Developing Functional (Design) and Evaluation Requirements for Cable Median Barriers

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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

There has been increased use of cable median barriers in recent years to address the growing problem of cross-median crashes. Cable median barriers are viewed as a highly effective means to mitigate the problem at a lower cost and in a shorter time frame. This has occurred despite limited current guidance on effective use of the various designs that have emerged over the past ten years. Research has discovered that cable median barriers are more sensitive to slope effects than was previously understood. In attempting to develop better guidance for the deployment of cable barriers systems, vehicle dynamics analysis was found to provide a method to determine effective positioning of such barriers on sloped median surfaces. The research evolved from using the vehicle dynamics analysis to understanding particular cross-median events to the generation of a series of nomographs that indicate the best lateral placement locations to assure effective vehicle-to-barrier interface. In the course of these efforts it became apparent that it was possible to determine the limits for override and underride for any median configuration and to use these to evaluate the potential effectiveness for any given barrier design. Further efforts, described in this paper, developed composite limits that are not median configuration biased. The limits are shown to have usefulness for specific regimes defined for the median area and maximum side slope conditions encountered. These are believed to offer usefulness to the design of new cable median barrier systems, consideration of the relative applicability of existing barriers for particular applications, and even a potential means to be assured that a given barrier application will provide the same level of crashworthiness as determined in testing. The information generated in this effort is believed to provide a robust basis for the development of improved (simplified) guidelines for cable median barrier design and placement.
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INTRODUCTION

Recent efforts to address the growing number of cross-median crashes led to the promotion of the use of cable median barriers. These systems represent upgrades over the cable barriers that were used since at least 1925. Generic, low-tension cable barrier designs have been installed in some areas over the last twenty years, but most of the new installations use the various proprietary systems that have emerged. As these systems were deployed in increasing numbers, it became apparent that 1) guidelines for their lateral placement were lacking, 2) the variations in the designs (i.e., arrangement of cables, posts and spacing, types of cable connectors) complicates the evaluation process, and 3) these various designs have been tested on level surfaces, making it hard to ensure acceptable performance on any sort of slope. Research using vehicle dynamics analysis (VDA) has been shown to be effective in providing the needed insights into the relationships between cable barrier design, and median configuration (i.e., width, side slopes, shape, and depth) and developing improved guidelines for deployment. The research has generated sets of nomographs for the various median conditions to indicate where in any given section the cable barrier line could be effectively placed. Since medians tend to vary in their configurations along a length of highway, many nomographs needed to be developed for any given project.

In 2009, analyses on cable median barrier placement culminated in an important finding based upon a synthesis of the various analyses undertaken over the previous 3-4 years. This paper provides a summary of those efforts and demonstrates how these results could be used as the basis for functional design and evaluation criteria. The results suggest that it is possible to define analytically-based, specific guidance for the heights of the top and bottom cables for various placement regimes within the median. They suggest that cable barriers tested in a given regime should be acceptable for use in any lateral position in that regime.

BACKGROUND

Over the past decade, cross-median crashes have grown to be a serious problem for a variety of reasons, including the growth of traffic, higher speeds, more variation in the mix of traffic, and/or driver issues (e.g., aggressive and distracted driving). Increased volumes alone increase the probability that a vehicle might leave the roadway, and if it traverses the median then the possible exposure to on-coming traffic is higher. The problem is particularly serious for older divided highways where narrow medians were used.

State DOTs have recognized the problem and have attempted to mitigate it in various ways. One approach has been to deploy cable barriers in the medians to redirect or capture errant vehicles before a cross-median crash can occur. Cable median barriers are considered attractive because of low costs, short implementation time, ease of installation, and adaptability for sloped conditions. Both generic and proprietary designs for cable barriers exist and have been improved in recent years in response to the needs of the DOTs. The general consensus is that median cable barriers are highly effective (some agencies citing over 90% effectiveness), but cases of underride or override have occurred with catastrophic results.
The FHWA has embarked on research to understand the causes for barrier-to-vehicle interface problems and improve the guidance to agencies to help get the maximum effectiveness possible. FHWA research has shown that cable barrier effectiveness is related to barrier design (number and height of cables, tensioning), configuration of the median (shape, width, slopes, and depth), and lateral position of the barrier within the median [1, 2, 3, 4, 5]. Insights on the problem were revealed through computer simulations (using a variety of software tools) and crash testing. These efforts laid the groundwork for efforts to develop formal guidelines under NCHRP Project 22-25 “Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems.” These NCHRP efforts are building on the findings from the FHWA studies to develop improved guidelines for the use of all types of cable barriers (roadside and median) on the wide variety of median configurations that exist, for the variety of crash conditions that are possible.

This document describes efforts undertaken to synthesize findings from analyses of various median configurations of v-shaped and flat-bottomed medians with varying widths and side slopes to generate generalized guidance for barrier placement.

