Vehicle Dynamics Investigations to Develop Guidelines for Crash Testing Cable Barriers on Sloped Surfaces

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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
Crashworthiness evaluations of roadside barrier testing have traditionally been conducted on level terrain to allow a convenient basis for comparison of alternative designs. The emergence of a new generation of cable median barriers to address cross-median crash problems has led to increased placement of these barriers on slopes. Recent research using vehicle dynamics analysis has shown that barrier effectiveness is influenced by slope conditions, barrier design, lateral placement, and median configuration. While there has been some testing of cable median barriers on slopes, there is not a prescribed procedure for testing on slopes, nor a means to evaluate crashworthiness across a range of slope conditions. Research by the FHWA has demonstrated the usefulness of vehicle dynamics analysis to understand barrier effectiveness on slopes. This paper describes an effort to apply vehicle dynamics analysis to determine basic considerations for the development of slope testing procedures. The analyses considered the need to test for both override and underride potentials. The analysis considered various median widths for basic v-shaped medians with 4:1 side slopes (the normal side slope limit). The analysis considered the dynamics for a pick-up truck, mid-sized sedan, and small car.

This study focused on impacts under the Test Level 3 (TL3) condition for cable barrier systems that are designed to work when placed anywhere in 4:1 or shallower medians. It was noted from previous research that the pick-up truck was prone to override while the small car more likely to underride a cable barrier. Since the mid-sized sedan was found to be over-represented in underride crashes, it was also considered in this analysis. The results suggest that slope testing procedures need to include an override test with a barrier placed at 10-12 ft from the nearside edge of the median and an underride test on the farside of a 40-48 ft wide median. It was noted that the mid-sized sedan had an underride potential similar to the small car, but that because of its higher mass, suspension and wheel forces were more than 20% greater than those forces of the small car. The results presented are expected to be validated with full-scale tests, but it is believed that the information generated provides a robust basis for the development of improved procedures for slope testing.
INTRODUCTION

Since the early 1990s, it became apparent that cross-median crashes were becoming a serious problem. These problems exist for all divided highways, but they are particularly critical for the many miles that were constructed to minimum median width standards. These standards were derived from research dating back to the 1950s and 1960s when vehicles were quite different and traffic levels considerably lower. These highways functioned safely under lower volume conditions because there was a lower probability of traffic conflicts in same direction traffic streams and when a vehicle crossed the median, due to a conflict or driver error, the probability was very low that there would be opposing traffic. The higher volumes for all situations increased the probability of cross-median crashes, which are characteristically severe.

Highway design practices have been to install barriers on flat or nearly flat surfaces adjacent to the roadway. Since barriers are tested on level surfaces, this has led to the belief that an accepted barrier installed on “nearly” flat surfaces will be expected to function in a similar fashion to meet the crashworthiness requirements. This has long been the accepted practice. The installation of barriers in median situations, however, poses new challenges. Medians characteristically are sloped to provide drainage, but the configuration of the median cross-sections has been shown to vary widely in terms of width, side slope, and shape (primary aspects of “median configuration”). Further, the medians along a highway are not uniform owing to changes in the geometric design of the highway to conform to the terrain, and the presence of other highway elements in the median (e.g., crossovers, bridges, and/or drainage structures). This poses a challenge for proper selection of a cable barrier design and its placement in the median, which will ensure greatest possible barrier effectiveness. While barrier design and placement are aspects that can be controlled, the nature of the median surface, the impact conditions, and vehicle loading cannot, making it difficult to always achieve the highest levels of safety.

Research sponsored by the FHWA has shown that the effectiveness of cable barriers on slopes is influenced by lateral placement for any given cable design and median configuration [1,2,3,4]. This research was initiated by cross-median crashes attributed to underrides of generic three-cable, low-tension systems placed in critical locations of v-shaped medians with 6:1 side slopes. The research found that even a three foot difference in the lateral placement made a difference in barrier interface and hence the propensity for underrides. This research attributed the problem to the vehicle dynamics effects resulting from suspension system compression and rebound upon leaving the level road surface and traversing the slope. Further research found that these vehicle dynamic effects varied with median configuration. Ultimately, these efforts led to the development of draft nomographs for the placement of cable barriers in various types of medians [5]. Research to translate the lateral placement findings into general design guidelines continues under NCHRP Project 22-25 “Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems.”

