Development & Validation of a Model to Evaluate the Safety Performance of Cable Median Barriers

Background

Cable median barriers are increasingly being used to reduce cross-median crashes on divided highways. They can be installed easily, have a low cost compared to other alternatives, can function effectively on sloped terrain, and do not cause the accumulation of drifting snow. Agencies installing these systems generally report significant reductions in cross-median crashes. This effort was initiated by the FHWA in response to a request from the North Carolina DOT. They noted that despite major reductions in crossover crashes, some crashes were still occurring after the installation of cable median barriers. The limited guidance and experience available to address this concern provided the impetus for this effort to enhance the means to analyze the performance of cable median barrier systems.

The task of investigating the causes of the cross-median crashes was directed to the National Crash Analysis Center (NCAC). The NCAC analyzed those crossover crashes that had occurred after installation of the cable median barrier in North Carolina, developed a finite element (FE) model of a cable median barrier to allow detailed analysis of the interactions of a vehicle and the barrier, and applied vehicle dynamics models to understand the terrain-induced effects on the vehicle interface with the barrier.

These efforts led to a better understanding of the problem, isolated the probable causes of cable barrier failures, identified the effects of vehicle dynamics on barrier performance, and developed methods and tools for the continued evaluation of cable median barrier design and placement options for new installations or retrofits. The primary objectives of this research were to:

- **Evaluate** the safety performance of standard 3-cable cable barriers under varying design and placement conditions.
- **Demonstrate** the use of the model to analyze changes to the design and placement to improve cable median barrier safety performance.

The models and insights gained from the efforts to meet these objectives set the stage for further model analyses of cable median barriers.

Approach

To meet the objectives, the NCAC team searched for viable vehicle and hardware models to analyze the problem. A set of viable vehicle models was found, but a cable median barrier model had to be developed. The effort to develop and validate the cable median barrier model is described below. Available data from tests to show compliance of a generic three-strand, low-tension, cable median barrier to the crashworthiness standards defined in NCHRP Report 350 were used to expedite the effort. Police-reported crossover crashes in North Carolina where the cable median barrier failed to redirect the errant vehicle were reviewed in detail to identify common factors and determine the appropriate vehicles to use in the analysis. The effectiveness of alternative cable median barrier design and placement practices on the barrier's safety performance were evaluated using the computer models developed. Full-scale crash tests at the Federal Outdoor Impact Lab (FOIL) validated the results predicted by the computer models and provided the confidence that the computer models could be used to analyze changes to the design and placement of cable median barriers to improve safety performance.

The following sections provide further details about each of the stages in this approach. The
final report for this project provides a full description of this research [1].

**Developing a Computer Model**

A finite element model was developed for the Washington State cable median barrier design [2]. Modeling the three-strand, low-tension cable barrier was no trivial task. To effectively simulate vehicle-to-cable barrier interactions, it was necessary for the model to accurately represent the characteristics and behaviors of the post, hook bolts, cable, and soil [3, 4]. The cable was modeled as series of discrete beam elements with elastic material properties to represent the steel strands. The beam elements had null element shells to allow sliding contact by the impacting vehicle. The posts were also modeled as a beam with geometry consistent with the actual post shape and properties equivalent to the steel material used to manufacture the posts. The cable hook bolts were described as beam elements with linear springs to represent the threaded ends of the hook (Figure 1). The stiffness of the spring was selected to represent the clamping force of the nut. The post embedment was represented by a cylindrical block of elements representing the resisting force of the soil on the post (Figure 2). Anchorages and related connections were modeled to create an entire cable median barrier system. The use of nodal-based projections provided good contact interactions between the cable and the vehicle.

The Chevy C2500 pick-up truck model developed previously by the NCAC was selected to serve as the large vehicle prescribed in the NCHRP Report 350 crash testing procedures [5]. No modifications were made to the vehicle model for the crash simulations.

**Determining the Viability of the Model**

To validate that the newly developed model for the cable median barrier was a good representation of the real hardware, crash simulations were run and the results compared to data from a full-scale impact test with the same barrier. The animations and data generated by the computer simulations indicated close reflection of the results from the NCHRP Report 350 test conducted to certify this cable median barrier system [2].

