



# Technical Summary

NCAC 2007-T-002

Nov 2007

## Effects of Shoulder Drop-Off on W-Beam Guardrail Performance

### Background:

Recent efforts by the FHWA determined that w-beam guardrail height has a significant effect on barrier effectiveness(1). Some agencies only resurface the travel lanes on highways (and not the shoulders) to stretch paving dollars. This results in a drop-off from the travel lanes to the shoulder that influences the effective height of guardrail adjacent to the shoulder. This effort analyzed the dynamics of a vehicle as it leaves the roadway and drops the distance equal to the thickness of the resurfacing layer. There is initially compression of the front suspension, followed by a lift when the springs rebound. These effects change the height of the vehicles front end, and thus the effectiveness of the interface with the guardrail. Potentially, the vehicle's bumper would not have full engagement with the guardrail that could lead to vaulting or underride of the vehicle. The vehicle's suspension may also be exerting an upwards or downwards force at the moment of interface, further complicating the interaction between the vehicle and barrier.

### Approach:

The NCAC staff undertook a two-pronged approach to the analysis of the effects of shoulder drop-offs. The first involved analyzing vehicle dynamics to determine how vehicles interfaced with standard w-beam guardrail barriers [G4(1S)]. The effectiveness of these barriers is predicated on an appropriate interface between the vehicle and barrier, given the design and placement of the barrier and the response of a vehicle's suspension system relative to the drop-off. If a vehicle's bumper does not interface with the barrier properly, then the vehicle will be more likely to vault over the barrier or underride it.

For this first phase of the work, the Human Vehicle Environment (HVE) analysis program was used. HVE is a robust, commercially-available software package which accurately

predicts vehicle dynamics as they traverse varying terrain conditions, such as leaving the traveled way and passing over a shoulder drop-off (2). The software considers the angle, speed, and weight of the vehicle for these conditions in computing the response of the suspension system. This software is particularly useful for tracing specific points on the vehicle – points on the front of the vehicle, for example -- to allow assessment of how the vehicle interfaces a roadside barrier and thus, the potential for a vehicle to “vault” or “underride” a barrier.

The second part of the analysis used crash simulation to look at the effects of potential underride events. The crash simulations provided insights on the forces that would be exerted on the barrier and whether these would result in failure of the barrier to safely redirect a vehicle with particular emphasis on the likelihood of post snagging. Severe decelerations associated with snagging have serious effects on the safety of the vehicle occupants.

For crash simulation, the more complex LS Dyna software was employed. LS Dyna is a commercially-available, finite element model-based tool that allows the effects of impact forces to be analyzed for crashes (3). It was used to analyze the potentials for the small vehicle to underride the guardrail and/or snag on the posts

These analyses were both undertaken following crashworthiness criteria defined in NCHRP Report 350 for roadside features. Therefore, the efforts involved analysis of impacts with a 2000 kg pick-up truck (Chevy C2500) and an 820 kg small car (Honda Civic or Geo Metro).

### Drop-off & Impact Conditions:

The study analyzed the effects of shoulder drop-off on guardrail performance for varying edge drop and shoulder width conditions (as noted in

Figure 1). Specifically, the analysis considered the following drop-off conditions:

- Pavement overlay drops of 2, 3, 4, and 5 inches (50, 75, 100, 125 mm)
- Guardrail offsets from the travel lanes of 2, 3, 4, and 5 feet (600, 900, 1200, and 1500 mm)

It was assumed for all cases that the pavement overlay edge would have a slope of about 45 degrees and the shoulder and roadside slope would be near level.

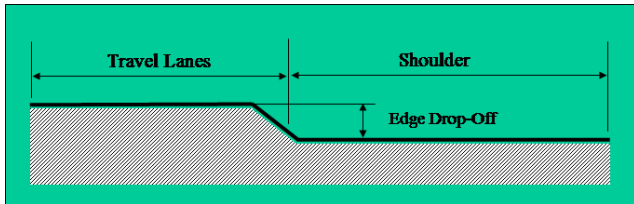


Figure 1 – Shoulder drop-off conditions.

