Analyzing the Effects of End-Anchor Spacing & Initial Tension on Cable Barrier Deflection Using Computer Simulation

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This working paper summarizes recent efforts and findings derived from NCAC research. It is intended to solicit feedback on the approach, scenarios analyzed, findings, interpretations, and implications for practice reported by the research team. The statements contained herein do not necessarily reflect the views or policy of the FHWA. Please forward comments or questions to the authors noted above. These efforts will ultimately be documented and made available to advance research efforts related to this topic and guidance for practice.

ABSTRACT

The dynamic deflection of a cable barrier during impact is an important characteristic for many reasons. Compared to semi-rigid W-beam barriers and rigid concrete barriers, cable barriers have much greater deflections, which is the reason that cable barriers typically are more forgiving to the impacting vehicle’s occupants. The elastic behavior of the cables absorbs energy during the impact and thereby reduces the deceleration forces exerted on the vehicle’s occupants. However, for the barrier to be safe, adequate space behind the barrier that is clear of hazards must be provided to accommodate the expected deflections. If deflections exceed the space provided, the errant vehicle could impact rigid objects behind the barrier or, worse yet, in median applications cross into opposing traffic on a divided highway.

Crashworthiness requirements for cable barriers are contained in National Cooperative Highway Research Program (NCHRP) Report 350 and have recently been updated in the Manual for the Assessment of Safety Hardware (MASH). Under these requirements, dynamic deflections observed in the crash test need to be reported, but all design and installation features of cable barrier systems are not standardized. Thus, questions arise about performance, particularly relative to the different design features and installation configurations for the various proprietary designs that are available. At this
time, the crash testing requirements do not fully address the effectiveness of the various high-tension cable systems.

The purpose of this study was to investigate the influence of different cable barrier design features and installation configurations on the dynamic deflection for high-tension cable barrier systems. Two basic design features were examined in the study: cable weaving effects (weaved and parallel systems) and number of cables (three and four-cable systems). The installation configurations investigated included varying end-anchor spacing (installation length) and initial level of cable tension (static tension).

The simulation findings indicated that the dynamic deflection increased with increasing distance between anchorages and the weaved system had lower deflections for all lengths. Weaved systems, either high or low tension, had lower deflections than either type of low or high tension parallel system. Lastly, three or four cable weaved systems had lower dynamic deflection than parallel systems.
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INTRODUCTION

The use of cable barrier systems on US highways has been on the rise and is expected to increase in the future. This increase is attributed to cable barriers’ success in keeping vehicles from crossing the median or leaving the roadway, its low initial installation cost, and its low impact severity. Several studies have shown that cable barriers reduce median cross-over events that could lead to some of the most severe and often fatal crashes [1,2]. Various cable barrier systems have been crash tested successfully and accepted for use on U.S. highways, but the specific effects of various design features and installation configurations is not yet fully understood. This is the case for high-tension compared to low-tension systems, as well as the specific barrier design features and installation configurations within each category. An understanding of the influence of these features relative to the advantages of lower deflection during impacts is critical to making effective selections from available cable barrier systems having varying features. The benefits or costs can be significant for agencies that are planning to install hundreds of miles of new cable barrier.

While cable barrier systems have been used to enhance highway safety since before 1920, their limitations and maintenance requirements led many agencies to limit their use. Over the last ten years, newer versions of cable barriers have emerged to meet the need for an effective barrier that can be deployed quickly, at lower costs, into a variety of situations. Guidelines for testing, application, and maintenance of cable barrier systems are evolving, but a viable national set of guidelines does not yet exist. Several state agencies have undertaken studies and/or developed guidelines over the past few years to facilitate making decisions relative to the installation and maintenance of cable barrier systems [1,3,4,5,6]. These guidelines, however, fail to address all of the installation and maintenance issues that arise as highway designers attempt to use cable barriers to improve safety.

This effort focused on isolating the effects related to three barrier design features and an installation configuration. The three design features considered were:

- Number of cables – Available cable barrier systems have either three or four cables.
- Cable arrangement – Finite element models of an interwoven (weaved) 4-cable barrier and a non-woven (parallel) 4-cable barrier were developed and validated.
- Initial cable tensions – Two cable tensions, 15 kN (3,375 lb) and 24 kN (5,400 lb), were used for the initial tension in the system before impact.

The installation configuration considered was:

- End-anchor spacings – Anchor spacings of 100 m (328 ft) (typical spacing used for NCHRP Report 350 crash tests), 500m (1,640 ft), and 1,000 m (3,280 ft) were used in the analyses.

