Analyzing the Effects of Cable Barriers Behind Curbs Using Computer Simulation

Dhafer Marzougui
Umashankar Mahadevaiah
Cing-Dao (Steve) Kan
The National Crash Analysis Center
The George Washington University
20101 Academic Way, Ashburn VA 20147 USA
Email: dmarzoug@ncac.gwu.edu

Kenneth Opiela
Turner Fairbank Highway Research Center
Federal Highway Administration, USDOT
6300 Georgetown Pike, McLean VA 22101-2296 USA
Email: Kenneth.opiela@dot.gov

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

In past few years, computer simulation has been used more often for designing and evaluating roadside hardware. Recent advancements in computer technology, vehicle enhancements to dynamics and finite element software, and a growing body of experience and expertise have made it possible to predict the behavior of automobiles as they impact roadside hardware. In this paper, computer simulations were used to analyze the effects of placing curbs in front of cable barriers. This was motivated by the increasing deployment of cable barriers and the need for guidance relative to applications in various situations. Five different types of curbs were analyzed using vehicle dynamics and finite element simulations. Three different sizes of vehicles (i.e., pickup truck, mid-sized car and small car) were selected to span the range of vehicle types on U.S. roads. Different approach angles (i.e., 5, 15, and 25 degrees) and speeds (i.e., 50, 70, and 100 km/h) were taken into consideration to determine the interface envelopes for varying impact conditions for each curb type. To obtain the interface envelopes, two critical points are defined on the front of each vehicle to represent the primary structural region that would be expected to engage one or more of the cables. The first point was selected such that if a cable impacts below this point it goes under the vehicle and the second point was selected such that if cable impacts above this point it goes over the vehicle. If the cable impacts between these two points it is expected to remain in contact with the vehicle during impact. Vehicle dynamics tools were used to plot the trajectories of these points as the vehicles cross the curb and the area behind the curb. These trajectories for different cases were combined together to establish maximum height curves for the bottom cable and minimum height curves for the top cable as a function of distance from the curb to the cable barrier for five common curb types. These maximum and minimum curves provide a basis for determining whether a given design of cable barrier will have an adequate interface at a specific position behind the curb for level or near level conditions. While the vehicle dynamics tools were validated by others, finite element simulations (similar to those used in a recent NCHRP study of guardrails behind curbs) were used to provide confidence in the findings.
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INTRODUCTION

There has long been concern over the use of curbs on roadways because of their potential to cause drivers to lose control. Curbs typically extend 75 to 200 mm (3 to 8 inches) above the road surface for appreciable distances and are located very near the edge of the traveled way. The AASHTO highway design policy discourages the use of curbs on high-speed roadways, defined as roadways with design speeds of 80 km/h or more. While the use of curbs is discouraged on higher-speed roadways, they are often required because of restricted right-of-way, drainage considerations, access control, delineation, and other curb functions [1]. Curbs also present a possible hazard for motorists who may encroach the roadside, as they influence the trajectory of the vehicle which can lead to non-optimal interfaces with roadside safety hardware placed beyond the curb.

Longitudinal barriers of all types are influenced by curbs. Past efforts have focused on the effectiveness of W-beam guardrails when placed behind curbs. NCHRP 537 "Guidelines for Curb and Curb-Barrier Installations" [1] was the most recent effort that has addressed the vehicle-to-guardrail interface behind curbs. In this effort, finite element simulations in conjunction with full-scale crash tests were used to parametrically study varying impact speed, curb type, and guardrail offsets from the curb to generate a matrix of optimal barrier heights for various guardrail offsets. In this effort, all the simulations were performed using a C2500 pick-up truck with an impact angle of 25 degrees.

Cable barriers have recently become an increasing popular form of roadside hardware for use on higher-speed roadways as median barrier systems. These are used to contain and/or redirect errant vehicles that depart the roadways. These barriers gradually redirect an impacting vehicle by stretching of the cables, minimizing forces on the vehicle and its occupants. They are best suited for locations where there is sufficient space to accommodate the large lateral deflections that may occur. Due to their low installation cost, reduced impact severity, and high success rate (some claim over 90%) in keeping vehicles from crossing the median, the use of cable barrier systems is growing rapidly across the United States [2][3]. Guidelines for the selection and installation of cable barriers has not, however, kept pace with the interest in deploying them. Guidelines for the use of cable barriers behind curbs is one area that has not been addressed.