The analysis was conducted for a wide range of impact conditions:

- Road departure angles from 5 to 45 degrees in 10 degree increments
- Road departure speeds of 30, 40, and 60 miles per hour ( about 50, 70, and 100 km/hr)

It was discovered at the outset of the analysis that different practices exist relative to how guardrail height is measured. The AASHTO Roadside Design Guide (RDG) prescribes that guardrails should be mounted with their center points at 22 inches (550 mm) above the base reference. The base reference for the height of guardrail was found to use one of two basic referencing schemes, namely:

- Edge Reference – Guardrail height is measured relative to the pavement surface at the edge of the traveled lane.
- Low Reference – Guardrail height is measured relative to ground height at the location of the barrier.

The RDG suggests the use of the “edge” reference, but the practice in many agencies is to use the “low” reference because it is easier for field crews to measure. To account for this difference, the analysis was undertaken for each reference scheme.

For this study, two critical points on the w-beam guardrail were defined for determining barrier effectiveness as noted in Figure 2. If the point at the center of the vehicle’s bumper (Figure 3) contacted at or above the top of the upper guardrail hump, it was considered likely to vault over the barrier. Similarly, if the point on the

bumper of the small car contacted at or below the top of the lower guardrail hump, it was considered likely to underide the barrier.

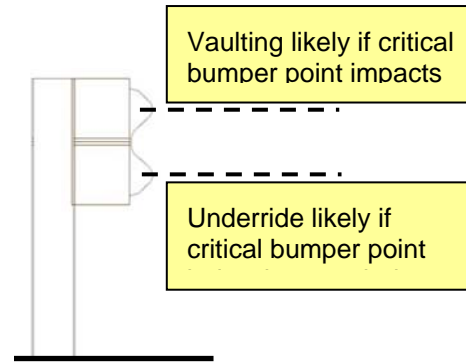


Figure 2 – Barrier effectiveness criteria.

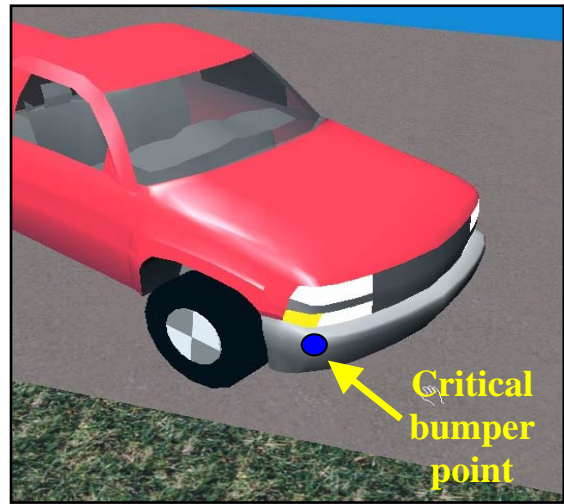


Figure 3 – Critical bumper point for the pick-up.

Figures 4 and 5 depict the effectiveness criteria for the edge and low reference schemes for the drop-off conditions and the guardrail placement locations analyzed.

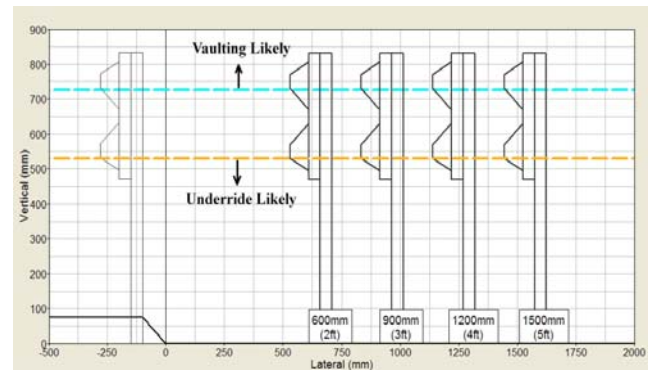


Figure 4 - Edge reference scheme and criteria for effectiveness.

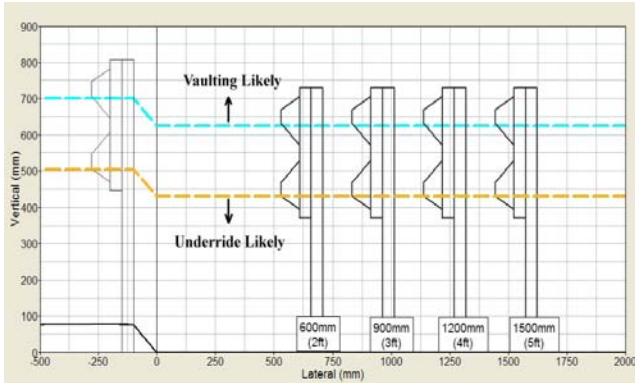


Figure 5 – Low reference scheme and criteria for effectiveness.