While the nomographs and guidelines (soon to be released) provide a more robust means to determine the most effective placement for cable barriers, they do not indicate how the crashworthiness evaluation results of specific cable barrier system designs relate to its placement. Crashworthiness evaluations for all barrier testing have traditionally been conducted on level terrain to allow a convenient basis for
comparison of alternative designs. The slope testing that has been undertaken has used different median configurations, making direct comparison of results difficult.

The Manual for Assessment of Safety Hardware (MASH) sets the testing requirements for various types of roadside hardware and features [6]. Since it carries the AASHTO endorsement, it represents the national standards for crashworthiness evaluation in the tradition of NCHRP Report 350 “Recommended Procedures for the Safety Performance Evaluation of Highway Features” and its predecessor documents [7]. It states that the prescribed testing procedures are intended to focus on “practical worst conditions” for barrier installations on flat surfaces. Given the need to use all space in the highway right-of-way, there is a need to consider placement of barriers on slopes and to have procedures that support common testing for the same.

The research reported here attempted to lay the groundwork for the development of protocols for slope testing that might be considered in amendments or updates to MASH. This is a complex process that will take analysis and testing to provide data that can be the basis for developing a consensus on a viable slope testing standard.

**RESEARCH APPROACH**

This research applied a Vehicle Dynamics Analysis (VDA) approach to study the implications of various median configurations that might be considered for slope testing. Vehicle dynamics simulations were conducted to compute the trajectories of vehicles as they traverse a median on a diagonal path. This 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 an animation showing the resulting scenario [8, 9]. This software applies the Adam’s model with 16 degrees of freedom to calculate the trajectory for any type of vehicle. Vehicle libraries define dozens of specific inputs defining the vehicle geometry, suspension, steering, weight, and other features of the vehicle. Previously, FHWA had done some field testing to validate the results; additional testing is planned for the fall of 2010. There has been independent validation by users in the automotive industry that has supported commercialization of the product. In these analyses two points were defined for each type of vehicle considered to represent the primary interface (engagement) region on 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 for different types of vehicles 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.
Differences in vehicle mass and size influence the critical areas for override and underride. Figure 1 shows the vehicle types used in this analysis and the assumed primary structure region on the front of each vehicle. The vehicles included:

- Mid-sized Ford Crown Victoria Passenger Car (1600 kg)
- Large Chevrolet C-2500 Pick-up Truck (2000 kg)
- Large Dodge Ram 1500 Pick-up Truck (2270 kg)
- Small Dodge Neon Passenger Car (1100 kg)
- Small Geo Metro Passenger Car (820 kg)

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<th>820C Geo Metro</th>
<th>1100C Dodge Neon</th>
<th>2270P Dodge Ram 1500</th>
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Figure 1 – Assumed Vehicle Frontal Structural Regions for Effective Barrier Interface

The analyses were based upon a common v-shaped median with 4:1 side slopes. The median width was varied from 16 to 56 ft to indentify worst case scenarios. Standard impact conditions prescribed in MASH were used. MASH testing for longitudinal barriers requires that a small 1100 kg car and a 2270
kg quad cab pick-up truck be safely redirected in impacts at 100 km/h at an angle of 25 degrees. Since placement can influence the propensity for both vehicle override and underride, it was necessary to consider both cases in the analysis. The analysis assumed the following:

- The median would provide a firm surface (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.

These are factors that might influence the outcome of any crash, but are typically considered in crashworthiness evaluations.

