	5787	CABLE FIELD SPLICE SECTION	700'	R.H.T.	NONE	676.4
1	5786	CABLE FIELD SPLICE SECTION	675'	R.H.T.	NONE	652.3
1	5785	CABLE FIELD SPLICE SECTION	650'	R.H.T.	NONE	628.3
1	5784	CABLE FIELD SPLICE SECTION	625'	R.H.T.	NONE	604.2
1	5783	CABLE FIELD SPLICE SECTION	600'	R.H.T.	NONE	580.2
1	5782	CABLE FIELD SPLICE SECTION	575'	R.H.T.	NONE	556.1
1	5781	CABLE FIELD SPLICE SECTION	550'	R.H.T.	NONE	532.1
1	5780	CABLE FIELD SPLICE SECTION	525'	R.H.T.	NONE	508.0
1	5779	CABLE FIELD SPLICE SECTION	500'	R.H.T.	NONE	484.0
1	5778	CABLE FIELD SPLICE SECTION	475'	R.H.T.	NONE	459.9
1	5776	CABLE FIELD SPLICE SECTION	450'	R.H.T.	NONE	435.9
1	5775	CABLE FIELD SPLICE SECTION	425'	R.H.T.	NONE	411.8
1	5769	CABLE FIELD SPLICE SECTION	400'	R.H.T.	NONE	387.8
1	5768	CABLE FIELD SPLICE SECTION	375'	R.H.T.	NONE	363.7
1	5767	CABLE FIELD SPLICE SECTION	350'	R.H.T.	NONE	339.7
1	5766	CABLE FIELD SPLICE SECTION	325'	R.H.T.	NONE	315.7
1	5765	CABLE FIELD SPLICE SECTION	300'	R.H.T.	NONE	291.6
1	5764	CABLE FIELD SPLICE SECTION	275'	R.H.T.	NONE	267.6
1	5763	CABLE FIELD SPLICE SECTION	250'	R.H.T.	NONE	243.5
1	5762	CABLE FIELD SPLICE SECTION	225'	R.H.T.	NONE	219.5
1	5761	CABLE FIELD SPLICE SECTION	200'	R.H.T.	NONE	195.4
1	5760	CABLE FIELD SPLICE SECTION	175'	R.H.T.	NONE	171.4
1	5759	CABLE FIELD SPLICE SECTION	150'	R.H.T.	NONE	147.3
1	5758	CABLE FIELD SPLICE SECTION	125'	R.H.T.	NONE	123.3
1	5757	CABLE FIELD SPLICE SECTION	100'	R.H.T.	NONE	99.2
1	5756	CABLE FIELD SPLICE SECTION	75'	R.H.T.	NONE	75.2
1	5755	CABLE FIELD SPLICE SECTION	50'	R.H.T.	NONE	51.1
1	5754	CABLE FIELD SPLICE SECTION	25'	R.H.T.	NONE	27.1
1	5840	CABLE FIELD REPAIR SECTION	5'	R.H.T.	L.H.T.	10.8

PARTS LIST - PRE-CAST CONCRETE FOOTING - OPTION #3

QTY	PART No	TITLE	Lbs / Each
1	5747B	SLEEVE CAP - CASS-TL POST	0.15
1	5836B	CONCRETE REINFORCING RING	0.88
1	33982G	27" POST SLEEVE - IN CONCRETE	14.48

PARTS LIST - CONCRETE FOOTING IN MOW STRIP OR PAVEMENT

QTY	PART No	TITLE	Lbs / Each
1	5747B	SLEEVE CAP - CASS-TL POST	0.15
1	33968G	15" POST SLEEVE - CONCRETE POST	8.00

PARTS LIST - CASS-TL3 POST - IN DRIVEN SLEEVE - POST OPTION #6B

QTY	PART No	TITLE	Lbs / Each
2	5700B	CASS & TL3 CABLE SPACER	0.11
1	5707T	CASS-TL - POST STRAP	0.23
1	5708B	SLEEVE COVER - CASS-TL POST	0.11
1	5724B	CASS-TL POST CAP	0.17
1	33953G	CASS-TL3 POST - CONCRETE	29.36
1	33976A	30.75" CASS-TL3 POST SLEEVE w/ SOIL PLATE	30.09

Figure 73. Trinity CASS TL-3 S-Post System Details [39]

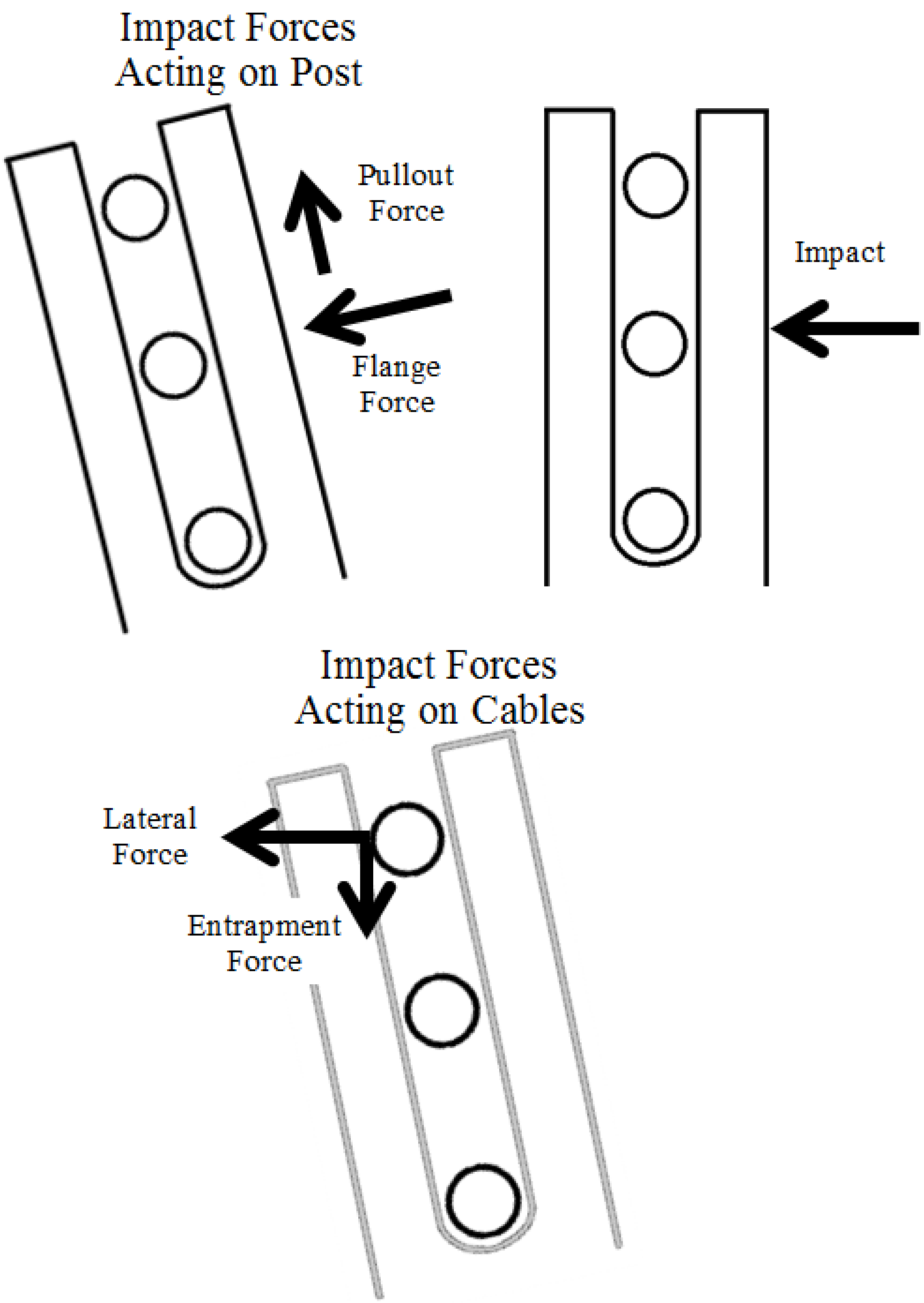


Figure 74. Entrapment Forces Acting on Cables in Center Post Slot

8.1.3 Brifen TL-3 Wire Rope Safety Fence (WRSF)

The TL-3 Brifen WRSF is typically comprises proprietary Z-posts with rollers supporting the cables vertically, as shown in Figures 75 through 77. Virtually all Brifen systems utilize ground sockets for easy post replacement, though a post with soil plate option was also available. Four cables are used in the system, with one cable woven around the posts and mounted at 19 ½ in. (495 mm), two cables cross-woven and mounted at 26 in. (660 mm), and an additional cable in a slot cut in the top of the post, mounted at 28 ⅜ in. (720 mm).

Typically, plastic retainer caps were used to retain the top cable in the Brifen WRSF. Other cables were constrained by the interaction with adjacent posts. For each of the middle and lower cables, vertical rise was only resisted by friction, whereas the lower roller supported the cable from being pushed down by the impacting vehicle. Because of the cable weave, the Brifen cables often sagged after a moderate-speed crash into the system in which more than two posts were disengaged from the cables. The weave significantly reduced average dynamic deflections and provided a smooth ridedown deceleration, but the system was susceptible to underride penetrations. Rollovers were sometimes associated with wheel entrapment by the lower woven cable. Underride penetrations were frequently caused by vehicles prying the bottom cable upward. This was because the bottom cable had low resistance to vertical uplift. These factors will be discussed in greater depth in Chapters 9 and 11.

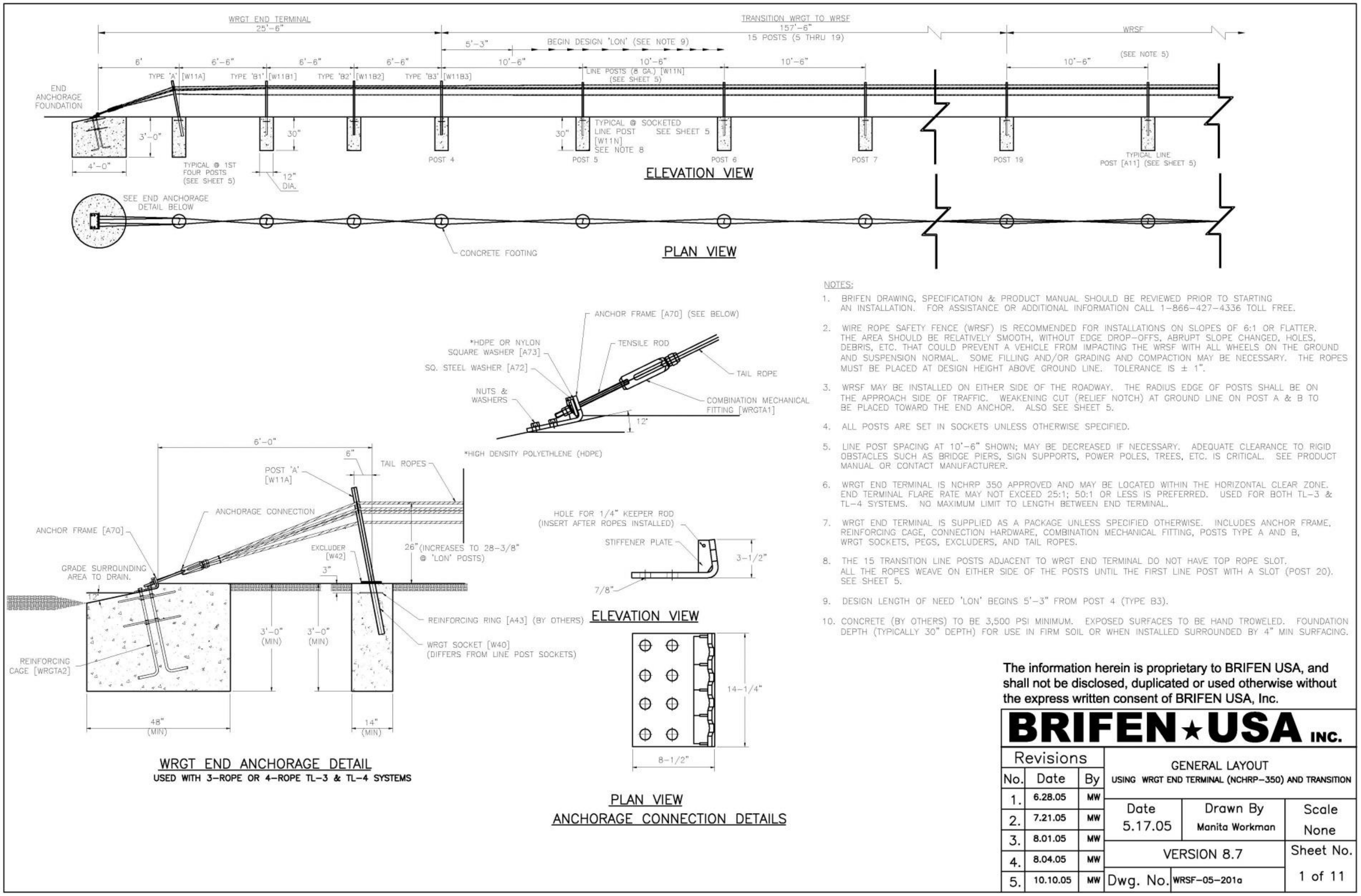


Figure 75. Typical TL-3 Brifen WRSF Design Details [40]

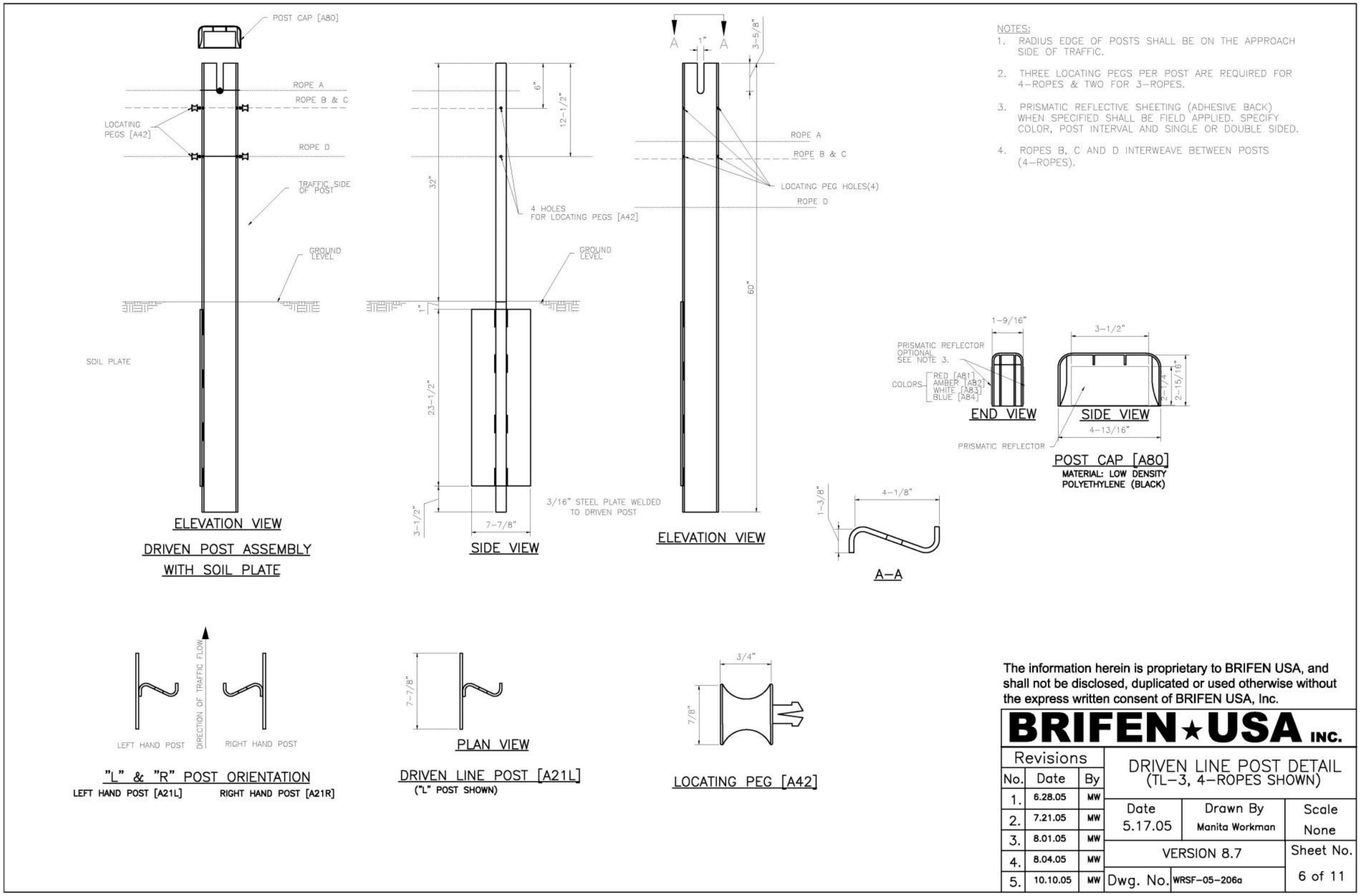


Figure 76. Typical TL-3 Brifen WRSF Design Details [40]

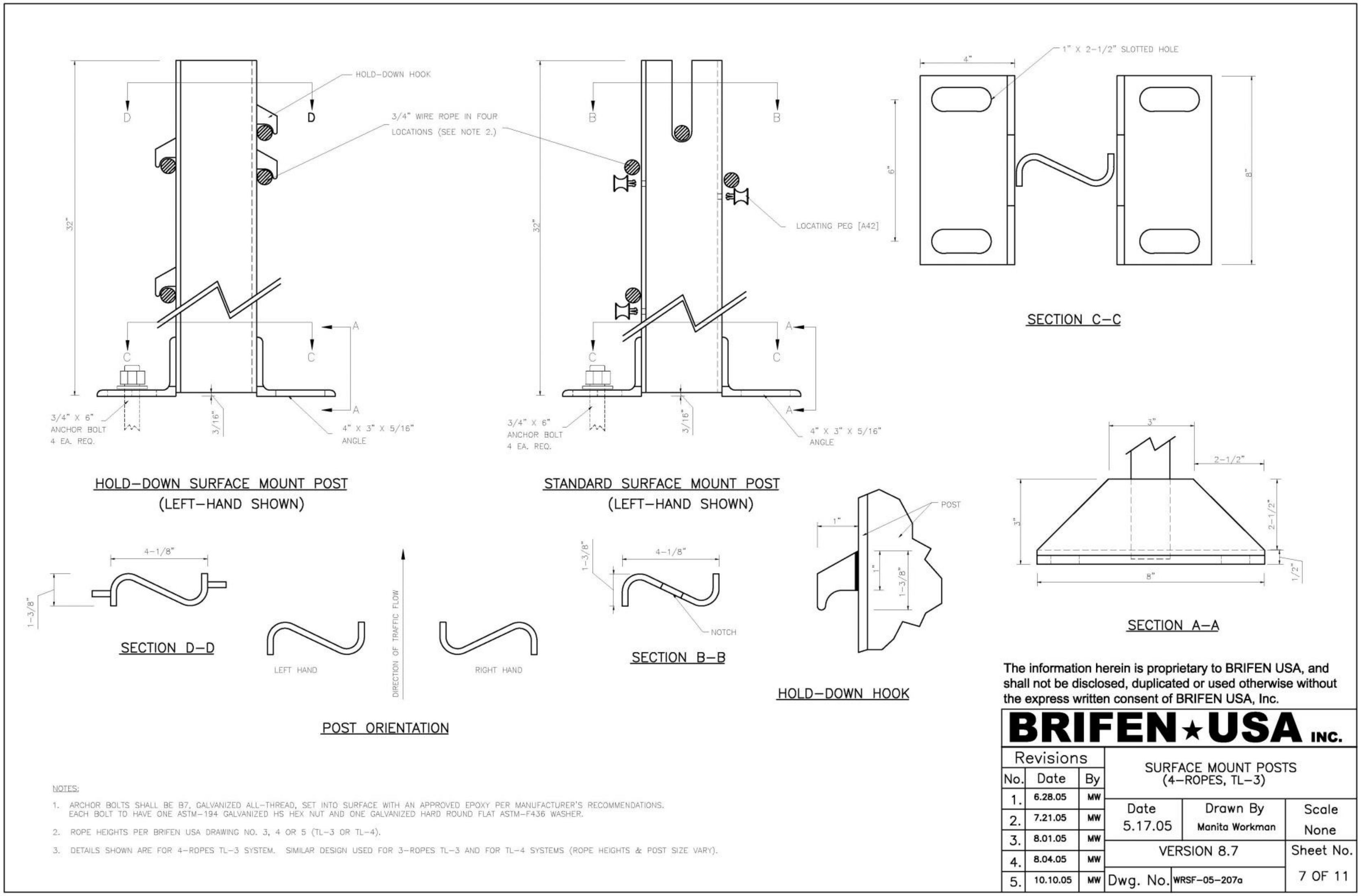


Figure 77. Typical TL-3 Brifen WRSF Surface-Mounted Post Design Details [40]

8.1.4 Low-Tension, 3-Cable Median Barrier

Several low-tension, 3-cable median barrier designs have been tested and were originally approved by FHWA according to TL-3 crash conditions in NCHRP Report 350. One low-tension, non-proprietary 3-cable median barrier was developed through testing and evaluation by several state DOTs, including New York and Washington [e.g. 41-42]. Several other states have installed many miles of low-tension cable median barrier, and in North Carolina and Missouri, the combined length of barrier exceeded 1,400 miles (2,253 km). It was estimated that the low-tension, non-proprietary 3-cable median barrier currently accounts for more than 40% of the cable median barrier mileage installed in the United States, though the exact percentage is unknown.

The low-tension, 3-cable median barriers installed in Missouri, Washington, and North Carolina were very similar. Examples of the North Carolina's low-tension, 3-cable median barrier standard plans implemented in 2002 are shown in Figures 78 through 83. In each of the low-tension, non-proprietary designs, tension spring compensators were used to retain tension in the cables during very warm weather and to prevent excessive tension increases during very cold weather. The cables were tensioned to between 900 and 950 lb (4.0 to 4.2 kN) at approximately 70º F (21º C), and frequently used wedge splitter cable splice connections, as shown in Figure 81. End anchors for these designs frequently used the end terminal developed by New York, which was approved under the guidelines presented in NCHRP Report 350 [43]. North Carolina later modified the standard cable median barrier plans in 2006 to address penetration concerns after conducting some performance improvement studies [44].

8.2 Overview of Crash Data

Based on the statistical analysis presented, the crash data were analyzed individually and crashes were categorized by system type. The types of containment failures in each cable median barrier crash were determined using scene diagrams, narratives, vehicle damage indications, and photographs when available. When the cause of the penetration crash could not be identified, the case was identified as Unknown.

A total of 213 crashes with determinable causes of penetration were identified. Seven primary causes of vehicular penetrations were identified and tabulated, and are shown in Table 32. One of the categories, "Large Vehicle", included all medium to heavy truck crashes, including single-unit trucks, buses, tractor-trailers, construction vehicles, and other vehicles which are not typically used in a cable barrier full-scale crash testing program for TL-3 impact conditions. However, because this type of failure was linked primarily to vehicle type, penetrations involving large vehicles were easily linked and virtually no large vehicle crashes were included in the "Unknown" category. As a result, these types of crashes were disproportionately identifiable relative to the other crash types.

The failure causes shown in Table 32 were not intended to demonstrate relative frequencies of penetration crash types between systems. Many of the penetration crashes did not have determinable causes. The purpose was to demonstrate the types of failures which were discernible per each system type to observe general trends in the data. Unfortunately, systems such as Gibraltar and Brifen had very few discernible causes of penetrations due to the lack of available scene diagrams and data about penetrations.