An effective interface between the vehicle and barrier is critical for any barrier to be effective. Characteristics of cable barriers such as deflection, may imply that interfaces are more critical to viable safety performance. Vehicle dynamics analysis was effectively used to study the interfaces of a given type of median barrier placed on a surface that can alter the trajectory, particularly vertically, such as a sloped cross-section of the roadside or median. Naturally, a curb as an element of the cross-section can affect the trajectory of a vehicle crossing over it. The features of the curb influence the vertical impulse to vehicle dynamics and hence trajectory. The amplitude and location of the trajectory affects interfaces with the barrier. An ineffective interface of the vehicle could lead to not fully engaging the cables and consequently under-riding or over-riding the barrier. While it is not possible to ensure adequate cable engagement in all cases, basic alignment of the primary frontal area and the capture area relative to the position of the cables for a given design must be attempted.

The purpose of this analysis was to establish relationships between the trajectories of vehicle frontal interface areas, cable heights, and the distance between the curb and cable barrier (i.e., offset) for different types of curbs. These relationships provide the basis for setting placement standards,
determining the adequacy of interfaces for a particular situation, and/or aid the design of new barriers. Vehicle dynamics analysis and finite element simulations were used to generate vehicle height trajectories when going over curbs at different speeds and approach angles to represent the domain over which the barrier will be expected to perform. Trajectories from vehicle dynamics analysis were compared to finite element simulations to verify the results. The results are presented as plots showing the maximum height of the lower cable and the minimum height of the upper cable as a function of distance between the curb and barrier for five types of curbs.

**CURBS ANALYZED AND VEHICLES CONSIDERED**

According to the AASHTO ‘Green Book’ [4] the curbs can be defined into two basic types (as shown in Figure 1): vertical curbs and sloping curbs. Vertical curbs usually have a vertical or nearly vertical face and are used for various purposes, including discouraging vehicles from leaving the road, drainage, support of walkway edges, and pavement edge delineation. Since at high speeds and high encroachment angles, vertical curbs can introduce vehicle instability that may even be large enough to cause vehicle to rollover, they are usually restricted to low-speed facilities [4].

![FIGURE 1 Typical AASHTO highway curbs](image)

Sloping curbs have a sloped face and are configured such that a vehicle can ride up and over the curb. Sloping curbs are designed so that they do not significantly redirect a vehicle. They are used in situations where redirecting a possibly damaged and out-of-control vehicle back into the traffic stream is undesirable. They are used on median islands and along shoulders of higher-speed roadways for delineation and other reasons.

In this analysis, the effect of curb types A, B, C, D, and G (Figure 1) on vehicle trajectories were evaluated and, based on these trajectories, the vehicle to barrier interactions were analyzed. It is useful to note that these curb types were the same as analyzed in NCHRP Report 537 [1].
The vehicle models that were used in the analysis include a pickup truck (Chevrolet C2500) and a small car (Honda Civic) to represent the two test vehicles as recommended in the NCHRP Report 350. A mid-sized sedan (Ford Crown Victoria) was also included in the analysis. This type of vehicle is critical for the cable barrier performance because its sloped front-end profile and its mass is close to that of the pick-up truck. Previous NCAC studies have shown that it represents a class of vehicles prone to under-ride cable barrier systems [5].

ANALYSES
Vehicle Dynamics Analysis
This research focused on analyzing the trajectory of the interface area on the front of a vehicle going over a curb to develop improved guidelines for the selection and installation of cable barriers in such situations. As the vehicle goes over a curb its trajectory is changed due to both vehicle factors and impact conditions. The vehicle’s mass, wheelbase, and suspension properties have major influence, but variations in the speed, and impact angle cause varying effects on the trajectory. These change dynamically over the duration of the roadside excursion and hence are not “back of the envelope” calculations.