The crash simulation was conducted for an impact by the C2500 pick-up truck at 100 km/hr and 25 degrees. This impact scenario represents the “strength” test for this barrier as prescribed in NCHRP Report 350. The views of the test video and computer animations shown in Figure 4.
reflect the comparisons. It was noted that the crash caused a displacement of 10-12 feet in the barrier, but the vehicle was redirected without appreciable roll or pitch. The similarity of the comparisons of the visual results and the accelerometer data from the simulation and from the full-scale crash test led to the conclusion that the cable median barrier model was sound and it could be used for analysis of various cable barrier design and placement options.

Figure 4 – Comparison between actual test and simulated impact based upon Washington State cable barrier design

Modeling the North Carolina Design
The North Carolina cable median barrier design was very similar to the Washington State design that had been crash tested. Post spacing and length were the same. The position of the lowest cable is the same at 21 inches, but the North Carolina design had slightly more space between the individual cables (see Figure 5). Thus, it was easy to alter the computer model to create a representation of this system.

Figure 5 – Comparison of North Carolina and Washington State cable median barrier design features

North Carolina Cable Median Barrier Experience
The North Carolina DOT initiated a program to install cable median barriers in the late 1990’s on their interstate highways constructed with narrow medians. They used the standard three-strand, low-tension cable barrier design that complied with the NCHRP Report 350 crashworthiness criteria. These cable barriers were installed in “v-profile” medians which had side slopes of 6:1. The barrier was placed 4 feet from the center (invert) of the median. The North Carolina DOT noted that some cross-median crashes were still occurring after the installation of these cable median barriers and launched an investigation to determine the causes. In the investigations they collected data on:
- the side of the cable barrier hit, relative to the configuration of the cables (1- or 2-strand side),
- the angle of impact,
- the type of vehicle and its dimensions,
- vehicle weight and bumper heights, and
- crash outcomes.

The site shown in Figure 6 was typical of the median configuration and barrier installation at the crash sites.

Figure 6 – Median configuration and barrier installation at the crash sites
One of the crashes investigated occurred on 11/13/2001 which involved a 2000 Mercury Grand Marquis passenger car. This vehicle was estimated to weigh 1777 kilograms. It hit the cable median barrier at 11 degrees (as can be noted in the site photo) at an estimated 60 mph (100 km/hr). The vehicle underrode the cable median barrier and crossed into oncoming traffic.

Detailed investigation of thirteen other similar cross- median crashes were also undertaken. It was suspected initially, that the side of the hit on the cable median barrier might be influencing the outcomes. Of the 14 cases analyzed, six crashes which penetrated the barrier from the side of the cable median barrier on which one cable was attached. There were fewer crashes when the side of the barrier on which two cables were attached was struck. Further analysis of this data, considering speed and impact conditions as well, concluded that which side of the barrier the vehicle struck was not a factor.

Further analysis found that the type of vehicle (and hence dimensions), weight, and impact angle also did not have a strong relationship to the propensity to underride the cable median barrier. The fact that most of these vehicles were passenger cars with sloped front-ends may, however, have contributed to the vehicle not engaging a cable on impact. However, since a strong relationship was not found between vehicle size and weight, and the instances of barrier underride, the researchers decided to scrutinize the design and placement of the cable median barrier relative to the median configuration.

**Analysis**

**Crash Simulation Analysis**

Computer simulations were used to analyze the influence of various cable median barrier design and placement factors.

Initially, the simulations focused on the effects of different impact angles for a Ford Crown Victoria vehicle (similar to those noted in several of the North Carolina crashes) on level terrain with impacts at 100 km/hr. Simulation results showed that the vehicle was redirected in 25 degree impacts, but not in the 45 degree impact. It was concluded that the higher angles involved energy levels above the capacity of this type of barrier.

Figure 7 shows the relative static position of the front of a vehicle to the cables for the 4 foot offset placement on 6:1 side slopes used in the North Carolina installations. It is easy to see how the vehicle could get under the lowest cable and hence underride the barrier. For less severe impact angles, the relative positions of the hood and cables are similar.

Since the vehicle is a sprung-mass, a static analysis is not sufficient to determine the effectiveness of barrier design and placement conditions. The degree of compression or extension of the vehicle’s front suspension at the instant the vehicle makes contact with the barrier can significantly affect the height of the nose of the vehicle, with potentially dramatic influence on the barrier’s effectiveness. To fully understand the interaction between the vehicle and barrier, it is necessary to analyze the dynamics of the vehicle.
as it leaves the roadway and traverses the shoulder and median side slopes.