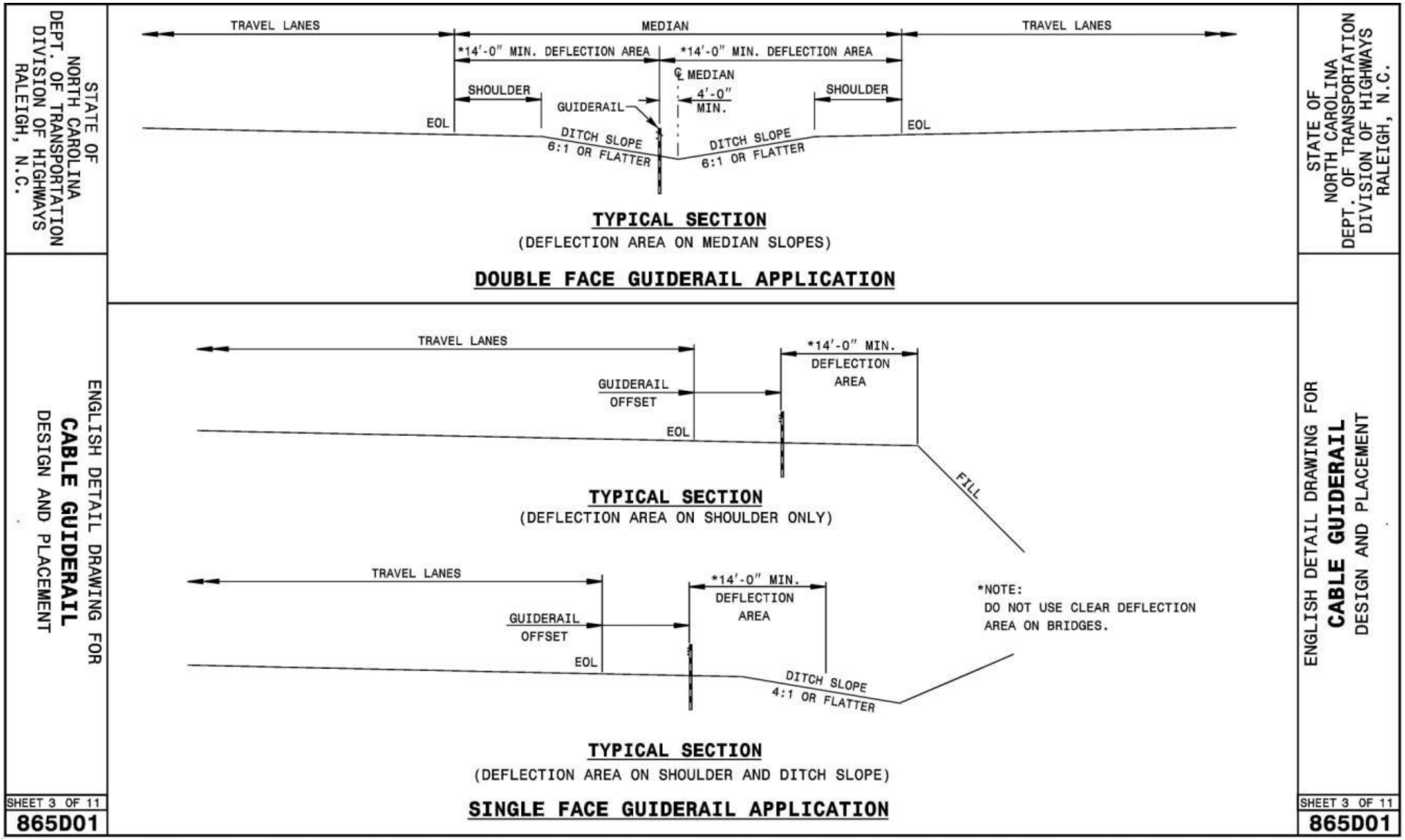


Figure 78. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002

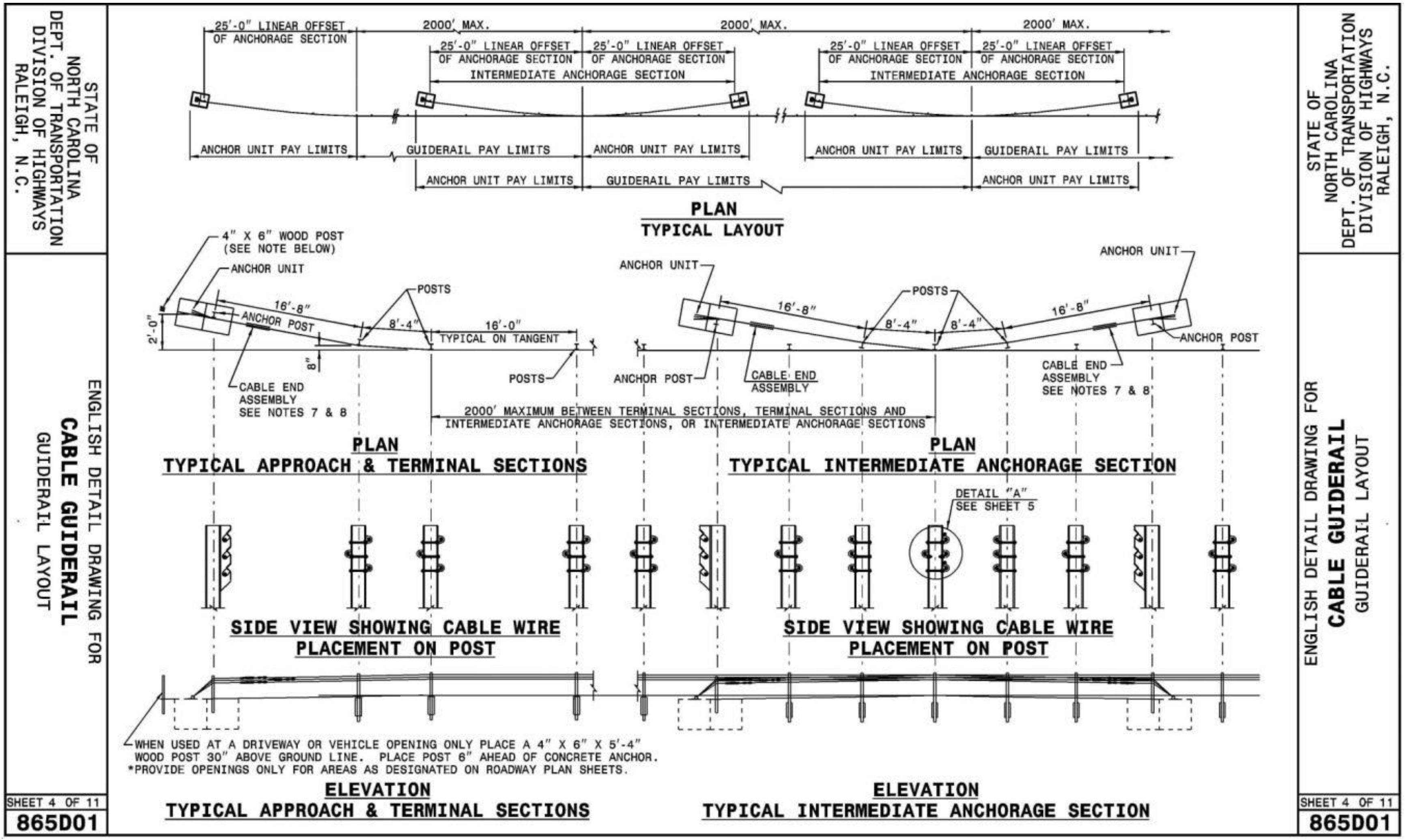


Figure 79. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002

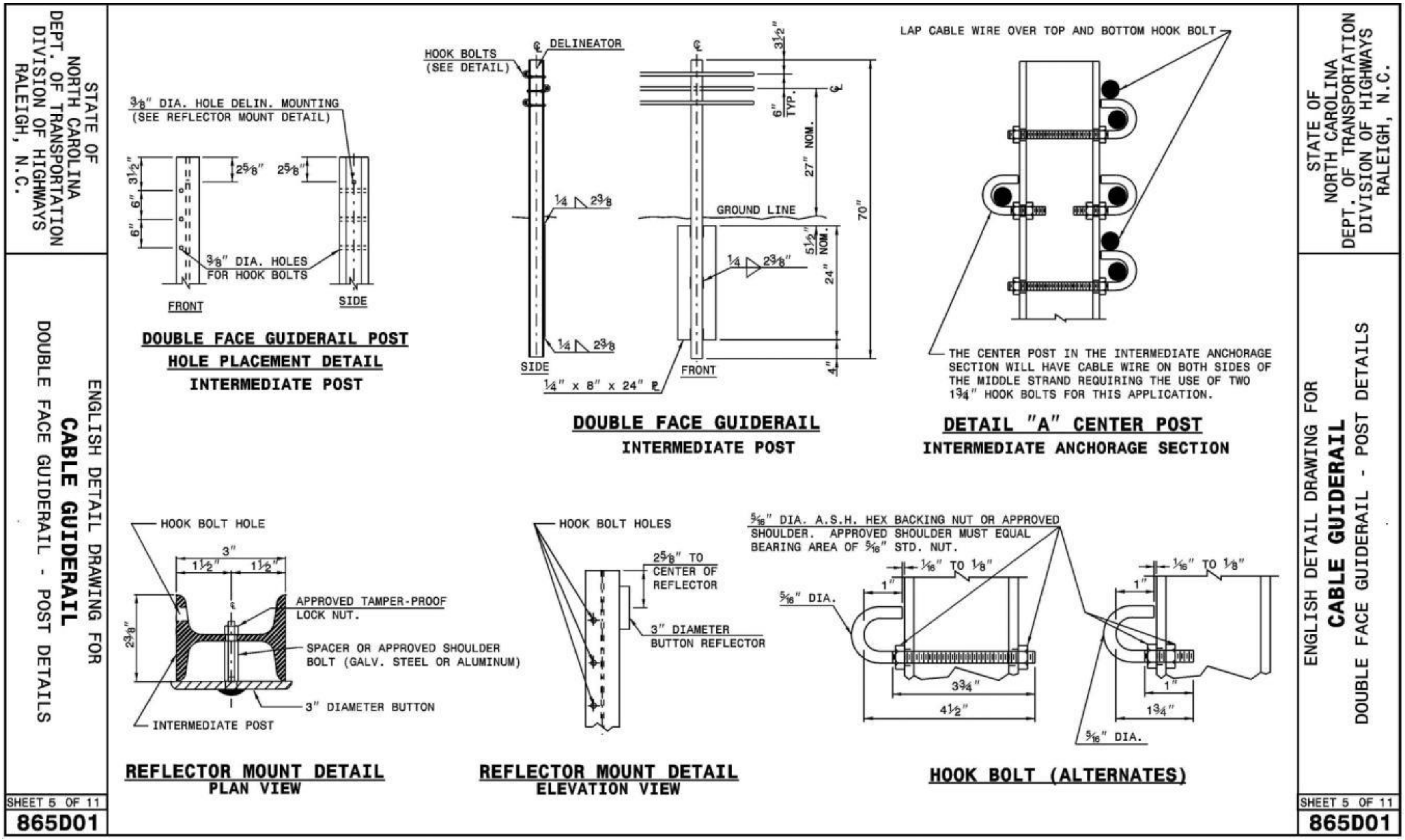


Figure 80. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002

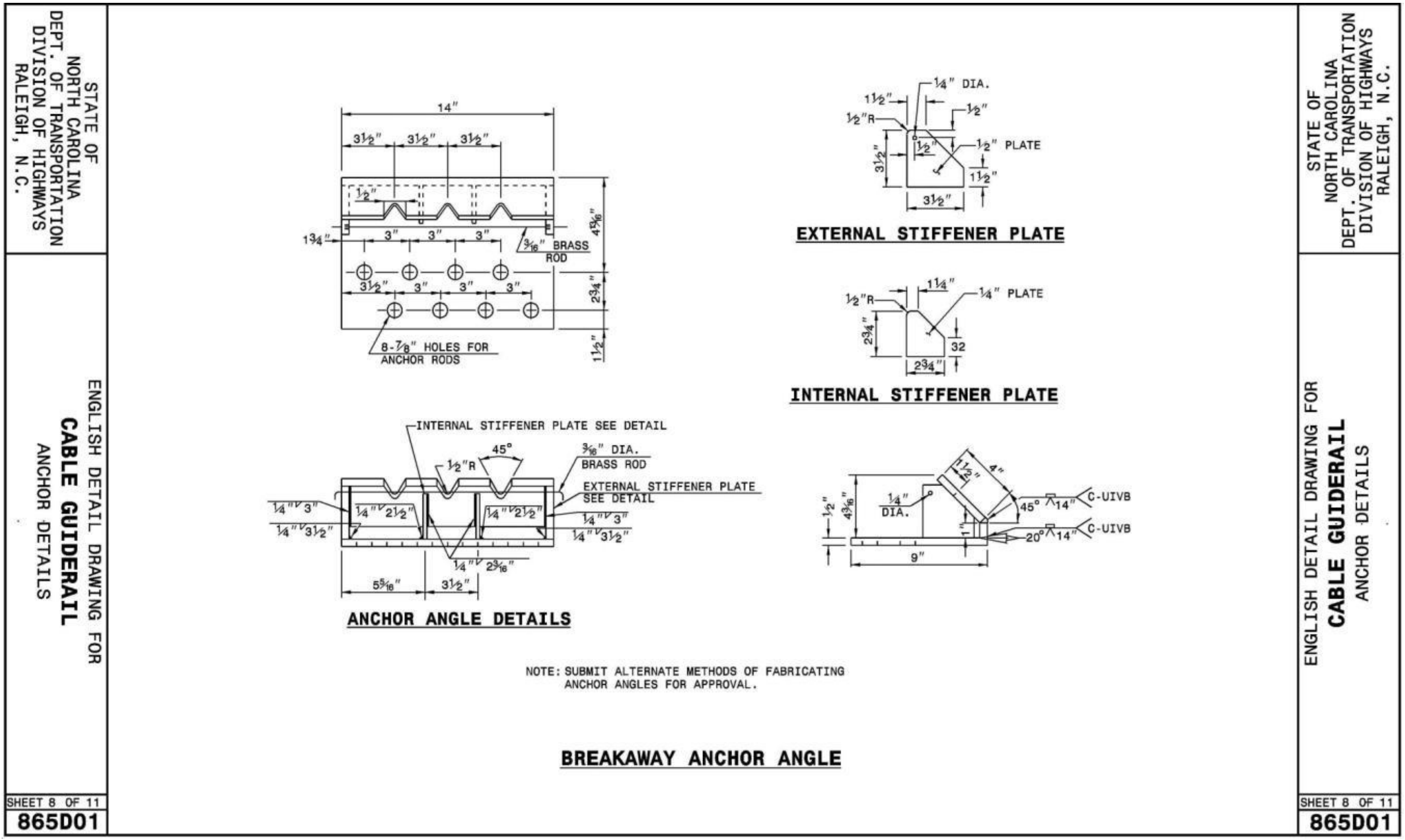


Figure 81. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002

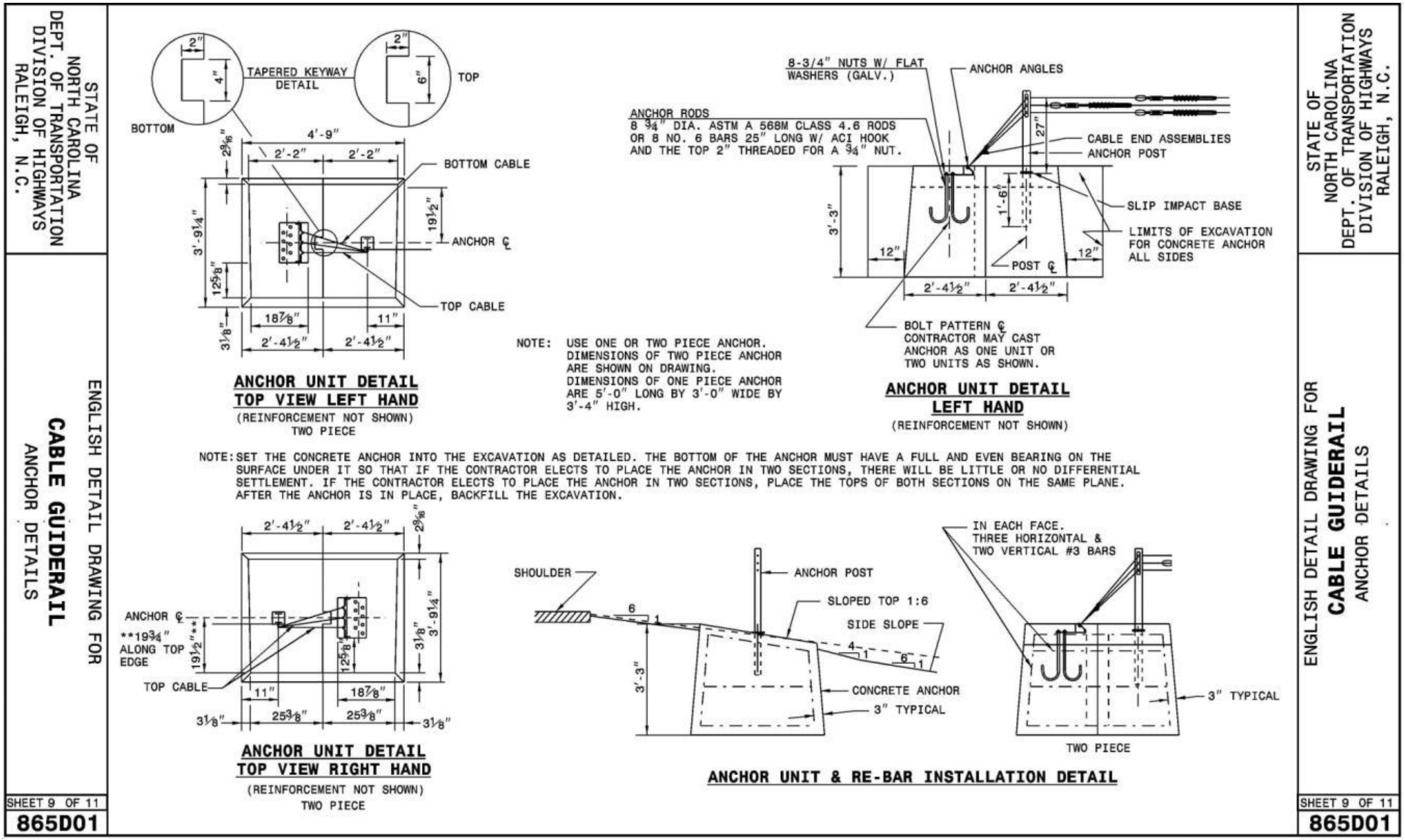
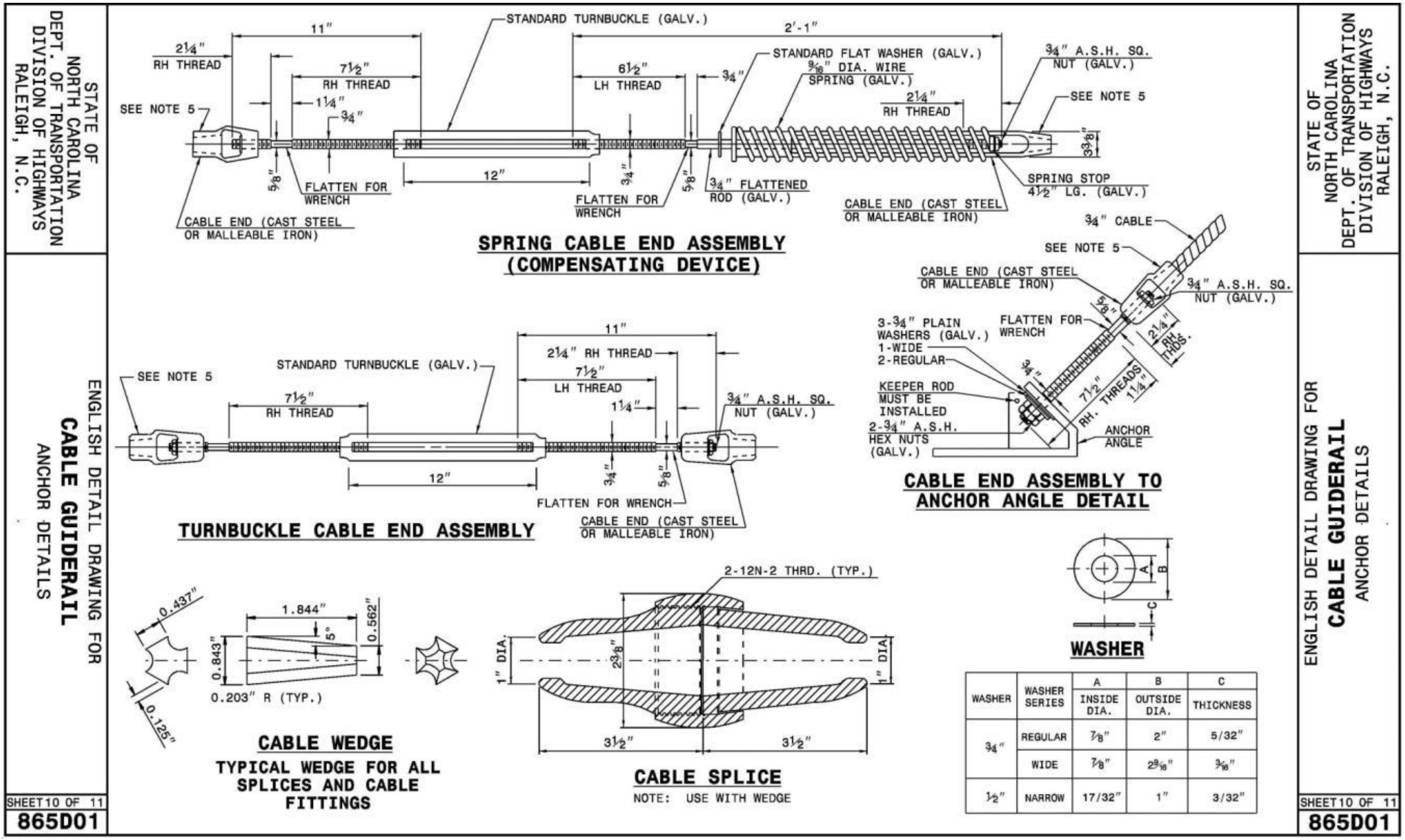


Figure 82. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002



WASHER	WASHER SERIES	A INSIDE DIA.	B OUTSIDE DIA.	C THICKNESS
3/4"	REGULAR	7/8"	2"	5/32"
	WIDE	7/8"	2 9/16"	3/16"
1/2"	NARROW	17/32"	1"	3/32"

Figure 83. Low-Tension 3-Cable Median Barrier Standard Plans, North Carolina DOT, 2002

Table 32. Causes of Penetrations

Penetration Contributor	Description	Number of Penetrations Recorded					
		Nucor	CASS	Brifen	Gibraltar	Generic	**Total**
Diving	Front end of vehicle protrudes beneath cables and lifts cables up and over the hood. This condition is most common with passenger cars.	10	2	1	1	22	**36**
Prying	Vehicle protrudes between or below cables and pries the cables away from the system due to the slope of the vehicle body, resulting in either underride or through-cable penetration.	20	26	5	1	30	**82**
Override	Wheels of vehicle pass over the top of the cables, forcing them below the undercarriage. This category includes launching but excludes rebound off of slopes which causes override.	27	26	1	-	8	**62**
Bounce-Over	Specific to rebounding off of slopes; vehicle strikes ditch and rebounds up and over the barrier due to suspension compression and unloading.	-	2	-	1	1	**4**
System Failure	Penetration caused by a breakdown of system components, design, or installation, either releasing tension in the cables or eliminating post contributions.	-	-	-	-	2	**2**
Large Vehicle	Tractor-trailers, buses, large trucks, camper vehicles, and construction vehicles. No cable barrier is currently designed for these types of impacts; however, these impacts are frequently severe.	5	7	-	1	8	**21**
Total		**62**	**63**	**7**	**4**	**71**	**207**

Furthermore, many states had a significant number of miles of one particular barrier type installed. This contributed to some additional uncertainty due to roadside design practices utilized in each state. For example, median widths in Ohio routinely exceeded 50 ft (15.2 m), and barriers on relatively shallow slopes were typically installed either at or near the center of the ditch or near the shoulder slope break point. As a result, very few crashes would result in a “bounce-over” type of failure, since “bounce-over” crashes involve vehicles rebounding vertically after bouncing on changes in the median slope.

Similar constraints affected the Brifen system overall. The only crashes applicable in this study involved barriers located in wide medians or adjacent to shallow slopes, effectively eliminating any opportunity for a “bounce-over” impact to occur. Although no “bounce-over” impacts were observed on the Brifen, Gibraltar, or Safence systems, there is currently no proprietary or non-proprietary design which is not susceptible to “bounce-over” failures.

Most of the impacts in the database occurred with 3-cable barrier variations of each system type, with standard hardware and cable spacing. A total of 18 crashes occurred in the state of Ohio with a 4-cable Nucor barrier, which was the only TL-4 system involved in crashes which had available scene diagrams and supporting photographic evidence to determine the causes of failure. Two penetrations and two rollovers occurred in two crashes on this system. In one crash, barrier penetration contributed to a rollover. In a separate crash, the rollover caused the vehicle to override the barrier.

Although the causes of barrier containment failures were mutually exclusive, contributing factors to the failures were not. Contributing factors included: system-dependent factors, installation-dependent factors, and vehicle-dependent factors. Of these domains, the system-dependent and installation-dependent failures will be discussed in detail in Chapter 9. A brief summary of typical conditions associated with each type of penetration factor is provided below.

8.3 Types of Penetrations

8.3.1 Diving Penetrations

Diving-type penetrations were defined as crashes in which the median geometry caused suspension compression, causing the leading edge of the vehicle bumper to dive below the bottom cable and lift all of the cables above the bumper and onto the hood. Diving penetrations were characterized by mechanical levers: once the impacting corner of the vehicle protruded under the cables, prying action through the longitudinal axis of the vehicle lifted the cables up in the same manner as a small force on a rod at a sufficient distance can lift or displace a boulder.

Diving failures were not restricted to particular vehicle classes. Examples of vehicle makes involved in diving crashes included a Saturn Aura, Mitsubishi Galant, Ford Fusion, and Ford Mustang. These vehicles did not conform to any identifiable front-end patterns except that the height of the leading edge of the hood was not "large," or was below approximately 27 in. (686 mm) in each case when the vehicle was at rest. Other underride penetration types were heavily dependent on the geometry of the impacting vehicle.

8.3.2 Prying Underride Failures

In prying-type underride penetrations, cables were pried up above the hood, thus allowing the vehicle to pass under the cables. The prying differentiation was used to separate crashes which did not heavily depend on median terrain; any underride containment failure occurring on a flat shoulder adjacent to the travel lane was therefore a prying-type penetration. Prying underride penetrations had a strong correlation with the orientation angle and vehicle shape.

Prying penetrations were analogous to mechanical wedges, which can split logs when struck with enough force. Analogously, for low-angle prying events, the prying action is similar to a "seesaw," in which a small child located far from the fulcrum can lift an adult. Similarly, the motion of the rear of the vehicle can cause prying on the front corner to lift the cables, or vice-versa. Both diving and prying penetrations shared similar failure mechanisms. However, median geometries and vehicle types varied widely between the two containment failure datasets, prompting researchers to treat each type independently.

Non-tracking skid crashes, in which the entire side of the vehicle was engaged with the cable barrier, frequently resulted in adequate vehicle capture and low risk of rollover. Conversely, engagement along the front or rear planar surfaces of the vehicle frequently resulted in penetrations.

During high-orientation angle impact conditions, the vehicle engaged the barrier in a condition which may promote cable separation, lifting, or compression. The increased risk to impacting vehicles was due to a combination of the following factors: (1) higher front-end and rear-end stiffness prevented the cables from creating "furrows" or grooved contact patches on the vehicle, which tended to retain the cables throughout impact; (2) the "approximate equivalent" vehicle profile which came into direct contact with the barrier system changed; and (3) vertical motions of the front or back of the vehicle were exaggerated relative to cable motion at orientation angles approaching 90 or -90 degrees.

8.3.3 Bounce-Over Penetrations

A bounce-over penetration was a specialized crash event in which the impacting vehicle rebounded off of a median slope and passed over the top of the barrier system. This type of crash is more common with smaller passenger vehicles since large vehicles more frequently "dig in" to the medians and either roll over or are captured by the barrier.

Bounce-over crashes occur most commonly on medians steeper than 8:1; most bounce-over crashes occurred on medians between 6:1 and 4:1. Medians which are in this steepness range are often used to facilitate large rain runoff from the road; as a result, many medians have moist or wet soil through much of the year, even in dry climates. The softer median terrain does not facilitate bounce-over for larger vehicles since a large amount of soil is typically displaced after a heavy vehicle engages the slope. Soil displacement dissipates much of the energy which contributes to "bouncing." Smaller vehicles, which frequently have much lower pitch and yaw inertias and overall masses, bounce due to median impact without displacing much soil. This is why frequently only small to mid-size cars were engaged in bounce-over impacts in this crash database.

8.3.4 Override Penetrations

Override penetrations corresponded to a vehicle passing over the top of all of the cables before passing to the non-impact side of the cable median barrier. Note that "bounce-over" crashes, in which the impacting vehicle rebounded off of the median slope and passed over the barrier, were segregated from override penetrations due to median slope contributions.

Override crashes occurred due a combination of factors including vehicle profile shape, vehicle orientation angle at impact, cable entrapment at a post, ramp formation, or excessive cable sag. Of these possibilities, cable entrapment, ramp formation, and vehicle orientation at impact were the most common causes. Virtually every large ½-ton or ¾-ton pickup truck class has a rear end bumper height which is approximately 3 to 5 in. (76 to 127 mm) higher than in the front. Since many cable median barrier systems have a top cable mounting height less than 35 in. (889 mm), many rear-leading pickup and large SUV crashes resulted in penetration that likely would have been adequately captured if cable barrier systems were taller or if the vehicle had struck with the front end. MASH crash testing with the 2270P vehicle could demonstrate this type of behavior.

8.3.5 Low CG Trajectory Angle Penetrations

A broad class of penetrations that spanned multiple penetration mechanisms consisted of low-CG trajectory angle crashes which resulted in penetration. Low-angle impacts leading to barrier penetration occurred on every barrier make. According to the results of NCHRP Report No. 665 [22], approximately 55% of all run-off-road crashes occurred with CG trajectory angles less than or equal to 15 degrees. Due to the difficulty in determining when a penetration crash occurred, it is likely that the number of low-angle penetrations is underrepresented in the penetration crash database.

Low-CG trajectory angle penetration crashes frequently occurred concomitantly with contributions cable entrapment on posts, front-end profiles and bumper heights which increased susceptibility to penetration, and low energy associated with the lateral component of velocity (IS value energy) available for stable crush to occur. Barrier-specific interactions also contributed to penetration propensity. Both override and prying underride penetrations occurred at low CG trajectory angles.

The risk of severe crash result associated with this containment failure was dependent on multiple factors. If the low-CG trajectory angle crash resulted in penetration when the barrier was installed on the traffic-side shoulder or approach slope, the vehicle entered the median. Then, the vehicle could enter the opposing lanes, come to rest in the median, or redirect toward the initial travel lanes. Crashes in which the vehicle came to rest were not severe in general, whereas moderately low-angle cross-median trajectories were frequently severe but relatively uncommon. When the barrier was installed near the center of the V-ditch, vehicles involved in low-angle penetration crashes nearly always came to rest in the median.

Roof crush was a major contributor to severe low-CG trajectory angle penetration crashes. Vehicles which became entrapped beneath the cables were frequently at a higher crash severity risk than vehicles which either completely penetrated beneath the system or were redirected. Low-CG trajectory angle penetrations did not occur on systems located on the back side of median slopes, but did occur when the barrier was installed on the opposite-side shoulder.

8.4 Approximate Equivalent Vehicle Profile

Penetration crashes into high-tension cable median barriers shared many common characeristics. Narrow-profile vehicles or vehicles with smooth front ends alter the expected interaction between the vehicle's front end and the cable barrier during high-orientation angle crashes. As the orientation angle approached either 90 or 270 degrees to the barrier system, differences arose as the vehicle engaged the cable barrier system with the entire front or back surface instead of a concentrated impact at a corner. Impacts occurring along vehicle corners could be analyzed as a wireframe object with corresponding mass as well as roll, pitch, and yaw moments of inertia impacting the cable barrier. Front- or rear-leading impacts instead engaged the cable barrier with an entire surface, which engaged the barrier with a contour corresponding to a cross-section of the vehicle at a given time. This concept is illustrated in Figure 84.

The observation of the differences between impact orientations gave rise to the concept of an approximate equivalent vehicle concept, which consisted of a block striking a string in a two-dimensional plane. If the block strikes the strings with an orientation angle other than 0, 90, 180, or 270 degrees, contact will be made along a leading edge, and the tensioned string will remain engaged with leading edge until the block redirects and contact is made with the trailing edge. Prying underride penetrations occurred when the leading edge contact caused cable separation or lifting. If the vehicle orientation at impact was 0, 90, 180, or 270 degrees, an entire surface contacted the cable. Rounded or smooth vehicle front-end surfaces caused separation or lift when impact occurred near the midspan. This susceptibility was amplified when crashes involved vehicles with aerodynamic, sharply-contoured front ends. Large vehicles were also sometimes able to push the cables down and override the barrier if bending waves propagating through the cables caused the cables to disengage from the front bumper.

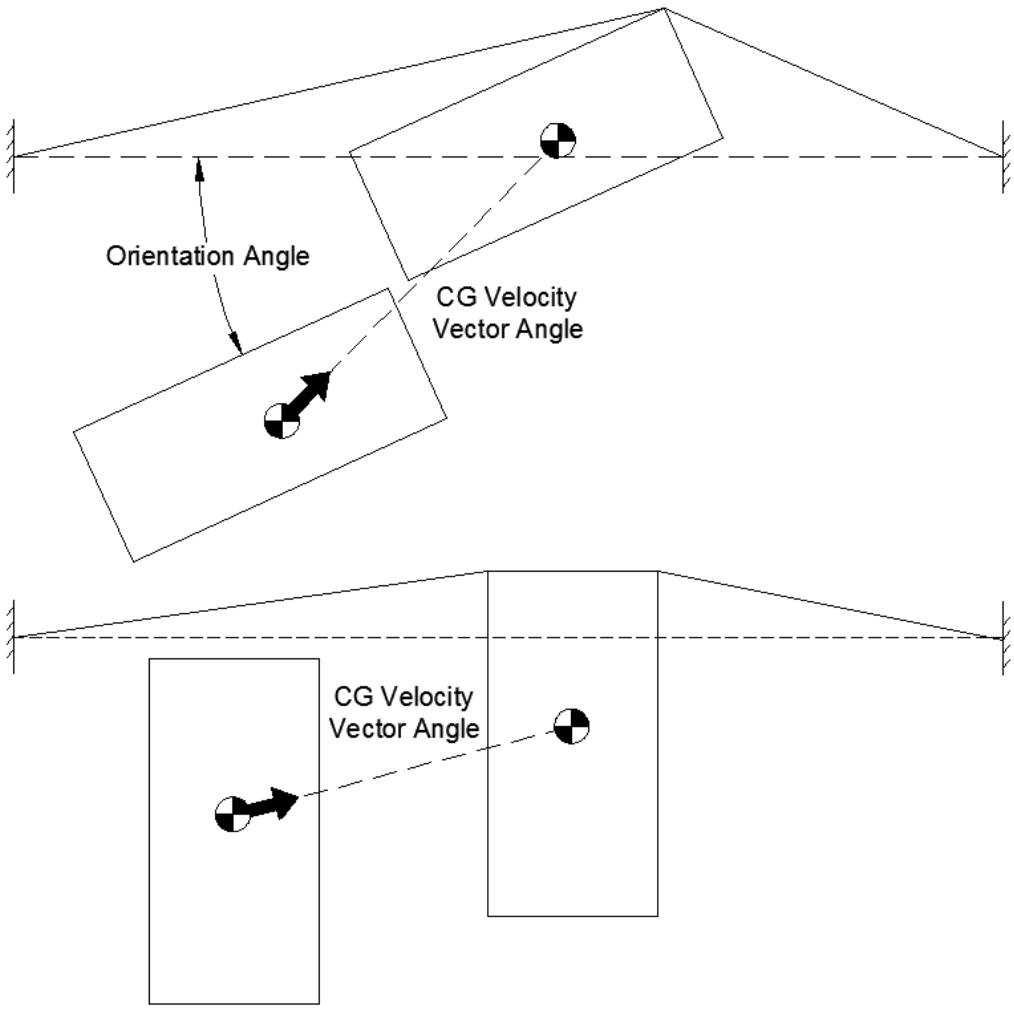


Figure 84. Approximate Equivalent Vehicle Profile Concept

The major difference associated with the performance in high orientation angle crashes near 90 or 270 degrees was that contact was distributed. With non-localized contact along the entire front or rear of the vehicle, contact pressure was distributed and local contact forces were low. Cable barrier systems are tension systems which have a lateral force-deflection curve only dependent on the total force acting over a given span. Thus, for the same lateral deflection of the cable, the reduced contact force resulting from distributed pressure did not surpass the elastic limit of the front-end components on the vehicle. Elastic deformations were negligible in comparison with cable barrier deflections. Thus, vehicle reacted similarly to a rigid body, and lifted cables above the bumper and hood, separated the cables and allow the vehicle to penetrate through, under, or over the cables, depending on the shape of the vehicle’s front end.

8.5 Cable Tension and Dynamic Deflection

As discussed in Chapter 5, there was an increased risk to occupants of errant vehicles in any high-tension cable median barrier crash that appeared to be associated with the higher tension in the cables. Although higher cable tensions do tend to reduce dynamic deflections, the effect was not as pronounced as many engineers have assumed previously. Dynamic deflections in tests conducted on cable barrier systems, including roadside systems, were plotted by against impact severity. Impact severities were derived from crash test results submitted to FHWA for eligibility status for use on the NHS, as well as testing agency reports. Results were included through 2010 and are shown in Figure 85.

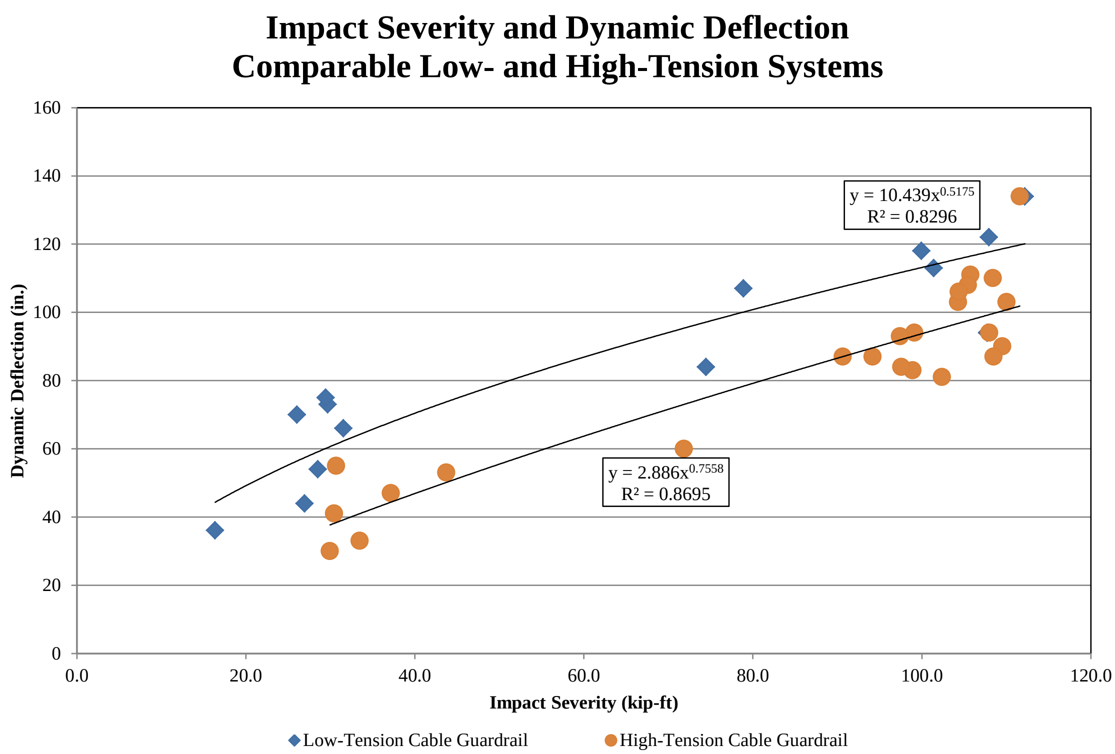


Figure 85. Dynamic Deflection Comparison, Low- and High-Tension Cable Barriers

As shown in Figure 85, at IS-values below 40 kip-ft (54 kJ), high-tension barriers exhibit up to a 33% reduction in dynamic deflection compared to low-tension cable barriers. However, the difference in dynamic deflection between low- and high-tension cable barrier systems was approximately 15% with an IS value of 102 kip-ft (138 kJ). This IS value is typical of the standard impact condition for TL-3 impacts using a 2000P test vehicle according to NCHRP Report 350. Reported rates of dynamic deflections were always higher than the 15% average determined from full-scale crash testing. It should be noted that the high-IS value crashes with high-tension cable median barriers very closely corresponded to, and occasionally intersected, the approximate deflection curve from low-tension crashes; the primary "benefit" of high-tension dynamic deflection reduction occurs at low IS-value crashes. This low-IS value benefit is likely the result of decreased post spacing and total cable system lengths less than 300 ft (91 m) in many of the high-tension cable median barrier systems. However, the low-tension systems exhibited much lower average crash severity than high-tension systems, which may be correlated with the lower cable tension.

Reasons that higher cable tensions do not produce a substantially lower dynamic deflection at high IS values include the following: (1) most high-tension cable barrier systems used weak, proprietary posts which were not as strong in strong-axis bending as S3x5.7 (S76x8.5) posts used in low-tension cable barrier systems; (2) higher tension on the cables produced a lateral redirective force with an approximate correlation to the sine of the angle formed between the deflected cable and adjacent supports, meaning weaker adjacent posts cannot sustain as much load as stronger posts used in low-tension 3-cable median barrier systems could and the cable deflection angle between adjacent posts was frequently less than in low-tension systems; and (3) higher-tension systems frequently redirected vehicles with fewer numbers of cables since the higher restorative forces in the cables tended to allow vehicles to override lower cables or slip under higher cables. While there was a tangible benefit to using higher-tension systems, the associated detriments must also be weighed in accordance with that decision.

8.6 Energetic Capture Concept

The increased risk of penetration due to high orientation angle had roots in classical physics and mechanics. The cable capture phenomenon was strongly related to energetic constraints during redirection. When vehicles engaged cable barrier systems with standard crash testing conditions, with both CG trajectory and orientation angles of 25 degrees, the front bumper corner absorbed the initial impact through headlight fracture and crushing of the front fender panels. As the fenders were crushed by the cables, local energetic minima were generated which tended to cause the cables to interlock with the vehicle. Cables which were engaged in those energetically-favorable crush locations would have to undergo additional stretch to climb out of the energetic minima around the crush. This same concept is utilized to maintain cables or wire ropes in sheaves and pulleys, which have flanges which require the cables to stretch in order to release. By the natural tendency to minimize potential energy, including strain energy, cables which engaged vehicle sheet metal and interlocked most commonly remained engaged until the vehicle was captured or redirected.

When vehicles impacted cable barrier systems with orientation angles approaching 90 or 270 degrees with respect to the barrier system, energetic constraints were altered. Localized crushing was typically reduced, preventing the energetic minima from being generated. As a result, the cables did not have a stable engagement with the vehicle and were only constrained by frictional interaction with the components, rather than a sheave-like groove. Unless intermittent locations of energetic minima were created (i.e., the grill cracking, headlights fracturing, hood lifting or prying, or the windshield or crown of the hood catching the cable), the cables frequently slipped up and over the vehicle. The large stiffness of the most vehicle front and back planes often prevented localized contact stresses from exceeding the elastic limit of the impacting components and prevent the initial capture engagement in some crashes.

Higher cable tensions further decreased cable response times and increased sensitivity to transverse wave motions. High-tension cables closely follow classical wave propagation equations for tensioned strings since the bending contributions become negligible compared to low-tension cables. As a result, wave speeds were functionally dependent on cable tension.

Bending waves caused cables to disengage from the impacting vehicle in some crashes. Higher CG trajectory angle crashes were also susceptible to these types of prying underride or cable-slip override phenomena.

8.7 Overall Discussion and Recommendations

As stated previously, low-tension, 3-cable median barriers had the lowest average rate of severe crashes and severe outcomes of all of the barrier types. Researchers postulated that this result was actually the culmination of multiple effects.

First, low-tension cable median barriers are frequently historical systems. Most low-tension cable median barrier currently installed in the United States were installed before high-tension cable median barrier systems became prevalent. Working knowledge of the barrier and the difficulties associated with mowing and ditch erosion around posts were also expressed in research reports and DOT experience as the prominence of high-tension cable median barriers increased. As a result, many state DOTs began to place high-tension cable median barrier adjacent to the travel lanes on the shoulders in the hope that the problems experienced by roadside maintenance crews could be mitigated. Additionally, barrier placement on shoulders frequently improved ease of repair by maintenance crews since the workers were able to park vehicles in the median and repair the system at a safe distance from adjacent traffic.

However, crash severity is strongly correlated with the associated IS value at impact. Although systems in median centers experienced a higher frequency of crashes with high CG trajectory angles, the speeds of the crashes were almost always lower than when barrier systems were located on the shoulders adjacent to the roadways. This fact was particularly evident when comparing crash results of states with widely-varying median configurations. In Utah, median barriers were commonly installed at 1 ft (0.3 m) or not less than 8 ft (2.4 m) from the center of the V-ditch but as far from the travel lanes as possible, per Utah installation standards. Utah's large separation distance between the cable barrier and the travel way contributed to the lowest rates of A+K crashes compared to other aggregate severities of high-tension cable barrier installations in other states. However, frequent wet or snowy weather in the Interstate 15 corridor also contributed to lower-speed and lower-angle crashes, which also reduced crash severities. Conversely, in both Wisconsin and Washington, similar systems were frequently installed on barrier shoulders since medians were steeper and narrower to accommodate increased drainage and narrower right-of-ways. In both of these states, the crash severity on the same barrier type was considerably higher than in Utah. These effects had never been previously documented, and all three states were acting in compliance with the state-of-the-art in cable barrier installation practices and recommendations made by transportation safety agencies. Furthermore, many miles of the system with the same shape of posts, same types of connections, and similar speed roadways adjacent to the system minimized individual discrepancies which could occur.

An analysis of the median data in Ohio indicated that, although penetration propensity increased to more than 17% when barriers were located within 4 ft (1.2 m) of the center of the V-ditch, crash severities were lowest when barriers were placed near the center of the ditch verses on traffic-side shoulder, opposite-side shoulder, approach slope, or back slope. In fact, penetration propensity was nearly twice as large when barriers were installed near the center of the ditch compared to anywhere else in the median. One exception was the traffic-side shoulder, which had a penetration rate nearly equal to the penetration rate of the barriers installed near the center of the median. Yet the percentage of serious injury and fatality crashes for barriers in median centers was less than half as large as when the barrier was installed anywhere else in the ditch.

In addition, nearly all severe crashes near the center of the median were caused by penetrations, occasionally resulting in cross-median crashes or rollovers. If penetration crashes can be prevented when cable median barriers are placed in ditch centers, the potential to reduce severe crash risk is very high. The results of the Ohio evaluation are shown in Table 33.

A chi-squared test was conducted on the severe crash, penetration, and rollover data, and the results were significant at the 10% confidence level; given the size of the data set at 857 crashes, the result should be interpreted as very significant since the data set is small with respect to A+K crashes.

Table 33. Ohio Cable Median Barrier Location Severity and Crash Result

Barrier Location	Crashes	Penetrations	Rollovers	A+K Injuries
Shoulders (Either Side)	20	20.0%	5.0%	15.0%
Traffic-Side Slope	485	8.5%	4.3%	4.5%
Within 4 ft of Ditch Bottom	*123*	*13.8%*	*2.4%*	*0.8%*
Opposite-Side Slope	229	8.3%	4.4%	3.5%
All Traffic-Side Crashes	494	8.7%	4.5%	4.9%
All Opposite-Side Crashes	240	8.8%	4.2%	3.8%
All Crashes Not in Ditch Center	734	8.7%	4.4%	4.5%
All Crashes	857	9.5%	4.1%	4.0%

Penetration and rollover crashes increased risk to occupants of errant vehicles compared to low-tension systems. However, penetration and rollover crashes typically constituted less than 55% of all severe cable median barrier crashes. Based on this finding, if penetration and rollover crash risks could be completely mitigated, many other severe crashes would still occur.

Ultimately, cable median barrier penetrations were caused by varied factors and were heavily dependent on barrier design. Therefore, changes in barrier design can lead to immediate reductions in the risk of penetration, as well as the rates of severe injury or fatality crashes. Based on the results of this study and the types of containment failures identified, improved barrier designs may be drafted, tested, and implemented. This could lead to the reduction of hundreds or thousands of severe injuries and fatalities.

9 PENETRATION CRASH ANALYSIS

9.1 Nucor TL-3 System on Flange Channel Posts

The Nucor NU-CABLE system was installed in many of the surveyed states, although the greatest quantity was in the state of Ohio. The most predominant causes of penetrations on the Nucor system were override events and prying crashes in which the vehicle pried cables upward and lifted them over the hood and bumper. Several crashes in which the strong cable-to-post attachments contributed to penetration containment failure occurred at CG trajectory angles much lower than are designated for full-scale crash testing in NCHRP Report 350 or MASH.

9.1.1 Override Penetrations

A total of 22 override penetrations were identified on the database of Nucor penetration crashes. Of these override crashes, 16 were linked to the strong cable-to-post attachment, 4 were due to vehicle launching over the barrier due to installation on a slope, and 2 penetrations were due specifically to the weak post-to-ground interaction. Photographs of the crashes were used to document failure types when available.

An example of a crash in which the strong cable-to-post attachments contributed to vehicular penetration through the barrier is shown in Figures 86 and 87. In this crash, an impacting pickup truck lost control due to slick roadway conditions and departed the roadway into the median. The CG trajectory angle was approximately 24 degrees, and the orientation angle of the vehicle at impact was approximately 110 deg. The vehicle impacted the cables and began to redirect. The first few impacted posts were pulled out of the ground as the pickup was redirecting, and the strength of the cable-to-post attachments retained the posts on the cables. Due to the high orientation angle at impact, the cables did not locally crush the fender at the front of the vehicle. Fender crush promotes good cable-vehicle interaction and was commonly associated with vehicular capture or redirection. Posts downstream from impact bent backward as the pickup truck progressed into the system. Because the cables remained attached to the posts as the posts fractured and bent at the ground line, cable heights were lowered relative to the vehicle. Eventually, the vehicle overrode the cables and struck the round wood posts on the back side of a W-beam guardrail system. Due to the high orientation angle of the truck, the posts acted as a tripping mechanism and the pickup rolled five quarter-turns.

Although the weak post strength and high vehicle orientation contributed to the penetration, the primary cause of the failure was due to the cable-to-post attachments which failed to release the cables. By preventing cable release, the posts were pulled out of the ground or fractured, which deposited the posts on the ground and lowered the cable heights in front of the bumper. This type of override penetration was therefore referred to as a “ramp formation” failure. If the cables had been released from the posts, cables would have remained engaged with the front of the vehicle.

The incident slope at the POI was 10.4:1, which was generally considered “flat” median terrain. Construction of the system was within recommended tolerance, and the vehicle bore a strong resemblance to the Dodge Ram pickup trucks used in many full-scale crash tests evaluating roadside hardware to MASH criteria. Other additional crashes occurred in which the

Figure 86. Penetration Crash Caused by Strong Cable-to-Post Attachment

Figure 87. Crash Result Due to Strong Cable-to-Post Connection

strong cable-to-post attachments caused override, but photographic evidence from those crashes was sparse.

A second example of the strong cable-to-post connection consisted of a combination of several component failures which culminated in the override penetration. Vehicle no. 1 hydroplaned on the roadway and struck an adjacent vehicle. The second vehicle swerved to avoid Vehicle no. 1 but was unsuccessful. After colliding with Vehicle no. 1, Vehicle no. 2 skidded into the median and struck a cable barrier, coming to rest on the opposite side of the system. Impact CG trajectory and orientation angles of Vehicle no. 2 were in the range of 10 to 15 degrees and 20 to 30 degrees, respectively. Unfortunately, a lack of vehicle trajectory photographs prevented more accurate photogrammetric techniques from being used to calculate the encroachment angles. Final vehicle orientation was approximately 205 degrees, relative to the vehicle's original travel direction. Crash photographs are shown in Figures 88 and 89.

The penetration event occurred due to a combination of the following three factors: (1) the posts were manufactured from high-strength, low-ductility steel, resulting in post fracture rather than bending at the ground line; (2) the cable-to-post attachments remained firmly attached to the cables, resulting in the accumulation of fractured posts in front of the vehicle; and (3) the top cable engaged the vehicle above the top of the bumper, but the large vertical resistance to cable disengagement from the post tore the bumper cover off of the vehicle. Based on the photographic evidence, it would appear that the bumper cover removal occurred early in the crash event, because no posts accumulated in front of the vehicle before the bumper cover was removed. Further, it is likely that the top cable engaged an opening between the bumper cover and the fender due to bumper cover deformation shortly after impact, snagging the bumper cover and retaining it in front of the vehicle for the remainder of the impact event.

The bumper cover disengagement from the vehicle is related to vehicle stiffness in the capture zone (CZ). The CZ refers to the front area of the vehicle between the upper bumper surface and the lower edge of the hood which is the predominant location intended for cable engagement with an impacting vehicle. The capture zone is generally composed of blunt surfaces concealing the radiator, the engine, and cavities in the body made for headlights and the wheel well. The CZ concept has frequently been invoked when discussing cable barrier placement in V-ditches and explaining both failures and successes of certain cable barrier systems.

Bumper cover disengagement resulting in vehicular penetration is a relatively rare event. However, the accumulation of fractured posts may be indicative of a systemic problem, because the post fractures during both redirection and penetration events, and post accumulation, were both widely observed.

Figure 88. Override Penetration Crash Caused by Strong Cable-to-Post Attachment

Figure 89. Override Penetration Crash Vehicle Final Position and Removed Bumper Cover

9.1.2 Prying Underride Penetrations

Through-cable penetrations were never identified for crashes involving the TL-3 Nucor NU-CABLE, flanged U-channel post cable median barrier system. All prying penetrations were caused by vehicle underride. Every Nucor prying underride penetration occurred with one of the following impact conditions: (1) a high orientation angle (typically a large oversteering angle) contributed to underride penetration because the bumper slid beneath the bottom cable; (2) small CG trajectory and orientation angles, combined with a downward slope in advance of the barrier, contributed to poor initial engagement of the impacting bumper corner; or (3) after redirection, the vehicle re-engaged the barrier at a low CG and orientation angle which then pried cables up before penetrating through the barrier. Vehicles involved in prying failures were either narrow-profile, sharp-nosed vehicles, such as the early 2000s-model Ford Taurus, or vehicles which had stiff, rounded back ends such as the Pontiac Grand Am and Grand Prix models.

Several examples of prying failures are discussed here in greater detail. In one prying-type crash, a 1999 Ford Taurus struck the Nucor 3-cable median barrier with CG trajectory and orientation angles of less than 10 degrees when the barrier was located at the edge of the shoulder. The vehicle remained in contact with the barrier for approximately 60 ft (18.3 m) before prying the cables above the hood and coming to rest in the median. No photographs were available for this crash.

