Slope Rounding Influences on the Trajectories of Vehicles

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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
Slope rounding is discussed in the Roadside Design Guide as a practice that breaks the sharp edge in a highway cross section and the side slope. There have been past studies aimed at understanding the influence of slope rounding on vehicle trajectories for various slope conditions. These studies were conducted about twenty years ago and only looked at a small subset of vehicle types despite the recognition that the size and weight of vehicles influences the slope rounding effects. This research effort analyzed two current vehicle types using vehicle dynamics analysis tools. These tools simulate the response of the vehicle to varying surface features for given road departure speeds and angles. The analysis considered various shoulder conditions and rounding treatments for the transition to 4:1 side slopes. The trajectory plots for the 1100C and 2270P vehicles departing the road at speeds of 30, 40, 50, and 60 mph and angles of 15 and 25 degrees were generated using simulation. The results show similarities to the previous research, expand the knowledge about the effects of slope rounding for other conditions, and suggest a means to systematically develop guidance for determining how and where to apply slope rounding.
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INTRODUCTION
A considerable amount of effort has recently been devoted to analyzing terrain effects on vehicle trajectories. Much of this has been stimulated by increased use of cable barrier systems in highway medians. Vehicle dynamics analysis (VDA) and testing have provided many new insights on how the dynamic effects of a vehicle’s suspension system affects trajectory in all three dimensions. Trajectory in the “z-direction” is directly related to the interface of the vehicle and the barrier. When the “bounce” of the suspension causes a vehicle to exceed the height of the barrier, undesirable override conditions occur. Recent efforts have focused on a myriad of factors that influence trajectory, but not “slope rounding.” Slope rounding involves grading the median such that there is a gradual transition from the profile near the shoulder to the slope itself. While there appears to be agreement that slope rounding can be beneficial and this practice is described in the Roadside Design Guide, specific guidance for its use is not provided.

The need exists to create a small range of rounding conditions and compare the trajectory profiles for a representative set of vehicles traversing “rounded” versus “non-rounded” slope breakpoints. The intent is to gain some insights on the degree of effect to help determine whether the existing procedures are in need of updating. It is expected that several slopes, departure angles, vehicle types, and speeds will be analyzed. This can be considered a pilot study to determine whether further research is needed.

Background
The analysis of the overall motion of a vehicle can be very complex, especially at higher speeds. However, the vehicle motion is primarily governed by the forces and moments generated by the interaction of the tires and the ground. In most vehicle dynamics studies, only six degrees of freedom are studied: longitudinal, lateral, and vertical displacement and the roll, pitch, and yaw angle. Generally, the vehicle-fixed coordinate system is associated with the center of gravity (CG) of the vehicle, but it is possible to generate metrics that allow the frontal interface region for each vehicle to be determined for the evaluation of potential barrier effectiveness given road departure speed and angle for the surface conditions associated with the roadway, shoulder, transition to the side slope, and the side slope.

Research by the Federal Highway Administration (FHWA) found that Vehicle Dynamics Analysis (VDA) provides a convenient tool for conducting such interface analyses fully considering the dynamic nature of a vehicle traversing a sloped surface. Software for VDA is commercially available and has been extensively used in the automotive industry. The VDA tools are quick and easy to use and offer a wide range of features. The software is believed to be robust, but there are questions about whether it has been adequately validated for roadside analyses. While preliminary comparisons between tests and simulations have been undertaken by FHWA and good agreement was observed, further testing and validation efforts are scheduled for 2011. This effort went forward using VDA to analyze slope rounding based upon its effectiveness in median analyses.

Objective
The objective of the efforts reported here were to apply vehicle dynamics tools to assess the effects of varying degrees of slope rounding on the dynamic response of vehicles, representative of the current fleet, leaving the roadway at different speeds and angles.
PREVIOUS RESEARCH

Slope Rounding Research
The Roadside Design Guide (RDG) discusses terrain effects on the placement and effectiveness of barriers. The RDG notes that “regardless of the type of roadside barrier being used or size and type of vehicle that strikes it, the best results will usually occur if, at the moment of impact, all of the vehicle’s wheels are on the ground and its suspension system is neither compressed nor extended” [1]. The key aspect of the RDG diagram in Figure 1 is the line labeled “Normal Path of Bumper Height,” indicating the trajectory of any selected point on the vehicle bumper for “optimal rounding,” which occurs when the above criteria for the vehicle contact with the surface are met. The curved line associated with the “normal” path is the “Actual Path of Bumper Height.” This line reflects the potential for the wheels to lose contact with the surface and the suspension system to compress and relax (or extend) accordingly. The “delta” measurements at various positions in the associated RDG diagram reflect the damping effect of the suspension system. Obviously, where the bumper height is the greatest at distance $L_M$ from the edge of the traveled way, effective interface will require that the barrier is higher than for the “normal” condition. Similarly, when the actual bumper point falls below the “normal” line there is potential for underride, particularly for cable barriers. It is important to note that this “actual path” is a function of the details associated with the vehicle type, the speed and angle of the departure, and the specifics of the shoulder, rounding (or non-rounding), and the slope.

