ABSTRACT
The primary purpose of longitudinal safety barriers, such as cable systems, 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 varying median cross-sectional configurations on lateral placement positions for effective interface of errant vehicles with the barriers. This analysis follows the approach used in previous efforts considering the five vehicle types and range of impact conditions. The variations in side slopes on opposite sides of the median were reflected in non-symmetrical override and underride limits. Consequently, effective lateral placement options were different than those derived from previous analyses. The placement effectiveness plots were generated for two different median barrier designs. The resulting nomographs can be used by highway designers for non-typical median configurations and/or situations where there is variation in the relative elevations of the roadways on a divided highway. They enhance the understanding of the effectiveness of median barrier placement for such configurations and situations.
Analyzing the Potential Interface Effectiveness for Median Barriers for Varying Cross Sections

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 can be highly effective (some agencies citing over 90% effectiveness rates), but cases of underride or override have occurred with catastrophic results. Other types of barriers may need to be considered, however, to address deflection, maintenance, or cost concerns in some situations.

The FHWA and NCHRP have conducted research to understand vehicle-to-barrier interface issues and to improve the guidance for achieving the maximum effectiveness for barrier deployments [1, 2, 3, 4]. FHWA research has shown that cable barrier effectiveness is related to barrier design (e.g., number and height of cables, tensioning), configuration of the median (e.g., 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 that focused on the vehicle to barrier interface. The interface analyses results have led to improved means and guidance for determining the placement of cable barriers for median and roadside applications of varying configurations. There has been limited efforts, however, in the application of interface analyses for other types of barriers.

This document provides an update on continuing analyses of vehicle-to-barrier interface for barrier placement in varying median cross sections. A set of twelve cross sections associated with a state DOT project provided the basis for the analyses. These cross sections were characterized by different slopes than previously analyzed as well as variations in median widths, slopes, and elevations of the individual roadways of a divided highway. Consequently, the guidance didn’t fit the conditions for the state and left unanswered questions about effective lateral placement in these situations. Further, new questions, such as the effects of differences in roadway elevations had not been addressed in previous median barrier research. A hypothetical set of median situations with roadway elevations 2, 4, and 6 foot differences was investigated for a 32 foot wide median. The medians included varying slopes and shapes for the transition between the roadways. The analysis was based, as before, upon the premise that a barrier will be effective only if there is a good interface between the vehicle and the barrier. Effectiveness in the context of barrier “strength” is also important, but not addressed in the efforts reported here. 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 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 (i.e., engagement) region. These points are labeled 1 and 2 in 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. The area between the individual traces for the points is defined as the trace envelope.

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 no or a low compression load on its suspension system). When the vehicle lands, 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 compression 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 median slopes. Effective lateral placement of the barrier involves finding the locations where the vehicle’s interface area matches the 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 angles of 5 to 25 degrees. Vehicles were assumed to cross the median on straight, diagonal paths.
Defining an “effective interface” for any 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 of the barrier should contact the vehicle above Point 1 (lower critical point in Figure 1).
- To minimize the potential for underride, the bottom of the barrier should contact the vehicle below Point 2 (upper critical point in Figure 1).

The barrier must provide adequate strength to contain and redirect the errant vehicle. For rail systems, this implies that the posts will deflect, or disengage as designed, and that sections remain connected. For cable systems, 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, 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.

These lines represent a useful metric for this median configuration, as the blue line is the Override Limit and green line the Underride Limit. These limits provide a means to determine the interface effectiveness across all lateral positions for any given barrier design. The three yellow lines in Figure 5 represent the vertical positions of the cables of a particular barrier design (in this case a generic three-cable barrier). It is assumed that there will be an adequate number of intermediate cables to prevent the vehicle from passing between the top and bottom cables. For rail systems, it indicates the top and bottom of the rail for any lateral position across the median. 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 plots 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
median position, the vertical height of the normalized plot to actual sloped surface is equivalent.