In a second prying case, a 1994 Chevrolet Camaro impacted the Nucor system with a sideslip angle of approximately 90 degrees. Photos of the impact are shown in Figures 90 and 91. In this crash, the vehicle oversteered into the median to avoid contact with another vehicle on the road, and struck a TL-3 3-cable Nucor barrier system with 20 ft (6.1 m) post spacing. The CG trajectory angle at impact was approximately 32 degrees, and the heading angle was approximately 118 degrees. The vehicle yawed and redirected away from the opposing travel lanes, coming to rest with an orientation angle of approximately 245 degrees. The vehicle engaged one post along the right side, and pushed the post downstream. The post did not disengage from the cables as the vehicle underrode the system.

The vehicle did not adequately engage the cables due to the geometry of the vehicle and the impact orientation angle. Unlike many other vehicles, the Camaro had stiff body paneling and a sloped front hood above the headlight, which changed the capture zone on the front of the vehicle to the area below the bumper level. In this crash, the adequate capture zone varied between a front-leading impact and a corner-leading impact. The front end of the vehicle would promote the tendency of the bottom cable to slide up over the leading edge of the bumper and above the hood. Conversely, orientation angles between 10 and 50 degrees, or 130 and 170 degrees, would likely promote cable engagement because the headlight cavities at the right-front and left-front corners of the vehicle extended upward to the leading edge of the hood. The variation in the capture zone based on orientation angle increases the difficulty of a “panacea” solution to cable mounting heights.

As the cables slid up from the top of the bumper over the hood, front windshield, roof, and rear windshield, the cables pried the hood upward and crushed both the front and rear windshields. The vehicle’s hood may have struck the front windshield, causing both left- and right-side windows to subsequently fracture. Other penetration and redirection crashes did not always result in windshield or window fracture; this result was strongly related to the high cable tensions of the Nucor system.

Partial penetration crashes were crashes in which the final position of the vehicle with respect to the barrier suggested penetration was imminent. Partial penetration crashes consisted of crashes in which the vehicle overrode the cables and came to rest with at least one wheel on the back side of the system and at least one wheel on the impact side of the system, or crashes in which the vehicle came to rest with cables resting on the roof with no cables on the impacting side of the system capable of redirecting the vehicle. If at least one cable remained engaged with the impacting side of the vehicle, the crash was not considered a partial penetration.

One such potential penetration crash occurred with a 2003 Pontiac Grand Am, which struck a cable barrier with a low but unknown CG trajectory angle and an orientation angle greater than 100 degrees. Photographs of the crash are shown in Figure 92. Vehicle engagement was initially acceptable as the lower cables crushed the right-front fender panel inward and fractured the headlight housing. However, due to the slope of the leading right-front corner of the vehicle and the strength of the cable-to-post attachments, the upper cable was forced up the vehicle’s A-pillar, lifting the lower cables and tearing the hood supports. The hood was removed from the vehicle and came to rest at an unknown location in the median. The force applied to the vehicle to remove the hood initiated a clockwise yaw by arresting the front of the vehicle. The second and third posts downstream from impact were struck by the rear of the vehicle and lifted out of the ground due to the prying action of the cables above the vehicle, but remained attached to the cables due to the strong cable-to-post attachments. The posts became wedged in the rear windshield, shattering the rear glass and crushing the roof inward.

Although the vehicle was brought to a stop in the median, the strong cable-to-post attachment could have seriously injured or killed an occupant in the back seat of the vehicle in this crash because of the retention of the post. Fortunately, no occupants were present in high-risk seat locations, and this crash resulted in only property damage.

Figure 90. Prying Penetration Crash on Nucor NU-CABLE Barrier

Figure 91. Prying Penetration Failure on Nucor NU-CABLE Barrier

Figure 92. Potential Penetration Crash on Nucor NU-CABLE Barrier

9.1.3 Diving Underride Penetrations

A total of 11 diving penetration crashes were identified in the Nucor penetration crash database. Of the 11 documentable diving penetration crashes on the Nucor barrier, 8 crashes occurred in medians with approach slopes steeper than 7:1 and when the barrier was installed close to the ditch center. In each crash, the CG trajectory angle was sufficient to cause suspension compression on the impacting corner, and the vehicle orientation angle was between 10 and 80 degrees to the barrier. No rear-leading or over-correcting diving crashes were documented, leading researchers to conclude that failures due to vehicular diving were sensitive to the impacting orientation angle.

One such diving crash that resulted in a penetration involved a 2009 Ford Fusion. Photographs of the crash are shown in Figure 93. A collision occurred with a second vehicle in adjacent travel lanes, causing the Fusion to veer off of the roadway into the median. The vehicle entered the median with an oversteering vehicle orientation, but the vehicle’s front suspension compressed as it interacted with the 5.2:1 approach slope, and the vehicle dove beneath the lower cables. Suspension rebound lifted the cables up, crushing and folding the hood and crushing the windshield. Many posts upstream and downstream from impact were pulled out of the ground due to the underride collision, rendering the system inoperable for subsequent impacts.

A second example of a diving collision involved a 2003 Ford Taurus. Photographs from the impact are shown in Figure 94. The vehicle had lost control on the icy roadway and entered the median with an orientation angle greater than 60 degrees and a moderately-high CG trajectory angle of approximately 21 degrees. After impact, the cables slid up the bumper and grill and onto the hood without crushing or becoming “seated” in the vehicle’s body. Cables adjacent to impact lifted posts out of the ground, and the posts pierced the windshield before the vehicle came to a stop. Both the windshield and roof were crushed downward by the cables.

It was determined that in addition to the smooth contour of the front end of the vehicle, suspension compression also contributed to this penetration crash. With the large orientation angle and moderately large CG trajectory angle, suspension compression and subsequent rebound had the effect of “bouncing” the cables upward and onto the hood and windshield. Significant occupant compartment deformation occurred, and the vehicle demonstrated a clear propensity for penetration since no cables were in optimum position to capture the vehicle after the vehicle came to rest; thus this crash was classified as a potential penetration and included with other penetrations in the analysis.

Figure 93. Diving Underride Penetration Crash on Nucor NU-CABLE Barrier

Figure 94. Diving Potential Underride Penetration Crash on Nucor NU-CABLE Barrier

9.1.4 Nucor NU-CABLE Penetrations Discussion

The Nucor NU-CABLE barrier had the largest volume of photographs available. It also had the highest average severity for all of the high-tension barrier types. The penetration severity increase factor (PSIF) of the barrier was low relative to other barrier types, as shown in Table 23. Based on the overall A+K rate near 4%, this indicates that non-penetration crashes tend to be more severe on average than occurred with other systems.

Strong cable-to-post attachments were disadvantageous in two ways: (1) the strong attachments tended to promote system override by forcing the cables to deflect downward with the posts on impact and (2) to the inherently weak post-soil interaction and analogous low embedment of the post in socketed foundations increased susceptibility to post pullout from the ground or sockets. Although both conditions increased risk to impacting occupants by enabling penetration crash conditions to occur, the weak post-soil or post-socket interaction increased occupant risk more than override conditions because displaced posts which remain attached to the cables became spearing risks to small cars.

9.2 Trinity CASS Cable Barrier

Most of the Trinity CASS crashes in the available crash database occurred with the Trinity CASS system with C-section posts. As a result, analysis efforts were focused on this system. However, penetration frequencies for all systems were virtually identical, and the same mechanisms contributed to vehicle penetration for each of the designs. Despite a large uncertainty associated with a relatively small dataset, the highest penetration crash frequency occurred with the TL-4 CASS system.

9.2.1 Ramp Formation Override Penetrations

Override penetrations were the most common type of penetration failure of the CASS system. Of the 26 penetration override events with distinguishable causes on the CASS barriers, 23 of the penetration crashes were caused by the vehicle striking a post before contacting the cables. All of the CASS system variations utilize a center slot which seats the cables in the post, which is designed to release the cables when the post bends over. When impacts occurred at a post location and the post failed to release the cables from the slot, a ramp was formed permitting the vehicle to climb up and override the barrier system. Furthermore, evidence of this type of impact can be provided simply by examining the vehicles involved in override penetrations. Small and mid-size cars comprised 31% of all override penetration failures on the CASS system. By contrast, excluding “bounce-over” impact conditions in which the impacting vehicle rebounded off of the median slope and penetrated over the top of the barrier, small to mid-size cars were typically involved in less than 15% of override penetrations on any other cable barrier system.

Because impacts at post locations contributed to cable entrapment within the slot in the web, this type of failure was referred to as a “ramp formation” failure. Oversteering impacts involving vehicles with large orientation angles at impact were the most common impact condition associated with ramp formation failures. Overcorrecting and fully tracking crashes only constituted 3 ramp formation override crashes. Unfortunately, crashes with photographic evidence of the ramp formation failure could not be shown to prevent violation of non-disclosure agreements.

An additional override crash involved a vehicle towing a trailer. Most of the crashes involving a vehicle towing a trailer resulted in unfavorable cable barrier performance, by causing trailer "tip-over." trailer penetration, vehicle rollover, or vehicle penetration. Frequently, these crashes were caused by oversteering gradients in the median. Trailers with high CG locations, higher bumper heights, flatter, stiffer body panels, and high rigidity, failed to engage cable barriers and increased penetration propensity. However, crashes involving passenger vehicles towing trailers were also infrequent. Thus, these crashes were not considered to be "failures" of the barrier, nor the fault of the DOT, construction or maintenance crews, or barrier designers.

9.2.2 Prying Underride Penetrations

Twenty-six prying underride crashes were identified in the CASS penetration crash database. Of the 26 identified vehicular prying penetrations, high orientation angle crashes accounted for 17 penetrations and low CG trajectory angle, low orientation angle crashes accounted for 9 penetrations.

One high-orientation angle, prying underride crash with a CASS cable barrier involved a 2002 Dodge Stratus. This crash was particularly notable because, of the 21 cable median barrier crashes involving similar Stratus vehicles, only one crash resulted in a penetration. The scene diagram from the penetration crash involving the 2002 Dodge Stratus is shown in Figure 95. Photographs of a 2002 Dodge Stratus, which was similar to the vehicle involved in the impact, are shown in Figure 96.

The vehicle departed the roadway due to slick road conditions, impacting the system with a CG trajectory angle less than 10 degrees, but with an orientation angle exceeding 60 degrees. Because of the large orientation angle, the cables did not become "seated" in either the grill cutout, headlights or quarter panels. The vehicle slipped beneath the lower cables and entered the median, coming to rest between parallel installations of cable guardrails.

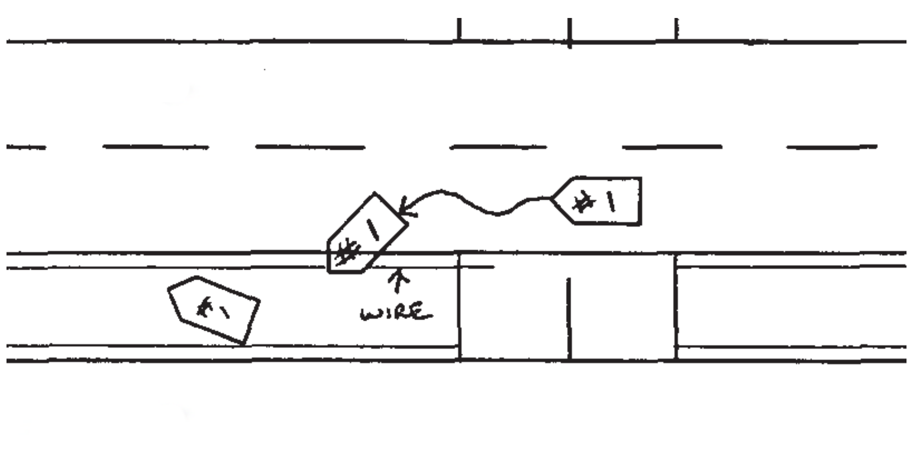


Figure 95. Scene Diagram of High-Orientation Angle Crash

Figure 96. 2002 Dodge Stratus Similar to Vehicle Involved in High-Orientation Angle Penetration Crash [45]

The Dodge Stratus was not typically involved in penetration crashes due to some unique features. The front of the vehicle was both broad and blunt, and the sides of the vehicle were relatively flat. There were multiple locations on the vehicle which promoted interlock with the vehicle, such as cutouts around headlights, a recessed grill area, and a concave trunk area which resisted cable slippage. Typical sill heights of the windows exceed 35 in. (890 mm), whereas the ground clearance averages approximately 16 in. (406 mm). Total vehicle height averages were approximately 55 in. (1,397 mm). This height provided a large surface over which vehicle capture was possible, which also required cables to rise substantially to pass over the top of the vehicle. Thus, this vehicle was uniquely positioned to resist cable median barrier penetrations.

Other high-orientation angle penetration crashes involving vehicles which were not traditionally susceptible to penetration were also observed in the database. These crashes supported the conclusion that high orientation angles increased propensity for penetration by altering the initial contact engagement sequence.

Other low-angle crashes also contributed to unexpected cable median barrier penetration crashes. The CASS system was susceptible to low-angle penetration crashes because continued engagement of the cable barrier system resulted in multiple posts deflecting downstream and releasing from the cables, allowing for even minor prying forces on the cables to lift cables out of center post slots after a sufficient number of posts were deformed. The low angle of engagement also typically corresponded to lower levels of cable damage on the vehicle, which reduced cable interlock. The cables were not entrapped on the vehicle body and were free to oscillate or shift along the body panels, and particularly, to rise above the hood and roof.

This problem was aggravated when crashes involved narrow-profile vehicles or vehicles with smooth front ends. When a vehicle's bumper protruded beneath the cables, the vehicle was able to pry upper cables out of the slot and away from the post. Higher cable tensions resisted this uplift prying force, but also resulted in more hood, roof, and windshield crush than cables with lower tensions.

9.2.3 Diving Underride Penetrations

Only two diving underride penetrations were observed in the CASS database. Both occurred on the Trinity CASS system with C-channel posts and occurred in V-ditches with slopes between 4:1 and 6:1. Not all crashes in which the vehicles interacted with slopes to compress the suspension prior to impact resulted in penetrations or partial penetrations. Diving crashes typically resulted in higher severity on CASS systems than other cable median barrier systems due to the potential for roof crush by the bottom or middle cables. If the bottom cable remained adequately engaged with the vehicle but did not adequately disengage from the posts, the cables occasionally caused occupant compartment crush.

The cable release load of the bottom cable in the CASS system was not available in published research studies. However, a brief mechanical analysis indicated that the weight of the cable, the cable tension, and friction with the retainer clip likely could develop a net vertical release load per post of approximately 900 lb (4.0 kN). However, due to the vertical resistance of the upper two cables, the vertical release of the lower cable could rise by a factor of as much as 2.5, to approximately 2200 lb (9.8 kN). For posts deflecting during impact, the vertical release load can be even larger. During a diving or prying underride crash, the propensity for the lower cable to crush the hood or windshield could be very large if the low vertical release load of the bottom cable was increased.

Scene diagrams were not available for several non-rollover, non-cross-median, severe CASS crashes with passenger cars. It was believed that partial or complete underride was likely responsible for the severe outcomes. However, this estimate could not be proven with the currently available dataset. Care should be taken to determine the cause of any serious crash involving the Trinity CASS barrier to ensure that the lower cables did not crush the occupant compartments of impacting vehicles.

9.2.4 Trinity CASS Penetrations Discussion

In general, placement of the cables in the post slot resulted in less desirable cable interaction with the vehicle. Although many crashes resulted in adequate containment with relatively low damage to impacting vehicles, and dynamic deflections were relatively low in most crashes because good cable engagement occurred, many crashes resulted in undesirable outcomes. By placing the cables within the center slot and constraining them, the cables are subject to the reaction of the posts and may not release properly, which increases penetration risk due to override and increased occupant risk due to underride. Barrier design improvements must be made to prevent these types of high-risk containment failures from occurring.

9.3 Brifen Wire Rope Safety Fence (WRSF)

The total number of Brifen cable barrier crashes exceeded 1,500, and cross-median crash rates of the Brifen system in Oklahoma were comparable with other systems used in the state. However, documentable cable barrier crashes, in which scene diagrams, photographs, and narratives were available, numbered approximately 120. Of this set, only 7 documentable cable barrier crashes resulted in penetrations. Thus, the penetrations were examined in great detail, but the relative frequency of each type of penetration event could not be determined.

9.3.1 Prying Underride Penetrations

Of the 7 penetration crashes available for further analysis, 5 were prying underride crashes in which the impacting vehicle struck and penetrated below the Brifen WRSF barrier. Slope contributions were not considered with this data set. The surprisingly high rate of prying penetrations, given the small data set, further illustrates the risk associated with low vertical release loads for the bottom cable. Vehicles diving under the barrier, or those which engaged the barrier such that the cables slipped over the bumper and were pried upward, experienced significantly increased risk of penetration, since the bottom cable could not resist vertical uplift prying forces.

An example of a Brifen crash which resulted in a prying penetration is shown in Figure 97. With sufficient details to complete a full crash reconstruction, it was determined that the 2000 Toyota Avalon impacted the barrier at approximately 50.7 mph (81.6 km/h) with a 16 degree CG trajectory angle and a 152 degree orientation angle, with respect to the barrier. The vehicle contacted the wire rope with the right-front corner leading.

Immediately after impact, the force of the redirection caused the vehicle to yaw with the right-rear corner turning into the barrier. These forces were eccentric to the vehicle’s CG and induced a counter-clockwise yaw, but the force required to initiate yaw were relatively low. As a result, the forces never exceeded the breaking strength of the front headlight glass casing and the cables did not crease into and engage the vehicle. As the vehicle’s back end rotated into the barrier, the cables slipped over the front bumper and hood corner due to the prying force and the vehicle penetrated under the barrier. The sunroof was shattered due to contact with the cables.

The vehicle struck and bent four posts. One impact occurred at the front bumper, two occurred with the right-side body panels, and one occurred at the right-rear wheel, as shown in Figure 97. The vehicle occupants were not injured in this crash. The approach slope in front of the barrier was 9:1, and soil foundation tubes supporting the posts were in excellent condition.

Figure 97. Prying Underride Failure on Brifen WRSF

Other prying penetration crashes were typical of this crash event. Vehicles impacted the barrier with large orientation angles, frequently with the right-side of the vehicle leading, and slipped under the wire ropes. These types of failures were predominantly due to the configuration of this barrier type. The lower cables on the TL-3 Brifen barrier were located at a height of 19½ in. (495 mm), but no vertical constraints were used to retain the bottom cable. Vertical release of the cables is largely resisted by gravity and friction with the post, but consequently the dynamic release loads tend to be very low.

9.3.2 Other Penetration Types

One override penetration and one diving penetration were recorded. The diving penetration crash occurred in an approved 6:1 V-ditch, in which the Brifen barrier was installed on the traffic-side approach slope. The vehicle exited the roadway at a relatively low angle, projected over the slope break point, then contacted the slope and began to rebound. During rebound, the vehicle partially redirected and yawed into and beneath the barrier.

The override penetration observed in the database was somewhat anomalous. In this crash, a heavy snowfall occurred prior to and during the crash. Control of the vehicle was lost, and the vehicle entered the median and struck the Brifen WRSF. However, the snow depth was so high that the barrier deflection was restricted, and the snow in front of the barrier contributed to ramping over the barrier. Such a penetration event is not expected in most impact conditions. Moreover, it would be difficult, if not impossible, to prevent such a penetration from occurring on other barrier systems; due to the snow and low travel speeds, this crash has low likelihood of cross-median crash result.

9.3.3 Brifen WRSF Penetration Discussion

The Brifen penetration database was limited, but some clear tendencies were observed. First, due to the low vertical resistance of the bottom cable, the Brifen TL-3 WRSF was susceptible to underride from prying and diving failure types. Prying failures were the most common type of failure and the most common type of impact condition in general, especially when barriers were located at or near the shoulder. Thus, special care should be taken to increase the vertical release resistance of the lower cable. One such improvement could consist of the addition of a cable retainer at the bottom of the post which has a sufficient vertical release load to resist or prevent prying-type penetration crashes from occurring. However, the optimum lower-cable release load threshold has not been determined.

9.4 Low-Tension Non-Proprietary 3-Cable Median Barrier

Approximately 128 severe cable median barrier crashes in Missouri between 2007 and 2009, 795 crashes in Washington between 1999 and 2008, and 22 penetration crashes in North Carolina between 2001 and 2004 were examined in detail to determine causes of penetration or rollover occurrence on low-tension, 3-cable median barrier systems. Results of the analysis are provided below.

9.4.1 Override Penetration Crashes

Override penetration crashes on the low-tension, 3-cable median barrier were much less frequent than override penetration crashes on high-tension cable median barriers. Out of 71 cable median barrier crashes with determinable failure causation, only 8 crashes involved passenger vehicles overriding the barrier.

Out of the 8 override crashes, 5 involved vehicles striking the cable median barrier at large CG trajectory angles approaching 90 degrees. Although the override occurrence was usually associated with only larger passenger vehicles such as pickups, SUVs, and vans, a Hyundai Tiburon (Tuscani) was also involved in an override crash. The vehicle swerved off of the road to the right, overcorrected, and redirected into the median at approximately 86 degrees before it vaulted off of the slope break point of the 4:1 median approach slope and overrode the barrier, which was installed on the traffic-side approach slope. Such a crash is highly unusual and likely exceeded the IS value required for testing at TL-3 impact conditions. No longitudinal barrier system has yet demonstrated the capability of safely redirecting a vehicle with similar impact conditions. Four other high-angle override crashes involved a large van and three pickup trucks. A sample scene diagram of a pickup high-angle override crash is shown in Figure 98.

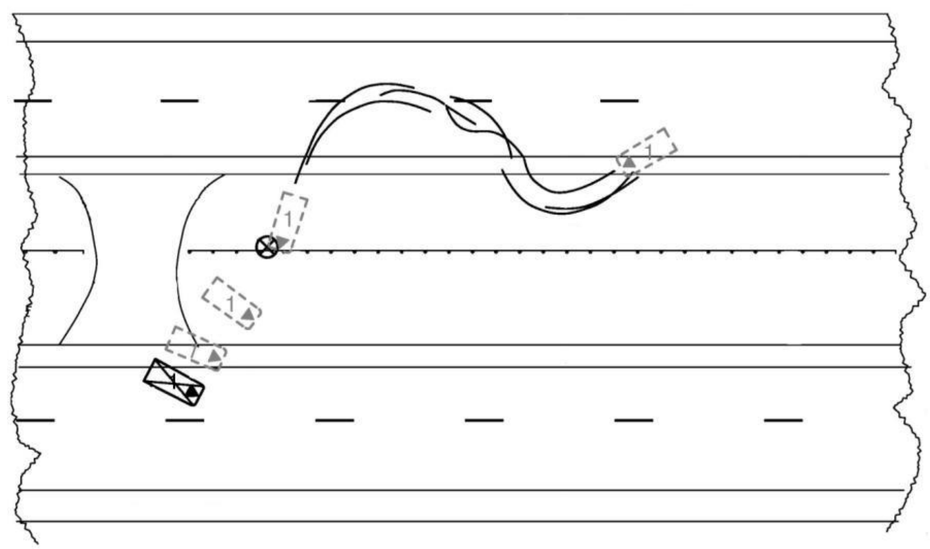


Figure 98. High-Angle Override Penetration Crash Example

The 3 other override penetration crashes consisted of very low CG trajectory angle, low orientation angle crashes. In two crashes, the impacting vehicles were pickup trucks, and in one crash, the vehicle was a large passenger car. The barriers were installed on relatively steep approach slopes, with unmeasured slopes likely between 4:1 and 6:1 based on visual estimation. The vehicles impacted the cable median barrier, sequentially bending the S3x5.7 (S76x8.5) support posts downstream, then overrode the cables. The override was likely due to the following two factors: (1) the low tension in the cables was insufficient to prevent sagging when multiple support posts were removed from the system, and (2) the large vehicles with stiff exterior body panels were less conducive to energetically-favorable cable engagement. This engagement was frequently caused by crushing the vehicle exterior and retaining the cables against the sides of the vehicle. As the vehicle bent the support posts, it was likely that the vehicles bounced or rode up the post after speeds were sufficiently reduced. Any vertical rebound of the vehicles increased the vehicles' CG heights and potentially drove cables downward beneath the wheels.

9.4.2 Diving Underride Crashes

A far more common type of penetration crash mechanism on the low-tension cable median barrier was a diving underride crash. Many studies have been performed to improve the performance of low-tension cable median barrier performance in V-ditches [e.g. 27, 28, 44]. Underride failures with contribution from V-ditches steeper than 6:1 have often been cited as the most common failure of low-tension cable median barriers, and mitigation of diving penetrations has received the most widespread attention.

Of the 71 low-tension, 3-cable median barrier penetration crashes with determinable causes, 23 were due to diving penetrations. The low-tension, 3-cable median barrier utilized a $^{5}/_{16}$-in. (8-mm) J-bolt. A study conducted at the Midwest Roadside Safety Facility (MwRSF) on the strength of the J-bolts, commonly referred to as hook bolts, determined that the peak horizontal pullout load of the $^{5}/_{16}$-in. (8-mm) J-bolt was approximately 719 lb (3.20 kN), and the peak vertical pullout load was approximately 636 lb (2.83 kN) [46].

Most diving underride crashes occurred when the bottom cable was on the opposite side of the post relative to the impacting vehicle travel direction. Although not recorded, several estimates of frequency were made regarding back-side penetrations, and suggest that at least 60% of all underride penetrations occurred at locations where the lower cable was on the opposite side of the post relative to the impacting vehicle.

The North Carolina penetration database supported this finding even though it was not a true "random sampling" of penetration crashes. However, causes of the penetrations and the associated crash circumstances in North Carolina were unknown to the researchers at the time of the crash investigations. It was observed that 15 of the 22 North Carolina penetration crashes, or approximately 68%, were crashes in which the bottom cable was located on the opposite side of the post from impact. Of these, it was determined that 8 of the back-side crashes resulted in the vehicles diving under the cables.

Although median slope rates did have an effect on diving penetration rates, median slopes alone did not completely describe the risk of diving underride penetrations. Many of the sloped medians were shallower than 6:1. One diving penetration occurred on a median slope of approximately 10:1. In that crash, the vehicle was traveling at a high rate of speed and plowed into the back-side slope of the the median approximately 4 ft (1.2 m) in front of the barrier, then dove under the cables. Photographs from the crash site are shown in Figure 99.

In general, slopes steeper than 8:1 were most susceptible to cable median barrier diving penetrations. Diving penetrations occurred less frequently if the impacting vehicle made contact with the barrier on the approach slope. The critical location to cause diving penetrations was approximately 3 to 6 ft (0.9 to 1.8 m) from the center of the V-ditch, based on analyses of ruts made in the soil in the crashes in North Carolina. This determination was supported by literature [28].

Figure 99. Diving Underride Penetration Crash in North Carolina

Although photographs were not available for crashes in the state of Missouri, median profiles were estimated based on site-specific analysis and limited photogrammetric reconstruction. In each Missouri diving underride crash, the median slope was steeper than or equal to 6:1, and the back-side slopes were also steeper than or equal to 6:1. In every diving underride crash in the database, back-side slopes were as steep as or steeper than the approach slopes into the median. This suggested that the approach slope steepness has a significant effect on the propensity to compress the suspension. However, the back side slopes had the strongest correlation with diving propensity when cable barriers were located near the center of the ditch. Steep back-side slopes caused more frequent penetrations than steep front-side slopes, and no diving crashes were observed when the cable median barrier was installed on a shallower slope. However, this type of installation may be subject to penetration, rollover, or other types of failures.

Despite the effect of suspension compression on the propensity for vehicle penetration through the barrier, the weak lower cable-to-post attachments strongly increased penetration propensity. The attachments disengaged from the posts at low loads and allowed the cables to slip above or below the vehicle. It was believed that in every recorded diving cable median barrier crash in this database, the diving tendency would be significantly reduced or eliminated if the bottom cable-to-post attachment strength was increased. This could have reduced diving penetrations by as much as 50%. Increasing the release load of the bottom cable would likely increase contact forces between the impacting vehicle and bottom cable, which could result in better engagement and formation of the familiar cable crease observed on vehicles involved in successful redirections. Additional examples of diving underride crashes are shown in Figures 100 and 101.

Figure 100. Additional Example of Diving Penetration Crash

Figure 101. Additional Example of Diving Penetration Crash

9.4.3 Prying Underride/Through-Cable Penetrations

Unlike most high-tension cable median barrier systems, low-tension, 3-cable median barriers were the most susceptible to through-cable barrier penetration. This type of penetration was restricted to prying type, although median slope and vehicle geometry also contributed to the penetration in some crashes. Median profiles of prying crashes varied dramatically from the diving penetration crashes, since by definition suspension compression and rebound was not the predominant cause of penetration in these types of crashes. Out of the 22 penetration crashes in North Carolina, all penetrations occurring on the median approach slopes were prying penetrations, and 5 of the 15 crashes where the cable median barrier was installed on the back slope were prying penetration crashes. Additionally in Missouri, only 1 of the 18 prying crashes occurred on the median back slope, while 2 prying penetration crashes occurred when the barrier was impacted on the opposite-side shoulder. Conversely, 13 prying penetrations occurred on either the approach slope or ditch center, and an additional prying crash occurred when the barrier was installed on the adjacent shoulder of the divided roadway.

Frequently, at least two prying risk factors were present in prying penetration crashes. Prying penetrations occurred when cables were lifted or separated and failed to engage the vehicle. As with the high-tension cable median barrier systems, prying penetrations were sensitive to impacting vehicle orientation angles. CG trajectory and orientation angles of vehicles in all crashes were plotted, with prying penetration crashes highlighted for comparison, as shown in Figure 102. No clear distinction could be made between the two crash distribution data sets. As with most penetration crash conditions, oversteering into the barrier was approximately 5 times more common than overcorrecting, although conclusions were limited due to the small data set.

Prying penetration crashes typically occurred via a combination of the following factors: (1) cables located on the back side of the post released from many posts because lateral forces exceeded cable-to-post attachment strengths; (2) large orientation angles promoted bumper protrusion between or below the cables contributing to underride or through-cable penetration; and (3) low contact forces prevented beneficial body panel crushing or headlight fracture, causing poor cable-vehicle engagement. Back-side cable release most commonly occurred when other cables failed to adequately engage the vehicle, so the entire redirection load was applied by one back side cable. Examples of penetration crashes in which the impacted back-side cable was removed from more than 10 posts downstream from impact are shown in Figures 103 and 104.

One unique penetration crash involved a Mitsubishi Montero equipped with a brush guard mounted on the front bumper. Crash photographs are shown in Figures 105 and 106. The vehicle struck the cable barrier system, and the angled surface of the brush guard forced two of the cables below the front bumper and one above the hood. The cable that was lifted onto the vehicle caused minor windshield damage and scratching on the vehicle’s A-pillar. However, most of the vehicle damage was due to an unrelated rollover which occurred on the roadside of the opposite travel lanes long after the barrier penetration.

Such an event was anomalous because very few impacting vehicles were equipped with these guards. However, the effect of the brush guard in this crash was a microcosmic representation of the effect of weak cable-to-post attachments on strong posts. Even large vehicles, which were typically excellent candidates for redirection on cable median barriers, were at increased risk of prying penetration crashes at high orientation angles. This further supports the conclusion that orientation angles can alter the energetically preferential interaction of vehicles with cable median barriers. If a sufficient contact groove was not made before the impacted cables began to slip on the vehicle, the likelihood of redirection was very low.

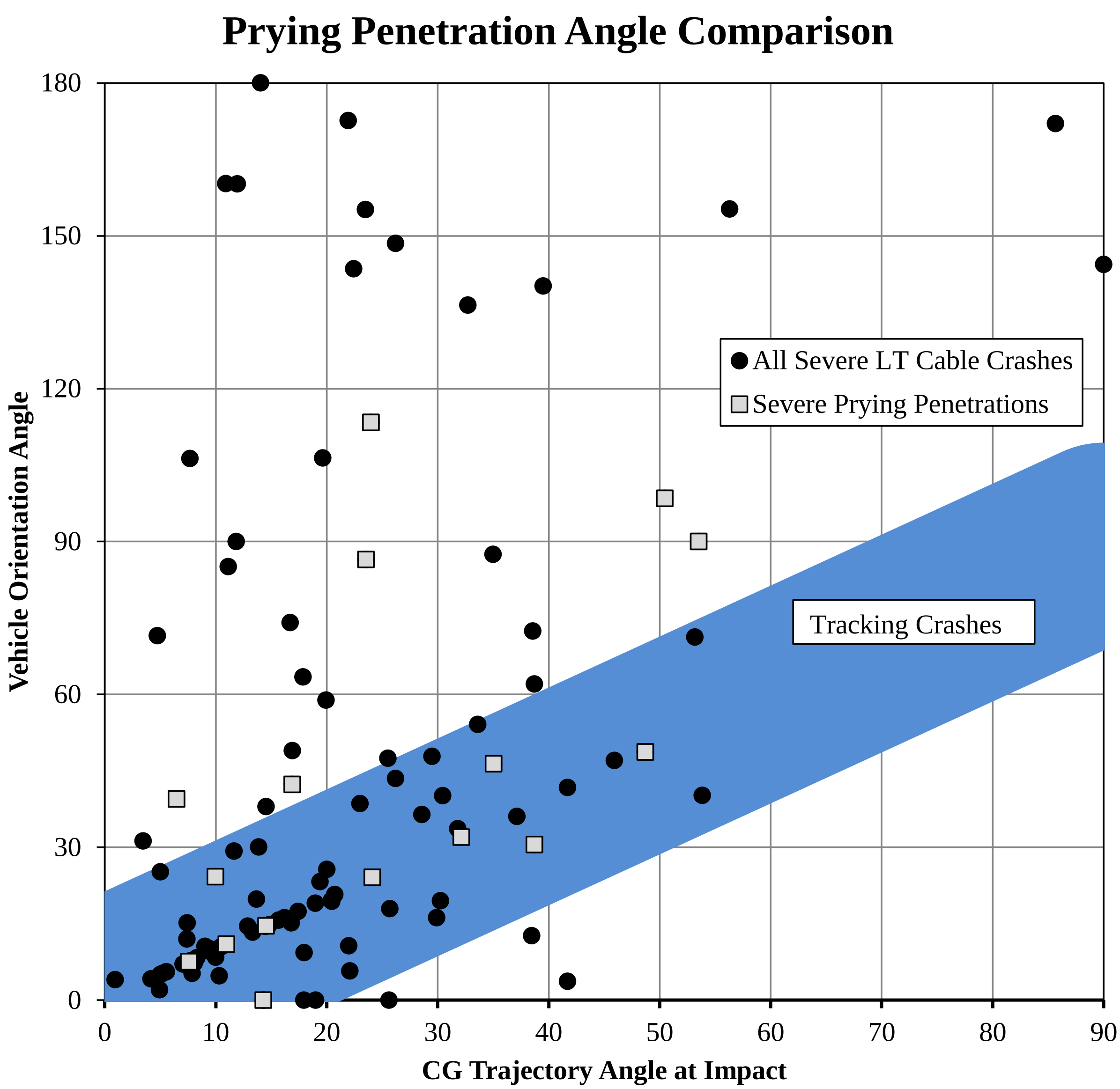


Figure 102. Comparison of Prying Penetration CG Trajectory and Orientation Angles

Figure 103. Back Side (Middle) Cable Release from Many Downstream Posts Resulting in Penetration

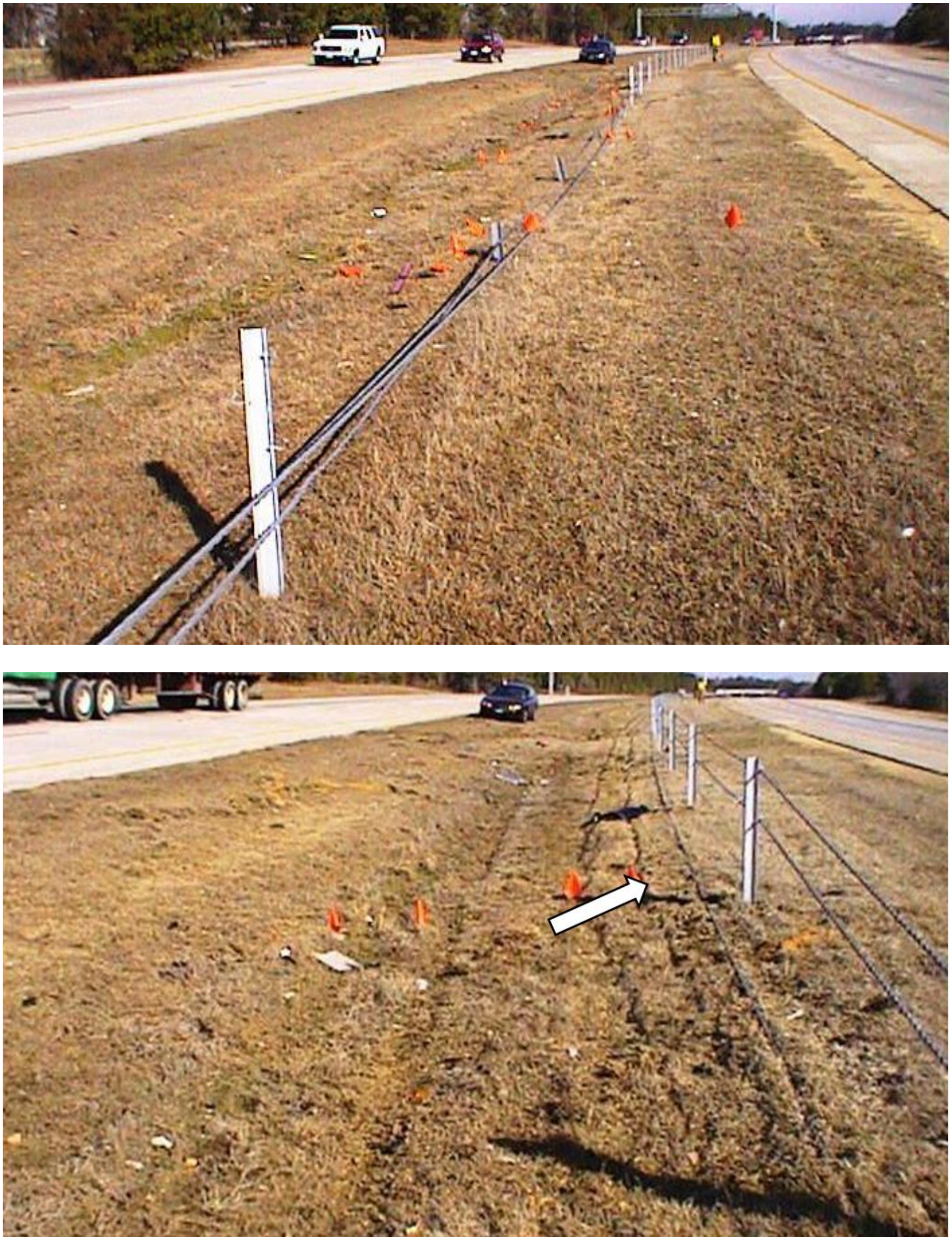


Figure 104. Back Side (Middle) Cable Release from 11 Downstream Posts Resulting in Penetration

Figure 105. Prying Penetration Failure with SUV Caused by Brush Guard

Figure 106. Brush Guard Prying Penetration with Cable Contact Striations on A-Pillar

9.4.1 System Failures

Two cases of system failures were noted in the low-tension cable median barrier penetration database. In both crashes, the vehicle adequately engaged the tensioned cables and at least one cable formed a contact groove, fracturing the impacting corner headlight casing and collapsing the grill and fender around the cable. However, in both crashes, the low-tension cable splice failed, allowing the tensioned cable to rebound away from the vehicle. In one crash, the back-side bottom cable engaged the grill and headlight. As the cable deflected with the vehicle, the splice disengaged releasing the cable at a splice location. Similarly, in the other crash, the back-side middle cable engaged the bumper and grill of the impacting vehicle, crushing the fender and grill. As the cable deflected with the vehicle into opposing travel lanes, high tension was developed in the cable and exceeded the splice limits. In both crashes, weak cable-to-post attachments contributed to splice failure. Photographs of the first crash are shown in Figures 107 and 108.