![Figure 1 – Roadside Design Guide Analysis of Slope Rounding Effects](image)

The Texas Transportation Institute undertook an analytical study of slope rounding for the Minnesota DOT in 1993 [2]. In this effort they compared the cross sections shown in Figure 2 to evaluate the influence of slope rounding. Vehicle dynamics analysis was used as embodied in the Highway-Vehicle-Object Simulation Model (HVOSM) to determine the actual paths for a vehicle across the various transitions to slopes of 6:1 to 3:1. Using this model they varied the side slope, width of the transition (i.e., rounded or non-rounded) section, and the speed and angle of vehicle departure. They assumed that the rounded section would be represented by a parabolic curve as shown in Figure 3. Their analysis focused on a small car (Honda Civic) and pick-up truck (GMC) at 100 km/hr (62 mph). The vehicle dynamics results were used to predict lateral accelerations and roll angles. The objective of their research was to determine the conditions for which slope rounding was cost effective. They used the HVOSM software to predict the potential for rollovers and other crash parameters at various speeds for a...
range of slope conditions. The results were translated into safety costs to be considered in the cost-benefit analyses that led to their recommendations on where slope rounding might be cost effective.

Figure 2 – Basic Cross Sections Considered in the TTI Study [2]

Figure 3 – Parameters for Parabolic Rounding between the Shoulder and the Slope [2]

Questions about slope rounding arose in recent efforts to update the RDG, but no other research on the subject was found.

Vehicle Dynamics Analysis Applications
The concept of using vehicle dynamics simulation software to analyze run-off-road vehicle behavior and motion is gaining popularity. McMillan in 1998 [3] conducted simulation studies to analyze driver response to roadway departure. This analysis was used to evaluate the ability of collision countermeasure systems to prevent run-off-road accidents. Similar analyses have been performed by Pape in 1996 and Hadden in 1997 [4, 5] where they extend the VDANL (Vehicle Dynamics Analysis, Non-Linear) model of the vehicle/driver to assess the effectiveness of the countermeasure system. Other studies have focused on the results of an off-road crash. Day and Garvey [6] used EDVSM (Engineering Dynamics Vehicle Simulation Model) to perform rollover simulations. They discuss the limitations of rollover simulation to help on-road and off-road accident reconstruction. The use of simulation software for the analysis of off-road crashes has been very broad. Claar [7] concentrated on suspension modeling for improving off-road ride comfort whereas some studies have focused on friction influences in the case of water or snow on the road surface, as did Mancosu in 2002 [8].
There has been little research using vehicle dynamics simulation software to analyze and enhance the roadway design itself. In 2004, Dean L. Sicking and King K. Mak [9] presented a paper which suggested that efforts should focus on developing better vehicle and roadside safety hardware models. Also, they indicated that significant effort must be devoted toward improving the capability of computer simulations to model run-off-road crashes. The NCAC (National Crash Analysis Center) staff used the HVE simulation program to study the effect of edge drops for guardrail roadside barrier performance [10]. They used varied initial conditions and different vehicles analyze the behavior of the vehicle encountering various edge drops. The NCAC used VDA to trace two critical points on W-beam guardrails to determine barrier effectiveness relative to vehicle underride or vaulting. Similarly, the NCAC made extensive use of VDA to analyze the effects of median configurations on the effectiveness of cable barrier placement [11, 12, 13]. Lastly, a study conducted at Pennsylvania State University [14] showed the utilization of a commercially VDA software as a tool to analyze the effect of highway median width along with slope on vehicle stability. Brennan and Hamblin used CarSim package simulation programs where they ran thousands of simulations using different vehicles, median widths and slopes, steering conditions, and initial conditions to generate various metrics, including roll and lateral velocity. These data were used to provide a preliminary assessment of tradeoffs in the size and slope of median profiles versus the types of accidents observed.