RESULTS

VDA simulations were conducted for each of the five vehicles noted above for each of the median widths indicated. The software provided data tables that indicated various metrics related to the dynamics of the vehicle for each thousandth of a second of time traversing the median. The data included the relative heights of points 1 and 2 during the median crossing event. Previous research has shown that override is more critical for the large vehicle and that underride is more likely for the small vehicle. Override occurs (or is likely to occur) when point 1 is higher than the highest cable on the barrier. Underride occurs when the upper point on the vehicle is at a position lower than the lowest cable. In general, then the concern becomes defining the lateral point where point 1 is the highest for the large vehicle and point 2 is the lowest for the small car for all median widths.

To analyze either of these cases, it was necessary to normalize the VDA data. This process translates the specific heights of trajectory points from the true surface of the median to a horizontal plane. Thus, measuring from the horizontal plane to any point on the true surface will give the same value. The advantage of this approach is that it allows different median configurations to be compared directly.

Figure 3 shows the results generated to understand override potentials. Each of the color-coded curves indicates the height of point 1 for the Dodge Ram pick-up truck for the varied median widths. The vehicles in this plot are traversing the median from left to right. The worst case for override is when point 1 is at its maximum elevation relative to ground level (i.e. the maximum points in the curves). These maximum points can be used to identify the critical lateral placement of the cable barrier (the lateral position at the maximum point indicate the location when the vehicle is at height position relative to barrier and has the most potential for override. If a barrier system is tested under this worst case condition and successfully redirects the large pickup truck vehicle, it would be safe to assume that most vehicles would not override the system if placed anywhere in a 4:1 or shallower median.

Each of the curves in Figure 3 show one or two peaks (maximum points). The first peak occurs in the nearside when the vehicle is airborne and is at its highest elevation relative to ground level. The second peak occurs in the farside and is the result of suspension spring rebound after impact with the surface. The first peaks are more critical because the vehicle speeds are higher just prior to interactions with the median. As the vehicle crosses the median there are natural losses in speed and additional losses due to tire and vehicle body contacts with the surface. It can be noted in this figure that the first peak occurs at the same location for all medians wider that 24 ft and that the lateral position is located between 10-12 feet from the edge of shoulder and beginning of the median. This would imply that any median width
that is wider than 24 feet would allow the maximum override condition to be represented. To achieve this worst case condition for override, the barrier should be installed in the near side at 10 to 12 ft from the edge of the median and impacted with the large pick-up vehicle.

A similar analysis was done for a C2500 pick-up truck. Figure 4 shows the maximum vertical heights for the Dodge Ram (representing the MASH 2000P test vehicle) and Chevy C2500 (representing NCHRP Report 350 vehicle) for the varied median widths. The lighter vehicle seems to have trajectories that are about one inch lower.
Figure 5 presents the normalized VDA results for the 1100C small car. In this case the focus is the minimum height of point 2. When point 2 is lower than the lowest cable, then the vehicle is likely to underride the barrier. Therefore the worst case for underride is when point 2 is at its minimum elevation relative to ground level (i.e., the minimum points in the curves). These minimum points can be used to identify the critical lateral placement of the cable barrier as well as the critical median width. It can be seen that the minimum points for the various widths considered occurs for median widths between 40 and 48 feet. These would be the most critical median widths for testing the worst case for the underride condition. The selection of lateral placement for the underride case is also important. This placement varies with median width as shown in Figure 6. The figure presents the non-normalized VDA results for the trajectory comparisons for the small car. It is simplified to show the trajectories for just the 24, 40, and 56 foot wide medians. The relative position of the low point is noted for each trajectory. This position varies from 2 ft for the widest median analyzed (56 ft) to 6 ft for narrowest median (16 ft). For underride critical median widths identified (40 to 48 ft), the critical lateral placement is between 2 and 3 ft. Based on these findings, to achieve this worst case condition, the barrier should be installed in the far side at 2 to 3 ft from the center of 40 to 48 ft median and impacted with the small car. If a barrier system is tested under this worst case condition and successfully redirects vehicle, it can be concluded that most vehicles would not underride the system if placed anywhere in a 4:1 or shallower median.

