Analyzing the Potential Interface Effectiveness for Cable Barriers in Asymmetrical Median Cross Sections

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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 primary purpose of longitudinal safety barriers, such as cable barriers, is to contain and/or redirect errant vehicles that depart the roadway, hence keeping them from entering opposing travel lanes or encountering terrain features and roadside objects that may cause severe impacts. In this paper, vehicle dynamics analysis is used to study the effect of asymmetrical median cross-sectional configurations to determine optimal lateral placement positions for effective interface of errant vehicles with the barrier. This analysis follows the approach that was used in previous efforts. Five asymmetrical median configurations are considered. This analysis involved consideration of the same five vehicle types and a range of impact conditions used previously. The variations in side slopes on opposite sides of the median were reflected in non-symmetrical override and underride limits. Consequently, lateral placement options were different than those derived from previous analyses. The placement effectiveness plots were generated for four different cable barrier system designs. These increase the number of nomographs available to highway designers and enhance the guidance about the effectiveness of cable barrier placement.
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INTRODUCTION
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 traffic volumes alone increase the probability that a vehicle might leave the roadway. If the vehicle traverses the median, then the possible exposure to oncoming traffic is higher. The problem is particularly serious for older divided highways where narrow medians were used.

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 rates), but cases of underride or override have occurred with catastrophic results.

The FHWA and NCHRP have conducted research to understand the causes for vehicle-to-barrier interface problems and to improve the guidance for achieving the maximum effectiveness for barrier deployments [1, 2, 3]. 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, depth), and lateral position of the barrier within the median. Insights on the problem were revealed through computer simulations and crash testing. The results have led to improved means and guidance for determining the placement of all types of cable barriers (i.e., roadside and median) for medians of varying configurations.

This document provides an update from continuing analyses of vehicle-to-barrier interface for cable barrier placement in varying asymmetrical median cross sections. The results are based upon the premise that a barrier will be effective only if there is a good interface between the vehicle and the cable barrier. A brief summary of the approach, assumptions, and interpretations from previous documents is presented along with the results.

ANALYSIS APPROACH
Vehicle dynamics simulations were conducted to compute the trajectories of the vehicle frontal interface region, as the vehicle traverses a median on a diagonal path. In these analyses, two points were defined for each type of vehicle considered to represent the primary interface (engagement) region. These points are labeled 1 and 2 on Figure 1 for a typical vehicle. 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 green lines on the lower portion of Figure 2.
Tests and analyses have noted that in moving from left to right, after leaving the roadway onto a sloped surface, a vehicle will become airborne (or at least have a low compression load on its suspension system). When the vehicle lands (or returns to a distribution of weight on all wheels), the suspension will compress to absorb the dynamic load. As the vehicle continues its movement across the median there will be a rebound of the suspension as it dissipates 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. For median applications, finding these locations is complicated by the need to have an effective interface for impacts from either direction.

The analyses considered five different types of vehicles including a Chevy C2500 pick-up truck (2000 kg), a Geo Metro (820 kg), a Dodge Ram pick-up (2270 kg), a Dodge Neon (1100 kg), and a Ford Crown Victoria (1600 kg). The specific weight, size, frontal geometry, and suspension system characteristics of these vehicles were incorporated into the vehicle dynamics analysis. Trace envelopes were generated for these vehicles leaving the roadway at initial speeds of 30 to 62 mph (50 to 100 km/h) and impact angles of 5 to 25 degrees. Vehicles were assumed to cross the median on straight, diagonal paths.

Defining an “effective interface” for any cable barrier design and any median configuration was accomplished 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).

A criterion was established for the number of cables that need to effectively engage the vehicle. 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.

Using vehicle dynamics analysis (VDA), the trace paths of Point 1 for both directions of a vehicle crossing a specific median were plotted in a normalized fashion as shown in Figure 3 with each individual trace representing a specific vehicle, speed, impact angle, and crossing direction (i.e., the
multi-colored array of lines). The heavy blue line represents the overall maximum heights for Point 1 for the set of impact cases associated with this median configuration. Similarly, plotting all cases for Point 2 yielded the array of lines in Figure 4 and the heavy green line represents the overall minimum heights for Point 2.

These lines represent a useful metric for this median configuration. The blue line is the Override Limit and green line the Underride Limit for a given median configuration. These limits provide a means to determine the interface effectiveness across all later positions for any given barrier design. The three yellow lines in Figure 5 represent the coverage range between the top and bottom cables of a particular barrier design (in this case a generic three-cable barrier). Where the blue line goes above the top yellow line, there is the opportunity for an override to occur. Where the green line falls below the lowest yellow line, the possibility of an underride exists.