Figure 5 – Coverage of a Generic Three Cable Barrier

The lower portion of Figure 6 shows the profile or cross section of the median related to the upper
graph. The green hatched portions indicate the lateral positions where this specific barrier would likely
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. The effective areas are mirrored on the other side of the median since the
conditions are uniform.
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 median barrier systems across all possible lateral positions for any given median configuration. This approach was applied to consider the varying median cross sections as described below.

**ANALYSIS OF VARYING MEDIAN CROSS SECTIONS AND BARRIERS**

Using the approach described above, plots were generated for each of the cases provided by the DOT using the same set of vehicles and impact conditions described above. The basic plots depict 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 interface requirements that any median barrier design must address in a given lateral placement to prevent barrier overrides and underrides.

The barrier interface area (i.e., cable heights, or top and bottom of the guardrail) for each design and each of the profiles 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 features of the specific barrier design. The red shaded areas reflect lateral
positions where one or both of the requirements are not met, and hence the barrier would not be fully effective. The generated plots provide useful insights about the influence of lateral placement of the barrier relative to the median configuration and 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.

Most of the previous research focused on general, uniform medians, although there had been some analyses of non-symmetric and elevated medians [5, 6, 7]. This led to a question from a DOT about the most effective placement divided highways with varying and irregular cross sections. Survey data was obtained for the edge of traveled way, shoulder, shoulder extension, side slope, and invert across the median. This cross section data is provided in Table 1.

<table>
<thead>
<tr>
<th>Section</th>
<th>TW width</th>
<th>SB width</th>
<th>Left shoulder</th>
<th>Shoulder extension</th>
<th>Left slope</th>
<th>Median center</th>
<th>Right slope</th>
<th>Shoulder extension</th>
<th>Right shoulder</th>
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<td>25.2</td>
<td>4.0</td>
<td>3.4</td>
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<td>Flat</td>
<td>5:1</td>
<td>Flat</td>
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</tr>
<tr>
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<td>23.0</td>
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<td>4.2</td>
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<td>Flat</td>
<td>6:1</td>
<td>Flat</td>
<td>4.8</td>
</tr>
<tr>
<td>C 250</td>
<td>41.3</td>
<td>25.1</td>
<td>4.2</td>
<td>4.6</td>
<td>7:1</td>
<td>Flat</td>
<td>7:1</td>
<td>Flat</td>
<td>3.4</td>
</tr>
<tr>
<td>D 270</td>
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<td>26.0</td>
<td>4.2</td>
<td>2.2</td>
<td>6:1</td>
<td>Offset v</td>
<td>5:1</td>
<td>Offset v</td>
<td>3.4</td>
</tr>
<tr>
<td>E 278</td>
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<td>24.5</td>
<td>4.8</td>
<td>2.0</td>
<td>4:1</td>
<td>Offset v</td>
<td>5:1</td>
<td>Offset v</td>
<td>4.3</td>
</tr>
<tr>
<td>F 325</td>
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<td>2.2</td>
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<td>5:1</td>
<td>Flat</td>
<td>3.0</td>
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<td>28.4</td>
<td>4.5</td>
<td>3.4</td>
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<td>4.5</td>
</tr>
<tr>
<td>I 471</td>
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<td>Offset v</td>
<td>5:1</td>
<td>3.4</td>
<td>4.7</td>
</tr>
<tr>
<td>J 500</td>
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<td>27.7</td>
<td>4.1</td>
<td>2.3</td>
<td>5:1</td>
<td>Flat</td>
<td>5:1</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td>K 516</td>
<td>41.7</td>
<td>27.0</td>
<td>4.3</td>
<td>2.6</td>
<td>3:1</td>
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<td>4:1</td>
<td>2.9</td>
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</tr>
<tr>
<td>L 521</td>
<td>41.3</td>
<td>26.3</td>
<td>4.4</td>
<td>2.8</td>
<td>4:1</td>
<td>flat</td>
<td>4:1</td>
<td>3.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

The variability of widths and slopes can be noted in the table. The median width varied from 38.8 to 46.4 ft. Most of the cross sections had a flat bottom section, but some had minimal width in the flat section. These had unequal side slopes and could be categorized as “offset v-shapes” since the invert was not in the center of the median. While not obvious in the data, the geometry includes variations in the elevations of the individual roadways. For all but two of the sections, the difference was less than 0.40 ft (less than 5 in), but Section E and I had differences of 1.0 and 1.3 ft respectively. In the hundreds of cross sections previously analyzed, the individual roadways were at the same elevation in all cases. These results provide useful indications of viable lateral positions, but 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.