**ANALYSIS APPROACH**

Vehicle dynamics simulations were conducted to compute the trajectories of vehicles as they traverse a median on a diagonal path. These simulations provided an understanding of how the vehicle’s interface area changed as it crossed the median. Commercially available software was used to do the computations and generate curves showing the trajectories [6, 7]. In these analyses, two points were defined for each type of vehicle considered to represent the primary interface (engagement) region on the front of the vehicle. These points are labeled 1 and 2 on Figure 1. If one is standing in the center of the median downstream from the point a vehicle leaves the roadway, the trace of points 1 and 2 on the front of the vehicle would be seen as the blue lines in Figure 2.

These same data points can be plotted on a diagram of the median cross-section (as shown in the lower part of Figure 2). It can be noted that in moving from left to right, after passing the breakpoint between the shoulder and the median, the vehicle will be airborne or at least has a low compression load on its suspension system. At some point the vehicle will land or return to a distribution of weight on all wheels, and the suspension will compress to absorb the load. As the vehicle continues its movement
across the median there will be a rebound of the suspension as the springs dissipate energy. Thus, as the vehicle traverses the median, the height of its interface area will vary depending on the state of the vehicle’s suspension system and the slopes of the median. Effective lateral placement of the barrier involves finding the locations where the vehicle’s interface area matches the barrier’s cable heights. This need to be achieved for different vehicle types leaving the road at different speeds and angles. For median applications, finding these locations is complicated by the need to have an effective interface for impacts from either direction.

The research considered a broad set of influencing factors for a diagonal crossing of the median as shown in Figure 3. This figure shows a typical divided highway where the median is the green area between the shoulders. The median can be of different widths and cross-sections. Paved shoulders with widths of 4 to 8 feet with negligible slopes were assumed, but the analysis only considered the vehicles crossing the median itself. The cable median barrier is placed somewhere in the median and can be hit from either side. For the situation shown in Figure 3, a vehicle leaving the bottom roadway would have a “nearside” hit on the barrier. From the upper roadway the vehicle would have a “farside” hit. A cable median barrier has to be located such that it functions effectively for both nearside and farside hits.

The study considered five different types of vehicles typically found on US highways, including:

- Chevy C2500 pick-up truck (2000P vehicle);
- Geo Metro (820C vehicle);
- Dodge Ram pick-up truck (2270P vehicle);
- Dodge Neon (1100C vehicle); and
- Ford Crown Victoria (mid-sized vehicle).
The specific weight, size, frontal geometry, and suspension system characteristics of these vehicles are incorporated into the vehicle dynamics analysis. Additionally, since vehicles can leave the roadway at varying speeds and angles, the analysis considered initial speeds of 30, 45, and 60 mph (50, 70, and 100 km/h) and impact angles of 5, 10, 15, 20, and 25 degrees. These variables resulted in a total of 150 simulation runs to get bi-directional results for each median configuration.

Defining “effective interface conditions” for any cable barrier design and any median configuration can be accomplished in various ways. For this analysis, effective interface conditions were determined by:

- Assessing relative positions of the vehicle to the barrier such that:
  - To minimize the potential for override, the top cable should contact the vehicle above Point 1 (lower critical point in Figure 1).
  - To minimize the potential for underride, the lower cable should contact the vehicle below Point 2 (upper critical point in Figure 1).
- Defining the impact conditions to be considered. One approach would be to follow NCHRP 350 or MASH requirements [8, 9]. In this analysis, a broader view was taken by considering that the conditions should reflect a broader range of approach angles, speeds, and vehicle types.
- Relating vehicle-to-barrier interfaces to specific median configurations (i.e., width, shape, side slopes, and depth).
- Establishing a criterion for the number of cables that need to be engaged for the barrier to be considered effective. For low-tension systems it has been assumed that a minimum of two cables need to engage and for a high-tension system one cable.

These criteria still need to be discussed among safety professionals and endorsed as viable guidelines.

The VDA involved many runs of the software to characterize the position (or trace) of points on the front of the vehicle for a range of possible paths in traversing the median. For comparative analysis, interface envelopes were developed to represent the aggregated range of trace points that would be created for combinations of vehicle types and impact conditions.

This analysis is based upon vehicle dynamics analysis which assumed the following:

- The median would provide a firm surface (i.e., ploughing into the surface by tires is negligible).
- Vehicles are “tracking” as they enter the median (i.e., vehicle’s initial speed vector is in the same direction at its longitudinal axis).
- Initial velocity occurs when the vehicle leaves the shoulder. Some deceleration is expected to occur for vehicles (3-5 mph was noted in the research) prior to the impact.
- There are no driver inputs (e.g., steering, braking) that affect the vehicle.
- A vehicle must have effective engagement with a minimum of one cable to be captured by the barrier.