Since this crash result was only recorded on low-tension cable median barrier systems, better splices may be necessary for future low-tension cable barrier systems. A study of cable median barrier hardware identified several other splices which could be used or adapted for low-tension cable barrier use [47].

9.4.2 Other Penetration Causes

Other penetration causes were identified that led to penetrations on low-tension cable median barrier systems, including impacts with large vehicles (i.e., tractor trailers-or single-unit trucks), and bouncing override penetrations due to median slopes. However, as with the high-tension cable median barrier counterparts, bouncing override penetrations were impact condition dependent, and no cable barrier system manufactured had been tested and approved to redirect large vehicles (i.e., tractor-trailers).

Causes for bounce-over of low-tension systems were virtually identical to other systems. Out of a recorded 70 cable median barrier penetrations on low-tension cable median barriers, only 2 resulted in a bounce-over. These two penetrations occurred when the barriers were installed near shoulders in relatively narrow ditches where vertical vehicle rebound was highest. Bounce-over penetrations may also be reduced by easy release of the top cable. The low-frequency of bounce-over penetrations is likely related to the low top cable release load.

Figure 107. Splice Failure Penetration

Figure 108. Splice Failure Penetration

9.4.3 Discussion

Low-tension, 3-cable median barriers were the most susceptible barrier type to prying and diving underride penetrations, and the least susceptible to override penetration based on crash results obtained in this research effort. Strong cable-to-post attachments are essential for bottom and middle cables in low-tension cable median barrier systems. By increasing the vertical resistance of the lower cable, diving penetrations could be reduced. However, care must be taken to prevent excessive stiffening of the cable against downward vertical motion on the post, or the lower cable will become a trip point for rollovers.

The advantage of the weak top cable-to-post connection is that with a low vertical release load, vehicles with low roof heights which passed beneath the cables did not experience occupant compartment crush due to the top cable, and overrides were very infrequent when the cables quickly released from the post but remained engaged with the vehicle. This stratification of cable-to-post attachment strengths has not been optimized by any cable median barrier system in use to date and could be necessary to further improve cable median barrier design.

There is no evidence yet that many (if any) penetration crashes were caused due to cables which drooped in one location due to a previous crash. This may be due to excellent DOT response of rapid barrier repair at crash sites, which prevented these conditions from occurring. However, crashes in which two or more vehicles struck the cable median barrier only resulted in penetration if one of the vehicles was either a tractor-trailer or was towing a trailer, based on the available database. In both of these crash types, the vehicles which struck the barrier were not within the designed performance limits of the barriers. Further, crashes in which multiple vehicles struck the cable median barrier constituted only approximately 3% of all crashes in the database. If such a correlation existed and penetration propensity was higher when vehicles struck near previous crash locations, insufficient data were present in the database to indicate this increase. Nonetheless, states with low-tension cable median barrier systems often mandate barrier maintenance and repair within 48 hours of the crash notification. Even when repairs happen up to two weeks after a crash, the repair timeframe appears to be adequate to prevent penetration events caused by previous cable barrier crashes from occurring. Shorter repair windows may be required during winter months when icy road conditions increase crash frequency.

10 PENETRATION CRASH SIMULATION AND ANALYSIS

10.1 Introduction

Cable median barrier penetration propensity is affected by many independent factors. These factors include vehicle geometry, crush stiffness, and suspension properties, system stiffness, post strength, cable tension, cable-to-post attachments, cable heights, median slopes, cable barrier offset from roadway, CG trajectory angle, and CG orientation angle at impact. Identifying what combination of these factors, or additional unlisted factors, contributed to a penetration crash can be daunting.

A series of simulations were created to identify the causes of cable median barrier penetrations in three separate crashes with photographic evidence. Factors which culminated in the penetration of the vehicle over, under, or through the cable barrier system were identified. It was determined that in each of the simulated crashes, system placement was in compliance with federal recommendations, system construction was acceptable, and impact conditions deviated from the typical impact conditions which accentuated penetration risk.

All median measurements were made with respect to the point of departure. Angles were always referenced from a tangent line to the road drawn at the location where the vehicle CG departed the lane edgeline, and were positive when the vehicle rotated counterclockwise as viewed from above. As a result, any median crash had a positive CG trajectory angle by definition. Orientation angles varied from -180 to 180 degrees, with positive angles occurring when the centerline of the vehicle was oriented toward the median and negative when the vehicle centerline oriented at the CG was oriented away from the median.

10.2 Simulation 1: TL-3 Nucor Cable Barrier System

The first simulation considered an impact of a 2009 Mitsubishi Galant into a TL-3 Nucor NU-CABLE cable barrier system. The median was comprised of five discrete segments, relative to vehicle initial direction of travel: a 12.5-ft (3.8-m) wide flat, asphalt-paved shoulder; a 15.5-ft (4.7-m) wide 6:1 approach slope, a 3.0-ft (0.9-m) wide flat grassy ditch bottom, a 19.0-ft (5.8-m) wide 7:1 back slope, and a 13.5-ft (4.1-m) flat opposite-side shoulder. The system was installed 13.5 ft (4.1 m) from the approach slope break point. Since the system was installed on a 6:1 approach slope, the system location was acceptable according to FHWA approval letters b96, b96a, b167, b183, b184, b184a, and b193.

The impacting vehicle lost control, swerving off of the road into the median. The vehicle departed the road with a CG trajectory angle of 32 degrees and an orientation angle of 62 degrees relative to the roadway. Based on a rudimentary crash reconstruction, the speed of the vehicle at the point of departure from the lane was determined to be approximately 58.1 mph (25.6 m/s), based on skid marks on the road and shoulder, tire marks in grass, post deformations, and vehicle damage energy estimates. Photographs of the crash site are shown in Figures 109 and 110.

Figure 109. Crash Scene Photographs, Simulation No. 1

Figure 110. Post-Crash Vehicle Photographs, Simulation No. 1

10.2.1 Component Models

The posts in the system were 4 lb/ft Rib-Bak ® posts manufactured from ASTM A499 steel with a yield stress of approximately 80 ksi (552 MPa) and a tensile strength of approximately 100 ksi (689 MPa). Post models were comprised of four separate parts: base flanges measuring 0.272 in. (6.9 mm) thick, a 0.143-in. (3.6-mm) thick, dual-leg web, 0.227-in. (5.8-mm) thick ribs, and a 0.196-in. (5.0-mm) thick short flange.

All post parts were modeled using type 2, Belytschko-Tsay shell elements in LS-DYNA v. 971 R5.1 [48]. To simulate the soil stiffness, rigid tubes closely matching the dimensions of the post were created. The tops of the soil tubes were located 1 in. (25 mm) below the ground to allow for small deflections at the top of the ground, but posts in the real-world crashes tended to fracture at the ground line or pull out of the soil or soil foundation tubes. The soil tube-to-post clearance was approximately 0.12 in. (3 mm).

The ground slopes were modeled with rigid walls intersecting at sharp angles. This was an approximation, since slope rounding was present at every slope transition. Although slope rounding does minimize the sharp transition and reduces the abrupt reactions with the suspension, the radius and position of the slope rounding was not known and could not be measured from photographs or satellite photography.

During the crash event, two posts were completely fractured and retained by the high-tension cables. To simulate post contact with the ground, each post web and flange section was partitioned into upper and lower parts. The lower parts were used in contact definitions with the rigid soil tube, and the upper part was included in the part set that could contact the ground.

Cables were attached to the posts with curved cable clips. The clips had diameters of 0.2725 in. ± 0.0010 in. (6.92 mm ± 0.025 mm). The clips were attached to the post with a lower curved leg and an upper threaded shank with a nut. The clips were made of steel with 60 ksi (414 MPa) tensile strength. An approximate tensile load to cause rupture of one leg would therefore be 3.5 kips (15.6 kN).

The clips were modeled using a process described in reference [50]. Solid element models of a rod of equivalent diameter to the cable clips were created and simulated in tension, bending, and torsion using material properties consistent with available material properties found from Nucor clip specifications. The resulting tension-strain, bending moment-curvature, and torque-rate of twist curves were inserted into beam element models of the clips using the *MAT_MOMENT_CURVATURE_BEAM material model with a type 2 Belytschko-Schwer beam element section. The nut on the end of the cable clip was modeled using solids and made rigid. A rigid nut approximation was reasonable because nuts typically experience minimal damage during impact, and the solid elements dominated the timestep.

Because contact between beam elements and shell element edges can result in node snagging, beam elements with null material properties (i.e., zero-stress) were used in a ring around each hole in the smaller flange. The holes in the post were oversized by 0.020 in. (0.5 mm), and the diameter of the null beam elements was 0.020 in. (0.5 mm). The cables were modeled with beam elements according to the process described in reference [29]. The cables were tensioned over 400 ms prior to impact using discrete beam elements, which were switched from deformable to rigid just before impact.

The cables in the system comprised of models recommended in literature [29]. Cables were tensioned to 5.0 kips (22.2 kN) over 350 ms prior to impact using discrete beams and the *MAT_CABLE_DISCRETE_BEAM model with a ramp loading curve to apply a controlled ramp load. The cable tensioner at the boundary of the cable was switched from deformable to rigid approximately 50 ms before impact. Contacts between the cables and the posts and vehicle were of the automatic node-to-surface type, and contact between cables and beam element cable-to-post attachments utilized an automatic general contact type, which more accurately treated beam-to-beam contact.

10.2.2 Vehicle Model

A Dodge Neon model created and maintained by the National Crash Analysis Center (NCAC) at George Washington University (GWU) was selected for similarity with the Mitsubishi Galant. Unfortunately, some major differences between the Mitsubishi Galant and Dodge Neon vehicle model were observed.

The suspension properties of the Dodge Neon model were not capable of reproducing the load-deflection reaction of highly-impulsive load applied by the opposite-side slope after the vehicle overrode the barrier. As a result, the simulation was terminated after the vehicle contacted the back slope.

Second, the front bumper of the Mitsubishi Galant was composed of a smooth-faced aluminum bumper cover with a crushable plastic cartridge for energy dissipation. The Dodge Neon model incorporated a thin plastic bumper cover and polystyrene bumper for energy dissipation. To improve cable-to-bumper interaction, the front bumper of the Neon was smoothed with a layer of shell elements over the front of the opening of the bumper and included in the contact definitions. Additionally, the Neon bumper cover was large, measuring 13.4 in. (340 mm) tall, whereas the Galant bumper cover was only approximately 9 in. (229 mm) tall, and the Galant bumper cover was attached with screw-on tabs.

Finally, the weight, height, length, wheelbase, track width, and roll and yaw moments of inertia of the vehicles were markedly different. Using data from the Expert AutoStats program, the wheelbase of the Neon was 20 in. (508 mm) less than the Galant, the weight was nearly 900 lb (408 kg) less, and the track width of the Neon was 4 in. (102 mm) less than the Galant. Nonetheless, the simulation was still able to approximate the override event sequence.

10.2.3 Results of the Simulation

Sequential photographs of simulation no. 1 are shown in Figures 111 through 114. The vehicle projected over the top of the slope break point and struck the cable median barrier while airborne. The top cable of the Nucor system contacted the vehicle’s bumper and was forced below the bumper. The high tension in the cable pulled the bumper cover downward and pulled against the attachments supporting the bumper cover. As the cable deflected, lateral force from the cables caused the second cable to rebound, followed by the first. The vehicle then contacted the back slope and rebounded upward, and the steering linkage was torqued, causing the vehicle to redirect downstream. The rear tires contacted the cables and fractured posts and continued to deform the cables downward.

Most events in the simulation matched physical evidence from the crash. The vehicle projected over the slope and overrode the cable; however, in the crash, the downward pull of the cables deformed the bumper cover attachments, and ultimately tore the bumper cover off of the vehicle. It is likely that, due to a combination of slope rounding and the differences in vehicle profiles, that the top of the bumper cover actually slipped beneath the top cable facilitating bumper cover removal. These crash results were anomalous. Without more accurate vehicle, tire, bumper cover connection, and slope rounding models, such an event could not be replicated. Nonetheless, the override tendency was clearly obvious based on the sequential photographs.

Two root causes of this penetration were identified. First, the high CG trajectory angle of the vehicle into the barrier resulted in higher CG height at impact than was suggested by Mongiardini et al. for sedan or small car vehicles [20]. As a result, the vehicle struck the barrier at a much higher energy level and CG height relative to similar vehicles in nominal TL-3 impact conditions.

Although the placement of the cable median barrier anywhere on a 6:1 slope is permitted by FHWA and most state DOTs, agencies such as NCAC have recommended that low-tension cable median barriers not be placed between 1 ft (0.3 m) and 8 ft (2.4 m) from the center of the V-ditch [28]. Some state DOTs have mandated this practice for all cable median barriers. However, some high-tension systems have been tested and approved for use anywhere in 6:1 V-ditches, based on the expectation that a vehicle departing the road with a CG trajectory angle of 25 degrees and a speed of 62.1 mph (100 km/h) will not override most cable median barrier systems based on nominal bumper trajectories. Following several cable median barrier placement studies, FHWA issued a memo revising acceptable barrier placement locations. Detailed studies analyzing vehicle trajectories in V-ditches have recently generated concern that MASH vehicles can display sensitivities not witnessed in testing conducted according to NCHRP Report 350 [20].

Unfortunately, high-angle departures from the road generate very difficult scenarios for capturing errant vehicles. This problem will be present for all sloped medians to some degree; for 6:1 V-ditches, significant deviations of the CG height relative to the ground are observable at 28 degrees, and for 4:1 slopes, significant differences between CG heights can be observed even at 20 degrees. In a limiting case, the angle of departure which generates a “free fall” condition will result in bouncing as well as potential for override. An optimum solution to prevent these types of override or underride crashes in V-ditches with slopes of 6:1 or steeper is to use taller, more robust cable median barrier systems, such as TL-4 cable median barriers. States should consider adopting TL-4 cable median barriers as a standard to prevent these overrides and underrides.

The second cause of this penetration was that the cable-to-post attachments for the Nucor system were too strong, as detailed in Chapters 8 and 9. The high cable-to-post attachments prevented the top cable from releasing from the posts, and dragged the top cables downward beneath the vehicle. This was particularly evident from the post-crash photographs, which showed two fractured posts displaced downstream of impact, still attached to the cables. The cable-to-post attachment strengths should be stratified to prevent the top cable-to-post attachments from becoming overly strong and dragging the cables downward. There are additional benefits to low top cable attachment strengths, including low risk of vehicle occupant compartment crush during underrides, higher rates of cable entrapment preventing rebound into adjacent travel lanes, and better reaction on sloped medians. An ongoing study has attempted to identify the critical performance metrics for top and mid-post cable-to-post attachment heights [49].