Other design and configuration factors were not varied or were kept as their nominal standard in these efforts. For example, post spacings were kept at the standard 3.2 m for the weaved system and 3.0 m for the parallel system. These tensions represent typical “hot weather” 38°C (100°F) and “average weather” 10°C (50°F) conditions, respectively, for high-tension cable barriers.

The results from these efforts were expected to help determine whether the higher cost of requiring these features and/or configurations in cable median barrier procurement would be justified by an increase in performance. While insights about the effects of the above factors is important, it is recognized that
other aspects still need to be addressed, including placement on sloped terrain and curved medians, end-anchor size, transitions into other systems, post design and spacing, post foundation and embedment, and cable arrangements (e.g., number, height, and spacing). The effects of these aspects and their interactions are the subject of other ongoing or planned research.

**STUDY APPROACH**

Simulation was considered to offer a highly cost-effective means to evaluate the influence of critical design features and installation configurations. Multiple, high-cost crash tests would be needed if a traditional approach was to be followed. Also, conducting full-scale crash tests with very long cable barrier installations [500 m (1,640 ft) and longer] is often not practical and beyond the capabilities of some test facilities.

Previous research funded by FHWA demonstrated that it was possible to develop and validate a viable FE model of a cable barrier system and to evaluate its performance in impacts with standard test vehicles (e.g., 2000P pick-up truck) [7,8,9]. Finite element (FE) models of the various cable barriers systems and models of the test vehicles were used in computer simulations of crash events. A fundamental element of these past modeling efforts that provided credibility to such an approach is the availability of validated models, particularly of vehicles. Therefore, in this study, a number of simulations were performed to analyze the effects of different design features and installation configurations.

The study approach involved developing FE models of the cable barrier designs of interest, finding viable vehicle models, validating the simulation model (i.e., the combination of the hardware and vehicle models in a crash scenario), demonstrating the validity of the crash simulation model by comparing the results to existing crash test results, systematically altering parameters to reflect differences in barrier design and configuration, and then comparing the results.

**Developing Hardware Models**

In this study, FE models of high-tension cable barrier systems with varied designs, lengths, and initial tensions were created following the same basic modeling approach (i.e., the cables represented as a connected series of beam elements covered by shell elements) that was successful in the previous research. The models included two types of cable systems: weaved and parallel. There is only one weaved barrier design available (because of a patent), but several variations of parallel designs are available. A generic version of a parallel design was created for general comparison purposes (although somewhat influenced by available crash test data). These two barrier designs are depicted in Figure 1.

![Weaved Design](image1)

![Parallel Design](image2)

Figure 1 – Weaved and Parallel Cable Barrier Designs
In each case a cable barrier system was modeled to reflect the length of the system and anchorages that would occur at either end as shown in Figures 2 and 3. Anchorages were modeled as straight or flared depending on the tested design for that system. Three- and four-cable versions of both weaved and parallel systems were included in the study. For each system, computers models with different anchor spacings [100 m (328 ft), 200 m (656 ft), 300 m (984 ft), 500 m (1640 ft), and 1000 m (3280 ft)] were created. Additionally, models with varied initial cable tension levels [15 kN (3,375 lb) and 24 kN (5400 lb)] were developed.

Highly detailed computer models of cable barrier systems were created and used in this study. A sophisticated modeling approach was used in creating these models to ensure that they would accurately capture the barrier response during the crash. The approach used in the models is described in the following paragraphs.

To create the finite element models of the cable barrier systems, several key features were carefully examined and appropriate modeling techniques were used to ensure that the models were accurate representations of the actual systems. First, explicit geometry of all components of the system was incorporated in the model. This included the cables, the posts, the sleeves, etc. This step was important to ensure that the correct mass, inertia, and stiffness of the different components were reflected in the
model. The soil and concrete were also explicitly modeled using solid elements. The shape of the post/sleeve was incorporated in the soil or concrete mesh to simulate post/soil interactions. The cables for the models were created using beam elements with the cross-sectional and material properties of the specified cable. To replicate the cable-to-vehicle and cable-to-post interactions accurately, each beam was surrounded by shell elements with null properties. The beams were connected to the null shell elements using nodal rigid body connections. The necessary initial stress was applied to the beam elements in the initialization phase of the simulation to simulate the tension in the cables.