The frontal interface area of a vehicle is that region of the vehicle’s front that can be expected engage the vehicle. For cable barriers, there is significantly less interface surface to be captured and their shape can allow it to slip past structurally solid areas. For this analysis, two critical points were selected on each of the three vehicles to define a primary interface area. These two points are located at the corner of the vehicle (front-left) that first comes in contact with the barrier. Figure 2 shows the location of these points for the mid-sized sedan. The locations of these two points are chosen based upon whether or not a cable would be able to engage the vehicle. The first point was selected such that the cable would go under the vehicle if the cable impacts the vehicle below this point. Similarly, the second point was selected such that the cable would go over the vehicle if the cable impacts the vehicle above this point. In the region between these two points, the cable will remain in contact with the vehicle during the impact. These selections were made based upon knowledge of the frontal structures of the three vehicles and experience in crash tests.
Vehicle dynamics analysis was initially used to get the trajectories (with a focus on the vertical heights) of the critical points as the vehicle goes over a curb. From the trajectories, a plot was generated which established the relationship between height of the vehicle interface area relative to the vehicle’s location in crossing the median. Figure 3 shows an example of a vehicle’s trajectories and the resultant plot obtained using vehicle dynamics analysis for traversing a median. It can be noted that there are pronounced dynamic effects ranging from the vehicle being airborne (i.e., at least one of the tires not in contact with the surface), bottom-scraping when the vehicle lands on the up slope, and then a rebound as the energy stored in the compressed front suspension is released. Vehicle dynamics effects for crossing curbs is based upon the same fundamental principles of physics, but the abrupt vertical thrust of the curb typically does not generate the same degree of effect.
Even though these trajectories have components in the three directions (longitudinal, lateral and vertical), the plot reflects only two directions that are important in this analysis, namely the lateral and vertical directions. The region between these two trajectory lines (shaded area in Figure 4) depicts the position of the primary interface area and hence the area where a cable would engage the vehicle. The efficacy of a cable barrier at different positions in median can be seen in Figure 4 by noting where the red lines representing the position of the cables cross the interface band. This plot was generated for a situation where a sedan leaves the road at 100 km/h at a 25 degree angle and traverses a narrow median with 6:1 slopes. In these cases, the height of the cables is measured from the elevation at the edge of the travel lane in accordance with AASHTO Roadside Design Guide (RDG) recommendations.

Using vehicle dynamics analysis, a vehicle passing over a curb was simulated and a trajectory plot generated. Figure 5 shows the trajectory plot of critical points on a C2500 pick-up truck when moving over a type G curb at 100 km/h with an approach angle of 5 degrees. In the figure, the red lines reflect the trajectory of the vehicle interface area had the vehicle not encountered the curb. The blue band shows the jump in vertical position that occurs when the front wheel first strikes the curb. There is a rather gradual rise, which would be expected for a type G sloped curb. There is some rise above the height of the curb associated with the response of the vehicle’s suspension system. After the initial jump, the trajectory follows the higher surface behind the curb uniformly for the 20 feet of offset considered.

![Figure 5: Trajectory plot as the vehicle goes over a curb](image)

The trajectory effects will vary with speed and angle. Figure 6 shows these effects for impacts at 50, 70, and 100 km/h for a 5 degree impact. The differences are small for the type G curb, but noticeable. Figure 7 shows the effect on trajectory for impacts at angles of 5, 15, and 25 degrees at a speed of 100 km/h. More dramatic differences between the individual curves is apparent, but they are small.
Since it is necessary to design and place barriers to serve a range of impact speeds, angles, and vehicle types, the analysis involved considering 27 different combinations of these factors for each curb type. Figures 8 and 9 show the multiple trace plots (reflected in the light, multi-colored lines) that were generated for the lower and upper points for each curb type. The extent of variation is apparent by the scatter of the individual trace plots. For some vehicles and impact conditions there is an abrupt impulse close to the curb. In some cases, the effect is more gradual. After a point (about an offset of 13 feet) the dynamic effects stabilize.
These trajectory plots of point 1 (lower point) serve a useful purpose when the aggregate maximum is highlighted as noted by the heavy green trace labeled Minimum Height of Top Cable for a given type of curb (type G here). This minimum height represents a design requirement to provide effective interface for any type of cable barrier system placed at any offset behind a given type of curb. Similarly, trajectory plots of point 2 (upper point) were combined together to get Maximum Height for the Bottom Cable, as shown by the heavy red line in Figure 9. When these two curves can be combined on a single plot, as shown in Figure 10, it is possible to determine if a given cable barrier design will be viable for any offset. In this case, a typical generic, three-strand, low-tension cable barrier system is depicted by the yellow lines. It is clear that this system can meet the design requirements of the maximum or minimum curves because they are both within the range of the top and bottom cables associated with this system. It should be noted that barriers may function adequately even if there is not ideal interface, but
in the absence of empirical data from in-service evaluations it is difficult to set a range of confidence relative to the degree of interface.

![Graph](image)

**FIGURE 10 Cable height limits relative to the heights of a typical 3-strand cable barrier system**

Since the range of heights of the cable encompasses the maximum and minimum, it can be concluded that there will be effective interface at any offset.

To generate the trajectories plots, commercially available vehicle dynamics software was used. Human Vehicle Environment (HVE), by the Engineering Dynamics Corporation, is a computer environment developed for use by engineers and safety researchers to study interactions between humans, vehicles, and their environments [6]. It is a high-level simulation tool aimed at creating 3-dimensional models of vehicles and environments and allows the study of their dynamic interaction under selected conditions. This physical/mathematical vehicle model provides a detailed description of a motor vehicle trajectory that considers the influence of weight, suspension system, and other factors. A feature of the software is that it includes a library of common vehicle types (i.e., make and model) and their characteristics (e.g., width, suspension parameters, wheelbase, basic geometry) that allow analysis of dynamic responses for a variety of situations. The models in this library were validated with test data from the automotive industry.