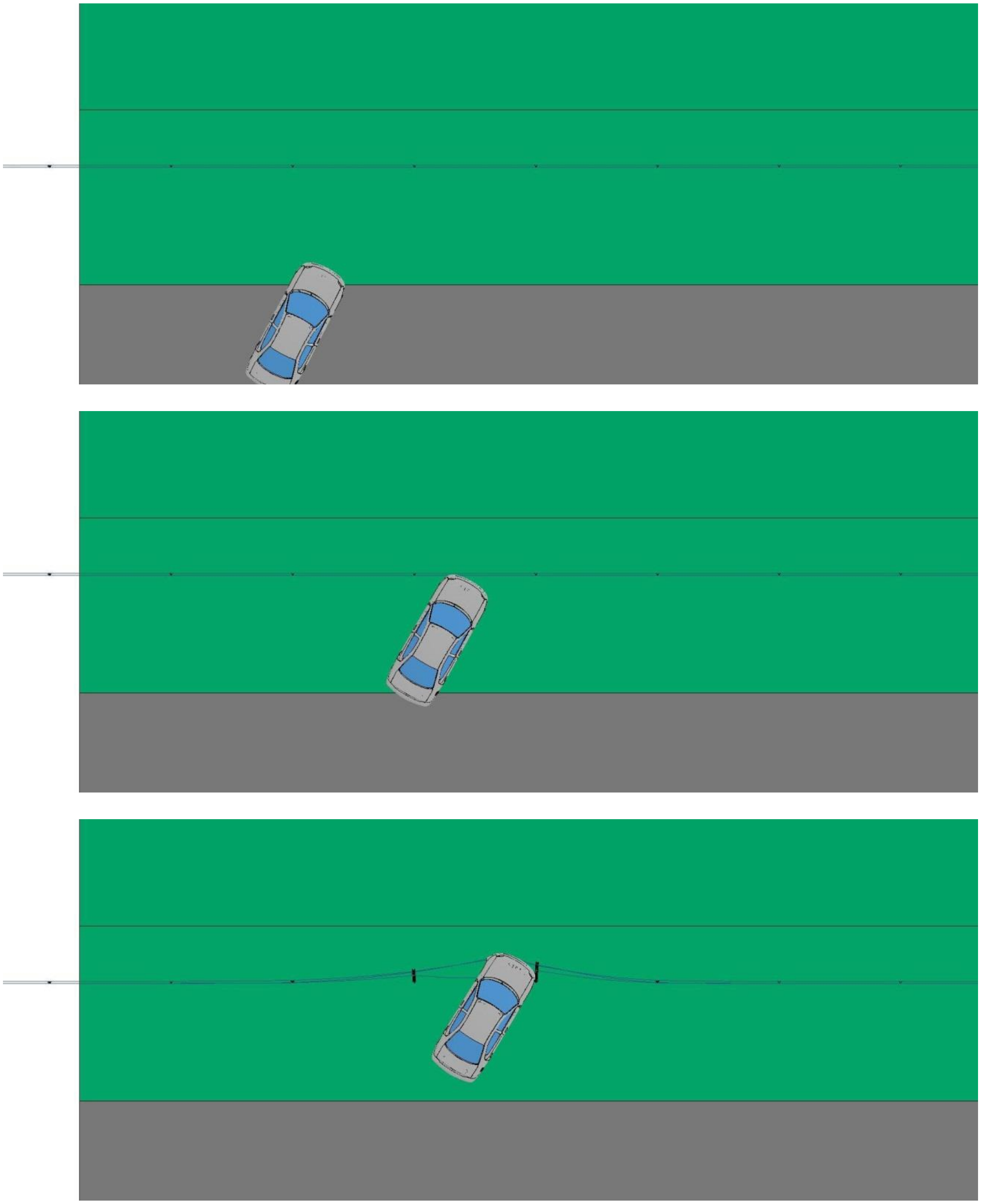


Figure 111. Overhead Sequentials, Simulation 1

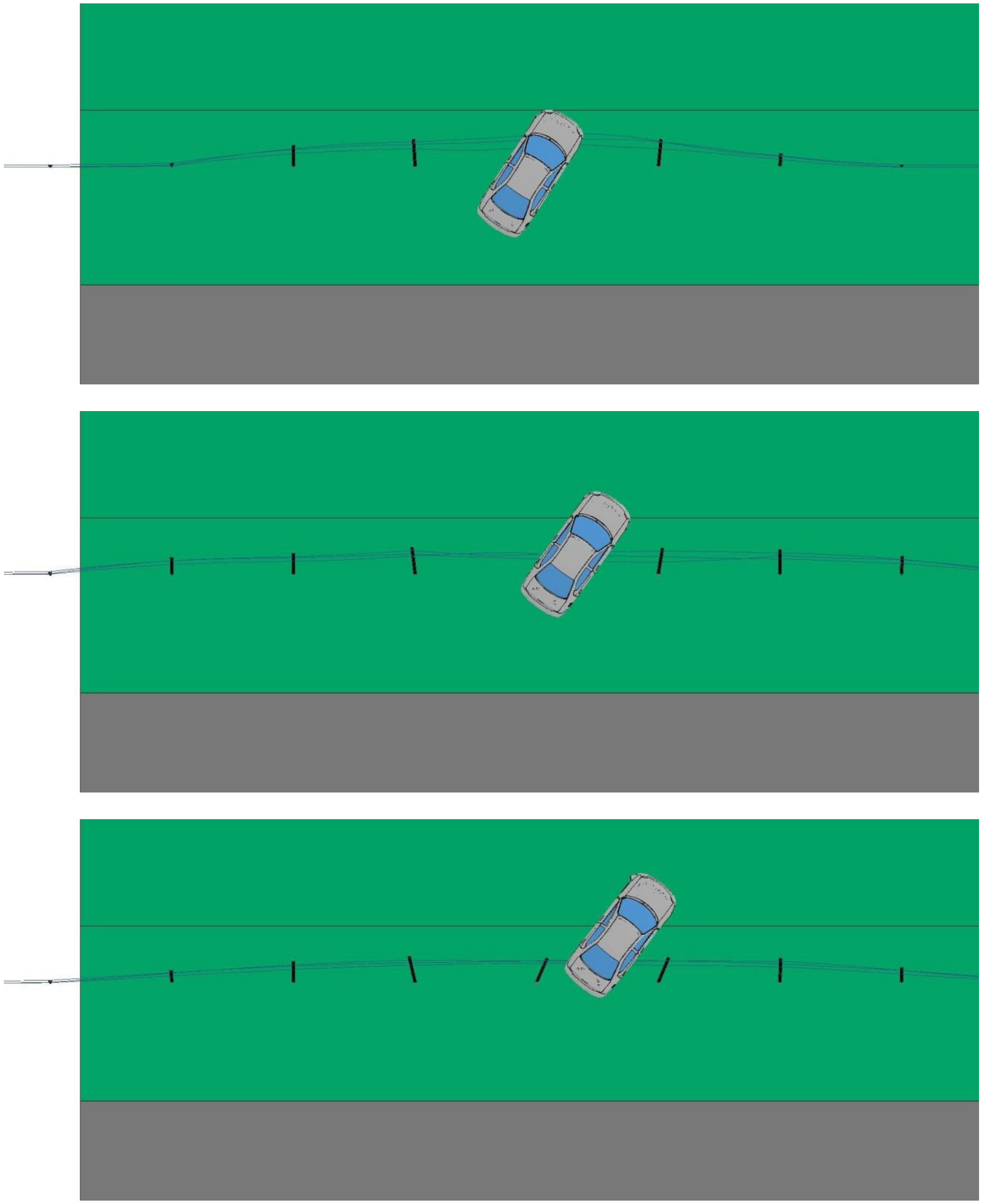


Figure 111 (cont). Overhead Sequentials, Simulation 1

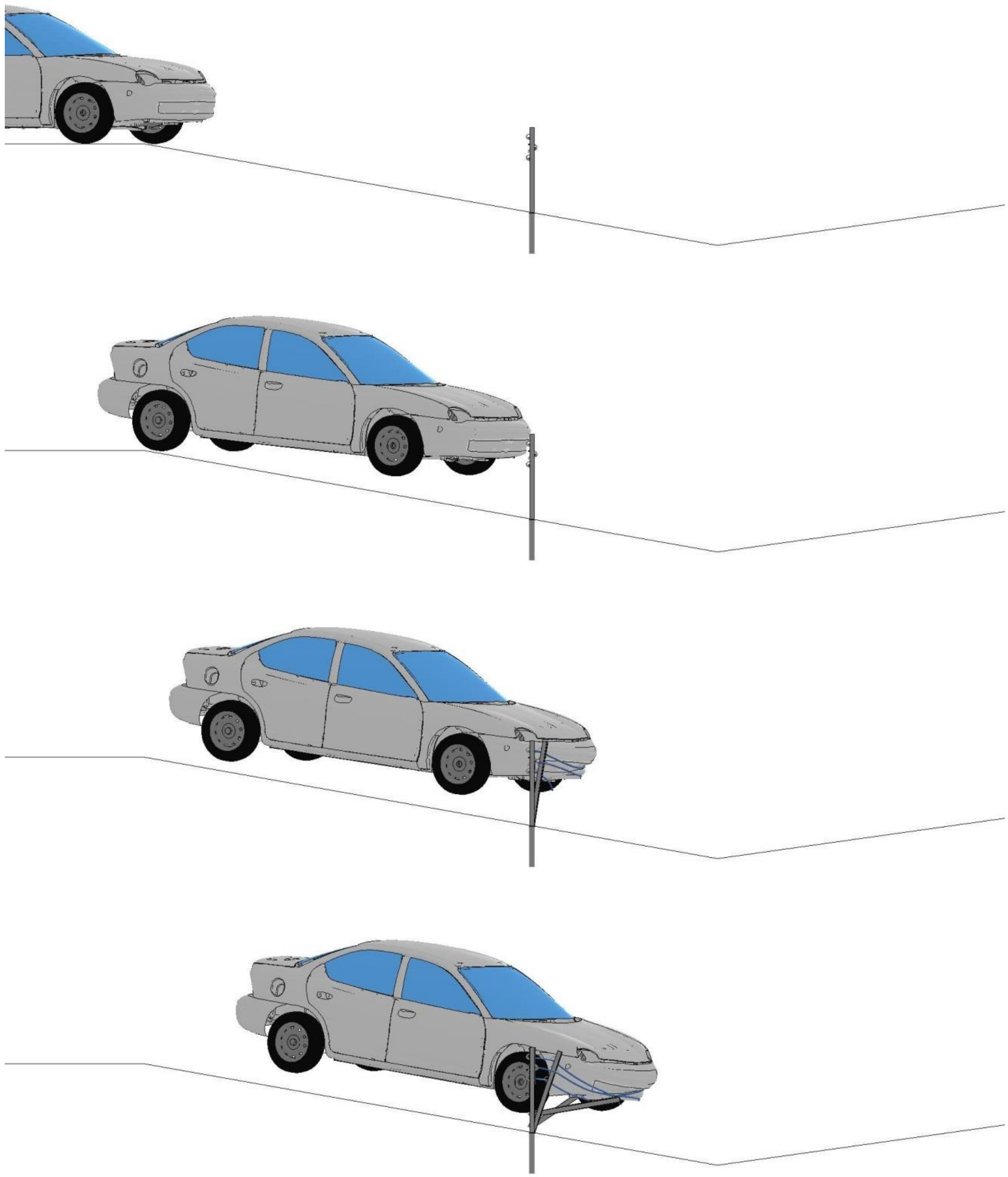


Figure 112. Downstream Sequentials, Simulation 1

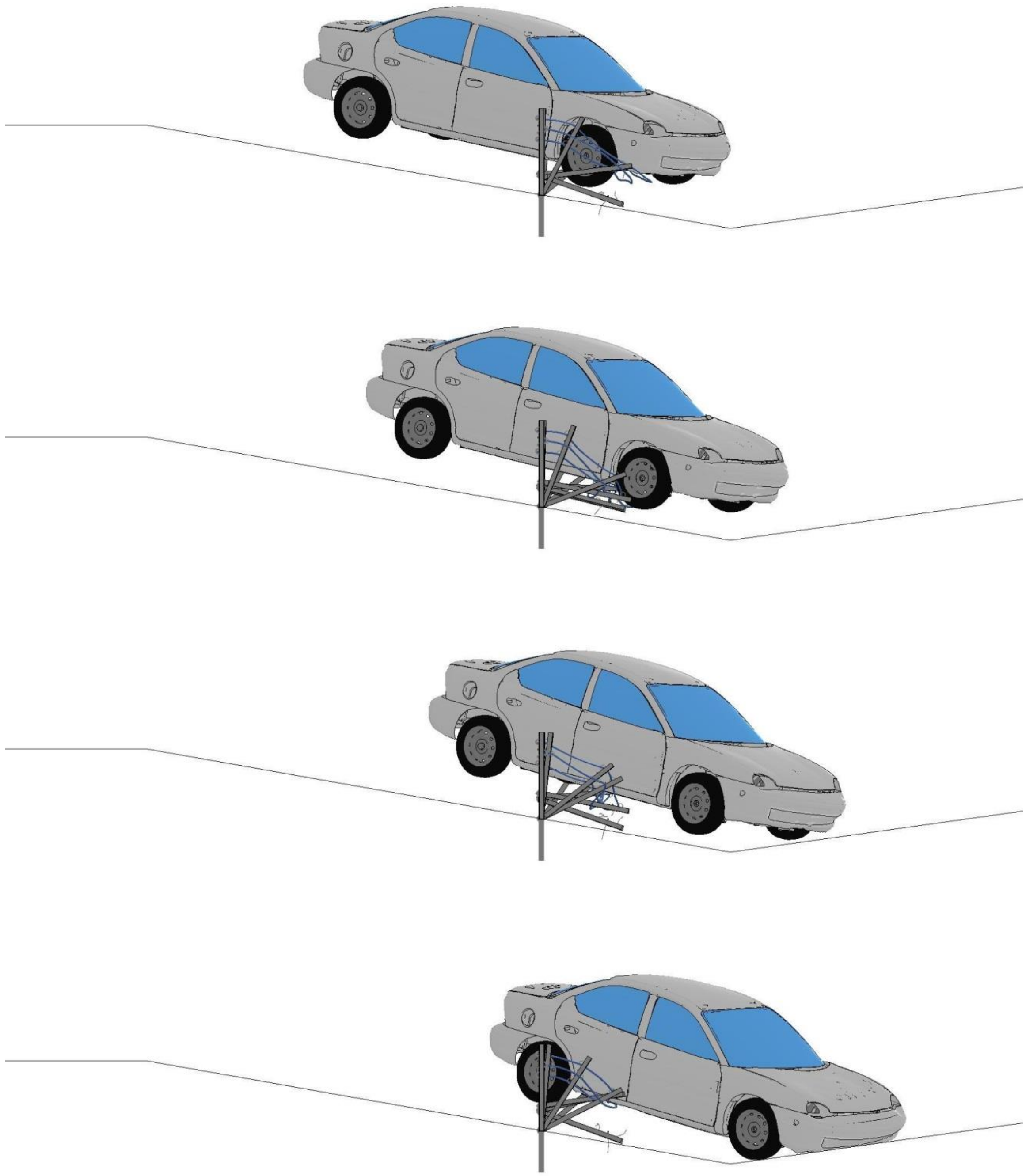


Figure 112 (cont). Downstream Sequentials, Simulation 1

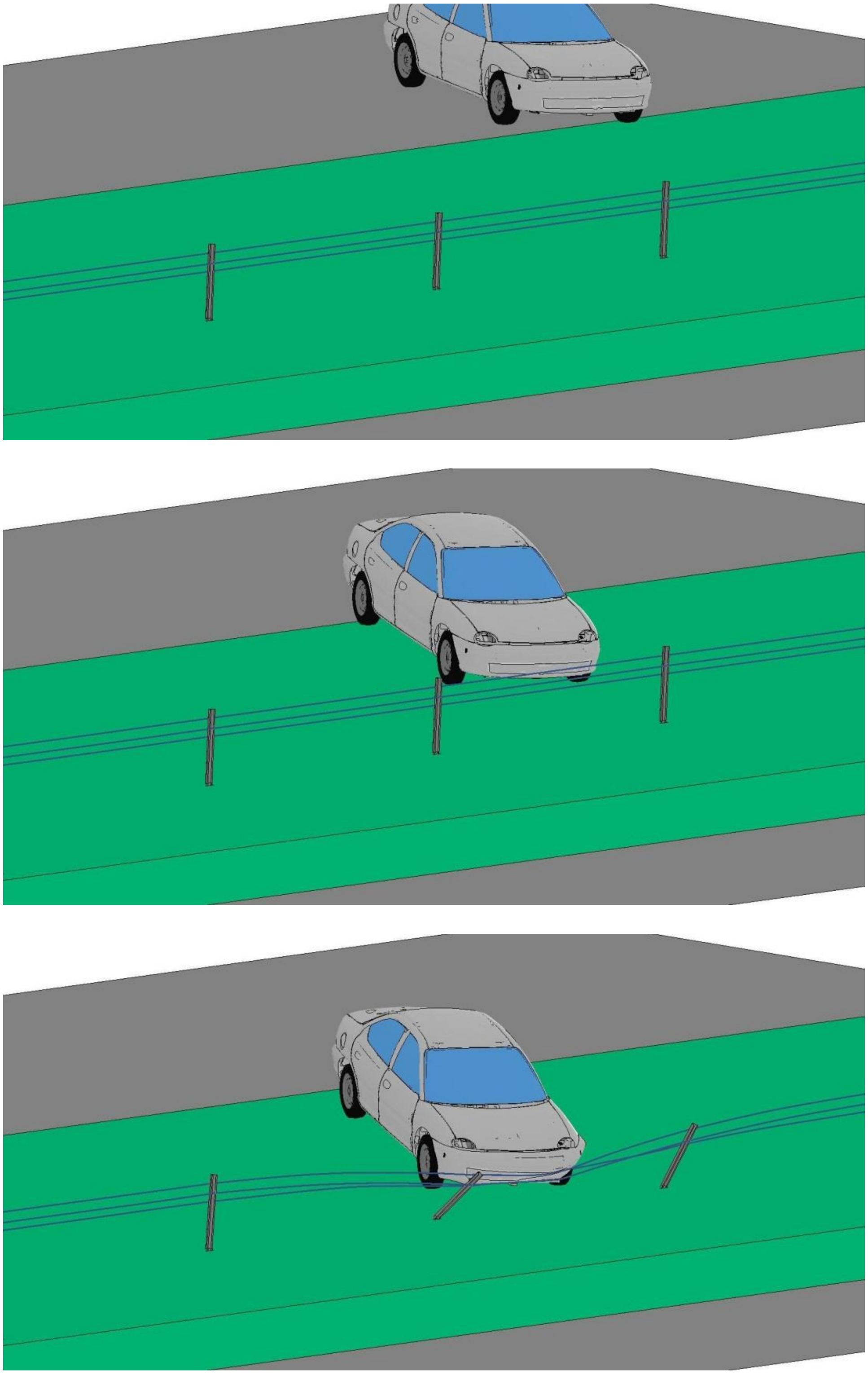


Figure 113. Downstream Behind Sequentials, Simulation No. 1

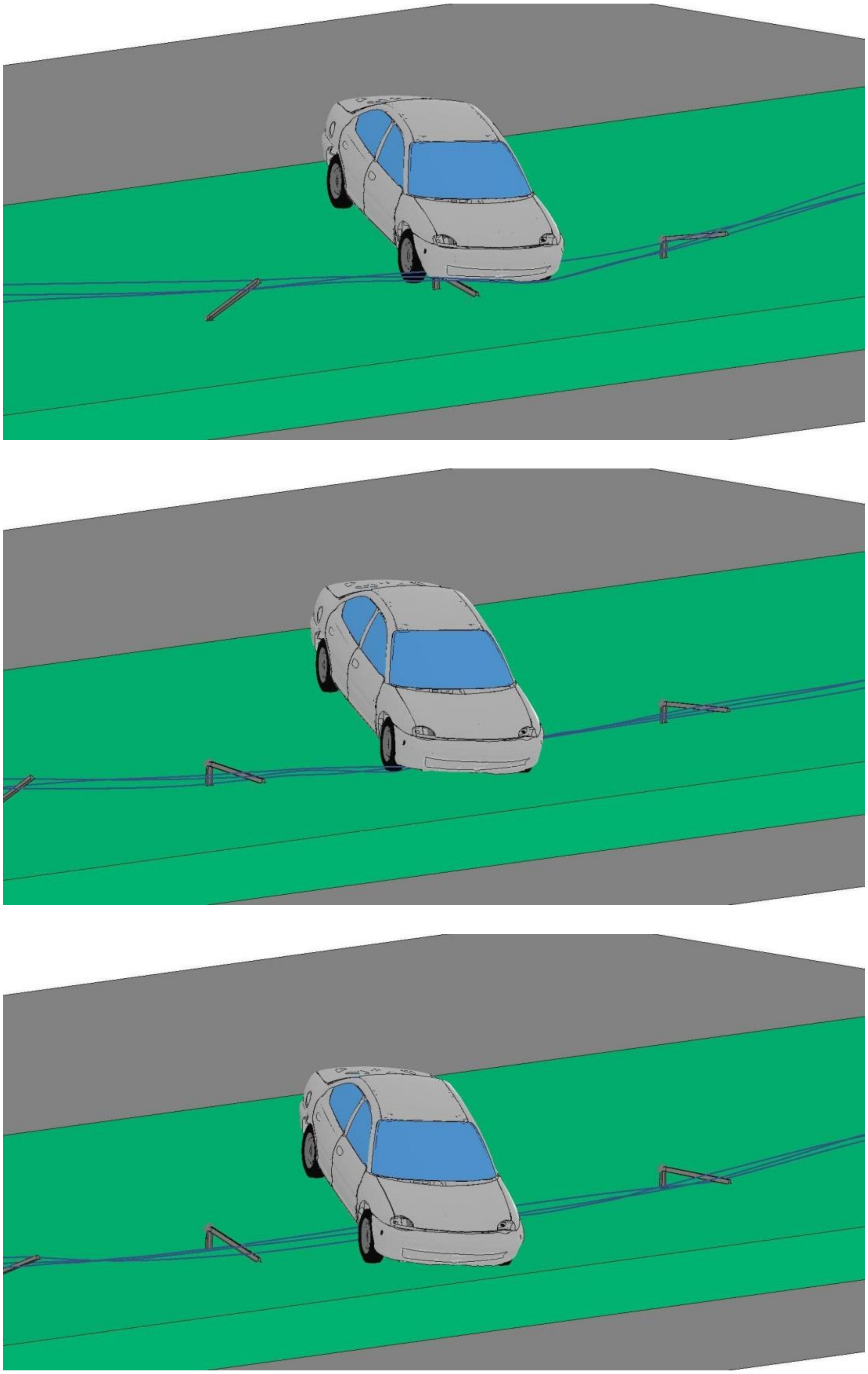


Figure 113 (cont). Downstream Behind Sequentials, Simulation No. 1

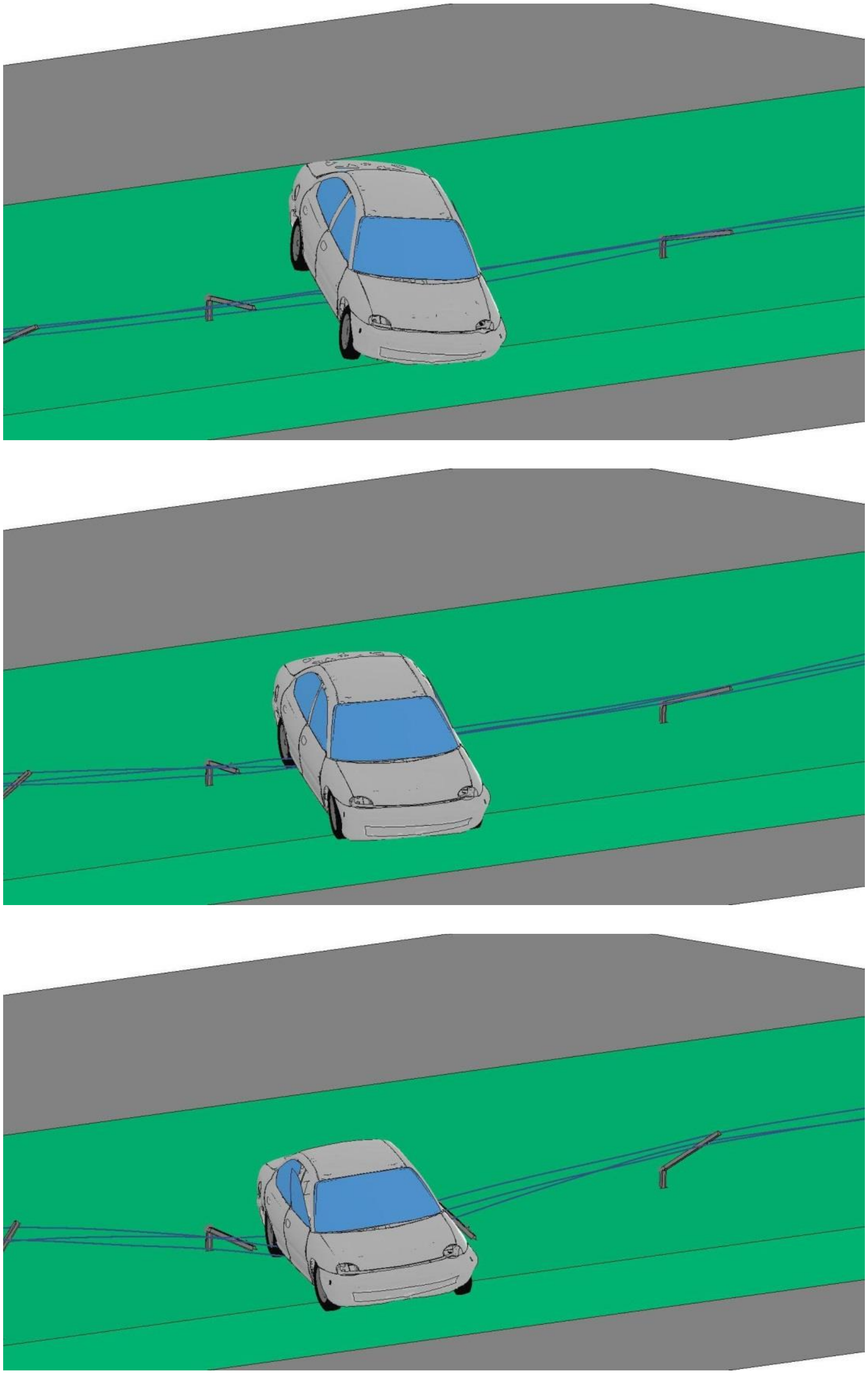


Figure 113 (cont). Downstream Behind Sequentials, Simulation No. 1

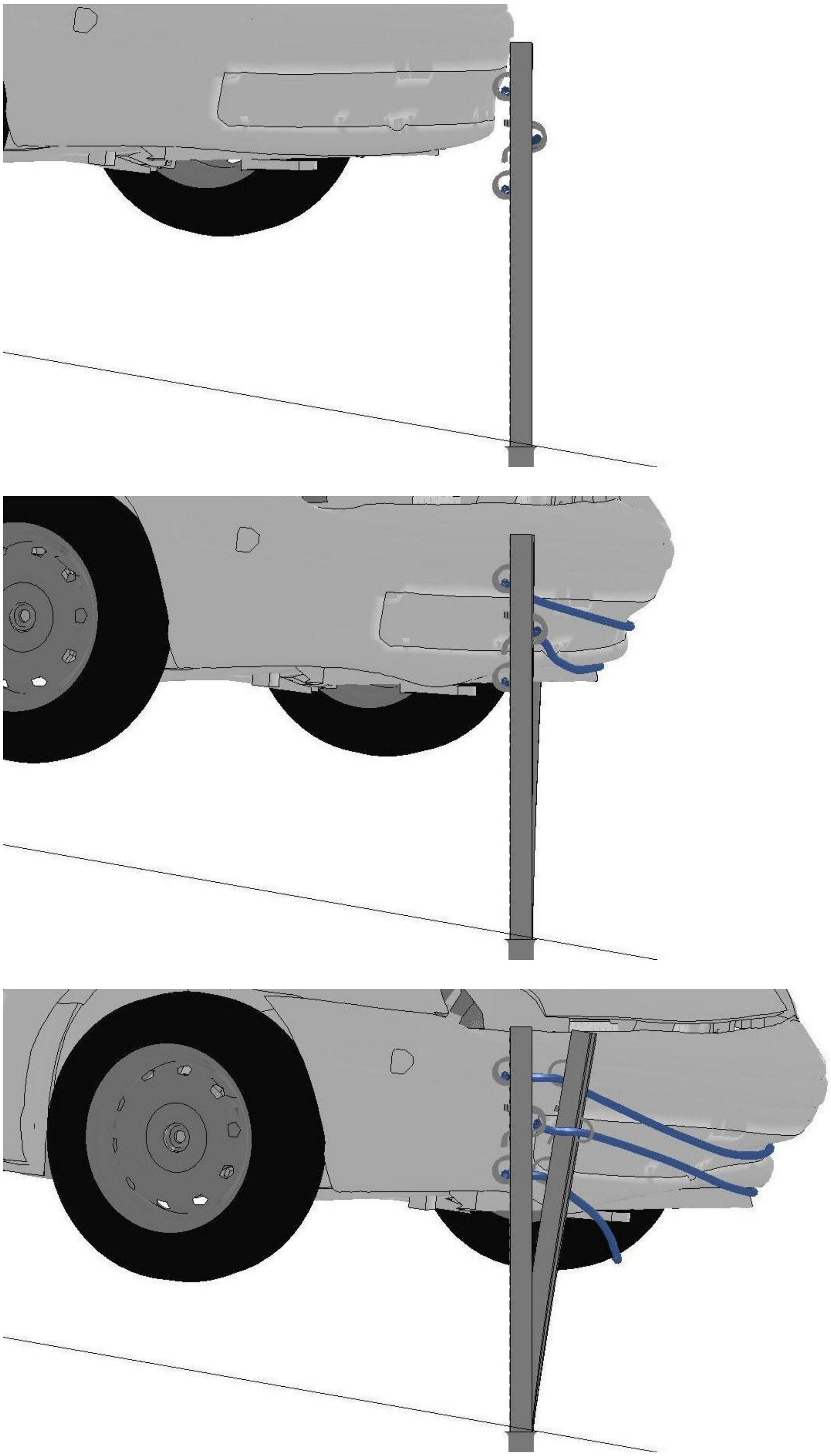
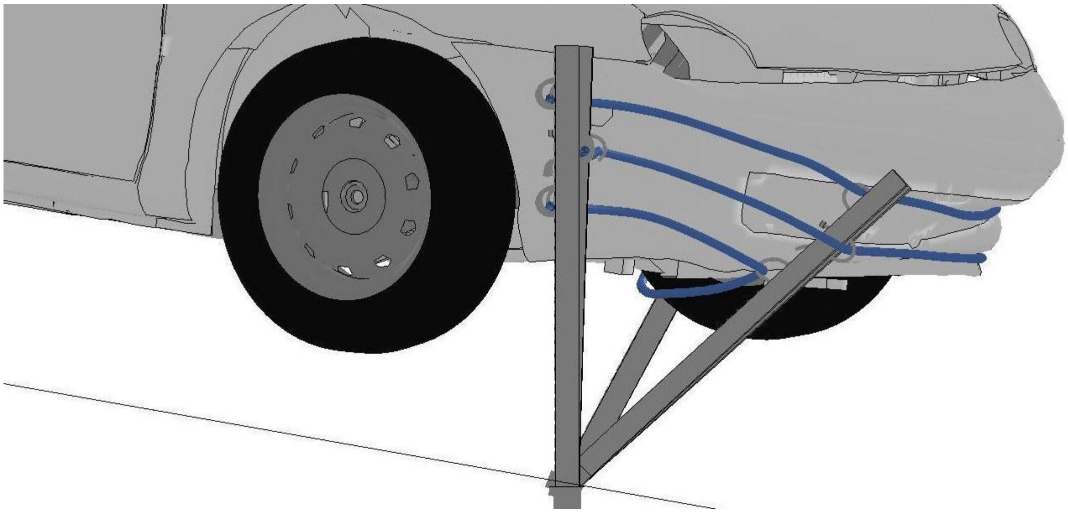


Figure 114. Sequentials of Critical Impact Sequence, Simulation No. 1



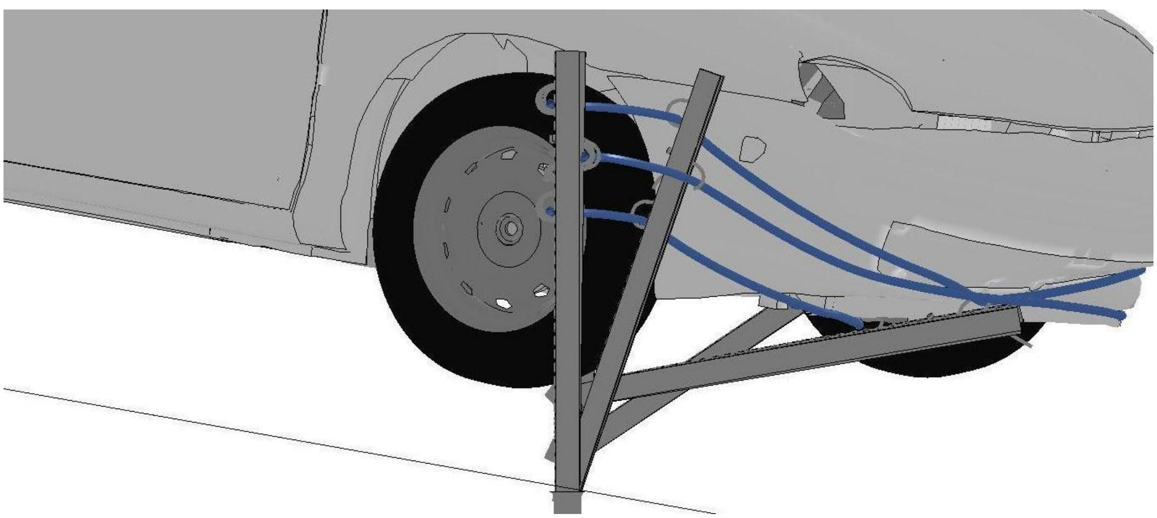


Figure 114 (cont). Sequentials of Critical Impact Sequence, Simulation No. 1

10.3 Simulation 2: TL-3 Brifen Cable Barrier

The second simulated cable median barrier penetration crash considered a Brifen 4-rope, TL-3 cable median barrier. The median profile at the point of departure consisted of five segments: an 8-ft (2.4-m) wide flat shoulder, a 22.7-ft (6.92-m) wide, 9:1 approach slope, a 4.6-ft (1.40-m) wide flat ditch center, a 22.4-ft (6.83-m) 8:1 back slope, and a 10.6-ft (3.23-m) wide opposite-side shoulder. The cable median barrier was installed at the center of the 9:1 approach slope.

The Brifen system, as previously detailed, involved 0.24-in. (6-mm) thick S-posts. roller cable supports locked on the sides of the posts, woven cables between posts, and posts placed in sleeves. The cable heights were at 19.7, 26.0, and 28.3 in. (500, 660, and 720 mm), with two cables woven on opposite sides of the post at 26.0 in. (660 mm).

The vehicle, a 2000 Toyota Avalon, struck the cable median barrier with CG trajectory and orientation angles of 16 and 152 degrees. Photographs of the crash scene are shown in Figures 115 through 117. This vehicle never departed the ground during impact, and the low CG trajectory angle and relatively flat approach slope enabled a straightforward crash reconstruction. Based on frictional values and post deformation energies, researchers estimated that the impact speed was approximately 50.7 mph (81.6 km/h).

10.3.1 Component Models

The vehicle model used in simulation no. 1 was also used in Simulation No. 2, but oriented at a 152-degree orientation angle and a 15.9-degree CG trajectory angle. Also, the front bumper cover slat was removed, since that portion of the bumper did not contact the cable barrier. The ground slopes were also created using rigid walls, similar to those used in Simulation No. 1.

The posts were modeled with type 2 Belytshcko-Tsay shell elements, with an element length of approximately 0.39 in. (10 mm). The posts were modeled as two parts: one part below ground was used in contact definitions with the foundation tube, and one part above ground used in the contacts with the rigid walls representing the ground.

The cable supports, which were effectively rollers pinned to the sides of the posts, were modeled using a thin, rigid, shell element casing. Shell elements were used in lieu of solid elements since the cables, modeled with beam elements, are better suited for contact with shell elements than solid elements. This effect was described in reference [50]. Rigid cable supports on each post utilized tied to nodes on the posts to model the clip engagement.

The cable on the top of the post was placed in a U-shaped slot. However, as mentioned, shell element edge contact with the beam elements can result in node snagging and instability. Thus, the U-channel slot was expanded by 0.039 in. (1.0 mm) and beam elements with a 0.039 in. (1.0 mm) diameter were lined around the U-channel slot, and assigned null material properties.

Figure 115. Crash Scene Photographs, Simulation No. 2

Figure 116. Crash Scene Photographs, Simulation No. 2

Figure 117. Post-Crash Vehicle Photographs, Simulation No. 2

The cables in the system comprised models recommended in literature [29]. Cables were tensioned to approximately 5.0 kips (22.2 kN) over 500 ms prior to impact using discrete beams and the *MAT_CABLE_DISCRETE_BEAM model with a ramp loading curve to apply a controlled ramp load. The cable tensioner at the boundary of the cable was switched from deformable to rigid approximately 50 ms before impact. Contacts between the cables and the posts, cable-to-post attachments, and vehicle were of the automatic node-to-surface type, and contact between cables utilized an automatic general contact type, which more accurately treated beam-to-beam contact.

Initial simulation results indicated vehicle capture instead of penetration. The vehicle struck the cable median barrier and the cables deformed the right-front fender inward toward the headlight housing. The low vehicle mass and yaw moment of inertia caused the vehicle to rotate around the right-front corner, enabling the back of the vehicle to strike the system. Sequential photographs of the vehicle redirection event are shown in Figures 118 and 119.

It was determined that the failure type in this penetration crash was an underride, likely caused by the lower cable sliding up and over the headlight and hood before the vehicle was redirected. The basic model of the Neon did not incorporate headlight glass into the model. The simulated fender terminated adjacent to a gap which corresponded to the headlight casing location in an actual vehicle.

A headlight assembly was modeled by creating a tangent surface to the hood and fender that filled the hole above the bumper. The headlight was assigned glass material properties and given a thickness of 3.5 mm. Because few material models of glass have shown acceptable modeling performance to date, and because the glass in the physical crash did not fracture, the glass material was prescribed to be elastic. The mesh was smoothed and attachment points were created between the fender and the hood, although the modeled headlight casing was not attached to the bumper cover.

10.3.2 Simulation Results

The updated simulation results are shown in Figures 120 through 122. The Neon projected over the 9:1 slope and into the cable median barrier. The vehicle struck the barrier with the right-front corner. The front headlight struck the bottom cable first, lifting the cable over the top of the right-front headlight, and over the right-front corner of the hood. The remaining three cables struck the right-front fender and hood and were also lifted above the hood. As the vehicle progressed into the system, it struck four posts, and all four cables were forced above the hood and roof. The struck posts dented the fender, door panel, and rear bumper, and struck the right-rear tire, just as occurred during the crash sequence.

Unfortunately, the differences between the Dodge Neon and the Toyota Avalon also contributed to differences between the simulation and penetration crash. The curb weight of the Avalon was 700 lb (318 kg) greater than the curb weight of the Neon model, the wheelbase was 2 in. (51 mm) larger, and the top bumper height of the Avalon was higher than in the Neon model, but the center-of-headlight height was nominally the same. This led to a sharper front-end profile of the Avalon than was present in the Neon model. However, results were still indicative of the physical crash.

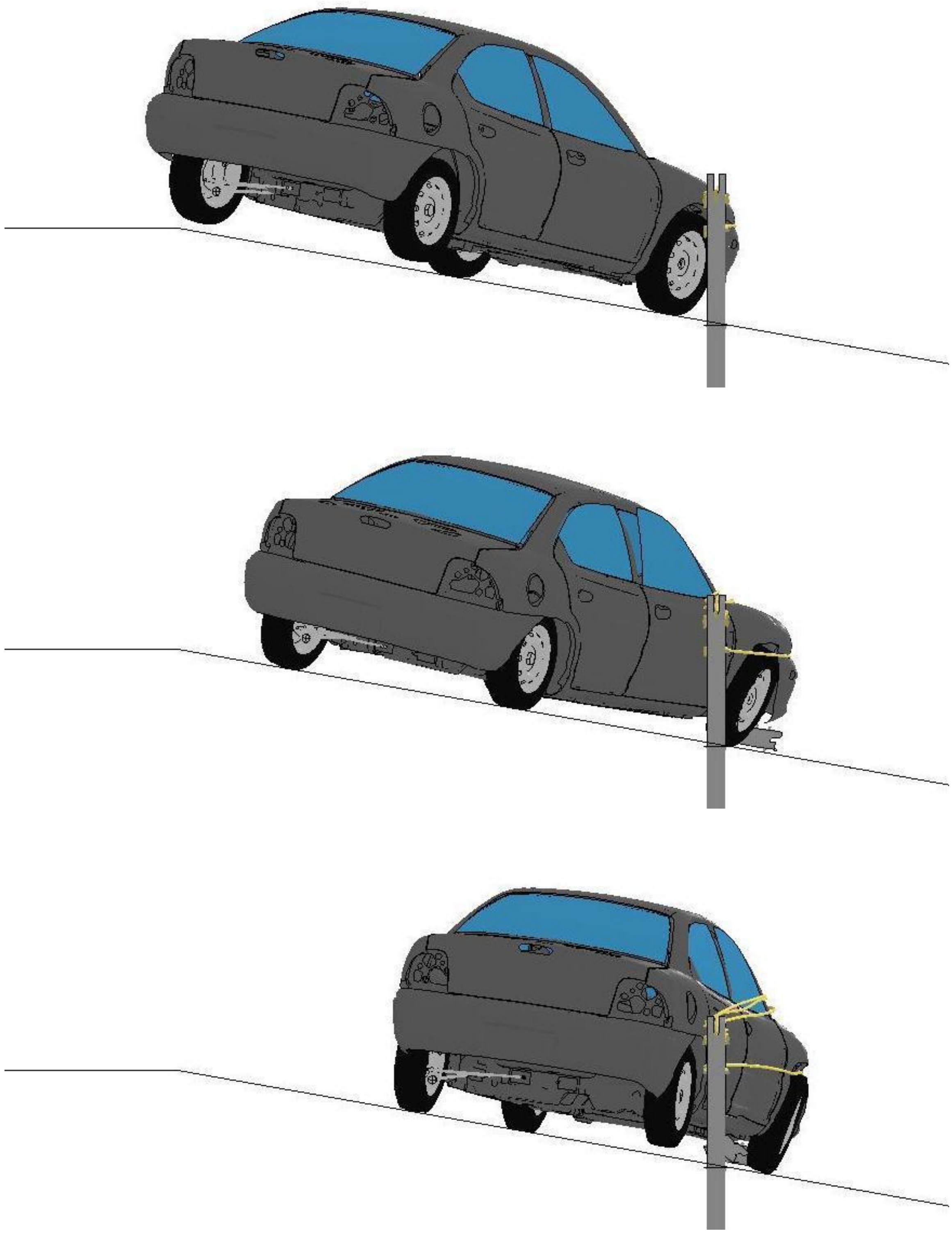


Figure 118. Downstream Sequentials, No Modeled Headlight Cover, Simulation No. 2

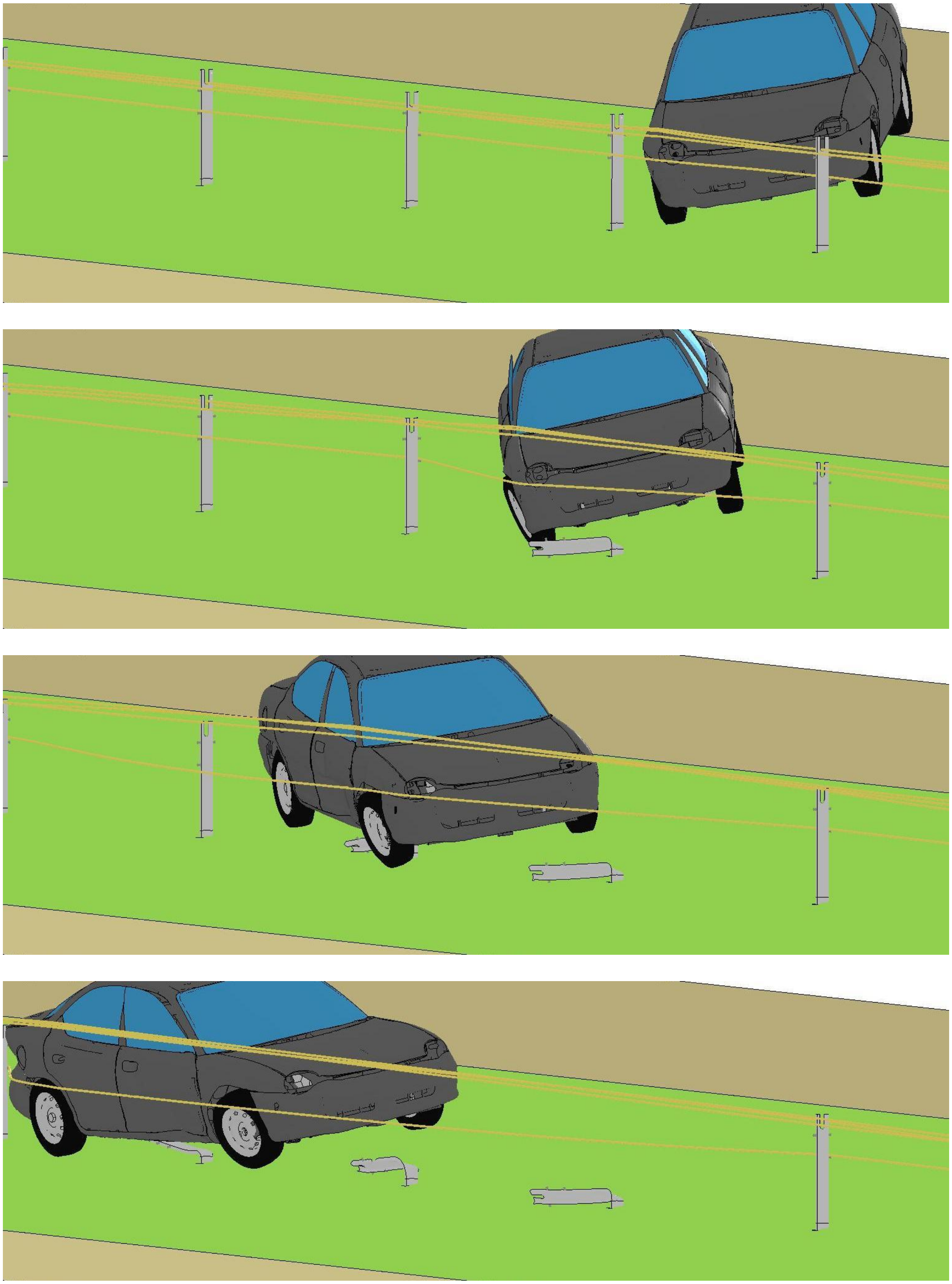


Figure 119. Upstream Behind Sequentials, No Modeled Headlight Cover, Simulation No. 2

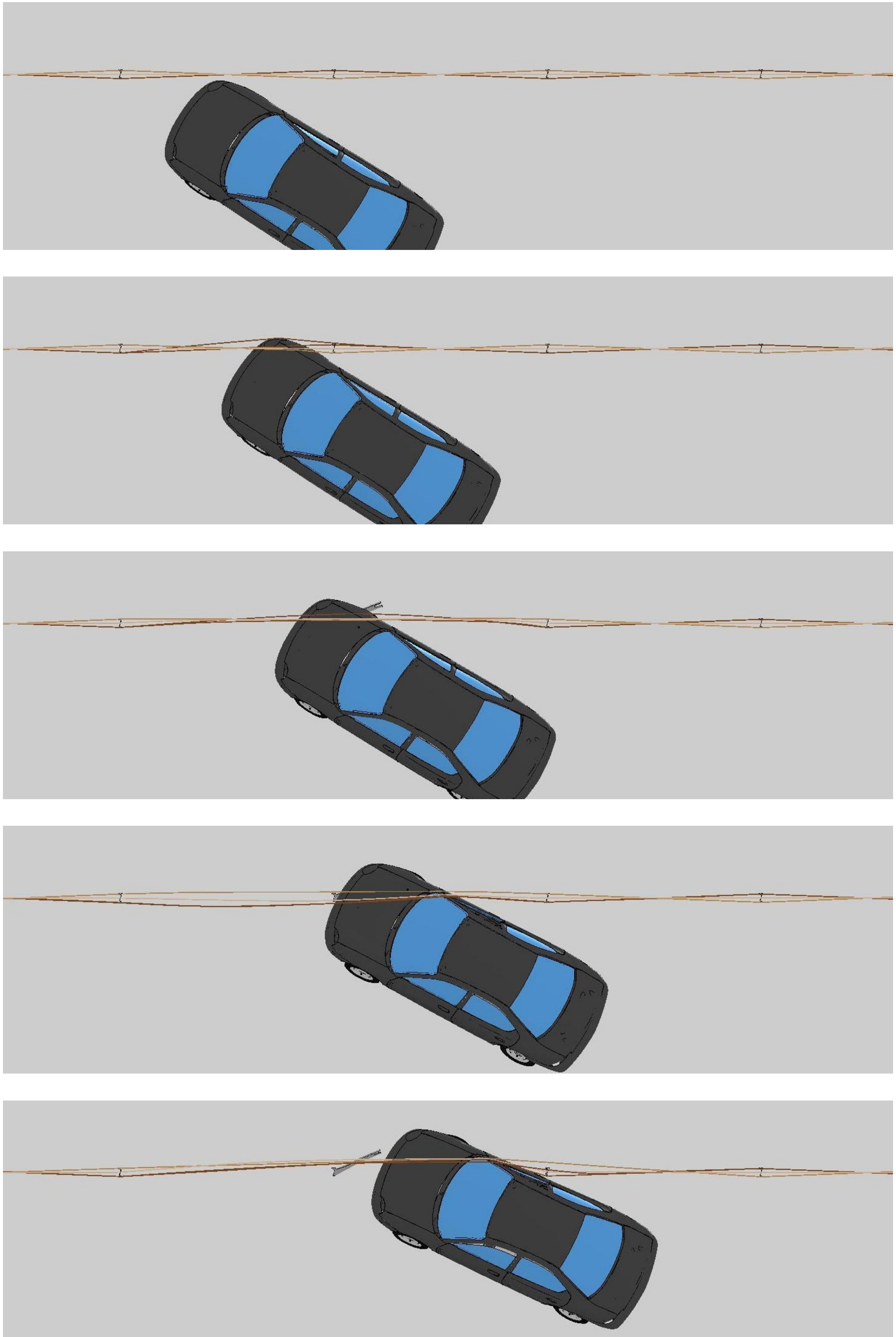


Figure 120. Overhead Sequentials, Stiff Modeled Headlight Cover, Simulation No. 2

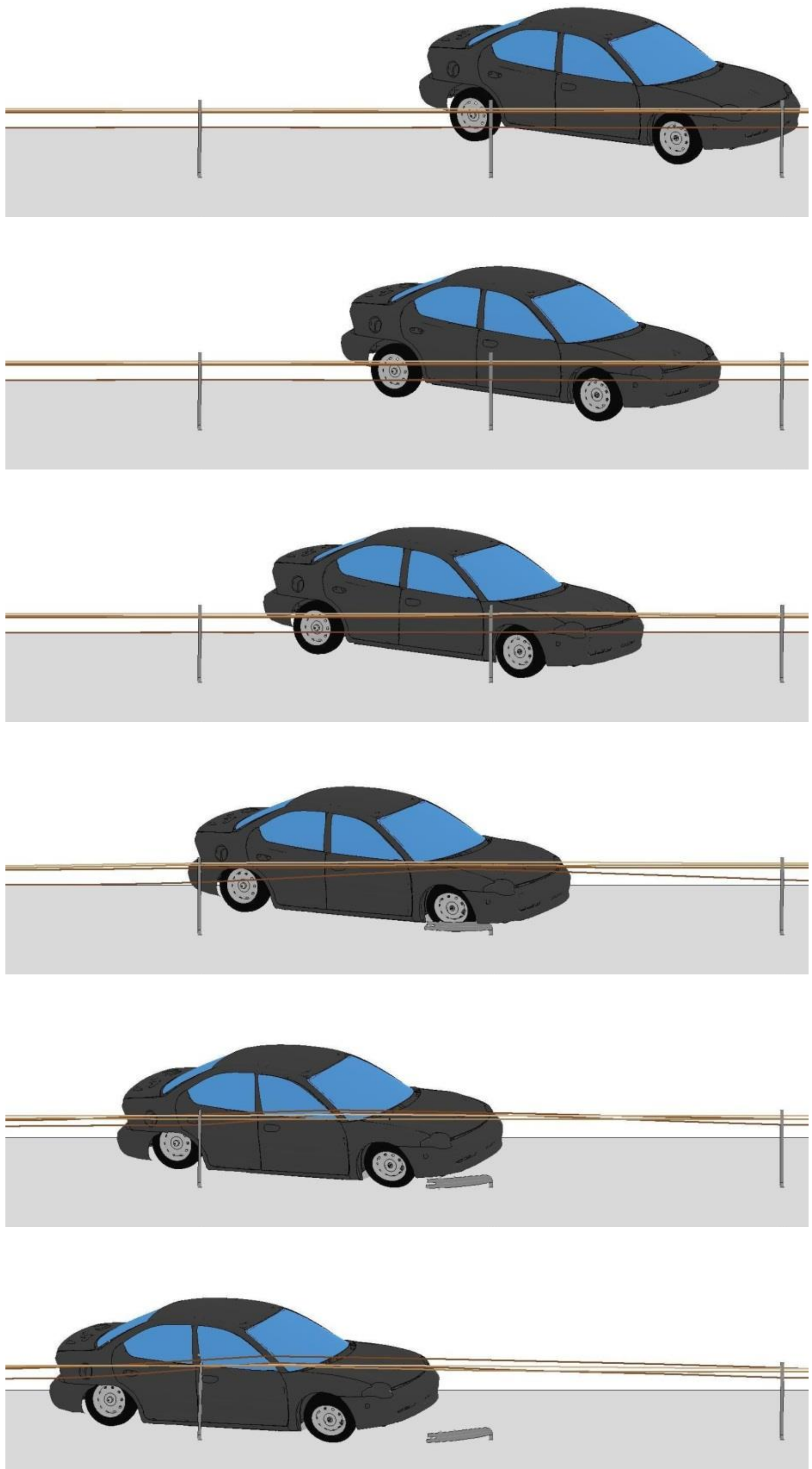


Figure 121. Behind-Barrier Sequentials, Stiff Modeled Headlight Cover, Simulation No. 2

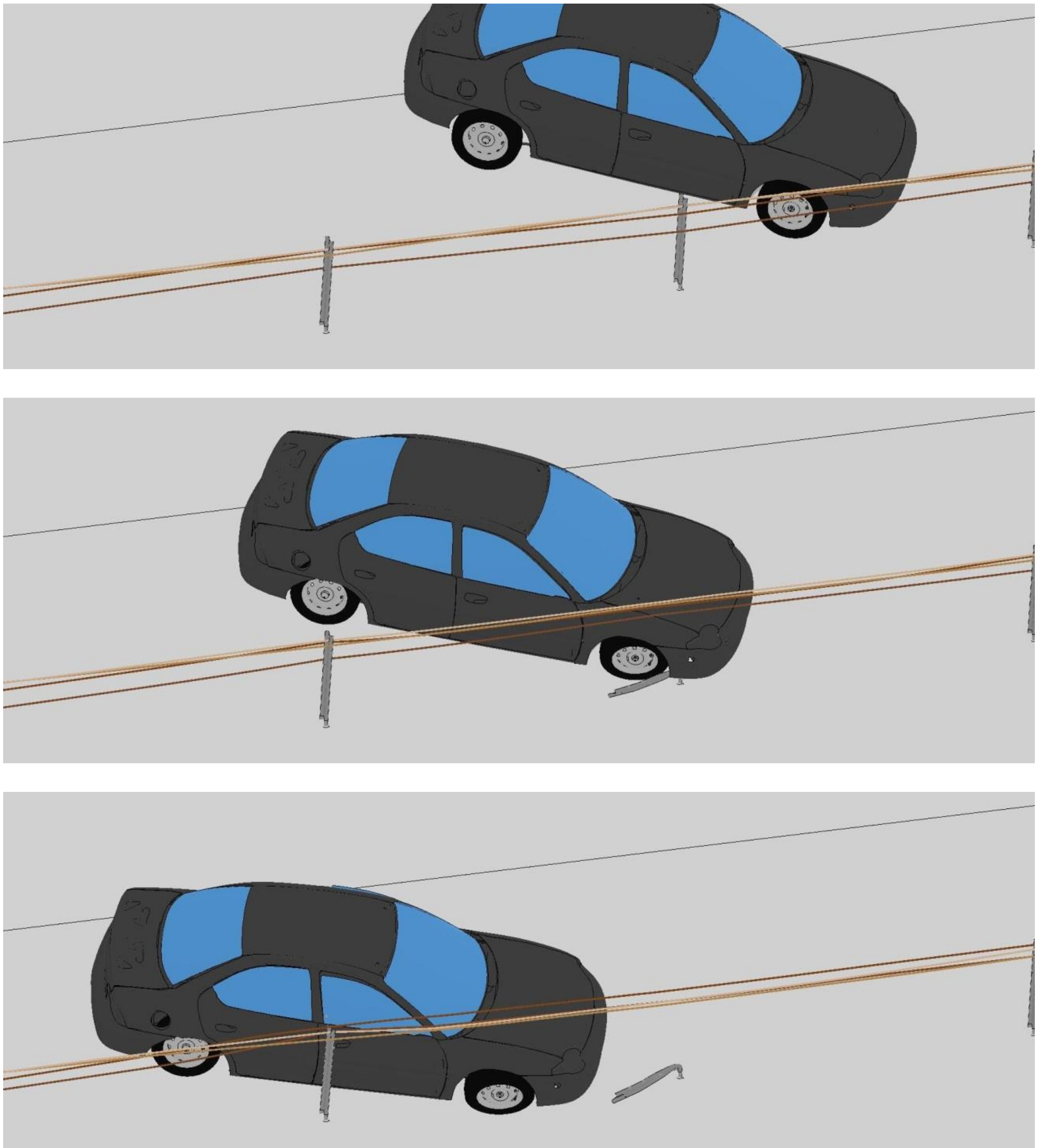


Figure 122. Downstream Behind Sequentials, Stiff Modeled Headlight Cover, Simulation No. 2

Two major contributors to this penetration crash result were identified. First, the low strength of the bottom cable-to-post attachment permitted the cable to rise up, over the headlight and hood without damaging the vehicle. By simply supporting the bottom cable with no vertical resistance load to lifting, the vehicle was able to pry the bottom cable up, and no other cable was in an optimum position to prevent penetration. This problem could be rectified by adding vertical resistance to the bottom cable on the post. Such a mechanism could be as simple as another snap-on roller attachment placed above the bottom cable to retain it on the post.

When a vehicle struck a cable median barrier system such that the headlight made tangential contact with the cables, a higher propensity for penetration always occurred. Side panels, including fenders, are nearly always more stiff than the vehicle front ends. This is because there is frequently crush room in front of the vehicle to safely bring a vehicle to a stop. Other non-structural components at the front end of the vehicle, including a crushable bumper, glass headlights which can fracture, and plastic components such as frontal grills or air dams tend to promote good cable engagement with the vehicle by deforming or fracturing and generating cable interlock locations. When the vehicle struck the barrier with an orientation angle between 90 and 180 degrees; however, the impact location was highly eccentric from the vehicle's CG, which contributed to induced yawing and facilitated disengagement of the cables from the vehicle front-end. Impact forces were not sufficient to cause fender crush or headlight fracture because yaw-inducing loads were below the deformation or fracture limits of the front-end components. It is likely that these factors were largely responsible for the large penetration rate for very high orientation angles.

10.4 Simulation No. 3: Generic Low-Tension Cable Median Barrier

The final crash simulated involved a low-tension, 3-cable median barrier constructed similarly to the system drawings shown in Figures 78 through 83. Posts used in the system were 6 ft-3 in. (1,600-mm) long, S3x5.7 posts with holes drilled in the flanges to accommodate 5/16-in. (8-mm) diameter J-bolts which supported the cables. Nominal cable mounting heights were at 21, 27, and 33 in. (533, 686, and 838 mm).

The median profile at the crash site consisted of four discrete slopes: a 4-ft (1.2-m) wide concrete shoulder, a 19-ft 10-in. (6.0-m) wide, 11.4:1 approach slope, a 19-ft 10-in. (6.0-m) wide, 11.4:1 back slope, and a 4-ft (1.2-m) wide concrete shoulder adjacent to the opposite-side travel lanes. The system was installed 5 ft (1.5 m) up the backslope from the median center.

Post-crash photographs are shown in Figures 123 through 125. Based on scene diagram and trajectory information, it appeared that the driver either became incapacitated or fell asleep. The vehicle, a 2000 Mercury Grand Marquis, drifted off of the roadway with a CG trajectory and orientation angle of 7 degrees. There were no visible signs of braking or steering throughout the departure event. The vehicle passed through the bottom of the ditch, which increased the CG trajectory angle to 11 degrees prior to impact because of the slope contribution. The vehicle remained engaged with the bottom cable for a sufficient amount of time to remove the bottom cable from more than 15 posts downstream of impact. The vehicle had a small steering angle to the left, which resulted in the vehicle overriding the bottom cable, redirecting up the back slope and colliding head-on with a different vehicle in the opposite travel lanes.

Figure 123. Crash Scene Photographs, Simulation No. 3

Figure 124. Crash Scene Photographs, Simulation No. 3

Figure 125. Crash Scene Photographs, Simulation No. 3

10.4.1 Component Models

Similar to the Brifen and Nucor simulations, post models in Simulation No. 3 consisted of shell element flange and web parts. Since the flanges of S3x5.7 posts were sloped, the thickness of the flanges was tailored to approximate the bending section of the real flange using a flat, constant-thickness flange approximation. The thickness of the shell flange was set to 0.26 in. (6.6 mm), and was positioned such that the distance between the outer contact surfaces of the front and rear flanges of the post were 3 in. (76 mm) apart, equal to the depth of a real post.

Because there was some surface soil displacement, the soil tubes were terminated approximately 2.5 in. (64 mm) below the surface of the ground. This permitted the posts to "rotate" through the upper effective 2 in. (51 mm) of soil. Some differences between the deformed post energy of the crash and model were expected because of differences between modeled and actual soil properties. The marginal contribution of soil, contributing to less than 1% of the overall energy dissipated, suggests that the modeling approximation was acceptable.

The 5/16-in. (8-mm) diameter J-bolt cable-to-post attachments were modeled using beam elements, similarly to the cable-to-post attachments used in the Nucor cable barrier system. Tension-strain, moment bending-curvature, and torque-rate of twist curves were determined based on the behavior of equivalent solid element rod models subjected to bending, torsion, and tension. The resulting curves were inserted into a *MAT_MOMENT_CURVATURE_BEAM material model, and the bolts were connected directly to the mesh of the post since none of the bolts fractured in this simulation. A comparison between the beam element models of the J-bolts and the documented tests on J-bolts indicated a difference of less than 5% of the nominal vertical and horizontal pullout strengths of the models and real bolts [46].

As with the other simulations, the cables in the system comprised models recommended in literature [29]. Cables were tensioned to 950 lb (4.2 kN) over 400 ms prior to impact using discrete beams and the *MAT_CABLE_DISCRETE_BEAM model with a controlled ramp loading curve. The cable tensioner at the boundary of the cable was switched from deformable to rigid approximately 50 ms before impact. Contacts between the cables and the posts and vehicle were of the automatic node-to-surface type, and contact between cables and beam element J-bolts utilized an automatic general contact type, which more accurately treated beam-to-beam contact.