For the three-cable-weaved system, the cables were placed at heights of 460 mm (18.1 in), 600 mm (23.6 in), and 720 (28.3 in) mm. The bottom two cables in this system were weaved around the posts, and the top cable was located in a channel at the center of the web. In the four-cable-weaved system, the cables were placed at heights of 470 mm (18.5 in), 620 mm (24.4 in), 780 mm (30.7 in), and 930 mm (36.6 in). In this system, the bottom three cables were weaved, and the top cable was located in a channel in the web. For the three-cable-parallel system, the cables were placed at heights of 530 mm (20.9 in), 640 mm (25.2 in), and 750 mm (29.5 in). The cable heights for the four-cable-parallel system were 530 mm (20.9 in), 640 mm (25.2 in), 750 mm (29.5 in), and 970 mm (38.2 in). In both parallel systems, the cables were located in a channel in the web and held in place by spacers.

For each of the systems the connection between the cable and anchor was considered rigid. The cables for the three- and four-cable-weaved systems were connected to a single anchor at each end using nodal rigid body connections. For the three- and four-cable-parallel system each cable was connected to a separate anchor post using nodal rigid body connections. The anchors were spaced at 1.9 meters in the direction parallel to the system installation and offset to either side so that the cables did not contact the anchor posts for other cables.

Vehicle Model
NCAC models for standard NCHRP Report 350 test vehicles were used to represent the impacts on the cable barriers. These included the Chevy C2500 pick-up truck (2000P) and the GeoMetro (820C) vehicle models. These vehicle models were validated and subsequently updated over years of application in many crash simulation efforts. These models conformed to the test vehicles reflected in the available crash test data. Since maximum dynamic deflections were the metric of interest, impacts at 100 km/hr (62 mph) and 25 degrees were the focus.

Figure 4 – Typical Vehicle and Barrier Simulation Set-up
Simulations with all of these model variations were carried out, and the results were compared to study the effect of end-anchor spacing, cable tension, and the number of cables on the safety performance of the barrier. A typical set-up for the crash simulations is shown in Figure 4.

MODEL VALIDATION

To have confidence in the simulation model results, a thorough validation was carried out. Five previously conducted full-scale crash tests provided actual data on the performance of various high tension cable barrier systems. For each case, the model, impact conditions, and terrain conditions were configured to match the crash test setup. The full-scale crash tests varied in installation lengths, post-to-post connections (weaved and parallel), and number of cables. Detailed comparisons between test and simulation results were undertaken. A summary of these comparisons are presented below:

- A C2500 pickup (2000P vehicle) impacts a cable barrier at a speed of 100 km/hr (62 mph) and impact angle of 25 degrees. The article tested was a 111-m (364 ft) length of a three-cable-weaved system on flat terrain with post spacing of 3.2 m (10.5 ft). In the crash test, one of the cables released from the anchor. Despite this, the vehicle trajectories in both the test and simulation were similar. The maximum deflections were also comparable with a maximum of 2.1 m (6.9 ft) in the test and 2.2 m (7.2 ft) in the simulation.

- A C2500 pickup (2000P vehicle) impacts a cable barrier at a speed of 100 km/hr (62 mph) and impact angle of 25 degrees. The article tested was a 111-m (364 ft) length of a four-cable-weaved system with post spacing of 3.2 m (10.5 ft) on sloped terrain (4H: 1V). The maximum deflection was 2.7 m (8.9 ft) in the test and 2.8 m (9.2 ft) in the simulation. The vehicle paths in the test and simulation were also comparable.

- A GeoMetro passenger car (820C vehicle) impacts a cable barrier at a speed of 100 km/hr (62 mph) and angle of 20 degrees. The article tested was a 111-m (364 ft) length of a four-cable-weaved system with post spacing of 3.2 m (10.5 ft) on sloped terrain (4H: 1V). The vehicle trajectories in the test and simulation were very close. The maximum dynamic deflection in the test was 1.2 m (3.9 ft) while in the simulation it was 1.35 m (4.4 ft).

- A C2500 pickup (2000P vehicle) impacts a cable barrier at a speed of 100 km/hr (62 mph) and angle of 25 degrees. The article tested was a 278-m (912 ft) length of a three-cable-weaved system with post spacing of 3.2 m (10.5 ft) on flat terrain. The vehicle trajectories in the test and simulation were comparable. The maximum dynamic deflection in the test was 2.6 m (8.5 ft) while in the simulation it was 2.7 m (8.9 ft).