The analysis approach described above allowed these varying median cross sections to be analyzed for the most effective lateral barrier placement locations. The results of these analyses are provided in Figures 9 through 20. In each figure, the cross section is provided at the top and the interface analysis for a generic four cable median barrier and a proprietary weak post w-beam guardrail system shown below. The four cable barrier assumes cables at 10, 16, 22, and 28 inch heights. The w-beam barrier was assumed to have a w-beam face from 21 to 28.67 in. The features of these barriers are depicted in
Figure 8. The override and underride curves shown in each graph were based on the set of vehicles and departure conditions noted in the analysis approach. These are based upon the specific median cross section, so they are the same for any barrier. The nature of the override would be similar if the interface with the barrier was inadequate, namely the vehicle would vault the barrier. There would likely be more deflection of the barrier with the cable system relate to a guardrail, but vaulting would be likely to occur. For the w-beam barrier, the underride phenomena would not be the same. Instead of the vehicle lifting the cable upwards and possibly passing underneath, the effect would be a wedging of the vehicle under the rail with the effect of severe snagging. It is possible that the rail could be lifted upwards, but that would take greater force than for a cable. The lower portion of the interface plots indicate lateral positions where the specific barrier will be effective as the green shaded area.

<table>
<thead>
<tr>
<th>Proprietary Weak Post W-Beam Guardrail</th>
<th>Generic Four Cable barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Diagrams" /></td>
<td><img src="image.png" alt="Diagrams" /></td>
</tr>
</tbody>
</table>

**Figure 8 – Median Barrier Designs Analyzed**

Looking at the twelve cross sections analyzed led to the following observations:

- Figure 9 (Section A) shows relatively similar results for the two barriers on 5:1 side slopes. The override and underride curves are uniform for each side of the median. Barriers would be most effective 3-4 feet from the slope break points.
- Figure 10 (Section B) reflects a section with different but relatively mild slopes. The greater interface area provided by the cable barrier provides more lateral positions where it would be effective. The skewed override and underride curves reflect the differences in the side slopes.
- Figure 11 (Section C) shows the analysis results for mild 7:1 slopes. The greater possible interface area results in more options for the cable barrier. The w-beam barrier has less lateral placement area due to the potentials for underrides.
- Figure 12 (Section D) shows the results for non-uniform and slightly steeper slopes. There is less possible interface area results in more options for the cable barrier. The w-beam barrier has less lateral placement area due to the potentials for underrides or snagging, particularly where the interface point is well below the bottom of the rail. There is also a slight variation in the elevation of the roadways that accounts for some of the skewing between the sides of the median.
- Figure 13 (Section E) shows the results for non-uniform and still steeper slopes (4:1 and 5:1). There is even less possible interface area, but due to the increased vertical variation in the override and underride limits, the effective area for either barrier becomes more similar. There is also a greater variation in the elevation of the roadways that account for some of the skewing.
between the sides of the median. It is not possible to discern whether the plots are affected more by the 1.0 foot change in elevation, or the different slopes.