RESEARCH APPROACH
In this analysis, vehicle dynamics simulations were performed to assess vehicles’ trajectories as they crossed from the traveled way to the side slope with varying shoulder and rounding treatments. Simulations were conducted with varied vehicles, speeds, and departure angles. A total of 400 VDA simulations were performed for this analysis.

Vehicle Dynamics Analysis
The tool used to undertake vehicle dynamics analyses in this effort was the commercially-available software package called CarSim [15]. CarSim is a non-linear vehicle simulation model (commercially-available via CarSim®) capable of analyzing vehicle-roadway interaction. CarSim has global acceptance by the world’s largest vehicle manufacturers because its physical/mathematical vehicle model provides a detailed description of the vehicle’s trajectory that considers the influence of weight, suspension system, and other factors. It provides capabilities of working with third party control development tools such as MATLAB/Simulink to extend its possibilities even further. CarSim can perform simulations up to 15 times faster than real-time, and could be fully automated with MATLAB scripts. For these reasons, CarSim is considered essential for running large numbers of cases.

CarSim provides a vehicle dataset enabling users to carry out simulations using pre-existing vehicles described by the type and body style. Vehicles from this dataset can also be edited by modifying their properties, which are divided into four different categories: Vehicle Size and Shape, Systems, Front, and Rear. Each category contains different datasets. In the Vehicle Size and Shape category, the “Sprung Mass” or “Aerodynamics” datasets can be found. In the former, it is possible to edit vehicle weight, CG (Center of Gravity) position, dimensions, inertia properties, and unsprung mass properties such as track width or spin inertia. In the latter, it is possible to change air mass density, frontal area, ambient wind speed and heading. Forces and moments are nonlinear tabular functions of aerodynamic slip, pitch, and ride height.

In the Systems category, it is possible to define parameters for everything concerning the power train, steering system, and brake system. It is possible to edit properties like engine model, transmission
model, brake torque, fluid pressure, steering column properties, or kingpin geometry. Most of those parameters are nonlinear functions. The Front category includes suspension and tire properties for the front of the vehicle. It is possible to select tires and bring modifications to forces and moments, rolling resistance, and thrust. Changes can be made to the suspension types, spring properties, jounces/rebounds, shock absorbers, compliance coefficient, or unsprung mass and inertia. In the Rear category, there are properties of tires and suspensions of the rear vehicle part. Again, it is possible to choose different tires and act on the same properties as the Front category.

**Slope Rounding Conditions**
This research involved a straightforward comparison of the results generated by the CarSim software package for varying slope rounding scenarios with different vehicles and departure speeds and angles. In each case, for consistent comparisons, the simulation inputs for each scenario were identical. The scenarios encompassed the following conditions:

- **Side Slope** – This analysis focused on situations where side slopes were 4:1, which is generally considered the limit for vehicle traversibility. Other analyses considered milder slopes, but the greatest effects were noted to the sharpest slopes.
- **Traveled Way** – Vehicle movement was begun on the traveled way. The initial conditions assumed that the traveled way was essentially flat.
- **Shoulder** – The shoulders with a 20:1 (5%) slope and no slope (flat) were used in the analysis. Shoulder widths of 0, 4, 8, and 12 feet were considered in the analysis.
- **Transition Section** – The transition section occurred between the shoulder (or traveled way for the no shoulder condition) and the 4:1 side slope. Transition sections included no rounding, and parabolic rounding over 4, 8, and 12 foot widths to conform to the parabolic profile used in the TTI study.
- **Side Slope Surface** – It was assumed that the transition section and the slide slope would have firm surfaces such that furrowing of the vehicle tires had a negligible effect on the trajectories.

These were all considered to occur on highway tangent sections.

**Simulation Control**
All simulations were run assuming there was no driver input relative to braking or steering. The vehicle was started at the same distance from the shoulder with the same velocity and angle. The road friction was made identical in all runs using a friction coefficient of 0.9. The simulation software provided dynamics analysis results every thousandth of a second as the vehicle traversed the shoulder, transition sections, and side slope.

**Vehicle Characteristics**
In this effort, two vehicles types were considered: a 2270P pick-up truck and an 1100C smaller car (Figure 4). Parameters derived from the VDA software defining suspension features, tire and wheel sizes, distribution of mass, and other properties were the same for all simulations. There was no attempt to consider the effects of varied vehicle loadings, non-standard vehicle components, or non-tracking departures from the roadway, although it is recognized that these can have an effect on vehicle trajectories. A reference point at 22 inches high was assumed for each of the vehicles as shown in Figure 4. (Since this analysis is not explicitly addressing interface issues, any height would have been acceptable.)
RESULTS

The analyses focused on 4:1 side slopes that were adjacent to typical 5% sloped shoulders. This set of conditions was selected to replicate the earlier study. Since it was expected that simulations for the analysis for milder slopes would yield similar results that would have a lesser degree of effect, they were not run.