- A C2500 pickup (2000P vehicle) impacts a three-cable, parallel cable barrier at a speed of 100 km/hr (62 mph) and angle of 25 degrees. The test article was a 102-m (335 ft) length of a three-cable-parallel system with post spacing of 3.0 m (9.8 ft) on flat terrain. The vehicle trajectories in the test and simulation were very close. The maximum dynamic deflection in the test was 2.4 m (7.9 ft) while in the simulation it was 2.5 m (8.2 ft).

The results of the detailed comparisons between test and simulation results indicated that the FE models and simulation approach provided a viable representation of observed barrier performance. It was therefore concluded that simulation could provide effective measures of barrier performance for the factors noted above.
SIMULATION RESULTS

Upon completing the validations, several simulations with different cable barrier systems (weaved and parallel), varied number of cables (three and four), different barrier lengths [100 m (328 ft), 200 m (656 ft), 300 m (984 ft), 500 m (1,640 ft), 1000 m (3,280 ft)], and varied cable initial tension [15 kN (3,375 lb) and 24 kN (5,400 lb)] were set up and carried out. All the simulations were conducted using LS-DYNA for impacts of a 2000P vehicle at a speed of 100 km/hr (62 mph) and an impact angle of 25 degrees. The simulation results were compared to develop some conclusions on the effects of these variations. The cable barrier deflections from these simulations are summarized in Table 1. A discussion of the results is given below for the effects of end-anchor spacing, cable initial tension, and number of cables.

<table>
<thead>
<tr>
<th>System length</th>
<th>Weaved 3-Cables 24 kN</th>
<th>Parallel 3-Cables 24 kN</th>
<th>Weaved 4-Cables 24 kN</th>
<th>Weaved 4-Cables 15 kN</th>
<th>Parallel 4-Cables 24 kN</th>
<th>Parallel 4-Cables 15 kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>100m</td>
<td>2.2</td>
<td>2.47</td>
<td>2.09</td>
<td>2.12</td>
<td>2.25</td>
<td>2.35</td>
</tr>
<tr>
<td>200m</td>
<td>2.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300m</td>
<td>2.73</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500m</td>
<td>2.73</td>
<td>3.33</td>
<td>2.58</td>
<td>2.63</td>
<td>3.06</td>
<td>3.15</td>
</tr>
<tr>
<td>1000m</td>
<td>2.72</td>
<td>3.52</td>
<td>2.6</td>
<td>2.62</td>
<td>3.23</td>
<td>3.32</td>
</tr>
</tbody>
</table>

Deflections in m rounded to cm

End-Anchor Spacing Effects
To investigate the effects of end-anchor spacing on the barrier deflections, simulations with different cable barrier lengths are compared. Figure 5 shows the computer predicted deflections of two different systems (parallel and weaved) at different end-anchor spacings. The results clearly show that the deflection increases as the spacing between the end-anchors is increased. This result was expected since an increase in the cable length would allow more cable stretch and consequently allow increased deflection.

The results also show that effect of end-anchor spacing is different for different cable barrier systems. This difference is mainly attributed to the effect of the cable-post interaction. Higher friction forces between the cable and posts leads to less increase in the deflection. The simulations show that the deflection of the parallel system increased by similar increments between the 100 m (328 ft) and 300 m (984 ft)-anchor spacings. The ratio between the increase in length and the increase in deflection was less between the 300 m (984 ft) and 500 m (1,640 ft)-anchor spacings and even less between the 500 m (1,64 ft) and 1000 m (3,280 ft) anchor spacings, but deflections still continued to increase.
For the weaved cable barrier system, the deflection increased by similar increments between the 100 m (328 ft) and 300 m (984 ft) anchor spacings. The simulations showed that there was no increase in the deflection between the 300 m (984 ft), 500 m (1,640 ft), and 1000 m (3,280 ft) anchor spacings. In other words, for the weaved cable barrier system, dynamic deflection reaches a maximum at end-anchor spacings of about 300 m (984 ft) and does not increase with longer anchor spacings.

For both parallel and weaved systems, the simulations show a diminishing rate of increase in the deflections as the barrier length (anchor spacing) increases. This is mainly attributed to the fact that the friction forces between the cables and posts slow the migration of the impact-induced tensions away from the impact region, thereby reducing the stretch of the cables in regions away from the impact point. This could also be related to the resistance of the system to forces along the longitudinal direction. Systems that restrict the longitudinal sliding of the cables during the impact (by engaging the posts or other means) would lead to less deflection increase when the end-anchor spacing is increased.