It should be noted that the experience testing pickup trucks has shown that the pickup will not underride a standard guardrail installation. In the course of this study, therefore, only vaulting was considered a failure condition for the vehicle dynamics analysis of the pickup truck impacting the guardrail. Similarly, experience with small car impacts into guardrail installations has shown that vaulting is not an issue for the small car hitting a properly installed G4(1S) guardrail. For this project’s small car vehicle dynamics analysis, only underride was considered a failure condition.

### Vehicle Dynamics Analyses:

The first phase of the analysis involved multiple runs of the HVE vehicle dynamics software to trace the critical point near the center of the vehicle’s bumper as it left the traveled way and traversed a pavement drop-off. Figure 6 shows a view from a typical HVE simulation using the Chevy C2500 pick-up truck.

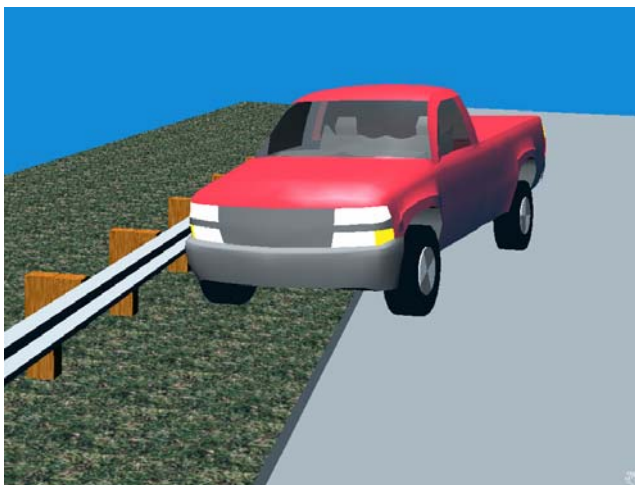


Figure 6 – Typical view of the C2500 pick-up prior to interfacing a guardrail after passing over a shoulder drop-off.

A total of 240 vehicle dynamics analysis runs were made. These were divided into 16 groups, with each group representing a combination of one of two vehicles, one of four drop heights, and one of two rail height measurement references. Each group was composed of 15 analysis runs, representing 5 departure angles times 3 impact speeds. The crash force effects on the guardrail were not analyzed. Only the vertical position of the critical bumper point relative to the guardrail at the instant of impact was considered.

The results of these runs were summarized in a series of plots of the positions of the trace point. For example, Figure 7 shows the plot of trace points for one group of impact conditions. In this case, the vehicle is the pickup truck, the drop height is 2 inches, and the low reference criterion is used (depicted by the dashed line). Each colored line is the trace of the critical bumper point, as the vehicle leaves the road surface, crosses the shoulder, and impacts the barrier, for one combination of departure angle and speed.

All four barrier placement offsets are shown on each plot. (So even though only 240 analysis runs were made, a total of 960 different conditions were considered in this phase of the work.) The key observation for each condition is the position of the critical bumper point relative to the guardrail at the instant the vehicle contacts the barrier. For these conditions, it appears that there is some likelihood of vaulting for the low reference criteria. This is indicated by some of the trace profiles being above the dashed line that represents the low reference criteria.

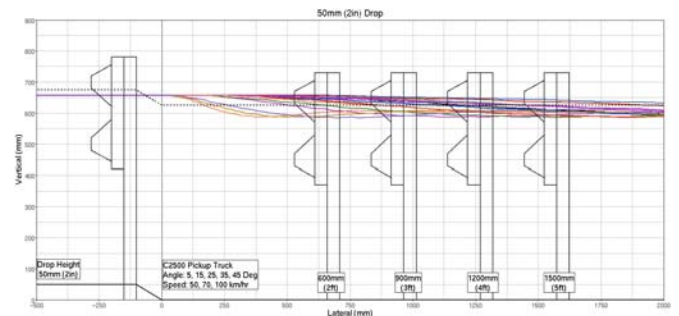


Figure 7 – Summary of trace plots for the pick-up truck under varying impact conditions for a 2 inch drop with a low reference.