- Figure 14 (Section F) shows the results for uniform 5:1 side slopes. The higher vertical interface area provided by the cable barrier provides the option for a center placement. There is slightly more effective area with the guardrail near the upper slope break points on both sides.
- Figure 15 (Section G) shows the results for uniform 5:1 side slopes with slightly greater width and a small variation in the elevation of the roadways. There is slightly more effective area with the guardrail near the upper slope break points on both sides.
- Figure 16 (Section H) shows the analyses for a 4:1 to 6:1 slope configuration with some variation in the elevations of the roadways. The override and underride curves indicate more interface variability on the side with the steeper slope. That corresponds to less viable lateral placement area on that side of the median. The greatest difference in roadway elevations occurs for this section.
- Figure 17 (Section I) shows the analyses for an equal 5:1 slope configuration with some variation in the elevations of the roadways. The override and underride curves indicate a little interface variability between the sides skewed to side of the lower roadway. That results in slightly less viable lateral placement area on the side of the median with the higher roadway.
- Figure 18 (Section J) results similar to those noted in Figure 17, but they are less pronounced because the elevation difference is smaller.
- Figure 19 (Section K) shows the analyses for 3:1 to 4:1 slope configuration with no variation in the elevations of the roadways in a slightly wider median. The override and underride curves vary considerable because of the steeper slope. For the two barrier designs considered there is only limited effective placement area at the top of the 3:1 slope.
- Figure 20 (Section L) shows the analyses for an equal 4:1 slope configuration with a little variation in the elevations of the roadways. The override and underride curves indicate more interface variability due to the steeper slopes. This results in virtually no viable lateral placement area on the low side of the median.

The interface analyses of these cross sections shows that there can be variations in effective placement areas associated with the specific median configuration. Steeper slopes generally exaggerate the override and underride limits reducing the potential effective placement area. Variations in roadway elevations in these cross sections is generally small (i.e., less than 0.4 feet), but influences on the limits can be noted.
Figure 9 – Profiles & Barrier Placement Analyses for Section A
Section 238+00

Elevation Difference – 0.20’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 10 – Profiles & Barrier Placement Analyses for Section B
Section 250+00

Elevation Difference – 0.00’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 11 – Profiles & Barrier Placement Analyses for Section C
Section 270+00

Elevation Difference – 0.32’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 12 – Profiles & Barrier Placement Analyses for Section D
Section 278+00

Elevation Difference – 1.00’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 13 – Profiles & Barrier Placement Analyses for Section E
Section 325+00

Elevation Difference – 0.16’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 14 – Profiles & Barrier Placement Analyses for Section F
Section 345+50

Elevation Difference – 0.20’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 15 – Profiles & Barrier Placement Analyses for Section G
<table>
<thead>
<tr>
<th>Section 468+00</th>
<th>Elevation Difference – 1.30’</th>
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</thead>
<tbody>
<tr>
<td>Generic Four Cable Barrier</td>
<td></td>
</tr>
<tr>
<td>Proprietary Weak Post W-Beam Barrier</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 16 – Profiles & Barrier Placement Analyses for Section H**
Section 471+00

Elevation Difference – 0.40’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 17 – Profiles & Barrier Placement Analyses for Section I
Section 500+00

Elevation Difference – 0.36’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 18 – Profiles & Barrier Placement Analyses for Section J
Section 516+00

Elevation Difference – 0.10’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 19 – Profiles & Barrier Placement Analyses for Section K
Section 521+00

Elevation Difference – 0.20’

Generic Four Cable Barrier

Proprietary Weak Post W-Beam Barrier

Figure 20 – Profiles & Barrier Placement Analyses for Section L
ANALYSES OF VARIATIONS IN ROADWAY ELEVATION

The effects of differential elevations of the individual roadways of a divided highway analyzed above raised questions about the general effect on effective placement. An analysis of the effects for a 32 ft wide median where the differential of elevation height ranged from even to 6 ft in two ft increments was undertaken. These analyses considered a gentle 6:1, and steeper 4:1 median slopes, as well as specific slopes that would be needed to accommodate median inverts at the center and offset. Twelve cases were defined and the interface analyses approach used above was applied to each case (Table 1). Case 1 served as a baseline or reference as the individual roadways were at the same elevation. It can be noted the depth of the median varied and in some cases “non-traversable” slopes were needed to fit a v-shape cross section between the roadways. Some of these cross section may not be practical from a roadway design and maintenance perspective, but the objective was to consider the dynamics of a range of vehicles negotiating these cross sections at various speeds and angles. These were then collapsed to generate override and underride curves as in the previous analyses. The steep slopes that were necessary in some cases led to rather extreme override and underride limits.