RESULTS

Using VDA, the trace envelope defined by the trajectories of Points 1 and 2 for both directions of a vehicle crossing a median were plotted as shown in Figure 4. The trace envelope for the opposite direction in any case was the mirror image. Such plots summarize the individual trace representing a specific vehicle, speed, impact angle, and median configuration. While these may be useful for analyzing a single median crossing event, they only provide limited input towards overall median and barrier design issues.
Figure 4 – Vehicle trace plot and relative interface effectiveness for varying cable barrier lateral placement for a 6:1 sloped v-shaped median for a 25 degree, 60 mph median incursion for a mid-sized vehicle

Figure 5 – Bi-directional traces of the maximum height of Point 1 for a given median configuration

The multi-colored array of lines shown in Figure 5 represents a broader set of vehicle trajectories covering all the median crossing cases for a particular median configuration (as depicted in the lower part of the graph). The traces shown represent the changes in position of the lower point (point 1) defined for the front of the vehicle. This construct provides very useful information as indicated by the heavy blue line. This line represents the overall or global maximum height for the set of cases associated with this median configuration. Similarly, plotting all cases for Point 2 yielded the multi-colored array of lines in Figure 6 representing the overall minimum heights for a given median configuration. The heavy green line represents the overall minimum heights for Point 2. Figure 7 isolates just the maximum and minimum curves which are labeled override and underride. They are the limits that an effective barrier will be able to accommodate. The effectiveness of a given barrier design, in this case the standard generic, low-tension cable barrier, is shown as the yellow horizontal lines by comparing the coverage to the override and underride limits. For this type of barrier to be effective it
must be located in one of the areas where both the override and underride limits are covered by the top and bottom cables for this particular median configuration. There are clearly some areas around the center of the median where the underride limit drops far below the lowest cable. There are also areas where the override limit passes slightly above the top cable.

Figure 6 – Bi-directional traces of the minimum height of Point 2 for a given median configuration

Figure 7 – Bi-directional traces of the maximum and minimum curves for a given median configuration

Additional plots were generated for different median profiles and barrier designs that can be used to define the vehicle-to-barrier engagement based on cable barrier lateral position and its cable heights. Figure 8 is an example generated for a 100 foot wide flat-bottomed median with 4:1 side slopes constrained to a depth of 4 feet. Because the vehicle dynamics for this median configuration become
more complicated, the override and underride limits are more varied (as noted by the heavy lines). This graph also shows the overall trace envelope as the shaded gray area. The same principles apply for evaluating the efficacy of various lateral positions for a given barrier design. The top cable needs to be above the override limit and the bottom cable below the underride limit. In this case, the viable lateral positions are highlighted on the lower part of the graph by the green shaded areas, while unsuitable lateral positions indicated by the red shaded areas. Dozens of these nomographs were prepared to aid agencies in determining the most effective lateral positions to accommodate the varied conditions along a freeway corridor. These served an important purpose and are viable for similar situations elsewhere, but it is still a cumbersome process to apply.

![Image of graph showing cable heights and vehicle trajectory](image)

Figure 8 – Sample normalized plot of the minimum and maximum cable height curves for a specific median configuration and cable barrier system

It was recognized that it might be possible to generate the normalized override and underride limits for a broad spectrum of the median configurations and overlay them on a single graph to create a composite representing all crossing and median cases. The software was used to generate the override and underride limits for all of the cases cited above. The various squiggly lines in Figure 9 represent the composite underride limits segregated by median shape, side-slope, and depth constraint. The graph therefore depicts the underride limits for v-shape and flat bottomed medians from 16 to 56 feet. Separate limit curves are provided for 4:1, 6:1, and 8:1 side slopes and 2, 4, and 6 foot depths. Similarly, Figure 10 shows the composite results for the override limits. These graphs are believed to be highly useful towards establishing design (functional) requirements, selecting among competing technologies, and relating the crash test results to specific design regimes.
Establishing the design requirements for a cable median barrier system involved determining the maximum lower cable height, minimum upper cable height, and other system features (not addressed here). To consider the general need for the height of the lowest cable in any cable median barrier design to minimize the probability of underride, one can look at the information provided in Figure 9. It is possible to discern via the variations in the curves two distinct regions – one for the side regions and one for the center. This composite includes (as noted in the legend) curves for medians with 4:1, 6:1, and 8:1 side slopes and depths of 2 to 6 feet for the flat bottom shapes. Figure 11 shows these “lateral regimes” defined as the “center” and “side” regions. The left and right side regimes are symmetrical.
It can be noted in Figure 11 that the lowest points for the curves in the side region (about 8 ft away from the center of the median) suggest that any cable barrier design that offers the lowest cable at a height of 14 inches would meet the requirements to minimize the probability of underride regardless of the side slope, shape, or width. Similarly, for the center region, systems that offer a cable height at 5 inches would address potential underrides for all median conditions. It is easy here to also observe how the guidance can be adjusted to specific design or regional terrain conditions. For example, assume that candidate section for the installation of a cable median barrier system has no side slope conditions greater than 6:1. Then, any system that offers a lower cable at 10 inches would work equally well in an interface context in the center region.