**Finite Element Analysis**

At the outset of the analysis there was concern that the HVE program was not effective at analyzing the most severe impulses that would be generated by curb types A, B and D. While the HVE simulations are less time consuming than the LS-DYNA simulations, the accuracy of the results was questioned. The heights of curbs types A, B, and D are greater than the others, leading to excessive forces applied to the tire and suspension. The vehicles tended to severely “bottom-out” and the resultant data was obviously inaccurate. To get comparable trajectory data, these cases were simulated using LS-DYNA. The simulations consisted of a 2000P vehicle (represented by the C2500 pickup truck model) at each of the speeds and impact angles. Figure 11 shows the trace paths generated by LS-DYNA. Simulations of impacts with a generic low-tension cable barrier system at a speed of 100km/hr and angle of 25 degrees was conduct. The barrier, in this simulation, was placed 6 ft behind a B-shape curb. The location of the barrier and shape of the curb were selected such that the most critical case scenario was simulated. The simulation showed the barrier successfully captured and redirected the vehicle. Figure 12 shows sequential views of the results of this simulation.
The computer simulations were run with LS-DYNA, an explicit, nonlinear finite element code for analyzing the transient dynamic response of three-dimensional solids and structure. It has been applied to a wide spectrum of problems, many involving large inelastic deformations and contact. LS-DYNA has numerous features such as various element formulations, material models, contact algorithms, connection and joints, etc. and is available from Livermore Software Technology Corporation) [8].
RESULTS
Using the methods and tools described above, a series of simulations were run to generate characteristic maximum and minimum curves for each curb type. Three different speeds (e.g., 50, 70 and 100 km/h), three different approach angles (e.g., 5, 15 and 25 degrees) and three different vehicles (e.g., 2000P Chevy C2500, 820C Honda Civic and Crown Victoria) were analyzed in combination to obtain cable height limits for each type of curbs. Figures 13 to 17 show the minimum and maximum height limit for top and bottom cables for different types of curbs. These plots can be used to assess whether a particular cable barrier design (i.e., the combination of the arrangement of cables and its placement relative to the curb) will have a viable interface for the range of vehicles on the road. The minimum and maximum height curves serve as general guidelines to determine effective placement of any type of barrier system. This is shown for the generic, three-strand, low-tension cable barrier system behind a curb. It should be noted that the height of cables are measured from the top of the curb in this case.

FIGURE 13 Cable height limits for Type A curb

FIGURE 14 Cable height limits for Type B curb
FIGURE 15 Cable height limits for Type C curb

FIGURE 16 Cable height limits for Type D curb
To verify that the results from the vehicle dynamics analysis and finite element simulations are comparable (i.e., where the height changes were not so severe as for curb type G) the trajectories were generated using both methods. Figures 18 to 19 show the comparison of trajectories from the vehicle dynamic analysis and finite element analysis. It can be seen that the results from HVE and LS-DYNA were closely comparable.
FIGURE 19 Comparison of trajectories from LS-DYNA and HVE
SUMMARY & CONCLUSIONS
The emerging use of cable barriers has raised questions about effective placement in various situations. A research effort was successfully undertaken to analyze the interface effects for cable barriers placed behind different kinds of curbs. In this analysis, cable height limits for 5 different types of curbs were evaluated. For this evaluation three different classes of vehicles were used, and effects of speed and approach angle were taken into consideration. Results from vehicle dynamics simulations were compared with that of finite element simulations to verify the accuracy of analysis. Further simulations and/or tests are necessary to ensure the cable will remain in contact with the vehicle during impact. Even though this study was focused on analyzing the effects of having curbs in front of a cable barrier, the method can be applied to any system where vehicle dynamics plays an important role.

It was shown that vehicle dynamics simulations provide similar results to FE simulations in less time, as long as the constraints are not violated. A broader range of possible impact conditions (i.e., speed and angle of impact) and range of vehicles than used in previous studies were considered in this analysis in generating the minimum and maximum height curves.

In conclusion, this analysis provides an example of the use of computer simulation to effectively and efficiently design and evaluate the performance of cable barrier systems. Vehicle dynamics and finite element tools were used to plot the trajectories of these points as the vehicles cross the curb and the area behind the curb. These trajectories for different cases were combined together to establish maximum height curves for the bottom cable and minimum height curves for the top cable as a function of distance from the curb to the cable barrier for five common curb types. These maximum and minimum curves provide a basis for determining whether a given design of cable barrier will have an adequate interface at a specific position behind the curb for level or near level conditions.

REFERENCES