Figure 8 shows the results from the pickup truck traversing the most severe edge drop – 5 inches. For a 5 inch drop at all barrier offset locations and all impact angles and speeds with the pick-up truck, it appears that there is a low likelihood of

vaulting when the edge reference is used in measuring barrier height since all of the trace curves fall below the dashed reference line.

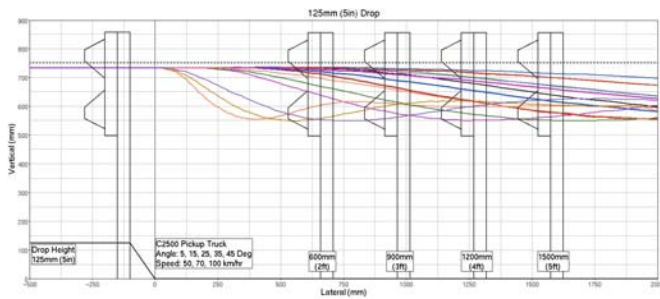


Figure 8 - Summary of trace plots for the pick-up truck under varying impact conditions for a 5 inch drop and edge reference.

In the analyses, forty-eight trace plots were generated for varying vehicles, impact conditions, and reference schemes. A range of effects was noted. In an attempt to discern a pattern of effects that might lead to the development of useful guidance, a summary graph for each drop condition and reference position was prepared. Each summary graph displays an envelope incorporating all of trace curves for the pick-up truck, and a second envelope enclosing the trace curves for the small car. For example, the two extremes of the analysis, the 2 inch drop and 5 inch drop, are shown in Figures 9 and 10. In each summary plot, the “red” envelope encloses all of the trace curves for the pick-up truck while the “blue” envelope depicts that for the small vehicle.

The differences in barrier effectiveness relative to the low & edge reference criterion can be noted by looking at pairs of these summary diagrams.

It can be seen in Figure 9 that vaulting or under-riding were unlikely for either vehicle for the 2 inch drop, because of limited “bounce” in passing over the drop-off using the edge reference criterion. In Figure 10, it can be noted that part of red envelope lies above the upper hump in the guardrail, suggesting that under some conditions, the pick-up would be likely to vault for the low reference criterion.

For the most severe edge drop considered -- 5 inches -- the trace envelopes are expanded and the potential for an unacceptable interaction between vehicle and barrier is increased, as shown in Figures 11 and 12.

The influence of the barrier height measurement reference position also becomes more apparent.

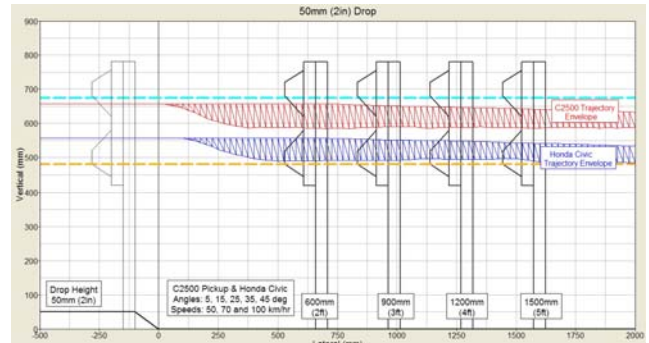


Figure 9 – Trace summary envelopes for the pick-up & small car for a 2 inch drop-off with an edge reference.

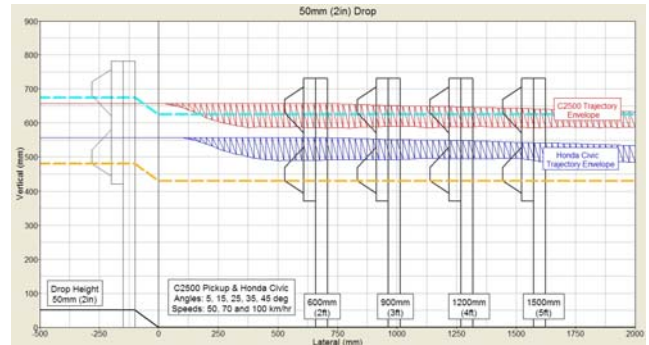


Figure 10 - Trace summary envelopes for the pick-up & small car for a 2 inch drop-off with a low reference.