The slope effect on vehicle trajectory is a function of the vehicle’s mass, geometry, and suspension system. In the vehicle dynamics analyses, the vehicle is considered a sprung mass. This implies that the suspension of the vehicle will absorb terrain effects that cause any sort of drop in the vehicle’s CG and the springs will progressively dampen this effect until equilibrium or steady state condition is achieved. This implies that the vehicle will move up and down while the damping action takes place.

The sample case analysis results are shown in Figure 5. The top graph in the figure depicts the terrain surface moving from the traveled way across the transition section and then the 4:1 side slope. The graph depicting the trajectory of the bumper point starts on the left side at the point that the vehicle starts to cross the shoulder. In the simulation shown in Figure 5, an 8 foot slope rounding transition was implemented. This surface is shown to scale as the solid black line. The dashed red line indicates the position of the trace point if the vehicle keeps all wheels on the surface and the suspension is in a steady state. Hence, the red line depicting the “normal” trajectory runs parallel to the surface with a constant 22 inch height. The solid blue line reflects the actual height of the trace point for the vehicle as it traverses the defined surface profile. VDA software was used to calculate the height of this curve for any position given the speed and departure angle for the vehicle. The effect of the suspension can be noted by the fact that this trace line moves above and below the reference line. The vertical variation at any point can be determined by scaling from the reference line. It is important to remember this effect in the context of the interface for any vehicle and a barrier placed on the slope.

A convenient means to analyze and compare vehicle dynamics effects is to normalize the reference line and trace paths. The bottom diagram in Figure 5 shows the normalized view for the above conditions. In the normalized view the variations in trajectory are indicated relative to a horizontal plane as opposed to the actual cross section surface. The blue line reflects the actual trajectory that would occur and the dashed line depicts the optimum scenario when the vehicle remains parallel to the surface. The blue line indicates that the difference in effects begins at the beginning of the transition section. The maximum effect is noted to occur adjacent to the rounded section of the slope. The difference between the reference line and actual trajectory curve in Figure 5 suggests about a 12 inch variation in the bumper.
reference point heights. That is also the area where the vehicle is first influenced by a change in the surface. The damping effect can be noted as the trace line moves towards the reference line as the vehicle traverses the slope. The wavy nature of the trace plot indicates the repeated compression and relaxation of the vehicle’s suspension system.

To investigate the influence of the slope rounding on vehicle trajectory, simulations with rounding widths of 0 (no rounding), 4, 8, and 12 feet were performed. These simulations assumed a flat shoulder leading to the 4:1 side slope and were conducted with the 2270P vehicle at 60 mph and a 25 degree approach angle. Figure 6 depicts the variations in the normalized vehicle trajectories for the different rounding widths. It can be noted from the plot that wider rounding sections lead to lower deviation from the optimum case where the vehicle remains parallel to the surface. The maximum variation was observed when there is no rounding. The variation is reduced to half when 12 feet of rounding is used.

It is useful to understand the factors that influence this slope rounding effect. The effects of vehicle speed, departure angle, and vehicle type were analyzed. For comparison of these factors, the simulations assumed a flat shoulder and an 8 foot rounding width leading to the 4:1 side slope. Figure 7 depicts the variations in the normalized trajectory of the trace plot related to vehicle speed. In this case, a 2270P vehicle traveling on a 25 degree departure angle is plotted for speeds of 60, 50, 40, and 30 mph. The solid blue line shows the trajectory for 60 mph. This trace plot shows the higher speeds have the most pronounced deviation from the optimum case. In the first cycle, there is more than twice deviation in the reference point at 60 mph compared to 30 mph. The plot also shows that the higher speed, the longer it takes for the vehicle to regain its steady state condition.

Figure 5 –Actual (Top) and Normalized (Bottom) Vehicle Trajectory Traces for a Sample Case

Figure 6 –Variations in the Normalized Vehicle Trajectories for Different Rounding Widths

Figure 7 –Variations in the Normalized Trajectory of the Trace Plot Related to Vehicle Speed
Figure 6 – Normalized Trajectory Traces for Various Rounding Widths

Figure 7 – Normalized Trajectory Traces for the 2270P Vehicle Leaving the Road at Various Speeds

Figure 8 depicts the effects of departure angle and speed for a 2270P vehicle traversing an 8 ft rounding width leading to a 4:1 slope. It can be noted that the same dark blue trace line represents the 25 degree departure at 60 mph. By contrast, the solid lighter blue reflects a much smaller effect for a 15 degree departure at 60 mph. The same general effect, although less pronounced, is noted by the dashed lines.
which represent the effects for 25 and 15 degree departures at 40 mph. The shallower departure angles result in considerably less variation in the height of the reference point.