Figure 6 shows a more complex application of this approach. The upper portion shows the normalized representation of the interface envelope, the minimum upper cable height curve, the maximum lower cable height curve, and the relative position isobars for a specific type of cable barrier (i.e., generic, low
tension, three-cable system). The Barrier Interface Envelope is the gray shaded area that surrounds all of the trace bars for different vehicles traversing the median at varying angles and speeds from both directions. These curves are “normalized” to relate the relative heights of individual cables in the barrier, or the height of the effective interface area on the front of a vehicle to a horizontal plane. For any position across the median, the vertical height of the normalized plot to actual sloped surface is equivalent.

The lower portion of Figure 7 shows the profile or cross section of the median related to the upper graph. The gray hatched portions indicate the lateral positions where this specific barrier will be effective. The red hatched area defines the lateral positions where the specific barrier has a cable arrangement that has a lower cable above the maximum lower cable height curve (green) and/or an upper cable below the minimum upper cable height curve (blue). Effective lateral placement occurs where both criteria are met.

![Figure 6 – Sample plot generated using the results of vehicle dynamics analysis](image)

In this research, it is important to note that the following conditions were assumed:

- The median has a firm surface. Ploughing into the surface by tires is negligible.
- Vehicles are “tracking” as they enter the median (i.e., following a straight path).
- Initial velocity occurs when the vehicle leaves the shoulder, but it will slow somewhat.
- There are no driver inputs (e.g., steering, braking) that affect the vehicle.

This approach can be used to determine the potential effectiveness for varying cable barrier systems (e.g., number of cables, relative heights) across all possible lateral positions for any given median configurations. This approach was applied to consider several benchmark and asymmetrical median cross sections as described below.
ANALYSIS OF ASYMMETRICAL CROSS SECTIONS

Three asymmetrical median cross sections were defined for analysis to reflect field conditions as shown in Figure 7 (profiles D, E, and F). Three benchmark profiles (Figure 7 profiles A, B, and C) were also analyzed to allow the relative differences in placement effects to be compared. The previous configuration labels are given in brackets. Plots were generated for each of the cases using the same set of vehicles and impact conditions noted above. The basic plots depict the vehicle trajectory envelope for each case by the gray, cross hatched area across the median. This envelope reflects the composite range of positions for Points 1 and 2 for all of the five vehicles analyzed. From this data, it was possible to determine the Minimum Upper Cable Height requirement (or Override Limit) shown as the heavy blue line. Similarly, the Maximum Lower Cable Height requirement (or Underride Limit) is shown as the heavy green line. These represent the basic requirements that any cable barrier design must address in a given lateral placement to prevent barrier overrides and underrides.

<table>
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<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>F [W3]</td>
<td><img src="image" alt="W3" /></td>
</tr>
</tbody>
</table>

Figure 7 – Median cross section configurations

In addition, four cable barrier designs were considered and superimposed on the basic plots. These designs and the associated cable heights included:

- Low-tension, generic three-cable system (cable heights 21", 25.5", and 30")
- Brifen 4-rope TL-4 (cable heights: 18.5", 24.5", 30.5", and 36.5")
- Gibraltar 3-rope TL-4 (cable heights: 20", 30", and 39")
- Trinity 3-rope 4:1 slope design (cable heights: 17.4", 29.5", and 41.7")
The associated cable heights (most importantly the top and bottom cable locations) for each design and each of the profile cases were plotted as a separate graph. The lower panel of each graph provides an effectiveness summary. The profile of the cross section is shown as the heavy black line. The green shaded areas indicate those lateral placement locations where both the Override and Underride Limits or requirements are met by the placement of the cables for the specific design. The red shaded areas reflect lateral positions where one or both of the requirements are not met. These indicate the areas in the cross section where the barrier would not be fully effective.

The plots generated provide useful insights about the influence of lateral placement of the cable barrier relative to the median configuration and cable barrier design. It can be clearly noted in looking at the graphs for the various profile cases that there are considerable variations in the range of lateral positions where the barrier would be effective from an interface perspective.

Figure 8 provides a comparison of the influence of median cross section shape on effectiveness where width and slopes are similar. The top graph shows the the Override and Underride Limits and effective areas for a flat-bottomed median with 6:1 slopes. The lower graph shows the same items for a v-shaped median. It can be readily noted that the Limits curves take different shapes with those for the flat bottom showing a greater vertical and horizontal spread than those for the a v-shaped median of the same width. Also noteworthy is the comparison of the lateral areas where the barrier would be effective. There are fewer lateral positions where this barrier would be effective for the flat-bottomed median. The reason for the differences is the different point where vehicles interact with the surface causing a suspension reaction and any associated dynamic differences.