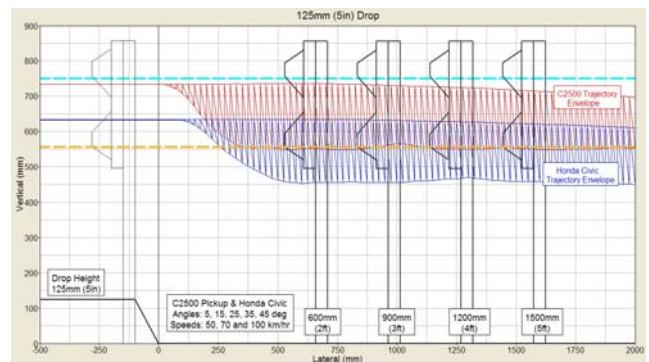


Figure 11 - Trace summary envelopes for the pick-up & small car for a 5 inch drop-off with an edge reference.

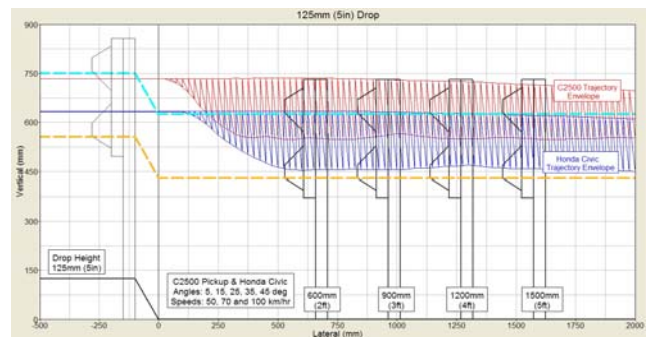


Figure 12 - Trace summary envelopes for the pick-up & small car for a 5 inch drop-off with a low reference.

In figure 11 clearly barriers installed using an edge reference would not be likely to produce vaulting of the pickup truck, but the small car would be prone to underride. In Figure 11, using the low reference, there was more potential for larger vehicles to vault the barrier, but there would not be problems for the small car. The critical nature of the barrier height measurement reference scheme is apparent.

In summary, the vehicle dynamics analysis revealed that:

- The effects of edge drops vary by vehicle type, speed, and impact angle
- The effects increase with the degree of the drop, but diminish with distance from the drop.
- As the height of the edge drop increases, the number of conditions likely to produce an unacceptable result increases.
- For drops of 2 inches, under the edge reference scheme, both the pick-up and the small car interface effectively with the barrier. But when a low reference is used, there are some conditions under which the pickup truck is likely to vault the barrier.
- For drops of 3 inches or more there is likely to be vaulting with larger vehicles (pick-up trucks) for the low reference. The small car however, would effectively interface the barrier under the low reference the effects of edge drops onto the shoulder vary by vehicle type, speed, and impact angle.

## Crash Simulation Analyses:

The viability of using finite element models and crash simulations to analyze barrier effectiveness has been demonstrated in various studies (1, 4, & 5). Crash simulations previously undertaken to evaluate the impact of guardrail height on barrier effectiveness provided the models for the current effort. In Marzoughi and Kan's guardrail height analysis(1), seven rail height variations were evaluated in simulated crashes with the C2500 pick-up truck. Full-scale crash tests validated the results of the simulations for four different rail heights, thus providing confidence that the influence of rail height can be modeled. The validated model was used to extend the analysis of shoulder drop-off effects for impacts by a small car.

For the shoulder drop analysis, additional LS Dyna simulations were undertaken to assess the implications of rail height and shoulder drop on the potentials for underride and post snagging by the small vehicle. Since these potentials are affected by shoulder drop and more critical for higher barriers, guardrail heights 3, 4, and 5 inches higher than standard were simulated with the small car. While the vehicle dynamics analysis used a Honda Civic model available with the HVE software, an FE model of that vehicle does not exist, so the NCAC GeoMetro model was used. These are considered comparable small cars. Impacts at 62 mph (100 kph) and an angle of 25 degrees were simulated. The basic interface considered in the crash simulation is shown in Figure 13.