A Ford Taurus model developed by NCAC was initially included in the model as a close match to the Mercury Grand Marquis. However, simulations frequently resulted in instabilities and early terminations, which originated with the vehicle model. Because improving the Taurus model was outside of the scope of this effort, the Neon model used in simulation nos. 1 and 2 was substituted for the Taurus. The front-end geometries of the Taurus and Neon were similar, but major structural differences were identified. The Taurus weighed more than 1,350 lb (612 kg) more than the Neon, was 40 in. (1,016 mm) longer with a 10-in. (254-mm) longer wheelbase, and had a 4-in. (102-mm) wider track width. To accommodate the increase in mass, several discrete masses were added to the system, and densities of frame elements were also increased to match the weight of the modeled vehicle to the vehicle in the crash.

10.4.2 Simulation Results

Sequential photographs of simulation no. 3 are shown in Figures 126 through 129. The vehicle followed a similar trajectory as the vehicle involved in the penetration crash. Upon impact, the middle and upper cable were pried upward and over the hood, as the bottom cable engaged the vehicle at the headlight location. The bottom cable crushed into the front fender less than 1 in. (25 mm) as it was displaced laterally by the vehicle, was stripped off of 10 posts downstream from impact, slipped down the vehicle bumper and fender, and was eventually run over by the tires.

The Neon model did not incorporate explicit steering control or modeling capacity, and had a considerably different front-end profile. Despite these shortcomings, critical features of the simulation and crash test were similar. The middle and upper cables slipped over the hood and roof in both events, and the bottom cable engaged the vehicle at the left-front fender corner. The bottom cable was removed from enough posts downstream of impact to allow the cable to droop when the vehicle trajectory became parallel with the system. The vehicle overrode the bottom cable, resulting in penetration, and became free-wheeling.

This simulation illustrated two major problems with the low-tension cable median barrier system. First, the bottom cable-to-post attachment is too weak to prevent these types of impacts from penetrating through the barrier system. In the simulation, this was further accentuated by the low but increasing CG trajectory angle, causing the middle and upper cables to make first contact with the left-side fender instead of the front of the vehicle. This generated a high-stiffness resistance to deflection, which generated the same fender stiffness problems observed in simulation no. 2.

Secondly, the bottom cable height was too high to prevent underrides from occurring in even flat medians. The bottom cable height of 22 in. (559 mm) was higher than the hood height of 1% of vehicles involved in cable median barrier crashes. A 3-in. (76-mm) deflection of the front end of the vehicle, which can occur due to suspension compression near the center of the V-ditch and can even occur due to bouncing on the approach slope, would then increase susceptibility to more than 5% of all vehicles involved in cable median barrier crashes. If the high rate of penetrations which occur when the bottom cable struck the vehicle above the center height of the headlight is taken into account, the risk increase for flat and sloped terrain in front of the barrier increases to 1.5% and 21% of crashes, respectively.

Excessive deflection of the back-side cable and bottom cable underride together accounted for over 70% of all low-tension cable median barrier penetrations based on data collected in this study, though the precise rate is unknown. To alleviate these problems, the bottom and middle cable-to-post attachments must be strengthened, and attachments with greater energy absorption on cable release from the posts are strongly recommended. An increase in the diameter of the J-bolt shanks, from 5/16-in. (8-mm) to 3/8-in. (10-mm), would result in an approximately 75% increase in pullout strength from the post. Such a modification would likely reduce backside-cable release-related penetration frequency by 50% or more, based on the results of this simulation and the distribution of vehicle masses involved in cable median barrier crashes shown in Figure 20.

In addition, a fourth cable may be necessary for low-tension cable median barriers, located between 15 and 18 in. (381 and 457 mm) from the ground. This additional cable could be added to existing low-tension cable median barrier systems with one of two methods: an additional hole could be drilled in the flange for an additional cable-to-post attachment, or a hanging bracket could be attached to the bottom cable location to support the lowest cable. In order to retain a 1,000-lb (4.4 kN) release force, the bracket could be strengthened with a cable tie near the cable location. Both methods would require simulation for concept development and full-scale crash testing to verify the crashworthiness of the design.

Fatalities are estimated to occur at a minimum of once per 40 miles (64 km) of barrier per every 3 years with the current system construction. A non-fatal to fatal crash ratio of 199:1 is expected in a given mile stretch, based on low-tension cable median barrier A+K rates of approximately 0.5% K crashes. Maintenance cost increases of $100 per crash were expected, due to the increased repair time and additional cable hardware. Additional costs per 40-mile (64-km) stretch of road would then increase $20,000 per fatal crash in a 3-year period. By using this method, ADTs, crash rates, and ROR departure frequencies are not necessary to complete this analysis. Thus, a maximum cost estimate for one fatal crash would reasonably be $270,000 per 40 miles (64 km) of barrier per three years.

Considering that 50% of fatalities are caused by underride or low cable-to-post attachment strength and expecting a 50% reduction in such penetrations due to these simple modifications, a resultant reduction of 35% of fatalities is expected over this same stretch of barrier. Using the FHWA fatal crash costs of $4,008,900 per fatal crash, a 35% reduction in fatal crashes over this expanse of road over a 3-year period would result in a cost savings of $1,403,115. The benefit-to-cost ratio of this modification to low-tension cable median barriers would then be 5.2:1.

Since the cost per unit of roadway defined in this benefit-to-cost analysis is much higher than is expected for state DOTs per fatality, and actual penetration rates for the barrier could decrease by more than 70% based on the penetration analysis, the actual B/C ratio based solely on fatality reduction should exceed 5.2. However, it should be emphasized that the current bottom and middle cable-to-post attachments must be strengthened at the same time as an additional cable should be added to the system. No top cable-to-post attachment changes are currently recommended.

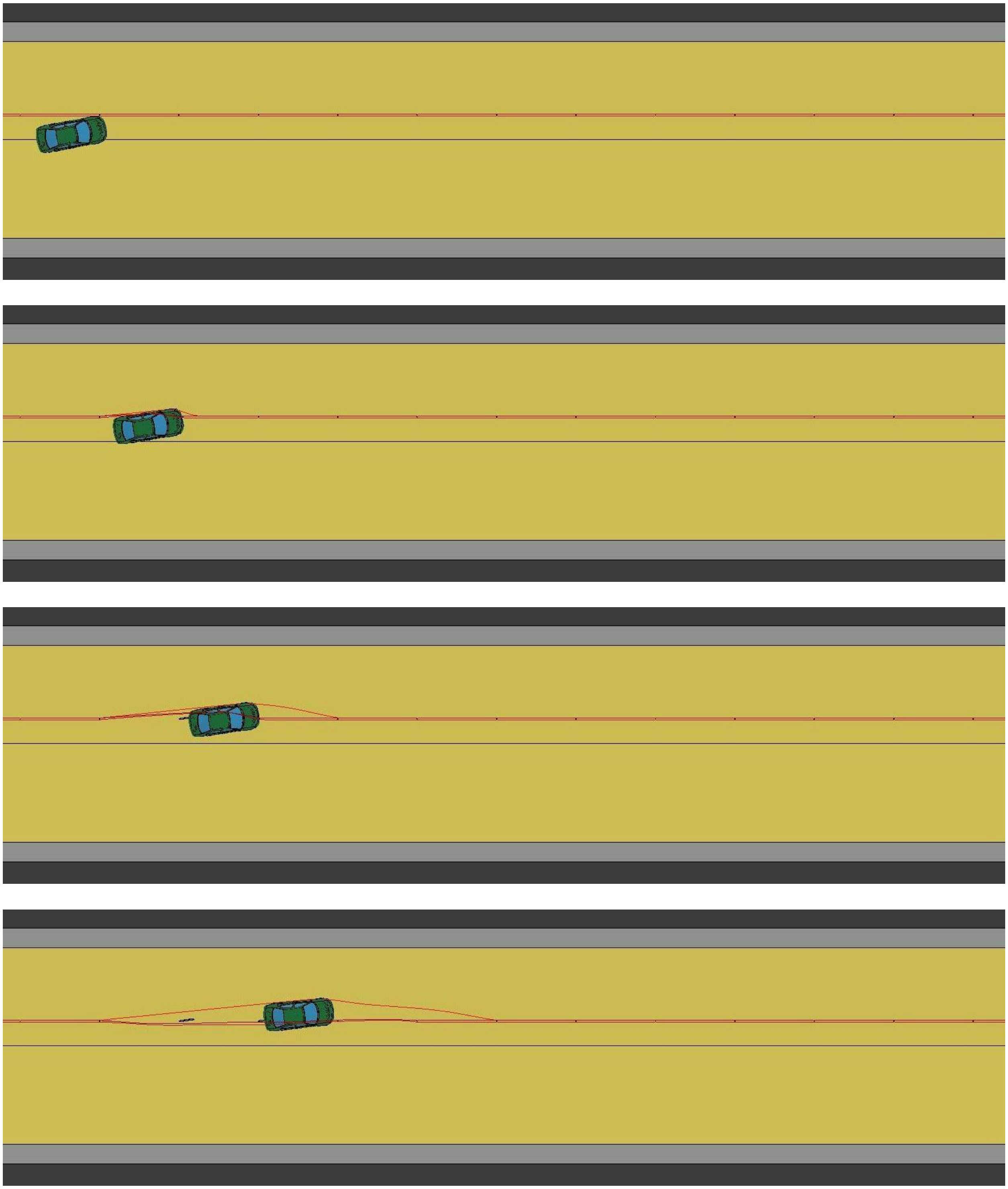


Figure 126. Overhead Sequentials, Simulation No. 3

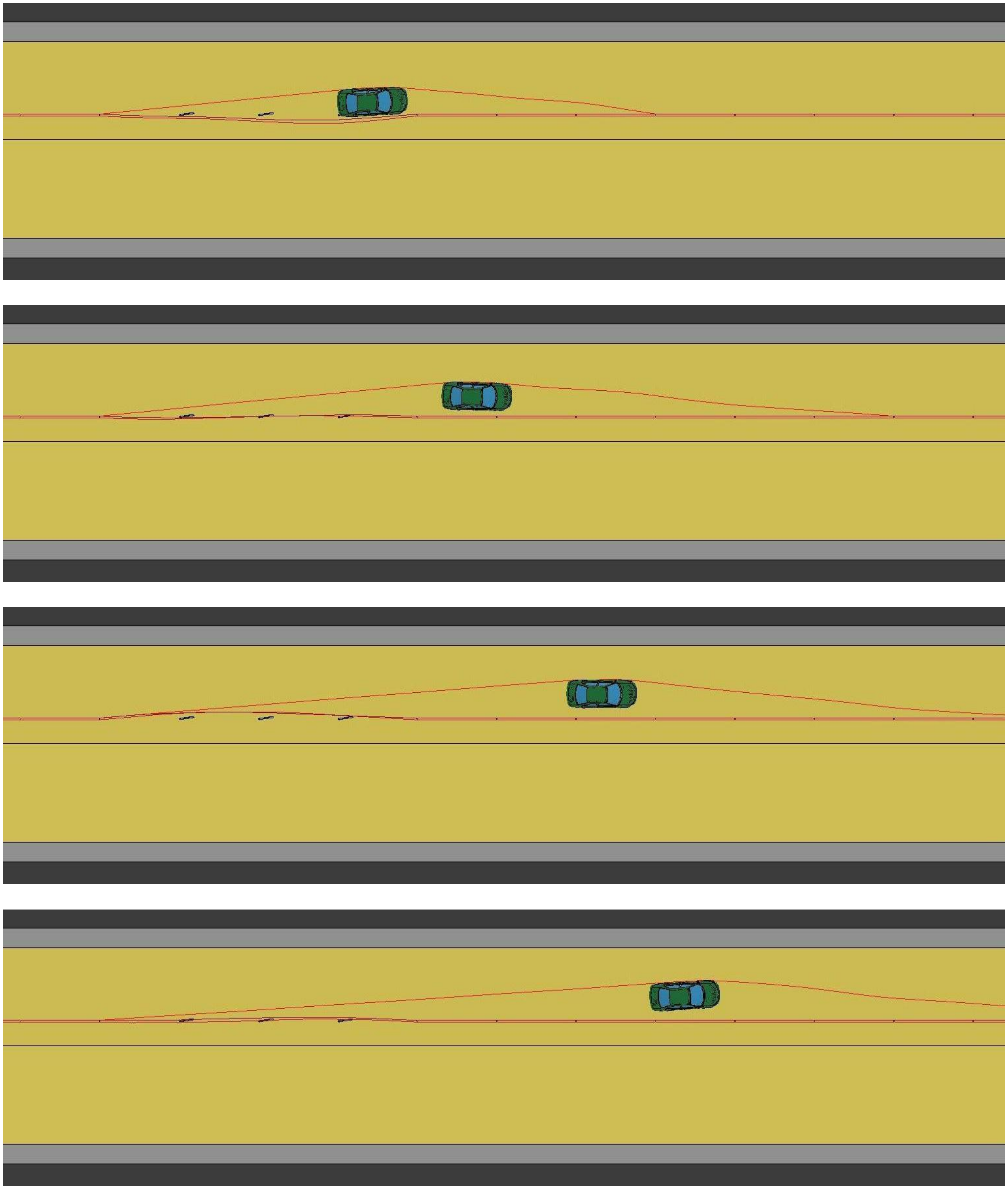


Figure 126 (cont). Overhead Sequentials, Simulation No. 3

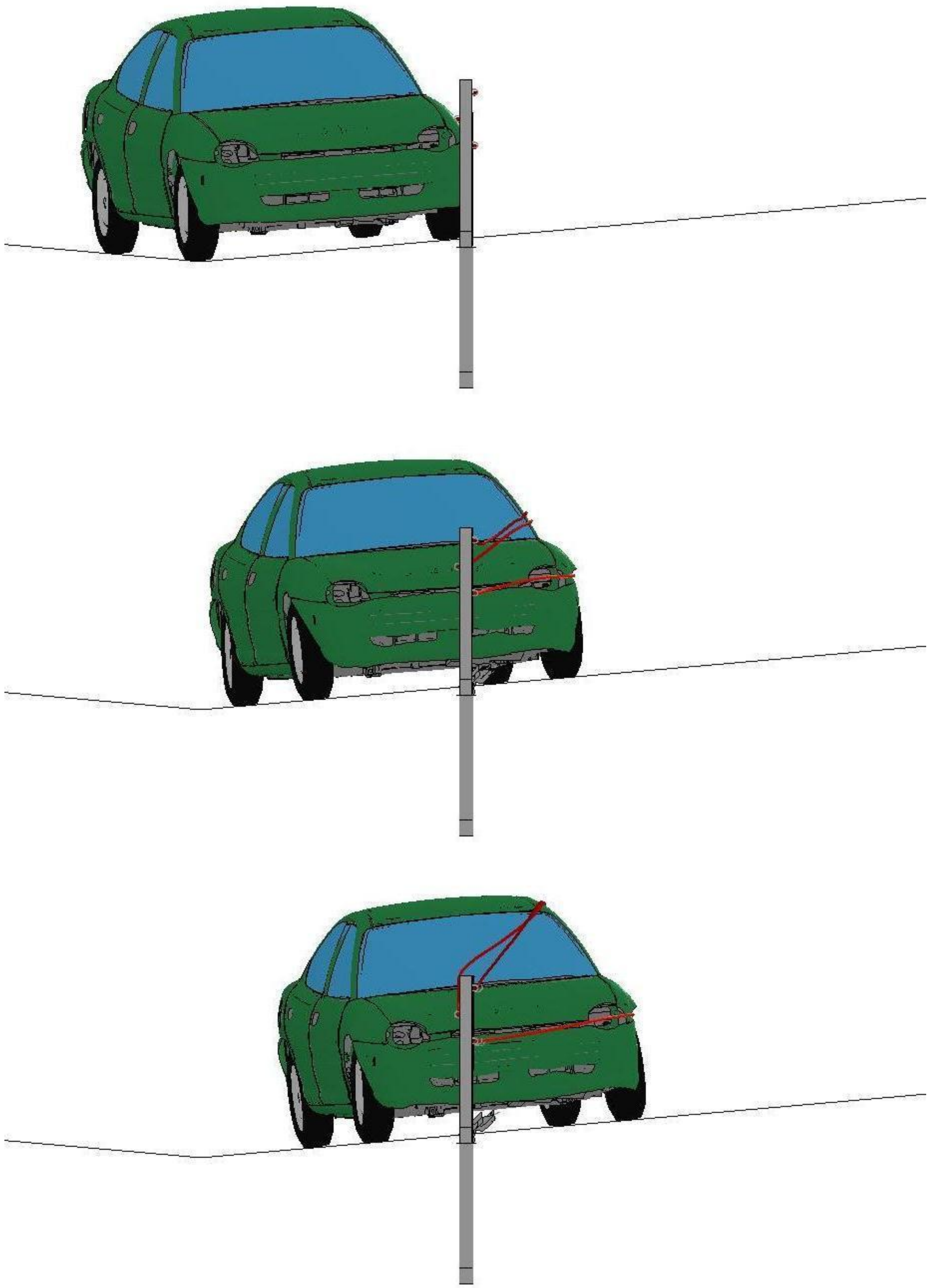


Figure 127. Downstream Sequentials, Simulation No. 3

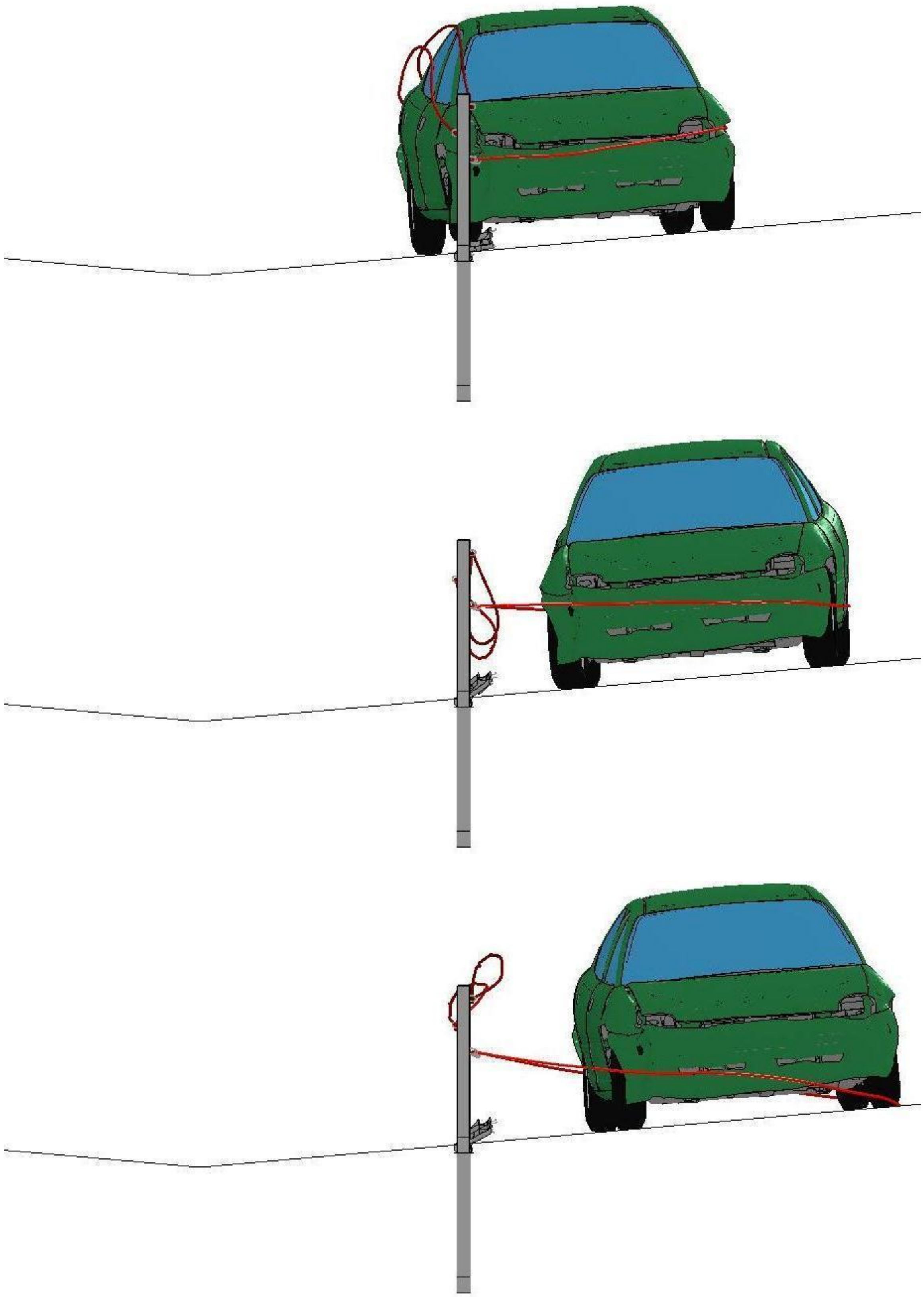


Figure 127 (cont). Downstream Sequentials, Simulation No. 3

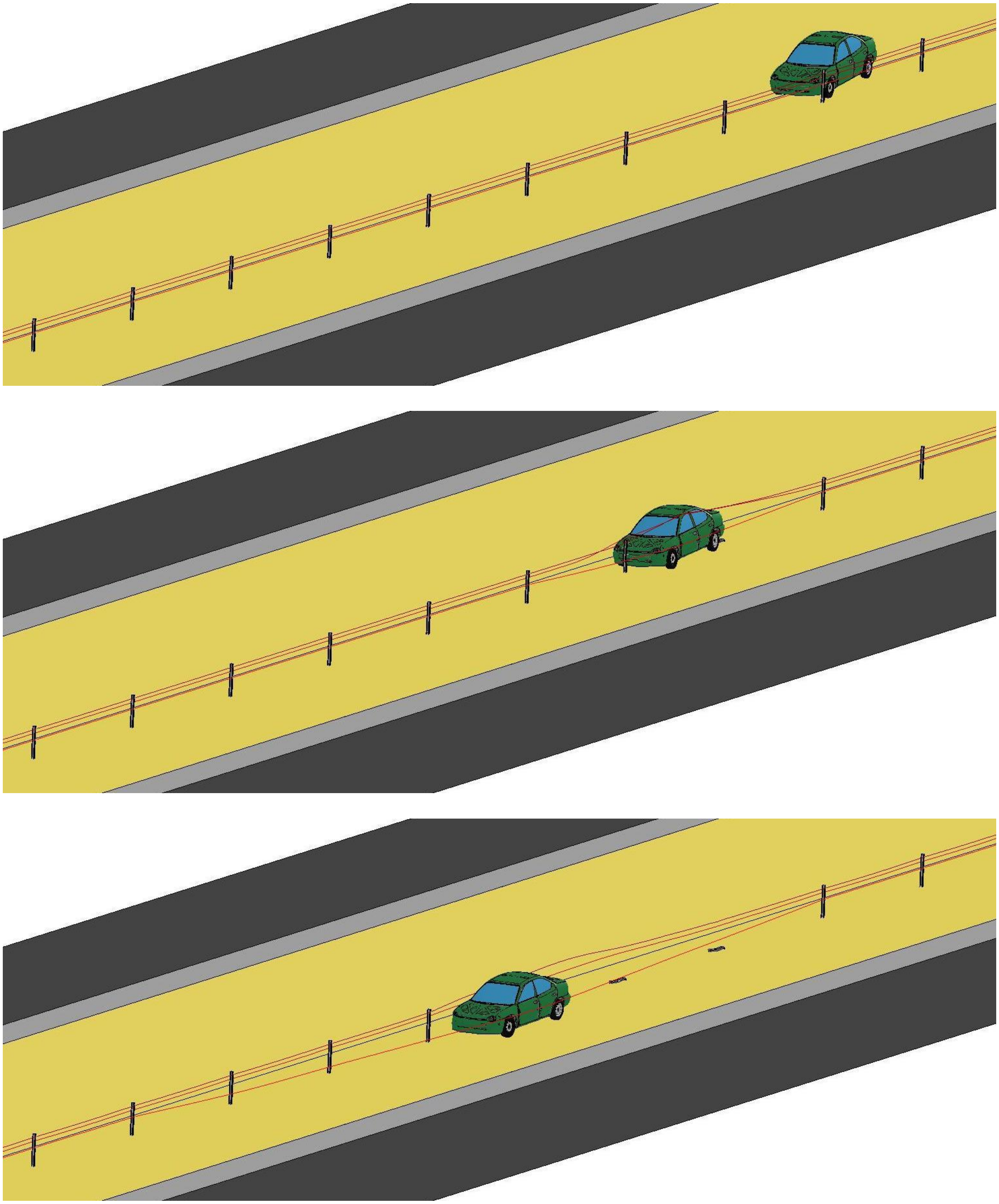


Figure 128. Downstream Behind Sequentials, Simulation No. 3

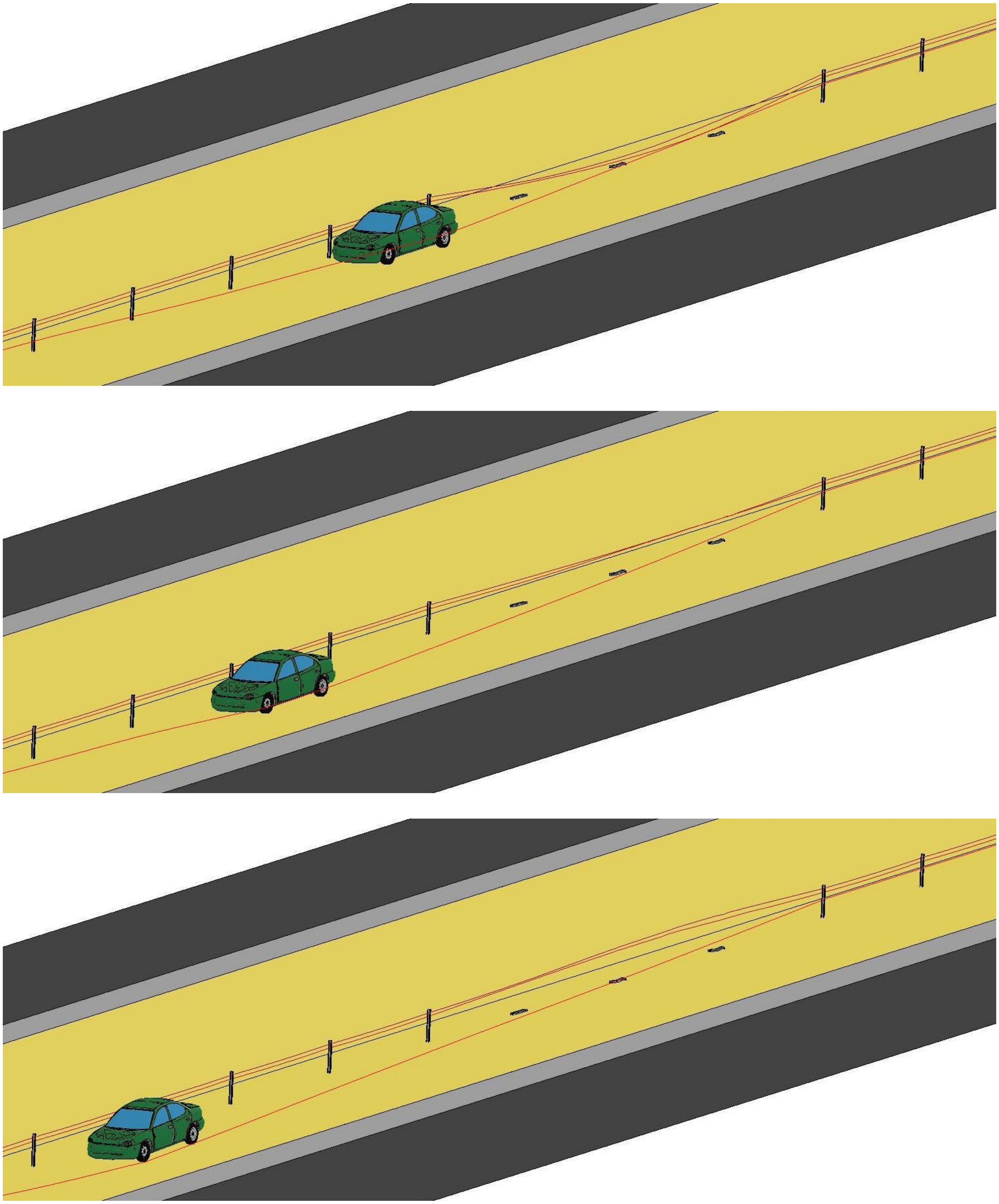


Figure 128 (cont). Downstream Behind Sequentials, Simulation No. 3

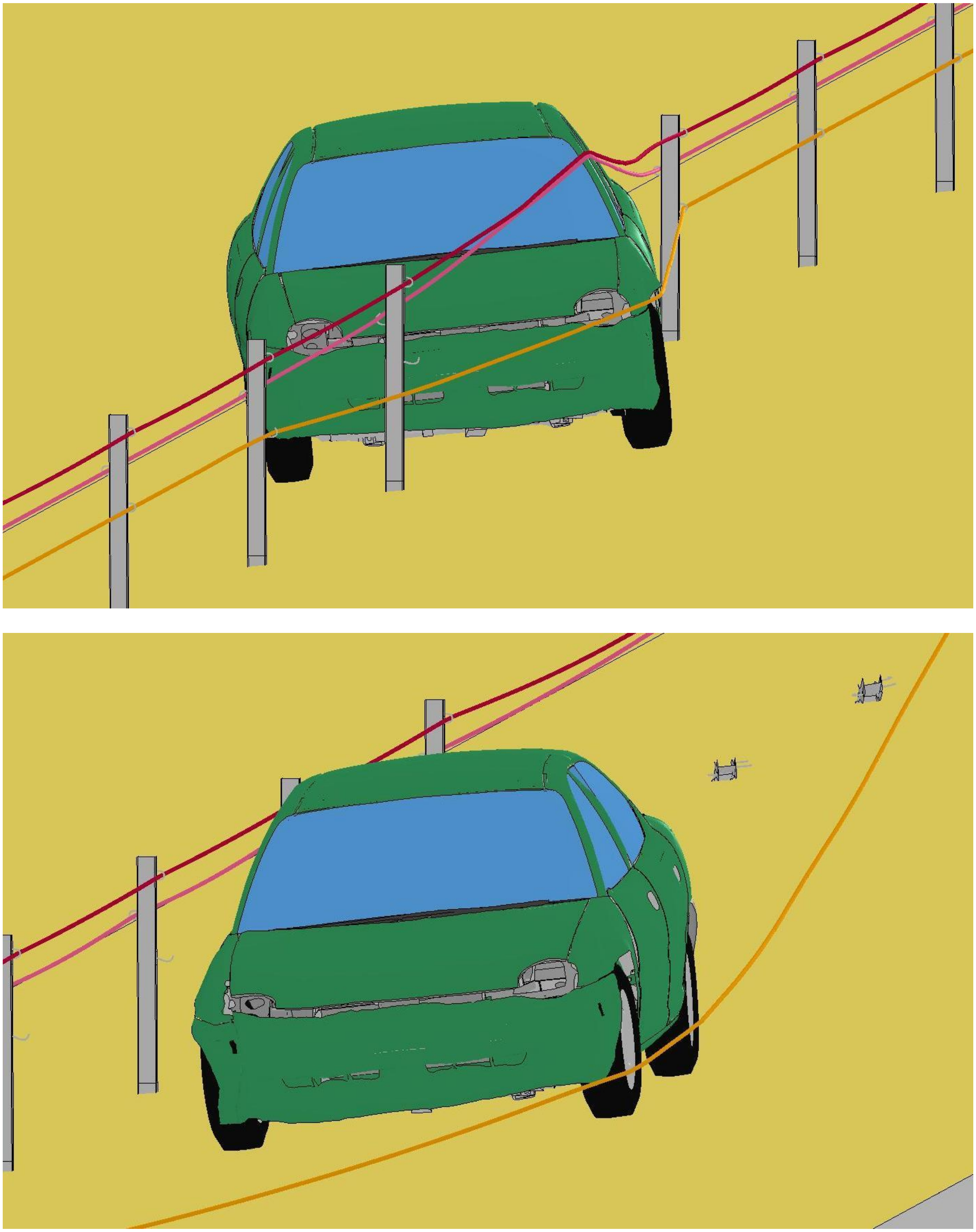


Figure 129. Critical Events Occurring in Both Simulation and Real-World Crash

10.5 Discussion and Conclusions

Difficulties associated with simulating real-world cable median barrier crashes arise from significant differences in vehicle front-end geometries, stiffnesses, material properties, weights, and vehicle shapes and inertial properties. The purpose of the simulations was not to replicate the actual crash results, but to replicate the mechanisms responsible for the penetration crash events. Because of this, variations between the simulation results and the crash results were tolerated.

In the first two penetration crashes, problems with the cable barrier system and general problems affecting all cable median barrier systems were both identified. High-angle crashes on slopes alter the intended interaction of the vehicle with the barrier system. If the CG velocity vector significantly exceeds the nominal value of 25 degrees used in full-scale crash testing, previous studies evaluating the testing and design limits of barriers in 6:1 slopes are no longer valid [e.g., 20]. In simulation no. 1, the high strength of the cable-to-post attachments also prevented the cables from cleanly releasing from the posts. Thus, the cables were overridden and the vehicle vaulted over the system.

Likewise, high orientation angle crashes can alter the outcome of a crash, as shown in Simulation 2. Instead of contributing to beneficial headlight fracture and the interlock with the deflected fender, very high orientation angle crashes can induce yawing or fail to engage by not crushing the fender or fracturing the headlight. In addition, in the second simulation, the low vertical release force of the bottom cable permitted the cables to slide up the post before impact instead of interlocking with the vehicle.

In the third simulation, the penetration mechanism was relatively unique to low-tension cable median barrier systems. The vehicle adequately engaged the bottom cable while the top two cables slid over the hood and roof. The low cable-to-post attachment strength of the bottom cable-to-post attachment was insufficient to retain the cable on downstream and upstream posts from impact. Following cable release from posts downstream of the vehicle, the cable had insufficient tension to remain at the contact height and drooped, permitting the vehicle to pass over the bottom cable and redirect toward the opposing lanes.

Simulations of cable median barrier crashes are typically very challenging and require careful examination of all the components in the system. For cable models, use of the model developed by Stolle and Reid is recommended [29]. Tensioning was efficiently and quickly produced in the cables using short sections of *MAT_CABLE_DISCRETE_BEAM parts with ramped load curves, tensioning the cables over the first 50 ms of impact. Researchers determined that for every 2 kip tension and 100 m length of cable simulated, one 6-in. (152-mm) length of tension was required. Four tensioners were used in simulations 1 and 2, whereas only one tensioner was used in simulation 3.

Cable to post attachments were also difficult to simulate. Each cable-to-post attachment was independently simulated and evaluated to determine if minimum manufacturer-reported maximum strengths and deformations were observed. Since beam elements have the best contact definitions with other beam elements, beam-to-beam contact should be used whenever practical, and beam-to-shell-edge contacts should always be avoided.

In each simulation, early models of each crash event indicated that redirection was possible. In the first simulation, the vehicle model incorporated a lower open section of the bumper cover at the air dam. The opening in the bumper cover permitted adequate cable engagement and the vehicle was redirected. This illustrated the effect that vehicle profile can have on vehicle redirection. Likewise, in the second simulation, the simulated vehicle was both lighter than the actual vehicle, and had no glass headlight. The vehicle was redirected in many variations of impact location along the barrier, and cable tension.

In the third simulation, weight was the most significant differences between the simulated and physical vehicles. When the vehicle was simulated at the nominal weight of the model, the vehicle was redirected and did not override the cable. However, when additional weight added to the model to bring the equal to the curb weight of the real vehicle, the vehicle did not redirect nearly as quickly with a higher dynamic deflection, and the vehicle ultimately overrode the cable. The increased energy at impact ultimately determined whether the vehicle was captured or penetrated through the system.

11 CAUSES OF CABLE MEDIAN BARRIER ROLLOVERS

11.1 Overview of Crash Data

Unlike cable median barrier penetrations, rollovers caused by cable median barriers have not been well studied. Frequently when rollovers were observed during full-scale tests on cable median barriers, results were largely dismissed as specific to an impact configuration or design concept failure [e.g. 51, 52]. Nonetheless, rollovers are real concerns for impacts with cable median barriers. In most states, rollover crashes were more severe but occurred less often than penetrations. Rollovers typically occurred in 3% to 8% of all cable median barrier crashes.

Rollover events were particularly cumbersome to reconstruct; since, rollover causes were subject to many more factors than were penetration crashes. An accurate determination for the causes of the rollover was extremely difficult to obtain as median profile and smoothness, vehicle roof stiffness, angle of roll eccentricity, vehicle weight, and trip speed all affect the path of a rolling vehicle and the predominant locations of vehicle damage. Further, scene diagrams represent estimates of responding officers regarding scene diagrams and are frequently inexact. One trait of all rollover crashes on cable median barriers is that, at the time of rollover, all vehicles were non-tracking. Vehicles involved in rollovers which initially contacted the barrier with tracking impact conditions all yawed to non-tracking conditions before tripping.

Despite the difficulty in gauging trip causation, common factors were identifiable through narrative, scene diagram, photographic, and median slope evidence. Common factors associated with rollovers enable researchers and manufacturers to recommend improvements addressing general classes of problems instead of addressing individual crashes. Rollover causes were largely independent of which system was installed, although rollover frequencies varied between systems. This finding was reasonable as all systems rely on three basic components: support posts to maintain cables at desired heights; cable-to-post attachments to maintain cable heights and transmit lateral and vertical load from cables to posts; and multiple tensioned cables. Similar to the determination of the causes of penetrations, a detailed investigation and analysis was conducted to determine the causes of rollovers on cable median barriers. A summary table of rollover causes is shown in Table 34.

Table 34. Causes of Rollovers with Cable Median Barriers

Rollover Contributor	Description	Number of Rollovers Recorded						Passenger Cars
		Nucor	CASS	Brifen	Gibraltar	Generic	**Total**	
Steep Median Slopes	Vehicle either impacts barrier installed on roadside shoulder and protrudes over median slope before a tire becomes snagged on the approach slope, or trips due to changes in the median terrain when barrier is located within ditch.	3	6	-	-	7	**16**	13%
Broadside Skid	Vehicle contacts barrier with large oversteering orientation angle. Frequently, sideslip angles in these crashes are approximately 90 degrees.	8	20	2	-	7	**37**	37%
Contact with Post	Vehicle struck cable median barrier and initially began to redirect. During redirection, vehicle tire snags on post or becomes entrapped by cable(s). Can occur when orientation angle approaches +/-90 degrees during redirection.	12	24	1	1	19	**57**	42%
Other Effects	Rollover caused by other effects, such as end terminals, tow-behind trailer attachments, or large exit angles following redirection. Relatively infrequent events.	1	2	-	-	2	**5**	25%
Large Vehicle	Tractor-trailers, buses, large trucks, camper vehicles, and construction vehicles. No cable barrier is currently designed for these types of impacts. Rollover crashes with these large vehicles are tolerated and better than penetrations.	1	4	-	-	2	**7**	-
Total		**25**	**56**	**3**	**1**	**37**	**122**	**36%**

11.2 Rollover Analysis

11.2.1 Steep Median Slope Rollovers

When vehicles encountered steep median slopes (i.e., steeper than 6:1), rollover frequency increased, as was discussed in Chapter 5. These types of rollovers may be difficult to mitigate because the slope contributes to vehicle instability, thus new cable barrier designs alone may not be sufficient to prevent these types of containment failures. The cable barriers frequently captured the impacting vehicle during these crashes, but the vehicle tripped and rolled before it was fully redirected.