The NCAC cable median barrier model was used to replicate the 11/31/2001 North Carolina crash with appropriate considerations of vehicle dynamics. An FE model of a Ford Crown Victoria (obtained from others) was used to represent the Mercury Marquis which had been involved in the crash (the Crown Victoria is structurally identical to the Mercury Marquis). With the barrier on a 6:1 side slope and offset 4 feet from the median centerline, an impact at 11 degrees and a speed of 100 km/hr was simulated. The sequence of views from the simulation (Figure 8, at the end of this technical summary) clearly showed that the vehicle underrode the three cables and continued across the median. The sloped front end made it easy for the vehicle to slide under all three cables. A vehicle with a higher, squared front end (like the pick-up truck) would have been more likely to engage more than one of the cables under similar impact conditions.

On flat terrain, simulations showed that both the North Carolina and Washington designs meet NCHRP Report 350 performance recommendations. Simulations showed that the cable barrier on a 6:1 side slope will redirect the pickup truck even if the barrier is offset 4 feet from the center of the median depression. But for similar side slopes, the simulations showed, and full-scale crash tests confirmed, that the cable barrier will not redirect mid-size sedans and small vehicles if posts are placed more than 1 foot from the center of a median.

Vehicle Dynamics Analyses
Since finite element crash simulations take a considerable amount of time to run, the Human Vehicle Environment (HVE) software was used to allow a quicker analysis of vehicle dynamics across a range of impact conditions [7]. The HVE software includes the descriptions and dynamic response characteristics for a large set of common vehicles. It replicates the dynamics of each vehicle as it traverses a given terrain (roadway to downward sloped median). The 6:1 sloped v-section median configuration was modeled for this analysis. The results were translated to animations to show the points of impact with the lowest cable for a range of vehicles for varying impact angles at an impact speed of 100 km/hr. The HVE model replicates the spring action associated with the vehicle to provide a measure of the relative position of the vehicle’s front end at the point it interacts with the cables.

HVE simulations were generated for a Crown Victoria at an impact angle of 25 degrees on a 6:1 slope with the cable median barrier offset 4 feet from the center of the median. Figure 9 shows one of the many animations generated for the vehicle to barrier interface analysis. The black band indicates the space under the lowest cable in the cable median barrier. The animations showed that the vehicle front end interfaced the band below its top, indicating a likelihood that the vehicle would underride the barrier. In studying the various data generated by HVE, it was noted that the front suspension is fully compressed at the moment when the vehicle reaches the barrier. The sloped front of the vehicle’s hood is at or near the level of the lowest cable, and at that moment the vehicle springs have begun to rebound, adding an upward force that promotes lifting of the cable and allowing underride.

![Figure 9 – Typical HVE view of the interface of a vehicle with the black band representing the space under the lowest cable](image)

In simulations with a Mitsubishi Mirage at an impact angle of 20 degrees on a 6:1 slope with a 4 foot offset, similar results were noted. However, it was also noted in these analyses that if the median barrier were located one-foot from the center of the median there would be better engagement between the barrier cables and front of the vehicle, and hence a lower likelihood that the vehicle would underride the barrier. Thus, a cable median barrier placement closer to the center of the median would be expected to function better. However, since in the field there will be more water closer to the center of the median, a one-foot offset is likely to mean that posts will be less secure and harder to maintain.
Since it is possible for the barrier to be hit from either side, it was necessary to analyze impacts from both directions. When the median barrier is on the far side of the median from the point of road departure, the vehicle travels through the center (invert) of the median before striking the cable barrier. From the near side, the vehicle will only travel a few feet down slope before impacting the barrier. The interface for a Crown Victoria at an impact angle of 25 degrees on a relatively flat 10:1 slope was analyzed to ascertain the differences in impacts from either side for the one-foot and four-foot offsets. The one-foot offset worked well for impacts from both directions. As noted earlier, the four-foot offset was likely to result in an underride for the far-side impacts, but it was found to function acceptably for near-side hits.

Crash Tests for Model Validation
Full scale crash tests were conducted that the Federal Outdoor Impact Lab (FOIL) to validate the results obtained from the computer simulations. Comparisons were made between computer model outputs and measurements in the tests of the following factors:
- Gross vehicle trajectories
- Velocity change profiles
- Crush damage and deformations
- Accelerations

The tests involved impacts at 100 km/hr and 25 degrees. A 1992 Crown Victoria (1800 kg vehicle) was used in each test. Two cable median barrier configurations were used:
- Test 1 – cable barrier @ 4 foot offset on 6:1 slope
- Test 2 – cable barrier @ 1 foot offset on 6:1 slope

The tests were conducted following typical NCHRP Report 350 protocols.