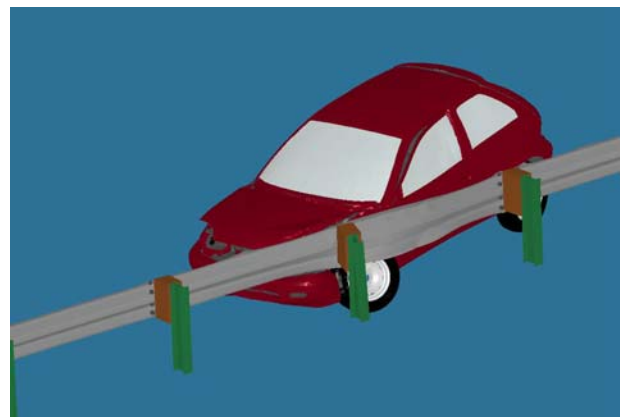


Figure 13 – LS Dyna model of the W-beam guardrail and the GeoMetro small car showing guardrail deflection but no snagging.

The crash simulation analyses provided deceleration measures and crash animations that served as the basis for the evaluations. In summary, the crash simulations revealed that:

- At the standard guardrail height a small car (GeoMetro) is safely redirected. There appears to be no snagging on the guardrail posts since the rail is at a height that there is good interaction with the vehicle bumper.
- Crash simulations for the case where the barrier is 4 inches higher than standard shows more underride, but no serious snagging problems were detected.
- For guardrails 5 inches higher than standard, significant snagging of the small car was noted.
- Deceleration forces would be within acceptable limits for the crashes conditions simulated.

These results are based upon an analysis of general conditions. The study did not consider the effects of road superelevation, the nature of the drop-off cross section i.e., angle & width), the actual condition of a vehicle's suspension system, or the implications of vehicle loading. These would potentially alter the results, but the results are consistent with barrier evaluation practices and useful for comparative analysis.

### Implications for Current Practice:

The findings suggest that agencies should:

- Limit edge drops in repaving.
- Assess the effect of the barrier height reference position they have adopted.
- Alert field crews to recognize the importance of shoulder drop-off to barrier performance, so that appropriate maintenance of the guardrail and/or shoulder can be provided.
- Recognize that the "bounce effect" will make an already low rail more vulnerable to vaulting.
- The higher profile of the proposed new pick-up truck in the upcoming update to the roadside safety hardware crashworthiness standards (NCHRP Report 350) will likely increase the propensity of the pickup truck to vault the barrier.
- These aspects need to be addressed in clarifications in the RDG along with rail height issues.

Since these results are focused primarily on the interface between vehicles and the barrier, they are transferable to other types of barriers.

### References:

1. Marzougui, Mohan, & Kan, "Evaluation of Rail Height Effects on the Safety Performance of W-Beam Barriers," NCAC 2007-R-003,
2. HVE Software, Engineering Dynamics Corporation, <http://www.edccorp.com>.
3. Hallquist, J. O., LS-DYNA User's Manual, Livermore Software Technology Corporation.
4. Marzougui, D., Zaouk A., and Kan, C.D., "Development of a C-2500 Pick-Up Truck Model for Roadside Hardware Impact", Transportation Research Board Annual Conference, 1996.
5. Marzougui, D., Kan, C.D., and Eskandarian, A, "Safety Performance Evaluation of Roadside Hardware Using Finite Element Simulation", ASCE Engineering Mechanics Conference, Austin, Texas, May 2000.

### For More Information:

See the NCAC Website ([www.ncac.gwu.edu](http://www.ncac.gwu.edu)) for more information including:

- A Power Point file providing the trace plots & animations.
- Materials from the guardrail height analysis efforts.
- Information on other NCAC efforts

Or, contact:

- FHWA Roadside Safety Team  
Dr. Ken Opiela, PE (Team Leader)  
202-493-3371  
[kenneth.opiela@fhwa.dot.gov](mailto:kenneth.opiela@fhwa.dot.gov)
- NCAC Staff  
Dr. Steve Kan, Director  
703-726-8511  
[cdkan@ncac.gwu.edu](mailto:cdkan@ncac.gwu.edu)  
Dr. Dhafer Marzougui  
703-726-8532  
[dmarzoug@ncac.gwu.edu](mailto:dmarzoug@ncac.gwu.edu)

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