There were three types of median slope-caused rollover failures. The first type was caused by entrapment, in which an impacting vehicle struck the barrier and the front (or rear) tires extended over the median slopes before the vehicle was redirected. Extension of the vehicle’s wheels over the slope lowered the impacting end of the vehicle. Then, the subsequent redirective forces resisting the vehicle pressed the wheels of the impacting end against the roadside slope, potentially causing digging in on the slope or generating large frictional resistive forces as the suspension compressed, potentially culminating in a frictional roll moment which caused rollover. An additional scene diagram of a rearward vehicle rollover crash occurring at a break point of a 6:1 approach slope is shown in Figure 130. The scene diagram was highlighted to indicate the locations of the median slopes.

The second slope-related rollover failure type was due to vehicle orientation near the center of a steep V-ditch. Vehicles were also captured during this type of rollover, but redirection frequently resulted in yaw displacement of the vehicle around the impacting end. Wheels on the other end of the vehicle were forced to climb the median approach slope, which generated large, dynamic vertical and sideslip forces. Due to a combination of large trip forces, vehicle instability, digging in to the slope, post impact, or rough median terrain, the vehicle then tripped and rolled.

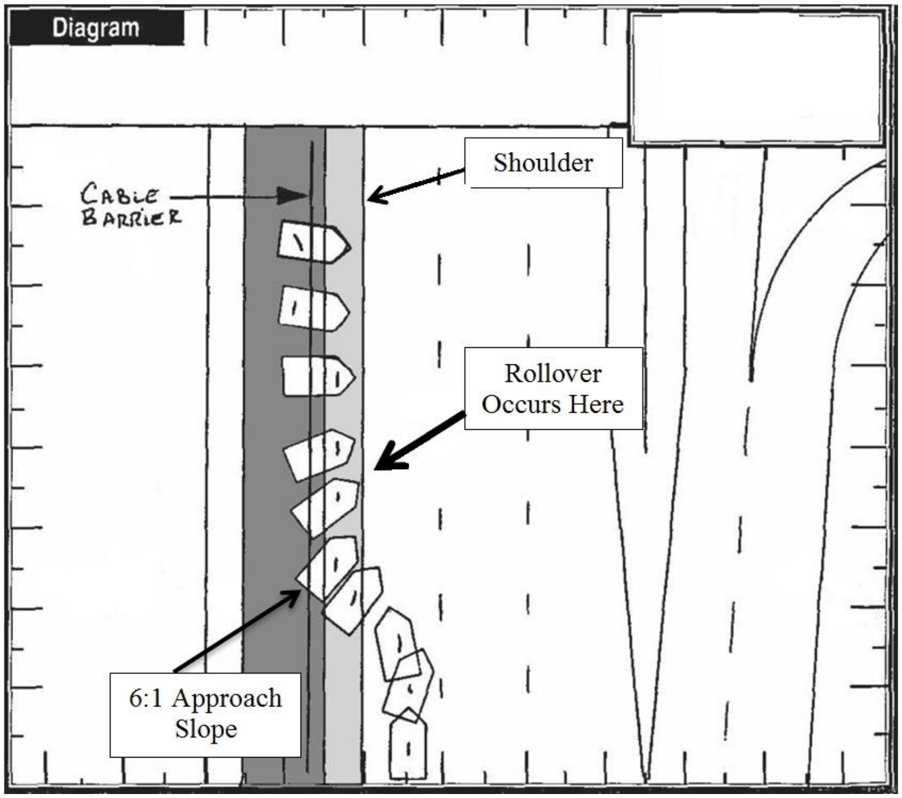


Figure 130. Entrapment Rollover Crash in which Vehicle Extends Over SBP of 6:1 Slope

The third type of median slope rollover was caused when vehicles struck a cable median barrier installed on a V-ditch back slope. After redirection, some vehicles skidded laterally into the median and tripped due to the slope transition in the center of the median. An example of this crash type is shown in Figures 131 and 132. In this crash, a Dodge Caliber struck the cable median barrier with an orientation angle of approximately 110 degrees and a CG trajectory angle of approximately 21 degrees. The vehicle displaced one post and yawed to nearly 180 degrees before being redirected, then rebounded down the back slope and tripped. It is believed that the vehicle made two and a half complete revolutions. Because the vehicle rolled through the center of the V-ditch and back up the approach slope, vehicle damage was extensive.

Pickup trucks, vans, and SUVs were found to be the most susceptible to the median slope-related crashes in which the wheelbase and suspension stroke were large. Passenger cars were involved in only 4 out of the 25 potential median slope-related rollovers. Of these, two were full-size cars, one was a mid-size “crossover” class vehicle, and one was a compact car.

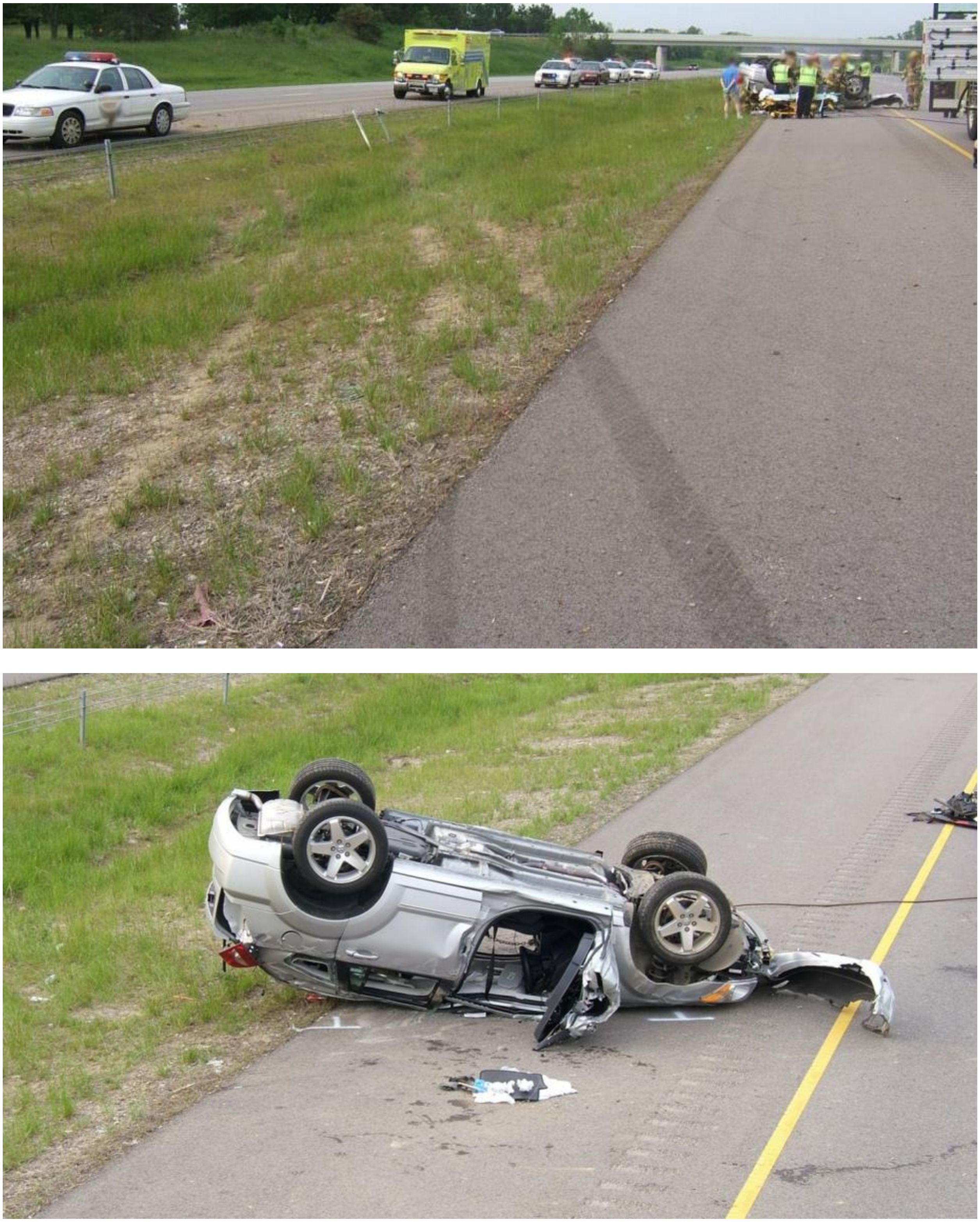


Figure 131. Example Rollover Crash Caused by High Redirection on Back Slope

Figure 132. Example Rollover Crash Caused by Redirection on Back Slope (continued)

11.2.1 Broadside Skid Rollovers

Rollovers which occurred when vehicles struck cable median barriers with broadside skid conditions were much more common than steep median slope-related rollovers. Vehicles involved in these crashes either impacted the cable median barriers with sideslip angles very close to 90 degrees, or yawed nearly 90 degrees after impact before rolling over. Broadside skid rollovers were distinct from both contact with post and median slope rollovers because the cables were the primary contributor to rollover. Passenger vehicles were involved in 35% of these types of rollovers, whereas SUVs, pickup trucks, and vans accounted for 65%. For those larger vehicles which rolled due to large oversteering angles, SUVs alone accounted for 29% of all rollover crashes.

Vehicle impacts at high orientation angles contributed to vehicle instability by increasing the overturning moment applied to the vehicle frame. A model and schematic diagram of the force interaction in a high-orientation angle crash is shown in Figure 133. During rollover crashes, new, energetically-favorable roll axes were generated through which the applied moments to the vehicle were maximized. The new roll axis was rotated with respect to the longitudinal axis of the vehicle to incorporate the contribution of a small pitch moment at the cable impact location.

Because of this shift in the vehicle’s trip axis, the leading back corner of the vehicle was typically the first location to contact the ground. Frequently, first contact of the vehicle’s upper body with the ground resulted in displacement of the upper frame rails, crushing near the rear-top corner of the vehicle, roof slant, and often an accumulation of dirt, grass, or median materials at the initial contact site. In addition to the increased pitch moment, vehicle-to-cable friction interaction caused yaw moments, which tended to increase the orientation angle. Thus, if the vehicle struck the barrier at a relative sideslip angle of 60 degrees, the frictional interaction with the barrier tended to accentuate vehicle yaw toward a 90 degree sideslip angle, increasing rollover propensity. Examples of oversteering rollover crashes are shown in Figures 134 through 136. In each of the crashes shown, the vehicle struck the cable barrier with the front end at a high orientation angle then tripped and rolled. None of the crashes were caused by an impact with a single post or series of posts. Median slopes contributed to some crashes, but wheels were not entrapped on a slope in any of the crashes. Further, no trailer attachments or towed units were present.

One crash involving a Jeep Grand Cherokee is shown in Figure 134. During this crash, the vehicle struck the cable barrier with the left-front corner in an oversteering configuration, yawed around the front end, and tripped as the vehicle approached a 90-degree orientation angle. The right-rear corner made first contact with the ground, shattering the rear windshield and right-rear window. As the vehicle rolled, the roof was crushed, but most of the remaining damage to the vehicle only occurred to the exterior body panels. A similar crash involving a Suzuki Grand Vitara which also yawed around the front end before tripping is shown in Figure 135.

A second high-orientation angle rollover crash occurred involving an Isuzu Rodeo, as shown in Figure 136. During this crash, as the vehicle descended into the V-ditch, the right-front bumper corner engaged the cables. Combined with the large frictional moment from the tires, the vehicle tripped with the right-rear corner leading, and made one complete revolution, coming to rest on its tires. Most of the damage was concentrated on the right side.

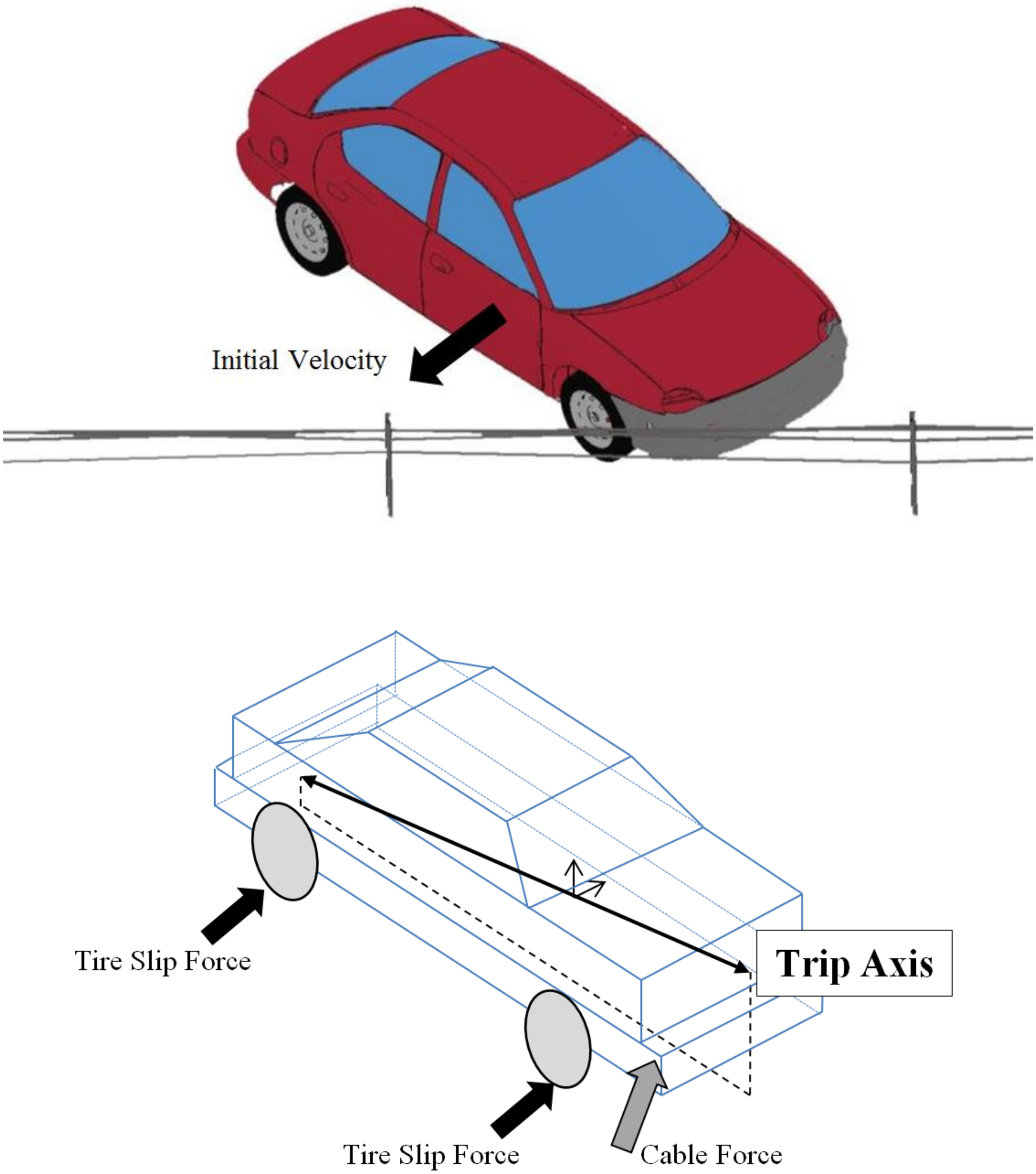


Figure 133. Impact at High Orientation Angle with Unbalanced Force Diagram

Figure 134. Example Rollover Crash Caused by High Orientation Angle at Impact

Figure 135. Second Example Rollover Crash Caused by High Orientation Angle at Impact

Figure 136. Third Example Rollover Crash Caused by High Orientation Angle at Impact

11.2.2 Contact with Post Rollovers

The most obvious cause of rollover crashes was attributable to vehicles contacting and snagging on posts, which can form trip points. Unlike other types of rollover crashes, vehicle contact with posts can accentuate rollover risk for all impacting vehicles, including small cars. When comparing vehicle data within each barrier make, lighter vehicles were found to be more susceptible to tripping, as shown in Table 34. Mid-size and small passenger cars comprised 24 out of the 55 rollover crashes caused by post snagging, or 44% of all rollovers involving vehicle contact with posts. Furthermore, no large cars were documented with this type of crash result, and only six out of the 29 SUV, pickup truck, and van rollovers related to vehicle contact with posts had weights over 4,400 lb (1,996 kg).

Rollovers caused by contact with posts were unique because the rollover initiator was wheel snag on a flange or web of the post. Although multiple compounding factors including friction contributed to most rollovers, contact with post rollovers also occurred in wet and snowy weather when roadside friction was reduced. The occurrence of these types of rollovers in low-friction conditions indicates that even weak posts can contribute to vehicle instability, which was noted historically [53]. Examples of post snag rollover crashes are shown in Figures 137 and 138.

Contact with post rollovers were the most sensitive to the make of cable barrier struck, since post strengths were critical to facilitating rollover. Post shapes and cable tensions are shown in Tables 35 and 36, and the several post section shapes are shown in Figure 139.

The cumulative rate of vehicle rollover on each system was plotted against calculated yield moments about the X and Y axes shown in Figure 139. Bending moments were calculated based on the assumption that no torsional warping occurred and that all loading occurred through each post section shear center. Scatter in the weak-axis bending moment direction appeared to be randomly distributed, as shown in Figure 140. However, a possible correlation was observed when rollover frequency was plotted against yield moments about the X direction, as shown in Figure 141.

Considering the large number of factors contributing to rollover events, these results suggested that there may be a strong relationship between post strength in bending along an axis parallel with the roadway and the frequency of rollover crashes. These results also indicate that post bending strengths along axes perpendicular to the roadway (i.e., the Y-axes) do not have a strong correlation with rollover frequency.

Note also that many rollovers occurring due to impacts with Nucor systems were caused as posts accumulated in front of the vehicle after being lifted out of the ground or sockets, or fracturing at the ground line. As the posts accumulated, the effective strong-axis strength of the next downstream post increased. This effect, unique to Nucor systems, may have increased the average rate of rollover if the cable-to-post attachment was weaker and if the posts-soil interaction was stronger. If the Nucor result followed the trend of the other high-tension cable median barrier systems, the expected rollover rate would be between 1.9% and 2.7%.

Figure 137. Example of Post Snag Rollover Crash

Figure 138. Example of Post Snag Rollover Crash

Table 35. Summary of Post Characteristics in High-Tension Cable Guardrail Systems

Cable Barrier System	FHWA Approval Letter	Post Installation Option	Post Shape	Post Size	Post Material	Galvanization	Yield Stress	Maximum Post Shear Capacity	Critical Cross Section Area	Critical Moment of Inertia		Critical Moment of Inertia		Plastic Section Modulus		Strong Axis Bending Moment	Weak Axis Bending Moment	Rollover Rate
										Ixx	Iyy	Sx	Sy	Zx	Zy			
							ksi (MPa)	kip (kN)	in.^{2} (mm^2)	in.^{4} (mm^4)	in.^{4} (mm^4)	in.^{3} (mm^3)	in.^{3} (mm^3)	in.^{3} (mm^3)	in.^{3} (mm^3)			
Nucor Steel Marion Inc. NU-CABLE	B-96 B-96A B-167 B-183 B-184 B-184A B-193 Revised	(TL-3) Driven Post with Trapezoidal Soil Plate Socked Post in Concrete Base	U	6 kg/m (4 lb/ft) U-Channel with 3/8 in. (10 mm) hole	Nucor Steel Marion Inc Grade SP-80	NA	80 (552)	51.6 (229)	1.176 (717)	0.606 (224800)	1.125 (477500)	0.496 (8121)	0.656 (10742)	0.519 (11782)	0.779 (17160)	**39.6 kip-in. (4483 kN-mm)**	**52.4 kip-in. (5930 kN-mm)**	**3.2% (~5.6% TL-4 System)**
			U	7.5 kg/m (5 lb/ft) U-Channel with 3/8 in. (10 mm) hole		NA	80 (552)	66.1 (293)	1.423 (917)	0.641 (266671)	1.433 (596622)	0.605 (9913)	0.802 (13141)	0.862 (14129)	1.338 (21931)	**48.4 kip-in. (5472 kN-mm)**	**64.2 kip-in. (7254 kN-mm)**	**N/A**
Trinity Highway Safety Products, Inc CASS	B-119 B-119A B-119B B-141 B-141A B-141B B-141C B-141D B-141E B-157	In Concrete Driven Base-Plated Driven Sleeve with Notch Driven Sleeve with Soil Plate	C	3.96 in. x 1.97 in. x 0.1575 in. (100 mm x 50 mmx 4 mm)	ASTM A 36	ASTM A 123	36 (250)	26.5 (117)	1.259 (812)	2.907 (1209901)	0.615 (288554)	1.477 (24198)	0.704 (11542)	1.858 (30447)	1.858 (30447)	**53.2 kip-in. (6050 kN-mm)**	**25.4 kip-in. (2886 kN-mm)**	**5.6%**
			S	S4x7.7 (S101x11.5) with 11/16 in. (17 mm) holes at groundline			36 (250)	27.0 (120)	1.285 (828)	2.781 (1157512)	0.188 (78364)	1.39 (22785)	0.131 (2148)	1.718 (28157)	0.263 (4301)	**50.1 kip-in. (5696 kN-mm)**	**4.7 kip-in. (537 kN-mm)**	**~3.7% Predominantly TL-3**
Hill & Smith Limited Brifen Limited WRSF	B-82 B-82B B-82B1 B-82C B-82C1	Driven Post Post in Concrete Footer	S/Z	3.93 in. x 1.26 in. x 0.236 in. (100 mm x 32 mm x 6 mm)	ASTM A36	A123	36 (250)	29.0 (128)	1.378 (888)	2.629 (1094355)	0.142 (59271)	1.336 (21887)	0.226 (3704)	1.702 (27889)	0.382 (6251)	**48.1 kip-in. (5472 kN-mm)**	**8.1 kip-in. (926 kN-mm)**	**3.2%**
				3.93 in. x 2.17 in. x 0.179 in. (100 mm x 55 mm x 4.55 mm)	ASTM A709 Grade 36	Galvanized	36 (250)	31.1 (138)	1.481 (955)	3.359 (1398162)	0.562 (234088)	1.706 (27963)	0.519 (8512)	2.034 (33334)	0.791 (12965)	**61.4 kip-in. (6991 kN-mm)**	**18.7 kip-in. (2128 kN-mm)**	**N/A**
Gibraltar Gibraltar Cable Barrier	B-137 B-137A B-137A1 B-137B B-137C (HSA) B-137C (HSSD) B-137D B-147A	Driven Post Socked Post-Rebar Tube Socked Post withTube in Concrete	C	3.25 in. x 2.5 in. x 0.15 in. (83 mm x 63 mm x 3.4 mm) slotted tube	ASTM A570 (A1011) Gr 60	ASTM F1043A	60 (410)	53.8 (239)	1.560 (1006)	2.232 (929049)	1.595 (663706)	1.373 (22506)	1.276 (20904)	1.688 (27654)	1.491 (24436)	**82.4 kip-in. (9227 kN-mm)**	**76.5 kip-in. (8571 kN-mm)**	**N/A**
Safence, Incorporated Safence Cable Barrier	B-88 B-88 B-88A B-88B B-88C B-88D B-88E B-88F	Plastic Sleeve in Concrete Footer Driven Post	I	INP 80	A 36 Hot Rolled	NA	36 (250)	11.1 (49)	0.529 (341)	1.869 (778000)	0.151 (62900)	1.187 (19450)	0.183 (2995)	1.421 (23285)	0.320 (5239)	**42.7 kip-in. (4863 kN-mm)**	**6.6 kip-in. (749 kN-mm)**	**N/A**
			C	0.1575-in. (4-mm) thick C-post	Cold Rolled from A36	A 123	80 (550)	38.9 (172)	0.840 (541)	1.034 (430199)	0.100 (41589)	0.646 (10593)	0.134 (2201)	0.827 (13544)	0.273 (4467)			**4.9%**
Low-Tension, 3-Cable Median Barrier	B-64 B-64 Sup B-147	Driven Post	S	S3x5.7 (S76x8.5) 72-in. (1,829-mm) Long	A 36 Hot Rolled	Galvanized	36 (250)	35.1 (156)	1.670 (1077)	2.520 (1048903)	0.455 (189385)	1.680 (27530)	0.391 (6400)	1.940 (31790)	0.656 (10749)	**60.5 kip-in. (6883 kN-mm)**	**14.1 kip-in. (1600 kN-mm)**	**7.8%**

Table 36. Standard Cable Heights and Tensions

Cable Barrier System	Cable Heights			Cable Design Tension at 70ºF (21ºC)	
	System	(in.)	(mm)	lb	kN
Nucor Steel Marion Inc. NU-CABLE	TL-3	15*	381*	5600	24.9
		21 1/2	546		
		25 1/2	648		
		29 1/2	749		
	TL-4 6:1 Slope or Flatter	15	381		
		27	686		
		31	787		
		35	889		
	TL-4 4:1 Slope	19	483		
		31	787		
		38	965		
		42	1067		
Trinity Highway Safety Products, Inc CASS	TL-3	20 13/16	529	4600	20.5
		25 1/8	638		
		29 7/16	748		
	TL-4	20 7/8	530		
		29 1/2	749		
		38 1/8	968		
Hill & Smith Limited Brifen Limited WRSF	TL-3	19 1/2	495	4250	18.9
		26	660		
		26	660		
		28 3/8	721		
	TL-4	18 1/2	470		
		24 1/2	622		
		30 1/2	775		
		36 1/2	927		
Gibraltar Gibraltar Cable Barrier	TL-3	20	508	4800	21.4
		25	635		
		30	762		
	TL-4 3-Cable	20	508		
		30	762		
		39	991		
	TL-4 4-Cable	20	508		
		25	635		
		30	762		
		39	991		
Safence, Incorporated Safence Cable Barrier	TL-3 Side-Mounted on O-posts	18.9	480	3020	13.4
		24.8	630		
		30.7	780		
		36.6	930		
	TL-4 I-post	18.9	480		
		22	559		
		25.2	640		
		28.3	719		
	TL-4 C-post	18.9	480		
		22*	559*		
		25.2	640		
		28.3	719		
	TL-4 C-post MASH on 4:1 Slope	19 5/16	491		
		30 15/16	786		
		34 11/16*	881*		
		38 7/16	976		
Low-Tension, 3-Cable, Non-Proprietary	TL-3	20 13/16	529	950	4.2
		25 1/8	638		
		29 7/16	748		

*Optional cable shown
** 1st, 2nd, and 3rd cables are interwoven between posts
*** Posts are installed on alternating sides of system

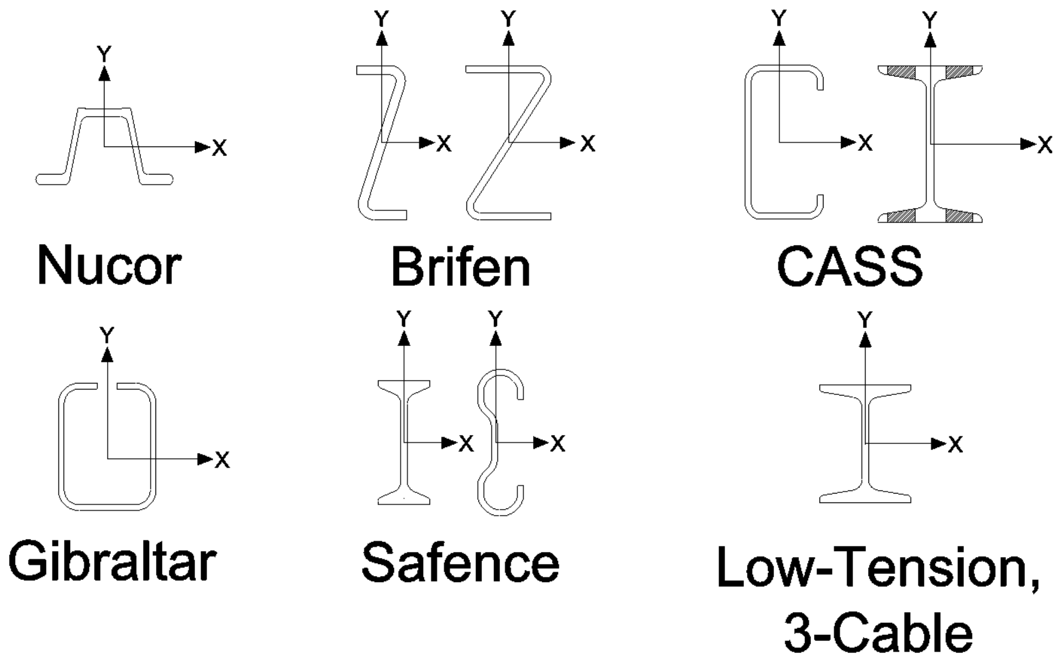


Figure 139. High-Tension Post Section Shapes

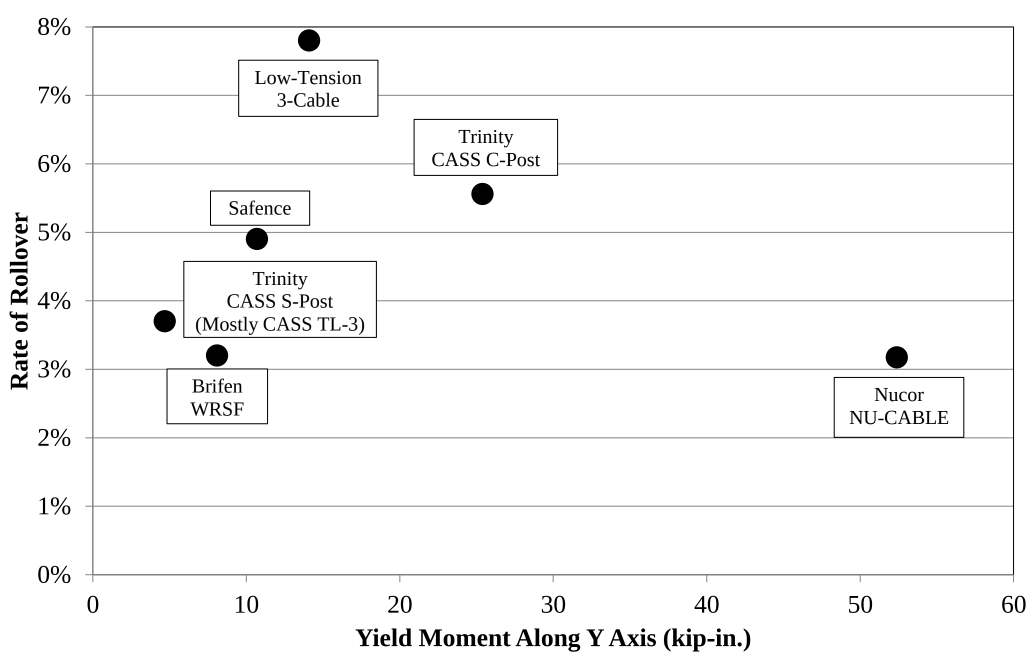


Figure 140. Y-Axis Yield Moment Relationship with Rollover Frequency

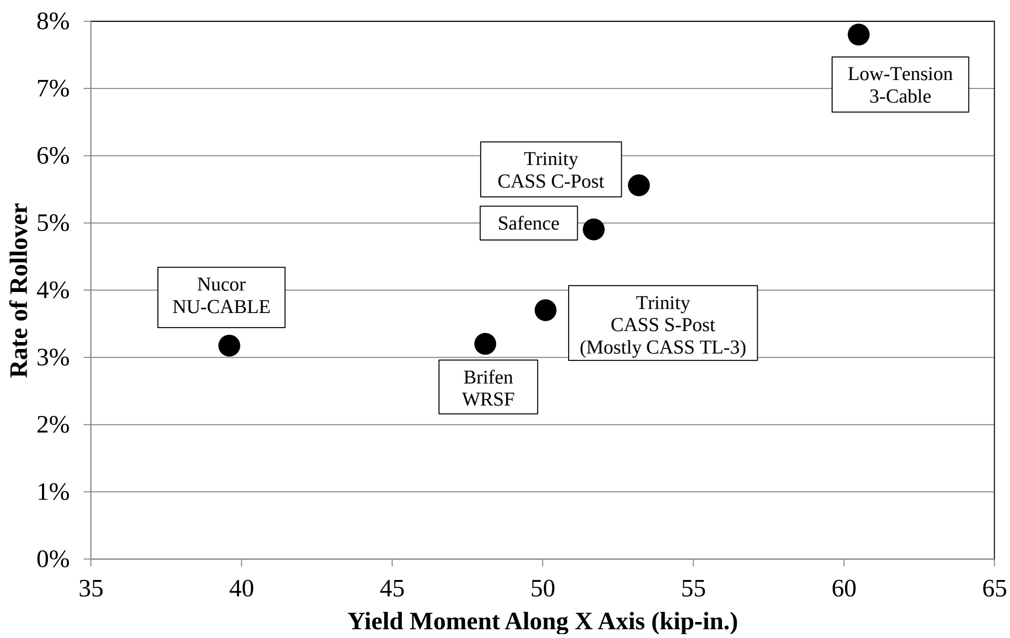


Figure 141. X-Axis Yield Moment Relationship with Rollover Frequency

11.2.3 Other Rollover Causes

Several other rollover causes were identified in the research study, although each cause was relatively unique. For these remaining rollover crashes, the most frequent rollovers involved large vehicles, such as tractor-trailers, buses, or single-unit trucks, as well as vehicles with tow-behind trailers. The increased rollover frequency for tow-behind units was likely the result of a high trailer center-of-gravity with respect to the towing vehicle. For example, the vertical CG height of many ½-ton to ¾-ton pickup trucks ranged between 25 and 30 in. (635 to 732 mm), but the storage floor height on most tow-behind units was at least the center axle height of the vehicle, typically 16 to 18 in. (406 to 457 mm). As a result, tow-behind trailers dramatically increased the effective CG height of the towing vehicle.

In particular, tow-behind camping units were particularly sensitive to rollovers. Over 60% of all vehicles with tow-behind campers were at least partially involved in a rollover event in the database, although trailer-related crashes were infrequent.

11.3 Discussion

In general, rollovers occurred less frequently than penetrations. However, this was not indicative of the difference in crash severities.

Rollover crashes increase risk of injury or fatality for the occupants of impacting vehicles. Occupants utilizing safety belts experience risk due to large accelerations, occupant compartment deformation or intrusion, or an appendage being pinned under the vehicle after flailing. Unbelted occupants are at higher risk of fatality due to bouncing and tumbling within the interior occupant compartment, as well as during ejection, in addition to the factors affecting belted occupants.

Rollover crashes contributed to more A+K fatalities than penetration crashes. After a vehicle penetrates a cable median barrier and the barrier does not crush the occupant compartment or contribute to rollover, then the vehicle can come to a stop in the median without causing occupant injury. Penetration crashes resulted in property damage only (PDO) in 73% of the crashes, and on average, 7.9% of penetration crashes were severe with the highest injury severity of A or K. Using data only from states with complete data sets, 35% of rollover crashes had a highest severity of PDO damage, whereas 17.3% resulted in A+K injuries. This indicates that, in the event of a rollover, severe crash outcomes are almost twice as likely as if the vehicle had penetrated through the barrier. Although prevention of cable median barrier penetrations is necessary to reduce the risk of severe crashes with cable median barriers, rollover crashes have higher associated severities in general and every effort should be made to mitigate these types of crashes.

High orientation angle crashes tended to promote a chaotic rollover path with combined roll and pitch motions. At high speeds, these types of rollovers were more severe on average than the other rollover types observed in this database. At lower speeds, more energy was transferred to the more energetic roll and pitch motions along the eccentric roll axis, as shown in Figure 133. These crashes had lower average severities than for other rollover types. High-orientation angle crash fatality risk was 50% greater than median slope fatality risk and nearly twice as likely than the risk due to contact with posts.

One way to reduce rollover propensity is to place the cable median barrier near the center of the V-ditch, within 4 ft (1.2 m) of the centerline. Whereas penetrations occurred more frequently in ditch centers, particularly in narrow V-ditches, rollovers occurred approximately 20% less often in ditch centers than anywhere else in the median. Despite these competing factors, median centers were associated with the lowest rates of severe and fatal injuries. Moreover, penetration crashes are easier to prevent than rollover crashes in general, so factors which reduce rollover frequency may still have high benefit-to-cost ratios by reducing overall average crash severity even if the countermeasures increase penetration frequency.

A different method of reducing rollover frequency is to alter cable barrier post design. The frequency of rollover events with CASS C-post systems was nominally higher than other high-tension barrier systems at 5.6%, but rollover events on CASS systems with weakened S4x7.7 posts only resulted in a rollover rate of 3.7%, as shown in Table 35 and Figures 140 and 141. Strong-axis post strength appeared to be closely related to rollover propensity. Unfortunately, this presents a difficult design problem for engineers: strong posts, with high strong-axis bending strengths, had higher rollover frequencies than weak posts with low weak-axis bending strengths. However, strong posts were able to exert more lateral force on the vehicle during redirection, reducing the number of posts damaged in a crash and potentially reducing dynamic deflection. This results in a trade-off between rollover mitigation and design deflection.

The Gibraltar dataset was very limited. As such, few conclusions could be made with regard to the Gibraltar rollover performance. However, Gibraltar utilized the strongest posts in bending about the X-axis. There is cause for concern that crashes with Gibraltar systems may be at elevated risk of rollover. Additional investigation with a broader accident database may be necessary.

12 DISCUSSION

12.1 Penetration Crashes

A maximum reduction in penetration crash frequency of 92% could be realized if all passenger vehicle penetrations were prevented. Practically, this is impossible due to the wide range of possible impact conditions and vehicle profiles the barriers would be subjected to. Penetration events can even occur on concrete median barriers, which are frequently cited as a replacement for cable median barriers with a history of penetrations leading to cross-median crashes. However, many of these penetration crashes can be prevented through improvements in barrier design, updated barrier placement guidelines, and by varying cable mounting heights on the posts.

There is a major advantage of high-tension cable median barrier systems over low-tension systems. Following most impacts on high-tension systems, the cables retain sufficient tension to minimize cable drop in the impact region where posts were disengaged from the cables. Crashes into low-tension cable median barriers frequently resulted in cable drop after impact. Some crashes involved two or more vehicles striking the low-tension cable median barrier in succession in Washington, Missouri, and in some non-penetration crashes in North Carolina. In many of these crashes, all errant vehicles were captured and redirected. However, state DOTs reported that crash sites were unsightly and suggested that any additional crashes at the same location could result in increased risk of penetration [23]. Higher-tension systems provided some sense of confidence that additional impact events would not result in penetrations.

The Gibraltar cable barrier system, with wide post spacings up to 30 ft (9.1 m) and installed on alternating sides of the cables, may exhibit a higher susceptibility to underride penetration crashes. Vehicles impacting at the location of a post on the opposite side of the cables can cause complete post disengagement. Although the hairpin cable-to-post attachment was relatively strong, as shown in Figure 142, upward vertical bracket release could occur during impacts with low-height, sharp-nosed and narrow front-profile vehicles, as shown in Figure 138.

For posts installed at the approved 20- to 30-ft (6.1- to 9.1-m) spacing, any cable-to-post disengagement of a given post would result in a 40- to 60-ft (12.2- to 18.3-m) unsupported cable length. With such large unsupported lengths, the barrier may experience an increased penetration frequency due to median slopes, low-profile vehicles, or vehicle crashes under non-tracking and high-orientation angle impact conditions. If more posts disengage from the cable, unsupported cable lengths could render vehicular capture difficult. Furthermore, since lateral cable loads are resisted by cable barrier posts, long unsupported lengths could contribute to excessive dynamic deflections and low probabilities of capture. Higher cable tensions, which were intended to reduce the likelihood of excessive cable deflections, alternatively increase the risk of rollover, windshield and window crush, and excessive occupant risk, in addition to increasing the soil foundation requirement of the cable anchors.

Whereas the Gibraltar cable barrier system may be more prone to underride in some crash configurations, the vertical release load of the cable-to-post attachment may be sufficiently small to prevent override penetrations. Based on a preliminary analysis, the hairpin bracket should vertically release away from the posts when posts deflect laterally, and impacts at posts will less frequently cause the cables to be pulled down by the deflected posts. More analysis will be necessary to conclusively determine the accuracy of this estimate.