In Test 1, the cable median barrier was located 4 feet from the center of the median invert. As can be seen in Figure 10 (at the end of this technical summary), the vehicle underrode the barrier in a manner similar to that depicted in the computer simulations. The front of the vehicle dipped under the lowest cable and the only thing the cable snagged was the side-view mirror. Test 2 involved a Crown Victoria traveling at 100 km/hr and impacting at an angle of 25 degrees. The cable median barrier was located 1 foot from the center of the median invert. This test resulted in the vehicle being arrested and redirected. A deflection of 12-13 feet was noted. This and other measures were all considered to be within acceptable ranges.

These tests confirmed the crash simulation and vehicle dynamics analyses.

Summary and Conclusions
Finite element crash simulations and vehicle dynamics analyses coupled with full-scale crash testing were performed in this research to identify the reasons for cable barrier underrides and to develop suggestions for design retrofits that would minimize their occurrences. To accomplish this it was first necessary to develop a finite element computer model of a cable median barrier. This model was successfully validated against full-scale crash test data on level terrain to demonstrate that the performance of cable median barriers could be replicated. The validated model was then used to investigate the effects of different design and placement options on sloped terrains to determine their potential to affect barrier performance.

The investigations led to the conclusion that barrier placement on sloped terrain can be a key factor in performance, particularly relative to underrides that lead to median crossovers. Vehicle dynamics models were used to compute vehicle trajectories as they crossed sloped medians, and to determine the points on the vehicle which first engaged the barrier. The speed at which these computations can be done with vehicle dynamics models allowed the evaluation of the relative performance of different vehicles for varying speed and angle impact scenarios on 6:1 slopes. At the end of this effort, two full-scale crash tests were performed on a sloped median to further confirm that models were capable of representing cable barrier performance on sloped terrains.

It was concluded from the study that on flat terrain, both the North Carolina and Washington State cable barrier designs performed similarly in meeting the NCHRP Report 350 crashworthiness criteria. On 6:1 sloped terrain, the simulations showed that the cable barrier will redirect the NCHRP Report 350 2000 kg pickup truck even if...
the barrier is 1.22 m (4 ft) offset from the center of the median. The simulation also showed, and full-scale crash tests confirmed, that the cable barrier may not redirect mid-size sedans and small vehicles if the barrier is placed more than 0.3 m (1 ft) from the center of the median. It was determined that the suspension on the mid-sized vehicles tended to be fully compressed due to dynamic forces imposed by the terrain, speed, and angle when the vehicle starts up the slope on the opposite side of the median. These conditions are likely to place the nose of the vehicle below the lowest cable and allow underride of the barrier.

It was concluded that cable median barriers can be effectively modeled for use in crash simulations. Crash simulation and vehicle dynamics software provides viable means to analyze their effectiveness of cable median barriers under varying conditions. It was demonstrated that alternative barrier design and placement options could be evaluated. It was further noted that the sloped front-end designs of many vehicles contribute to the problem of barrier underride. Variations in the specific suspension on a vehicle, its loading, steering input, and the stiffness of the median surface were not explicitly addressed, but could also influence the propensity to underride the barrier.

Further analyses are needed to develop a better understanding of alternative design and barrier placement options in varying median configurations. The analyses should include:

- Retrofit options for existing cable median barrier installations.
- Analyses of cable barrier performance on different sloped terrains.
- Considerations of adding a fourth cable, altering the spacing of the cables, using a closer post spacing, or making other modifications to the design.
- Using a stronger cable/post connection or incorporating ties to connect the three cables.
- Further review of alternative cable positions, mounts, and post spacing.
- Analysis of high-tension cable median barriers.
- Consideration of barrier performance behind curbs.

These design options need to be investigated to evaluate their effect on the safety performance of cable median barriers, to improve barrier designs, and to develop more robust guidelines for the placement of cable median barriers.

References

Information
See the NCAC Website (www.ncac.gwu.edu) for more information including:
- A Power Point file providing the trace plots and animations is available for downloading.
- Information on other NCAC efforts

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Figure 8 - Sequence of simulation results for the North Carolina design and placement
Figure 10 – Test 1 results for cable barrier at 4 foot offset with vehicle underriding the barrier