Table 2 – Median Parameters Used for Differential Roadway Elevation Analyses

<table>
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<tr>
<th>Profile</th>
<th>Width</th>
<th>Center</th>
<th>Slope 1</th>
<th>Depth</th>
<th>Slope 2</th>
<th>Elevation Difference</th>
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<td>6 : 1</td>
<td>0 (Base)</td>
</tr>
<tr>
<td>2 (Fig 22)</td>
<td>32</td>
<td>16.0 (mid)</td>
<td>6 : 1</td>
<td>2.67</td>
<td>3.4 : 1</td>
<td>2</td>
</tr>
<tr>
<td>3 (Fig 23)</td>
<td>32</td>
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<td>2</td>
</tr>
<tr>
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<td>32</td>
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<td>6 : 1</td>
<td>2.67</td>
<td>2.4 : 1</td>
<td>4</td>
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<tr>
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</tbody>
</table>

Observations

The placement effectiveness analysis results are summarized in Figures 21 to 32. For these cases, the same two barrier systems were considered. The following observations were made:

• Figure 21 – This is the baseline condition for gentle (6:1) slopes that reflects the vehicle behaviors when the roadways are at the same elevation. The override and underride limits depicts patterns similar to those seen in earlier analyses. Effective lateral positions are also similar.

• Figure 22 – For a 2 ft difference in elevations, it can be noted that the limits are no longer mirror images about the center and they tend to be more erratic. For the barriers analyzed here, there are no lateral positions on the side slopes were the barrier would be effective. This can be attributed to the need for a steep 3.4:1 slope to meet the opposite slope at the center.

• Figure 23 – This figure shows the effect of offsetting the invert of the median from the high side roadway. That reduces the slope required and leads to more reasonable override and underride
curves. For the two barrier systems, there are various lateral positions where the barrier can be effective. These tend to be on the side of the lower roadway.

- Figure 24 – This figure shows the effects of a 4 ft differential in roadway elevation. The limits curves are more erratic and even off the scale in some places. There are no places on the slope where these barriers would be effective.
- Figure 25 – This figure shows the effects of offsetting the invert as noted in Figure 23 for a 4 ft elevation differential. There are again various lateral positions where the barrier can be effective, with more on the side of the lower roadway, but options exist in the first five feet off the upper roadway.
- Figure 26 – This figure shows the results for a 6 ft elevation differential with the median invert at the center. As might be expected the results are similar to Figure 24, there are no places on the slope where these barriers would be effective due to the steep 1.8:1 slope.
- Figure 27 – This is the baseline condition for 4:1 slopes that reflects the vehicle behaviors when the roadways are at the same elevation. The override and underride limits depicts patterns similar to those seen in earlier analyses. There are no places on the slope where these barriers would be effective.
- Figure 28 – For a 2 ft difference in elevations, it can be noted that the limits are no longer mirror images about the center and they tend to be more erratic. For the barriers analyzed here, there are no lateral positions on the side slopes were the barrier would be effective. This can be attributed to the need for a steep 2.7:1 slope to meet the opposite slope at the center.
- Figure 29 – This figure shows the effect of offsetting the invert of the median from the high side roadway. That reduces the slope required and leads to more reasonable override and underride curves. For the two barrier systems, there are some lateral positions where the barrier can be effective. These tend to be on the side of the lower roadway.
- Figure 30 – This figure shows the effects of a 4 ft differential in roadway elevation. The limits curves are more erratic and even off the scale in some places. There are no places on the slope where these barriers would be effective.
- Figure 31 – This figure shows the effects of offsetting the invert as noted in Figure 23 for a 4 ft elevation differential. There is again various lateral positions where the barrier can be effective, with more on the side of the lower roadway, but options in the first five feet off the upper roadway.
- Figure 32 – This figure shows the results for a 6 ft elevation differential with the median invert offset well to the low side. This was the only case for the 6 ft differential where any effective lateral positions could be found, and these where possible only for the cable barrier due to the greater spread of the cable heights.