12.2 Rollover Crashes

Rollover crashes were more severe than penetration crashes on average; since, most penetration crashes involved vehicles coming to rest in the median with only property damage. Severe penetration events were limited to crashes in which the occupant compartment was deformed, barrier elements protruded into the compartment, or impacting vehicles were involved in a cross-median crash. Rollover crashes much less frequently resulted in property damage only. Low-speed, short-distance rollover events could also be severe if an occupant was ejected from the vehicle.

The cable entrapment within the vertical slots of the CASS barrier was found to contribute to penetration propensity when impacts at posts applied downward forces on the cables, preventing vertical cable release. This effectively created a ramp to allow the impacting vehicle to pass over the top of the barrier, which also was associated with a high rollover frequency.

The weakened S-posts utilized in the CASS TL-3 and CASS TL-4 systems was correlated with a decrease in rollover rates. Penetration frequency was unchanged for these posts. The major difference between the CASS C-shaped posts and the CASS S4x7.7 (S102x11.5) posts was a significant reduction in strong-axis post strength. Since the weakened/modified posts were nominally more flexible at the ground line and yielded at lower loads under the same impact conditions, the posts could not sustain lateral forces sufficient to cause rollover. This proprietary design was reflective of the improvement that can be obtained by weakening a nominally strong post section in terms of its strong-axis bending capacity. Note that the Nucor flanged U-channel posts are not installed with the strong axis parallel with the roadway, and thus strong-axis weakening is not expected to have a significant effect on rollover propensity. Although this improvement would likely assist other cable median barrier systems, untested post modifications are not recommended for use in any barrier system.

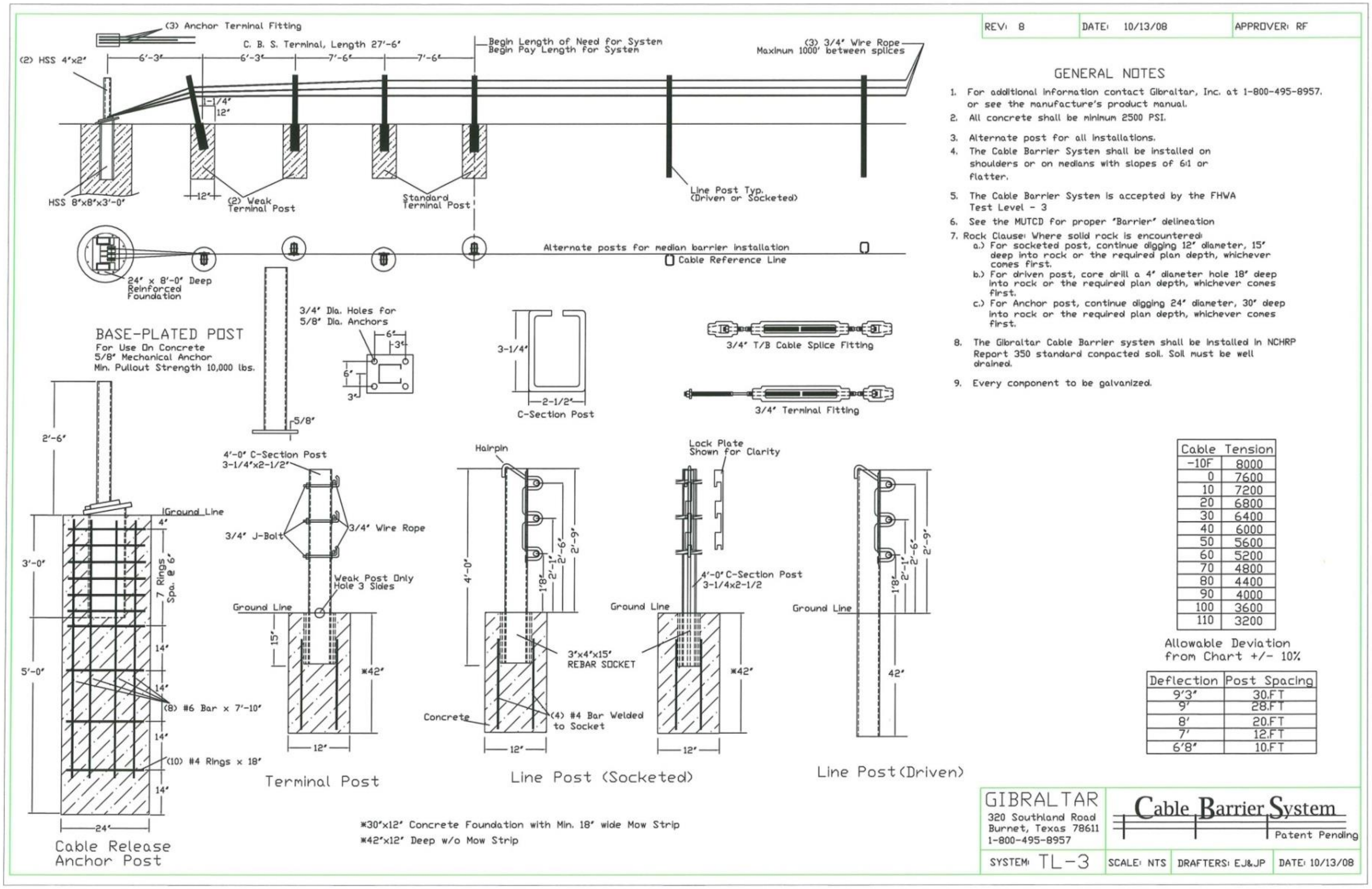


Figure 142. Gibraltar System Details, TL-3 System [54]

12.3 Barrier Placement and Median Grading

As stated in Chapter 5, Section 5.2.4, barriers placed in medians wider than 40 ft (12 m) had optimal performance when installed near the center of 6:1 or 8:1 V-ditches. Penetration crashes were reduced from over 10% on slopes flatter than 10:1 or steeper than 5:1 to less than 8% on slopes ranging between 9:1 and 6:1. Likewise, rollover frequency decreased from over 5% for slopes flatter than 8:1 and steeper than 4:1 to approximately 1% on slopes ranging between 7:1 and 5:1. However, barriers placed in narrow medians may not experience the same safety benefits observed in wide medians. Current standards are under development to establish meaningful crash testing procedures for evaluating barriers installed within relatively narrow, sloped median ditches [20]. However, crashes into systems installed in narrow, flat medians are expected to have very similar outcomes to crashes into systems with wide, flat shoulders.

Many studies have been performed to determine optimum barrier placement within medians located between divided highways [e.g. 26-28]. From these studies, the optimum location for placing a cable median barrier is at or near the center of the V-ditch in order to prevent the maximum number of nuisance impacts. Unfortunately, this barrier placement poses problems for state DOTs in terms of erosion control and mowing concerns, as cited by most of the states surveyed in this study. Most states prohibited the installation of cable median barrier within 1 to 8 ft (0.3 to 2.4 m) of the center of the ditch, which was consistent with placement guidance provided by FHWA. Barriers located near the center of depressed medians can cause increased difficulty with the maintenance and repair work of damaged cable barriers. In addition, post socketed and end anchor foundations may require greater depths, diameters, and/or reinforcement as the ditch bottom generally has a higher moisture content than the adjacent median slopes.

In response to these concerns, state design practice has historically tended toward installing cable median barrier close to one or both of the two shoulders, or on an approach slope or back slope as far away as possible from the travel lanes. Barrier placement alternatives were determined from full-scale crash testing results. In addition, state DOTs have historically installed cable median barriers near shoulders and on 6:1 or flatter slopes based on successful crash testing of barriers installed on level terrain.

Unfortunately, systems installed near shoulders were more likely to be associated with a severe crash than installations near the center of the median, as discussed in Chapter 5, Section 5.2.7. Approximately 15% of the crashes occurring with cable median barriers located on shoulders near the travel way were severe, although the sample size was relatively small. The severe crash rate was 4.4% for all crashes occurring further than 4 ft (1.2 m) from the center of the median. In contrast, the severe crash rate for barriers installed near the center of the median was 1.6%. Penetration frequency was 5.6% higher for barriers installed near the center of the median than on approach or back slopes, but rollover frequency was 1.2% lower for this same comparison. However, these conclusions applied to medians wider than 40 ft (12.2 m).

Flat medians enabled errant vehicles to oversteer and increase CG trajectory angles before crashing into the barrier. As the CG trajectory and orientation angles at impact increased, the likelihood of penetration or rollover increased as well. These roadside/median encroachments were usually caused by avoidance maneuvers or panic reactions to on-road conditions and/or situations.

Steeper median slopes can allow errant vehicles to launch into the air beyond the slope break point and potentially vault over a barrier. As a result, it would seem reasonable that the distributions of CG trajectory impact angles and impact speeds for barriers installed near shoulders as well as near V-ditch centers would be similar, although bumper and hood heights with respect to the barrier may not be similar. Higher-speed impact events were found to increase the severity of those crashes. Crash severity was also increased when vehicles were redirected back into adjacent travel lanes. In addition, vehicle redirection into adjacent travel lanes was more common when barriers were installed near median shoulders as compared to median centers.

Barriers installed near median centers significantly reduced the risk of re-entering adjacent travel lanes and potentially striking adjacent vehicles. Vehicles, which departed the road at low angles and were able to regain control, were also less likely to crash into the barrier, thus decreasing both nuisance hits and severe crash frequency. If barrier placement is not feasible near the center of divided highways, it is recommended that barrier placement occur as far as reasonably possible away from travel lanes using taller, more robust barrier systems.

The symmetric 6:1 V-ditch configuration also reduced the risk of override relative to steeper median slopes due to reduced propensity for “bounce-over”. As a vehicle was projected over the SBP and onto the front slope of a median, there was a physical separation which occurred between the nominal and actual bumper height positions above the ground [27-28]. The difference between actual and expected bumper positions in a crash increased with slope steepness. Steep-sloped ditches not only promoted override conditions due to vehicular launching over the SBP, but there was also a risk of the vehicle contacting the front slope and redirecting up the back slope, causing a redirective “leap” into or potentially over the barrier.

A risk analysis was conducted based on median terrain to determine bounce-over likelihood in 6:1 V-ditches wider than 40 ft (12.2 m). When allowing for a 20% difference between observed and actual bounce-over frequencies, vehicles were over 10 times more likely to underride the barrier than to vault over the barrier on slopes of 6:1 or flatter. Medians with 4:1 slopes more commonly resulted in “bounce-over” penetrations and overrides.

Some recommendations have been made regarding critical barrier placement in medians when considering the NCHRP Report No. 350 and MASH impact safety standards [28]. However, most prior crash testing studies were conducted using the NCHRP Report No. 350 or MASH crash test conditions at roadside departure. Due to the wide distribution of crash speeds, CG trajectory and orientation angles, and median slopes on a given section of road, barrier placement recommendations must be broad and incorporate a large spectrum of possible vehicle crash conditions.

All median barriers are roadside objects, and crashes with any roadside object can potentially pose a risk to occupants of errant vehicles. It was noted that for high-tension cable barrier systems, more than 50% of all severe injuries or fatalities were not caused by rollovers or penetrations. Even for low-tension cable barrier systems, the barrier-related A+K crashes constituted 30% of all serious or fatal crashes. As such, it is believed that a reduction in nuisance crashes into cable median barrier can also dramatically decrease the frequency of serious vehicle-to-barrier crashes.

12.4 Full-Scale Crash Testing

12.4.1 Background

Full-scale crash testing guidelines have advanced significantly since the introduction of such documents as NCHRP Report No. 153 [55] and the Transportation Research Circular (TRC) No. 191 [56]. Prior to the acceptance of NCHRP Report No. 230 [57] in 1981, crash testing was largely conducted ad hoc and according to engineering judgment. Standardized testing vehicles and impact conditions were required according to the criteria presented in NCHRP Report 230, but those guidelines were based on historical estimates of the practical worst-case impact scenarios, using subcompact small cars and large sedans as test vehicles.

As the number of light trucks and utility vehicles increased in the late 1980s, it became apparent that updates to the crash testing criteria were necessary. With the introduction and acceptance of crash testing criteria proposed in NCHRP Report No. 350 in 1993 [31], the standardized vehicles used to evaluate roadside appurtances at any test level were changed to an 1,808-lb (820-kg) 820C small car and a 4,409-lb (2,000-kg) 2000P pickup truck. These vehicles were selected for several reasons: (1) the small car had a low mass and front hood height, which could increase risk to occupants due to high decelerations, occupant compartment deformation, or underride; (2) the larger and heavier 2000P vehicle was useful for testing structural adequacy of roadside appurtances; and (3) the 2000P pickup truck was susceptible to instability, even rollover. These guidelines remained in effect for well over a decade, until MASH was accepted in 2009 [24].

With the introduction of MASH, criteria for conducting and evaluating full-scale crash tests were proposed based on real-world studies of more than 890 run-off-road crashes [22]. Vehicle selection was determined based on the 2nd and 95th percentile vehicles purchased in the United States based on data collected from vehicle sales between 2000 and 2004. A 5,000-lb (2,268-kg) 2270P pickup truck and a 2,425-lb (1,100-kg) 1100C small car were chosen as the most representative vehicles using similar arguments as were used following the acceptance of NCHRP Report No. 350. An optional mid-size 1500A vehicle weighing approximately 3,300 lb (1,497 kg) was also proposed if it was believed that barrier systems would be susceptible to crashes with this sedan-type vehicle.

12.4.2 Crash Observations

The vehicles selected for use in full-scale crash testing according to the criteria presented in NCHRP Report No. 350 and MASH were not selected based on a historically poor performance with certain systems. As a result, crash tests have rarely been conducted with the most critical vehicle types or crash conditions.

It has been frequently stated that the increased scrutiny applied to cable median barriers examined in this study places the barriers at competitive disadvantage with respect to other barrier systems. However, cable median barriers were the only barriers which show favorable performance on 6:1 slopes, and have the potential for application in steeper slopes. Cable median barriers will continue to be less expensive to manufacture and install in divided medians than other median barrier types. If the concerns addressed in this study are satisfactorily addressed, the associated reduction in severe crash risk would make cable median barriers the safest barriers available for use on divided roadways.

Furthermore, this study should be used as a springboard to apply this type of system-specific analysis to other barrier systems en route to more specific, comprehensive guidelines for roadside safety appurtance testing that can accurately predict worst-case scenarios and prevent serious crash occurrences. Without sufficient scrutiny applied to barrier system containment failures and methods to prevent such events from being propagated, it will be impossible to reduce the current rate of roadside fatalities with any meaningful and purposeful direction. In time, all barrier systems should be subjected to scrutiny on a crash-by-crash basis.

13 SUMMARY AND CONCLUSIONS

Cable median barrier crash data were collected from 12 state DOTs and analyzed to determine mechanisms of cable median barrier containment failures resulting in penetration and rollover crashes. It was determined that the composite rate of passenger vehicle penetration through cable median barriers was approximately 9.9%, and rollover occurrence was approximately 8.1%. Causation was also identified, and the crash database was segregated by predominant failure mechanism contributing to barrier penetration or rollover. By creating categories of penetration-related and rollover-related containment failures, the mutually exclusive rates of penetration and rollover were determined to be 9.3% and 5.1%, respectively. This observation led to a composite CMB containment failure rate of 14.6%.

Adverse weather conditions were determined to significantly reduce the propensity for rollover and penetration crash frequency. Barrier penetration and rollover rates were decreased by approximately 35% and 70%, respectively, during rain or snow precipitation. However, when roads were wet or snow-covered, penetration propensity was decreased by 6% and 49%, respectively, and rollover frequency was reduced by 76% and 47%, respectively. It is evident that friction has a significant effect on crash outcome in both penetration and rollover crashes. It was likely that the frictional contribution from adverse weather events decreased CG trajectory angle into the barrier, which in turn reduced the IS value of the crash during storms. The rate of penetration after storms was very similar to dry conditions, since vehicles returned to nominal travel speeds. Lower IS values at the time of impact somewhat reduced the likelihood of rollover and penetration. As a result, standard crash test conditions should not be altered from the nominally dry condition used in full-scale cable median barrier crash tests.

CG trajectory and orientation angles at impact were explored through a limited study of severe cable median barrier crashes in the state of Missouri. The high rate of high CG trajectory and orientation angle impacts in the severe crash database indicated a need to evaluate cable median barriers at higher CG trajectory and orientation angles. The 85th percentile impact condition for severe cable median barrier crashes was 39 degrees relative to a tangent line on the barrier. The currently-used 25 degree angle into cable median barrier installations only corresponds to the 70th percentile CG trajectory angle. Severe crash databases have historically been used to determine the “practical worst-case” impact conditions. These results are consistent with methods used in NCHRP Report 665 [22].

The performance of each barrier system was not equal, but there was also no “silver bullet” cable median barrier system. It was determined that the cable median barrier type with the lowest rate of A+K crashes was the low-tension 3-cable median barrier. The lowest rate of severity of high-tension systems occurred on the Safence 4-cable median barrier; however, only one other TL-4 barrier was evaluated in detail. Of the TL-3 high-tension cable median barriers evaluated, the Brifen WRSF had the lowest A+K ratio for crashes. The highest frequency of A+K injuries was observed with the Nucor 3-cable median barrier. With respect to only fatalities, both Nucor and Brifen systems were involved in fewer fatality crashes than with the Trinity CASS system, which was strongly related to the increased rate of rollovers.

Insufficient information was present to make definitive conclusions about the Gibraltar or Safence systems. The limited data available for Gibraltar systems suggested a high rate of rollover crashes, which was consistent with the rollover model shown in Figure 141.

Crash severities were related with containment failure rates, but the correlation was limited. Although many fatalities occurring with cable median barriers were caused by cross-median impacts or rollovers, other fatalities and serious injuries occurred in capture or redirection crashes. The highest correlation of containment failure with crash severity occurred with the 3-cable median barrier, with nearly 70% of all fatalities and serious injuries related to either rollover or penetration. If containment failures were equally reduced for every barrier system, the system with the highest expected rate of severe crash reduction would be the low-tension, 3-cable median barrier.

Penetration mechanisms were discussed in detail, and causes of penetrations were determined and analyzed for each system. The penetration mechanisms were classified into fundamental groupings: diving, prying, override, bounce-over, system failure, and large vehicle penetration events. Of these, the diving and prying penetrations were common on every cable median barrier system, while override penetrations were common on CASS and Nucor systems. Generic cable median barrier crashes had the fewest number of override events, likely because of the weak top cable-to-post connection, and insufficient data were available to make deterministic conclusions about override penetrations for Brifen, Gibraltar, or Safence systems. Based on the analysis of penetration mechanisms, higher bottom cable tension, lower top cable tension, stronger bottom cable-to-post connections, and weaker top cable-to-post connections were recommended.

Furthermore, it was noted that every future TL-3 cable median barrier system transition may require the use of 4 cables, with the bottom cable located approximately 13 to 15 in. (330 to 381 mm) above the ground. The bottom cable should have strong resistance to lifting on the post, but must be safely overridden when vehicles pass over the cable. To reduce the propensity for override penetrations, the top cable should be located a minimum of 35 in. (889 mm) above the ground.

Short post spacing was not strongly correlated with increased resistance to penetration. The smallest post spacing observed in the database was located in Missouri on a stretch of low-tension, 3-cable median barrier. For approximately 1 mi (1.6 km) of barrier, the post spacing was reduced to 4 to 6 ft (1.2 to 1.8 m) on center. The barrier was located adjacent to one shoulder and protected vehicles from entering a median with estimated 4:1 slope. However, two severe penetrations still occurred in this segment in a three-year period, both from the vehicles in adjacent travel lanes. If post spacing alone could prevent penetrations, it is statistically unlikely that a barrier with this small post spacing would encounter two severe penetration crashes in a 1-mi (1.6-km) stretch of roadway in only three years. As a result, it is unlikely that the reduced post spacing utilized on the low-tension, 3-cable median barrier can prevent penetration crashes without additional modifications, such as stronger cable-to-post attachments.

Some systems, such as Brifen WRSF and Gibraltar, rely on cable engagement with the flanges of adjacent posts in addition to or in lieu of strong cable-to-post attachments. In these systems, post spacing may have a more significant effect on penetration propensity than in the low-tension, 3-cable median barrier.

Rollover causes were also explored in detail. Whereas penetration events tended to occur in similar patterns based on barrier type, rollover events were similarly irrespective to barrier type. Rollovers which occurred on cable median barriers were most commonly caused by interaction with median slopes, high orientation angles at impact, or tripping on post members. Several other factors, such as trailer attachments and tire loss, were also briefly discussed. However, it would be infeasible to uniquely accommodate most of these infrequent rollover causes. As with penetration events, rollovers caused by impacts with large vehicles were not addressed, since no barriers in this study were designed to accommodate semi-tractor trailers.

Barrier improvements to reduce risk of rollover included the use of weak collapsing posts, reduced overall cable tensions or differential cable tension, and graded medians which favor moderate (i.e., 6:1 to 8:1) slopes for medians of 40 ft (12 m) or wider.

Cable median barrier installations are being erected annually at a rapid pace. Many cable median barrier systems resulted in reductions in severe injury and fatal crashes due to cross-median crash reduction. Nonetheless, modifications to full-scale testing conditions, barrier design, and roadside design must be made to ensure optimal performance of each barrier system. By implementing these design changes, it is expected that at least 50% of all cable median barrier related severe crashes could be mitigated, and that penetration rate by passenger cars could be reduced by as much as 80%.

14 RECOMMENDATIONS

14.1 Modifications to Barrier Designs

14.1.1 Cable-to-Post Attachments and Vertical Positions

An untested design concept has been proposed by researchers to address cable median barrier containment failures and involves a stratification of cable-to-post attachment strengths for high-tension cable median barrier systems. The stratification methodology is an attempt to reconcile post strength, post bending moment, vehicle geometry, vehicle crush strength, and principles of controlled redirection via energetically-favorable capture zones on the vehicle for optimum redirection performance for any barrier, whether located in a V-ditch or on flat ground. This design methodology would implement low-tension cables with low-strength cable-to-post attachments at the tops of the posts to minimize risk of excessively damaging the occupant compartments of small cars involved in cable barrier crashes. The upper vertical cable release loads should be low to prevent roof crush. Likewise, the upper horizontal cable release loads could be less than or equal to the load required to form a plastic hinge in the base of the post. Using this design principle, the top cable-to-post connection would be the weakest, but vehicles could still be redirected with a single, top cable.

The bottom cable on the posts could likewise have cable release loads which is proportional to the load required to initiate plastic hinge formation at the base of the post and should be located no higher than 15 in. (381 mm) from the ground. The vertical resistance for the bottom cable to be pushed down should be lower than vertical cable resistance to rising up the post flange. Because of the low bottom cable height and resistance to vertical uplift, underride events will be less likely. Furthermore, most windshield crown heights are at least 24 in. (610 mm) above the ground. As such, there is little risk of impacting vehicles to dive in the median and underride the bottom cable if it is located no higher than 15 in. (381 mm) and if the cable has a strong resistance to vertical rise. Fundamentals of this design concept are already being utilized in some high-tension cable barrier systems, but potential improvements to energy absorption through cable-to-post attachments, post strength, and post spacing can be made for every system. The design concept is shown schematically in Figure 143.

Low-tension, 3-cable median barrier systems sustained the lowest frequency of large orientation angle-related rollovers but the highest number of post snagging related rollovers. This reduction is likely due to the lower cable tension and resulting lower lateral force on the vehicles applied by the cables. Common S3x5.7 (S76x8.5) post sections used with low-tension cable median barrier systems should be weakened, and improved cable-to-post connections should be utilized in order to experience a significant improvement in safety performance. Bottom cable-to-post attachments permitted frequent underrides and occasionally through-cable penetrations. Both of these penetration types would be significantly reduced if the bottom cable-to-post attachment was strengthened. The top cable-to-post attachment appeared to be optimal for the low-tension, 3-cable median barrier since overrides were infrequent on this system. This cable-to-post attachment strength should be evaluated based on cable tension and height above the ground. Note that the nominal mounting height for the top cable in all low-tension, 3-cable median barrier systems in this study was 33 in. (838 mm).

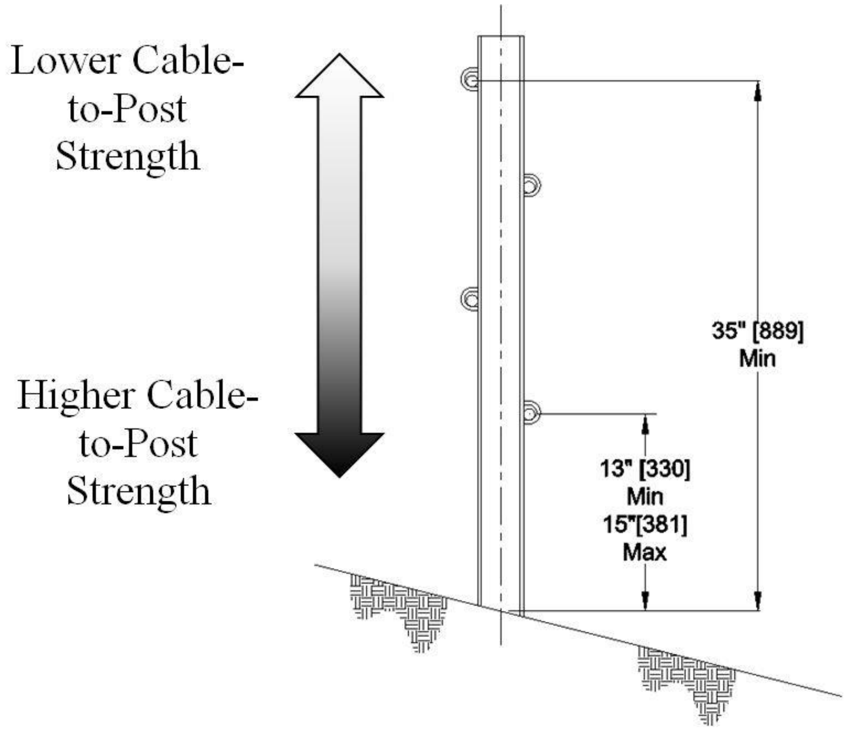


Figure 143. Cable Median Barrier Stratification Concept

14.1.2 Cable Tension

One design alteration, which may alleviate some rollover propensity caused by high-orientation angle crashes into high-tension cable barrier systems, is to reduce cable tension. A reduction in cable tension would decrease the lateral force imparted to a vehicle at the point of impact. Vehicles entering a V-ditch frequently have a pitch and roll displacement associated with the angled orientation in the ditch. As a result, interaction with cables in the ditch may cause an increased trip propensity due to roll and pitch moments imparted to the vehicle by the cables. Lower cable tension would permit a more gradual cable engagement with the vehicle and thus may reduce rollover propensity.

14.1.3 Number of Cables

One design improvement which would aid a low-tension, 3-cable, TL-3 median barrier system would be the addition of a fourth cable. The added cost of the fourth cable is an initial fixed cost which would not greatly increase annual maintenance costs associated with barrier repair. However, the anticipated safety improvement obtained by considering an additional cable is expected to be very high. Cost savings due to reduction in severe injuries and fatalities should far exceed the increased cost that the additional cable would add to system installations, as discussed in Chapter 10.

In steeply-sloped medians or to reduce the rate of tractor-trailer penetrations, a fifth cable should be considered for every cable median barrier system.

14.1.4 Summary of Design Improvements

Several cable design improvements for cable barriers are recommended for further evaluation and are shown in Table 37.

Table 37. Summary of Barrier Design Improvement Recommendations

Barrier System	Component	Problem	Recommended Design Improvements
Nucor NU-CABLE	Cable to Post Attachments	Strong attachment prevents cable release after post is struck or deflects, causing continued engagement and post pullout from the ground or post fracture.	Eliminate nut from upper and middle clips. Redesign lower clip to release at a load near to the bending capacity of the post.
	Post Embedment	Frequent post pullout from ground or sockets.	Extend embedment depth to optimum length determined by component testing. Deepen embedment in socket to optimum length determined by component testing.
	Cable Heights	Insufficient number of cables to prevent penetrations.	Increase the standard number of cables in the TL-3 design to 4. Place the top cable at least 35 to 38 in. (890 to 965 mm) above ground, and the bottom cable at approximately 13 to 15 in. (330 to 381 mm).
Trinity CASS	C-Shape Posts	Frequently contribute to rollover.	Drill weakening holes at ground line in corners of post to facilitate post collapse and reduce the strong-axis yield moment. Consider breakaway alternative instead of post deformation as primary failure mechanism.
	Post Slot	If vehicles make first contact with post instead of cables, posts can be pushed down while still retaining cables, increasing rollover propensity.	Weaken the flange or web via slot or saw cut adjacent to middle or upper cable(s) to reduce risk of posts pushing cables downward.
	Cable Spacer	Vehicles which "dive" under cables are subjected to large vertical loads which can crush occupant compartments or increase ridedown accelerations.	Add additional bottom cable to prevent underride. Consider independent cable suspension within the slot or removal of at least one cable from the slot.
Brifen WRSF	Cable to Post Attachments	Bottom cable attachments using "roller" to maintain cable height contributes to diving and prying underride failures.	Add physical attachment to resist vertical displacement of bottom cable. Lower bottom cable height to 13 to 15 in. (330 to 381 mm) to reduce underride potential. Vertically separate 2nd and 3rd cables in TL-3 system.
	Cable Weave	Cable weave on bottom cable has contributed to rollover when wheel on impact side of vehicle overrides cable and causes pinch point at post.	Consider eliminating bottom cable weave or reduce height of bottom cable.
	Override	Large passenger vehicles can override system.	Increase height of top cable in TL-3 system.
Blue Systems Safence	C-Shape Posts Post Slot Cable Spacer	Similar concern as Trinity CASS.	See comments on Trinity CASS.
Gibraltar	Post Spacing	Large post spacing significantly increases risk of penetration by reducing lateral constraints on cables.	Decrease standard post spacing. Limit maximum post spacing to 10 ft (3.0 m) on centers.
	Cable Hangar	Cable hangar can be pried upward, lifting all cables up and releasing them from the post, contributing to override.	Cable attachments should be independent, to allow cables to release from posts without adversely affecting all other cables.
	Alternating Posts	Impacts at back sides of posts entrap cables and create ramps, facilitating rollover and penetration.	Prevent impacts centered on the back sides of posts from pushing cables downward.
	Post Strength	Tube post section does not completely collapse on weak-axis impact and forms ramp contributing to rollover.	Add weakening element to tube posts to completely collapse after impact.
Low-Tension 3-Cable Median Barrier	Cable to Post Attachments	Bottom and middle cables release from posts at low loads, causing extensive cable displacements when one cable redirects vehicle, and can increase penetration propensity.	Increase bottom and middle cable pullout load vertically and horizontally. Consider use of a retrofit strengthener which adds pullout resistance.
	Cable Heights	Barrier is susceptible to diving and prying underride failures.	Add fourth cable between 13 and 15 in. (330 to 381 mm). Apply stronger cable-to-post connection resisting vertical uplift and back side pullout.
	Post Strength	Post strength frequently contributes to rollover.	Slot, cut, or alter posts to make weaker. Apply weaked tube or pipe-section posts which will flatten completely when impacted.

14.2 Barrier Placement in Medians

Many medians have slopes which may vary widely, even within a section spanning only one mile (1.6 km). As such, it is impossible to know *a priori* the actual slope in front of or behind a barrier before it is installed in the median. Thus, every barrier system should be crash tested and evaluated on the front and back slopes of a 4:1 V-ditch in the most critical configurations, which were determined and are discussed in Reference 20. Crash testing on the 4:1 slope or in a narrow 6:1 V-ditch may still be necessary if it is recommended for use on slopes shallower than or equal to 6:1 because of median geometry variations. These matrices should more adequately ensure that cable barriers can accommodate errant vehicles traversing sloped medians under tracking conditions.

Note that placing cable median barriers along both shoulders will not necessarily prevent all penetrations, cross-median crashes, or rollovers. Penetration crashes were nearly as common when barriers were impacted at the shoulders as occurred in the center of the ditch. Rollover crashes commonly occurred with low CG trajectory angles but high orientation angles. Rollover frequency was also greater when cable barriers were located adjacent to shoulders than in other locations since roadways typically have higher-friction surfaces which can increase the tripping moment on the vehicle and cause larger changes in CG trajectory angle with the same steering input applied. Whenever convenient, it is recommended that cable median barriers be placed as close to the center of the median as possible.

14.3 Full-Scale Crash Testing

14.3.1 Full-Scale Crash Testing on Slopes

Due to the wide range of possible impact conditions which could occur on any cable median barrier, a variety of underride and override barrier impact conditions should be considered likely unless impacts with similar conditions cannot be observed with regular frequency in real-world crash databases. Override penetrations, underride penetrations, and rollovers were observed for barrier systems regardless of approach slope, back slope, and median placement. Using crash data as indicators, it will likely be necessary to utilize much of the crash-testing matrix recommended in Reference 20. Testing in accordance with these matrices will likely prevent many future penetration and rollover crashes.

14.3.2 Impact Conditions

Based on the impact conditions observed in this report, the 85th percentile CG trajectory angle involved in serious cable median barrier crashes was 39 degrees. Since the severe crashes followed the trend of all penetration crashes, based on the observation of Missouri and North Carolina data, full-scale crash testing to evaluate propensity for penetrations should be conducted at the higher CG trajectory angle of 39 degrees in future testing.

Based on the plot of impact angle shown in Figure 11, many rollovers in Missouri were observed when the initial orientation angle was approximately 45 degrees. In fact, the only severe crashes which occurred with orientation angles between 35 and 55 degrees were either penetration or rollover crashes. An orientation angle of 45 degrees is recommended for full-scale crash testing, since crashes occurring at CG trajectory angles greater than 10 degrees were frequently oversteering crashes.

In order to test system susceptibility to low-CG trajectory angle, high-orientation angle crashes with SUV and light truck vehicles, the 50th percentile CG trajectory angle of 18 degrees is recommended. This angle is lower than the current 25-degree angle used in full-scale crash testing, but it should still be representative of a practical worst-case impact condition when combined with the 45-degree orientation angle.

The currently-used impact speed of 62.1 mph (100.0 km/h) appeared to be representative of the 85th percentile condition, although an actual speed distribution was not available. Impact speed estimates in each crash were provided by responding officers in Ohio. The median estimated impact speed was 60 mph (97 km/h), and the average estimated impact speed was 58.1 mph (93.5 km/h). Furthermore, the speed limit on interstates in Ohio was only 65 mph (105 km/h). This data suggested that impact speeds used in full-scale crash testing should not be reduced.

14.3.3 Vehicle Selection

The crash testing of cable barrier systems according to the TL-3 test criteria found in NCHRP Report No. 350 may not have been tested with the most critical vehicles. Although it may be argued that the 2000P pickup truck used in NCHRP 350 crash testing is critical based on vehicle analysis results, barrier systems should also be evaluated with widely-purchased vehicles which have the greatest propensity to cause barrier failure. Many of the vehicles shown in Table 28 are no longer being produced. As a result, an analysis of newer vehicle features consistent with the critical features identified in Chapter 7 should provide guidance for future vehicle crash testing efforts.

Very few small car crash tests have been conducted under recent impact safety standards on cable barrier systems. These crashes were not believed to be critical. Based on crash data collected in this study, small car crashes were only critical if an occupant made contact with the barrier, the vehicle penetrated over, under, or through the system, if cables crushed the occupant compartment or caused rapid decelerations, or if the vehicle tripped and rolled over. All of these conditions were infrequent in the available database of real-world cable barrier crashes. A small car test would likely waste valuable research money without providing much critical barrier performance insight.

14.3.4 Summary of Full-Scale Crash Testing Recommendations

The recommended impact conditions for consideration in future full-scale crash testing of cable median barriers are shown in Table 38.

These crash tests are recommended to replace the current TL-3 MASH crash test nos. 3-10 and 3-11 which are required for cable barrier systems and should be conducted on level, flat terrain unless otherwise specified. These tests are intended to supplement V-ditch testing of cable median barriers [20].

However, current limitations on crash testing procedures may limit the ability of agencies to conduct non-tracking and partially-skidding crash tests. Until the necessary apparatus are developed to conduct crash testing with the recommended impact conditions, full-scale crash tests should be conducted at the CG trajectory angles identified in Table 38 and in fully-tracking conditions. Additional research to develop crash testing apparatus to conduct full-scale crash tests with off-tracking conditions will be necessary.

If the roadside safety community intends to reduce the number and frequency of cable median barrier containment failures, updates to existing testing criteria should be considered to reflect the more realistic “practical worst-case” impact scenarios. Whereas data per each system were not historically available, better data are now available to guide the redesign of systems to obtain the maximum possible safety improvement. The matrix provided in Table 38 is expected to cover the most critical crash conditions. Test no. 3-10A may incorporate a small car if a small car is shown to be most critical, but currently there is no plan to incorporate a separate crash test specifically for small cars.

Table 38. Recommended Crash Testing Impact Conditions for Cable Median Barriers

Test No.	Impact Speed, V (mph)	CG Trajectory Angle, φ (deg)	Orientation Angle, Θ (deg)	Vehicle Class	Description
3-10A	62.1	39	45	Passenger Car	Passenger car penetration prying/underride test. Impact should occur 2 ft (0.6 m) downstream of post. Recommended vehicles include: Acura Integra, Chevrolet Impala, Chevrolet Lumina, Dodge Intrepid, Ford Escort, Ford Taurus (model years before 2008), Honda Accord, or Subaru Impreza.
3-11A	62.1	39	45	SUV, Pickup Truck, or Commercial Van	High-angle override test. Impact should be 4 in. (102 mm) upstream of post. Recommended vehicles include Chevrolet Blazer, Ford Explorer, Ford Escape, Toyota 4Runner, Toyota Tundra, or commercial van vehicles.
3-11B	62.1	7	7	SUV, Pickup Truck, or Commercial Van	Low-angle override test. Should be conducted in ditch on 6:1 approach slope. Vehicles should be similar to those in test 3-11A.

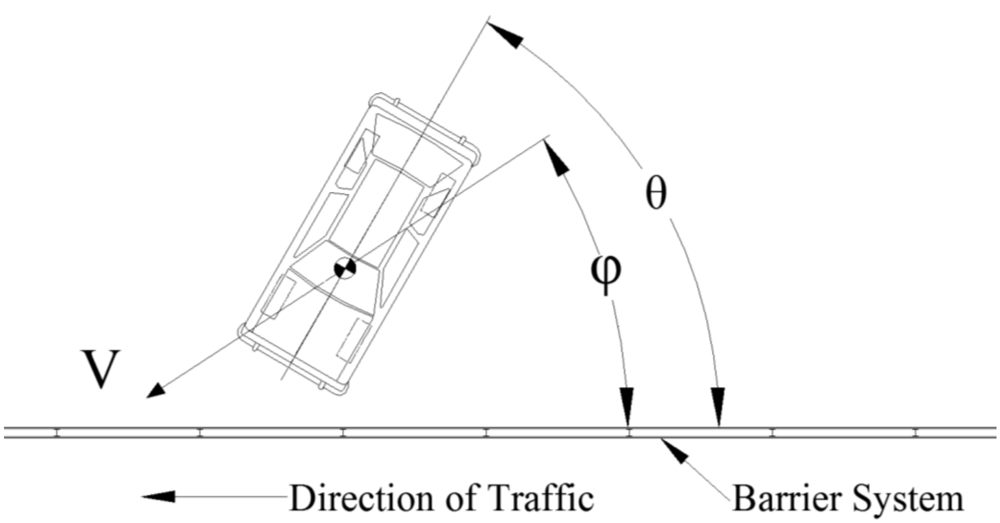


Figure 144. Representative Crash Testing Impact Diagram

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