Figure 8 – Normalized Trajectory Traces for the 2270P Vehicle Leaving the Road at Various Angles

Figure 9 – Normalized Trajectory Traces for the 2270P and 1100C Vehicles
Figure 9 shows the effect for different vehicle types. The heavier vehicle (2270P), depicted by the dark blue trace line, deviates more from the optimum trajectory than the lighter vehicle (1100P), depicted by the green trace line. The dashed lines show the effects for these two vehicle types when the speed is 40 mph. They indicate a similar relationship for the lower speeds between the vehicle types.

![Figure 9](image1.png)

**Figure 9 - Normalized Trajectory Traces for the 2270P Vehicle for Various Shoulder Widths**

The effects of varying shoulder width were analyzed by comparing the results for simulation of a 2270P vehicle departing the traveled way at 25 degrees and 60 mph. These results are shown in Figure 10. The figure shows the influence of shoulder widths varying from 0, 4, 8, and 12 feet for no rounding. The dashed red line indicates the trace plot for the optimal case. A slope of 20:1 (5%) was used for the shoulder. The greatest variation is noted for the no shoulder condition. The vehicle is coming off the crown of the pavement and immediately interfacing the 4:1 side slope. The effect is reduced where 12 foot shoulders exist.

**Figure 10 – Normalized Trajectory Traces for the 2270P Vehicle for Various Shoulder Widths**

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**SUMMARY AND CONCLUSIONS**

In this effort, the terrain effects on vehicle trajectories were determined using vehicle dynamics analysis tools. This effort focused specifically on the use of “slope rounding” to provide a smoother transition from the shoulder to the side slope. Slope rounding eliminates the hard break point created by the intersection of the shoulder slope and the side slope. VDA tools allowed the entry of data for specific vehicles that reflected differences in size, weight, suspension features, and other factors as well as the conditions of the cross-sectional surface for various conditions under which a vehicle can leave the roadway (i.e., speed, angle). The comparison of a point on the front of the vehicle provided a convenient means to compare the effects. The trace plots generated as the vehicle traverses the various cross sections reflected the effects of the suspension and provided useful insights into effects on the vehicle’s interface area relative to the surface. The latter aspect is a critical metric for determining the most effective lateral placement of the barrier.
The analysis used the definition previously established for “optimal rounding” to be that surface transition condition where all the vehicle’s wheels are in contact with the ground and that the suspension system is neither compressed nor extended to provide a reference line. The analysis was undertaken for the typical limiting slope condition, namely 4:1. A number of different cross sections and road departure scenarios were simulated. From these simulations, it was observed that:

- The vehicle trace does not usually follow the optimal reference line due to variations that are a function of the intrinsic features of the vehicle, the speed and angle that it leaves the traveled way, and the specific cross section surface of the shoulder, transition section, and side slope.
- Where there is no rounding (i.e., a hard break point at the intersections of the shoulder slope and side slope) the vehicle or at least some of its tires can become airborne. When the vehicle lands (encounters the surface), the suspension compresses to absorb the energy. This behavior results in reference plots that trace above and below the optimal reference line.
- Given that barriers typically have a constant height, there is a potential vehicle-to-barrier interface problem when the interface trace does not coincide with the barrier’s engagement area because it is above or below the reference line.
- The trajectory plots show a greater tendency for vehicle to become airborne for heavier vehicles and higher speeds.
- Trajectories are higher for the sharper departures angles and higher speeds.
- The trajectory plot more closely tracks the reference line when slope rounding is provided. This suggests a benefit for vehicle stability and reduced potentials for problems with barrier interface.
- VDA tools provide a useful means to analyze the effects of various slope rounding options in the context of other road features.

It can be readily noted that there would be a challenge to finding slope rounding designs that would provide equivalent benefits for all vehicle types and road departure scenarios. The implications of these results are that slope rounding can be beneficial in reducing the effects on the suspension of errant vehicles. It may be prudent to use slope rounding to minimize the effects for heavier vehicles or sharper slopes. This would be consistent with the TTI study conclusion that slope rounding would not be cost-effective for 6:1 side slopes. It is important to remember that some degree of “natural” slope rounding occurs over time due to settlement and erosion.

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