Overall this analysis suggests that for 32 ft wide medians the difference elevations of the individual roadways can significantly alter the interface effectiveness of median barriers. The greater the difference in roadway elevation, the greater the effects on the override and underride limits and hence the potential lateral placement options. Altering the median configuration by offsetting the invert can be useful in some cases.
Figure 21 – Barrier Placement Analyses for Case 1 with Gentle Slopes, Invert at Center, and No Difference in Roadway Elevations (Baseline)
Figure 22 – Barrier Placement Analyses for Case 2 with Gentle Slopes, Invert at Center, and 2 ft Difference in Roadway Elevations
Figure 23 – Barrier Placement Analyses for Case 3 with Gentle Slopes, Offset Invert, and 4 ft Difference in Roadway Elevations
Figure 24 – Barrier Placement Analyses for Case 4 with Gentle Slopes, Invert at Center, and 4 ft Difference in Roadway Elevations
Figure 25 – Barrier Placement Analyses for Case 5 with Gentle Slopes, Invert Offset, and 4 ft Difference in Roadway Elevations
Figure 26 – Barrier Placement Analyses for Case 6 with Gentle Slopes, Invert at Center, and 6 ft Difference in Roadway Elevations
Figure 27 – Barrier Placement Analyses for Case 7 with Steep Slopes, Invert at Center, and No Difference in Roadway Elevations (Baseline)
Figure 28 – Barrier Placement Analyses for Case 8 with Steep Slopes, Invert at Center, and 2 ft Difference in Roadway Elevations
Figure 29 – Barrier Placement Analyses for Case 9 with Steep Slopes, Invert Offset, and 2 ft Difference in Roadway Elevations
Figure 30 – Barrier Placement Analyses for Case 10 with Steep Slopes, Invert at Center, and 4 ft Difference in Roadway Elevations
Figure 31 - Barrier Placement Analyses for Case 11 with Steep Slopes, Invert Offset, and 4 ft Difference in Roadway Elevations
Figure 32 – Barrier Placement Analyses for Case 13 with Steep Slopes, Invert Offset, and 6 ft Difference in Roadway Elevations
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 effectiveness for the lateral placement of median barriers. This information can be used as a means to determine the lateral placement of 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 barrier height or make it easier for agencies to select barriers for the median conditions known to exist for a given project. Interface analyses is not alone sufficient for barrier selection and placement, however, given that there may be “strength” factors associated with various designs resulting from differences with post, connector, anchorages, and other features of the system. Understanding the joint effects of median configuration, barrier design, and lateral position can promote enhanced roadside safety.

The following is a summary of this research:

- The trajectory envelopes and resulting Override and Underride Limits were altered by the unequal slope conditions in the various 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.
- The analyses of these cross sections shows that there can be variations in effective placement areas associated with the specific median configuration. Effective lateral placement locations for all profile cases was not possible.
- Steeper slopes generally exaggerate the override and underride limits reducing the potential effective placement area.
- Variations in roadway elevations in these cross sections is generally small (i.e., less than 0.4 ft), but influences on the limits can be noted.
- A comparison of a cable barrier design and semi-rigid guardrail was undertaken using interface analyses under the assumption that a “good” interface with an errant vehicle is critical to the effectiveness of any barrier. The analyses recognized that there would be differences in the interaction of the vehicle and barrier due to stiffness. The profiles generated increased the number of cases for which lateral placement has been analyzed.
- Overall the analyses suggest that for 32 ft wide medians the difference in elevations of the individual roadways can significantly alter the interface effectiveness of median barriers.
- The greater the difference in roadway elevation, the greater the effects on the override and underride limits and hence the potential effective lateral placement options.

The following can be concluded from this analysis:

- The degree of slope and the configuration of the median influences the behavior of vehicles traversing the median. The greater the variation of slope, width, and shape of the median the greater the degree of vehicle instability and potentials for erratic override and underride limits.
- Variations in the elevations of the individual roadways increases the effects on the vehicle behavior and the subsequent override and underride limits. These tend to be greater on the side of the higher roadway.
- The greater the difference between the roadway elevations the greater the instability probably due to the steeper slopes needed to transition between roadways. Offsetting the invert of the median from the middle provides some opportunities to minimize this effect up to differences of 4 ft.
• The median guidelines produced under NCHRP Project 22-25 [NCHRP Report 711, September 2012] did not address this topic despite having analyzed hundreds of median configurations. An addendum to those guidelines would be appropriate.

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