Figure 5 - Normalized Trace Paths for the Upper Vehicle Interface Point for the Dodge Neon Small Car for Various Median Widths
A similar analysis was undertaken with the 820C small car and a mid-size sedan. Figure 7 shows the minimum vertical heights for various median widths for the Dodge Neon (1100C), Ford Crown Victoria (mid-size sedan), and Honda Civic (820C). The Civic was added to this analysis to represent the previous NCHRP Report 350 820C vehicle. It can be noted that the low points for the Neon and Civic are similar. The low point for the mid-sized vehicle is only about one inch different, but it occurs about 2 feet closer to the beginning of the median. The interesting consideration here is noted in Figure 8, which plots the maximum right tire force on landing. The models and simulations all indicate that the vehicle will at least be partially airborne for the conditions analyzed. The mid-sized vehicle’s right front tire, because of its higher mass, will impact the ground with 5000 pounds more force than the Dodge Neon.
In addition to the underride and override conditions, there is a possibility that a vehicle might penetrate between the cables. This scenario is more likely for cable barrier systems that are designed to work anywhere in the median and the cables have to be spaced far apart to cover the underride and override impact conditions. An additional full-scale crash test to address this scenario may be needed.

**SUMMARY AND CONCLUSIONS**

Vehicle dynamics analyses have been demonstrated to provide useful insights into the behavior of vehicles on sloped surfaces. The insights clearly indicate that the vehicle-to-barrier interface can be significantly affected by placement in some positions on sloped surfaces. The best barrier will not perform as expected if there is not an adequate interface with the vehicle. This has been shown here extensively for cable median barriers, but these findings are applicable to other types of barriers.

Agencies are often faced with severe space limitations relative to the placement of barriers. They have considered placement on mild slopes near the edge of the shoulder as acceptable and there seems to be no evidence to the contrary. There has been more latitude taken with the placement of cable median barriers in the absence of consensus design guidelines. The various vehicle dynamics analyses seem to provide an explanation for observed problems. The need exists to develop guidelines for median barrier placement that are supported by improved slope testing criteria. This will assist agencies in making effective barrier selection and design (i.e., placement) decisions. The results presented here are considered to offer partial rationale for improving slope testing protocols and acceptance criteria.

There is a need for additional research to add to the robustness of these findings and provide a full basis for developing a slope testing procedure and acceptance criteria. The topics to be addressed include:
• What constitutes an effective interface? FHWA 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.

• A means to depict the sensitive height range needs to be defined.

• The minimum space between cables has not been analyzed. It can vary by the weight and the frontal shape of the vehicles in the fleet, but needs to be assessed as there have been cases where the vehicle passes between the top and bottom cables.

• Expand the coverage of these composite curves to cover wider medians and other configurations.

A new slope testing procedure and acceptance criteria will also need for several topics to be addressed, including requirements for:

• Median Configuration – Barriers designed for installation on medians shall be tested on a typical cross-section that conforms to width, slope, and rounding parameters.

• Surface Conditions – The worst case for underride occurs when the soil beneath the barrier is soft and allows the vehicle to plough in it. This effectively further lowers point 1. Some specification for soil firmness is necessary to compare test results.

• Barrier Placement – Requirements for barrier length, lateral placement, and installation of typical end treatments or anchorages needs to be considered.

• Test Vehicles – Tests shall minimally be conducted with small and medium passenger cars and a large pick-up truck. The single unit truck is also candidate, possibly for optional tests on slopes for the Test Level 4 condition.

• Test Matrix – Consideration of an appropriate set of tests (i.e., matrix) for cable barriers on slopes is needed. This analysis was performed for TL3 condition and for systems that are designed to work anywhere in 4:1 or shallower medians. A set of tests to cover the probable impact conditions for varying test levels need to be formulated along with appropriate evaluation criteria.

It is believed that further vehicle dynamics analysis, validated by crash testing, can be useful in crafting a viable slope testing procedures. Further, the establishment of criteria will provide a benchmark for the barrier industry in their efforts to develop improved barrier systems.

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REFERENCES