Figure 9 compares a symmetrical median to an asymmetrical one. In both cases the slopes are gentle (i.e. 6:1 or less). It can be noted that there is a difference in the Override Limit that is skewed to the side with the sharper slope. The Underride Limit is similar between these cases. This can lead to slight differences in the effective areas as noted by the shaded portions of the lower part of each graph. The difference can be explained by the decreased suspension response for vehicles traversing from the side with the sharper slope due to a less severe rebound effect.

Figure 10 compares the effective areas for asymmetric median cross sections, Cases F and E, which have different degrees of slope sharpness. It can readily be noted that the Override and Underride limits are sharper and have a greater spread for the higher slope conditions. These Limit differences result in large difference in the effective area. The greater forces on the vehicles negotiating the steeper slopes explains the differences. Other such comparisons are possible with the data.

Figures 11 through 16 provide the comparison of each of the six cases defined in Figure 7 relative to the four cable barrier designs considered. It can be noted that the Override and Underride Limits are the same in each graph as these are based upon the vehicle dynamic response associated with the specific median configuration. Variations in the heights of cables for the four designs (oriented from the generic three-cable low tension system in the upper left corner to the Trinity 3 cable system in the lower right) are reflected in the difference in effective areas shown in each graph. These differences reflect options an agency may want to consider in selecting a system. For example, where the design allows placement in the center of the median there is likely to be fewer nuisance hits and lower maintenance costs.

While these results provide a valuable indication of viable lateral positions, it must be remembered that this only considers the interface. Impact dynamics and hence barrier abilities to redirect or catch an
errant vehicle may be affected by variations in the impact conditions such as actual angle, vehicle weight, soft soils beneath the barrier and other factors.

Figure 8 – Comparison of Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, & Effective Areas for Flat-Bottomed [A] and V-Shaped [B] Median Configurations with Similar Slopes
Figure 9 – Comparison of Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, & Effective Areas for Symmetrical [B] & Asymmetrical [F] V-Shaped Median Configurations with Similar Slopes
Figure 10 – Comparison of Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, & Effective Areas for Asymmetrical V-Shaped Median Configurations with 8:1 [F] & 4:1 [E]
Figure 11 – Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, and Effective Areas for Median Configuration A for Four Cable Barrier Designs
Figure 12 – Normalized Vehicle Trajectory Envelopes, Override/Uderride Limits, and Effective Areas for Median Configuration B for Four Cable Barrier Designs
Figure 13 – Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, and Effective Areas for Median Configuration F for Four Cable Barrier Designs
Figure 14 – Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, and Effectives Areas for Median Configuration D for Four Cable Barrier Designs
Figure 15 – Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, and Effective Areas for Median Configuration E for Four Cable Barrier Designs
Figure 16 – Normalized Vehicle Trajectory Envelopes, Override/Underride Limits, and Effective Areas for Median Configuration C for Four Cable Barrier Designs
SUMMARY AND CONCLUSIONS
These efforts demonstrated that useful information about the trajectory of vehicles crossing medians could be derived from vehicle dynamics analyses and applied to evaluate interface potentials for vehicles to barriers. This information can be used as a means to determine the lateral placement of cable median barrier systems that will provide the interfaces needed to capture and/or redirect an errant vehicle. The Override and Underride Limits derived represent a possible basis for formulating standard requirements for cable height or make it easier for agencies to select barriers for the median conditions known to exist for a given project. Although interface data is not alone sufficient given that there may be “strength” factors associated with various designs resulting from differences with post, connector, anchorages, and other features of the system. Facilitating making such decisions will allow agencies to move forward on implementing this technology.

The following is a summary of this research.
- Vehicle dynamics analyses was demonstrated to be an effective method to assess vehicle-to-barrier interface for several asymmetric median cross sections.
- The trajectory envelopes and resulting Override and Underride Limits were altered by the unequal slope conditions in the asymmetric cross sections. Generally, the Limits were exaggerated to the side of the median that had the sharper slope. The degree of slope effected the exaggeration.
- There were lateral locations for each profile case where the cable barrier could be effective.
- The cable barrier design relative to the heights of the top and bottom cable define the effective width of the barrier for various lateral positions, but since the spacing between cables was not considered there may still be the possibility that a vehicle could penetrate between the top and bottom cables.
- The profiles generated increase the number of cases for which lateral placement has been analyzed and nomographs generated.

The results of this analysis provide an improved means for agencies to decide where cable median barriers will be placed in existing medians conforming to these profiles.

Ongoing research is expected to enhance the robustness of these findings. This research will address various topics including:
- Additional validation with test data. While the vehicle dynamics tools have been widely used in vehicle design, and some comparisons to field data have good correlation, additional planned testing will increase confidence in these results.
- Assessing the sensitivity of these results to variations in post spacing, connectors, cable tension, and anchoring systems.
- Determining the minimum space between cables, which 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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REFERENCES