**Cable Initial Tension Effects**

To investigate the effects of pre-impact cable tension on barrier deflections, simulations using two different cable tensions were carried out and compared. The two different tensions were selected. In each simulation, all elements representing the cables were assigned the same initial tension and therefore uniform tension was assumed throughout the length of the cables.

Figure 6 shows the computer-predicted deflections. The figure shows barrier deflections for two different systems (weaved and parallel) at two initial tension levels [15 kN (3,375 lb) and 24 kN (5,400 lb)] and at three barrier lengths [100 m (328 ft), 500 m (1,640 ft), and 1000 m (3,280 ft)]. As expected, the simulations showed that lower initial tension leads to increased barrier deflection. However, the magnitude of the increase in deflection is smaller than expected. The results from these simulations are justifiable when one examines the change in cable tension during the impact. The simulations show the maximum tension reached by the cables at the end-anchors to be four to five times higher than the initial tension value. A reduction in initial tension from 24 kN (5,400 lb) to 15 kN (3,375 lb) (38%) would therefore have less of an effect on the significantly higher maximum tension and consequently small effects on barrier deflection are observed.
Full-scale crash tests, on the other hand, showed that barrier deflections from generic low-tension cable barrier systems are higher (almost twice) the ones observed in the high-tension systems. The reason for the significant difference between the deflection of generic low-tension systems and high-tension systems seen in the crash tests is attributed to the cable/post connections. Most high-tension systems have a significantly stronger cable-to-post connection (by weaving the cables, placing the cables at the center of the web, etc.) than the generic low-tension systems (which typically use open hooks to hold the cables to the posts). These stronger cable-to-post connections delay the release of the cable and lead to significant reduction in barrier deflection.
Three-Cable Systems vs. Four-Cable Systems
Simulations with three and four-cable barrier systems were conducted to evaluate the effects of the number of cables on the barrier deflections. Figure 7 shows the results from these simulations. The figure shows simulations for two barrier systems (parallel and weaved) with different numbers of cables (three and four). The simulation results showed that the four-cable barriers had less deflection than the three-cable barriers for both parallel and weaved systems. This is mainly attributed to the fact that the vehicle engaged two cables when impacting the three-cable barrier systems while three cables were engaged with the four-cable systems. The increased number of engaged cables leads to reduced tension in the cables and therefore less stretch is seen in the cables.

SUMMARY

Computer simulations using validated models were conducted to study the effects of end-anchor spacing on cable barrier deflections for varying pre-impact cable tension, cable number, and cable placement (i.e., weaved or parallel). In the study, different computer models of cable barrier systems were developed and validated against full-scale crash tests. Upon completing the validations, simulations with varied cable barrier lengths, initial tensions, and number and configuration of cables were carried out and the results compared.

The simulation results indicate that in impacts with cable barriers the maximum dynamic deflection is significantly affected by the end-anchor spacing. Greater end-anchor spacing leads to increased barrier deflections. The rate of increase in deflection is greater for short end-anchor spacings of less than 500 m (1,640 ft). The results also indicate that the effects of end-anchor spacings are different for different types of barrier systems. The deflection of a weaved cable barrier systems, which provide higher friction between the posts and cables, reaches a maximum at end-anchor spacings of 300 m (984 ft). The parallel system, on the other hand, shows continuing increase in deflection from 300 m (984 ft) to 1000 m (3,280 ft) anchor spacings.

The simulation results also showed that pre-impact cable tension can affect the barrier performance. Lower tension will lead to larger barrier deflections. However, the simulations showed that the increase in barrier deflection is relatively small compared to the effect of end-anchor spacing.

Finally, the simulations showed that four-cable systems have lower dynamic deflections compared to three-cable systems. Increasing the number of cables leads to a higher number of cables engaging the vehicle during the impact and increases the chance of capturing and redirecting the vehicle.

These results suggest that designers need to investigate the potentials for differences in deflections associated with the design and installation of the cable barrier system. Ultimately, it may be possible to develop correction factors that could convert the deflections observed in crash tests to those expected in the field where actual anchor spacings are much greater. These correction factors would account for the expected field installation lengths as well as the type of barrier system. Additional research for varying impact systems, alternative cable barrier designs, and performance on sloped surfaces will be needed to provide the comprehensive set of insights needed to create the factors.
REFERENCES