![Figure 11 – Composite plot of minimum lower cable heights for varying v-shaped and flat-bottomed median configurations](image)

More than 25,000 vehicle dynamics simulation runs were used to generate these curves. Additional efforts are possible to broaden the coverage of various median configurations to increase the applicability of these graphs. For example, it would be easy to include rounded-bottom medians.

Similarly, this approach allows establishing guidance for the height of the top cable. Looking at Figure 10 it can be seen that the area can be readily subdivided into two regions for sharp and gentle side slopes. It can be noted that there are two regimes that present themselves here also. The upper set of curves reflects the composite traces for median configurations for steeper 4:1 slopes. The lower set would suggest that for a highway where the median slopes are in the 6:1 to 8:1 range, any manufacturer that provides a cable barrier design top cable height above 30 inches would be acceptable. The composite curves in blue indicate the sharper 4:1 side slopes. For all cases, barrier designs that offer a top cable at 40 inches would perform effectively across the various median configurations. The requirements for the top cable at 30 inches are possible if the side slope conditions at all installation locations are less than 6:1. These requirements are shown graphically on Figure 12.
It is believed that these results represent a sound basis for generic guidelines for the selection of a cable median barrier system that is independent of median configuration. It may also be viewed as a design requirement for cable barrier manufacturers relative to the systems they offer. It may also help to define parameters for the acceptance testing of various cable median barrier designs.

The analyses presented here did not address the question of how many cables a system should include between the top and the bottom. It also is subject to assumptions about the number of cables needed for effective capture of vehicles (e.g., one or two cables). Resolving this question will require further research.

Now it might be possible to adjust the regimes in both the lateral and vertical directions to alter the performance regimes, but it is clear that it is possible to simplify the process for the design and selection of cable median barriers. It should follow, that any system tested for a specific regime should apply across the entire regime. The interface based nature of this analysis makes that premise easy to accept. It may require specific comparisons to crash test results to determine if the premise is undermined by the testing need to achieve dual override and underride objectives. This is, of course, subject to the acceptance of the underlying assumptions.

SUMMARY AND CONCLUSIONS

These efforts demonstrated that useful information about the trajectory of vehicles crossing medians could be derived from vehicle dynamics analyses. The information has value as a means to explain vehicle trajectories and interface potentials for individual median crossings as well as the cumulative limits for a given median configuration. Furthermore, it was shown that through normalization, the data could be combined to create composition limits covering a range of median conditions. The resulting
composite curves can serve a much more convenient nomograph for selecting acceptable cable barrier products and setting the optimal lateral positions. It can be used as a means to design barrier systems that will function equally well in a small set of median regimes. Thus various companies could design to meet the cable height requirements and make it easier for agencies to select barriers, although, there may still be differences associated with post, connector, anchorages, and other features of the system. It also serves to allow mapping of crash test evaluations for the comparison of specific systems. Facilitating making such decisions will allow agencies to move forward on implementing this technology.

The analyses for specific median and barrier combinations provided sound design guidance and insights about the factors influencing the safety performance of cable median barriers, but they did not provide simple guidance for agencies looking to implement cable barrier systems nor did they address the need to assure that the barrier system selected would be equally effective along a highway. It is well known that in most cases, there are variations in the median configurations (e.g., width, side slope, depth, shape) from the basic median design template.

It was noted that the limits curves that evolved from each specific median and barrier combination generated could be overlaid to provide a composite limit for the necessary height of the top and bottom cables in any cable median barrier design. Further, by overlaying the limiting curves for varying shapes and widths of median, it became possible to provide general design guidance.

There is a need for some additional research to add to the robustness of these findings. The topics to be addressed include:

- Defining an “effective interface” for low- and high-tension systems. Research has assumed that there is a need for two cables to engage the vehicle for low-tension systems. One cable is strong enough to hold an errant vehicle, but is more susceptible to being pulled out of position by the tire. A single cable has been shown to restrain vehicles in most cases in high-tension systems.
- Assessing the sensitivity of these results to variations in post spacing, connectors, cable tension, and anchoring system.
- Determining the minimum space between cables. It can vary by the weight and the frontal shape of the vehicles in the fleet.
- Expanding the coverage of these composite curves to cover wider medians and other configurations.

Continuing research addressing these questions will provide even more robust guidance for cable median barrier systems, and potentially all types of longitudinal barriers.

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