Evaluating W-Beam Guardrail Height Tolerances

Background:
W-beam guardrail may be the most widely used type of roadside safety hardware. It is intended to safely redirect an errant vehicle from fixed hazards on the roadside. It is designed to absorb crash energy by deflection in the rail, the posts moving in the soil and breaking or deforming while the rail remains continuous and in contact with the vehicle. For the guardrail to function as intended, its height becomes critical. The Roadside Design Guide (RDG) recommends that the top of the W-beam barrier be 27 inches above edge of pavement with a tolerance of +/- 3 inches, but it is not hard to find cases where the guardrail height is not within this range. Variations in rail height, either too low or too high, can occur as a result of poor installation, settlement, and/or successive overlays of the pavement.

The effect of the rail height relative to the vehicle has become more critical in recent years for three reasons. The first relates to changes in the nature of vehicles (i.e., fleet) operating on U.S. highways. The use of larger vehicles such as “Sport Utility Vehicles” (SUVs) and pick-up trucks has been in the rise in the U.S. since the late 1980’s and they now account for more than half of the vehicles in the fleet. These vehicles have higher bumpers and centers of gravity. These features make them more susceptible to overriding or rolling over standard barriers. Most w-beam barriers, were originally designed for standard-sized sedans, and thus could be less effective in engaging and redirecting SUVs and pickup trucks. The second reason is that road resurfacing has become a frequently used as a pavement management strategy, often without milling to lower the pavement before the addition of a new layer of material. The effect is a relative lowering of the height of the barrier. When agencies are faced with limited funds, they often do not make adjustments to the heights of barriers along resurfaced sections. The third reason relates to the limited attention to tolerances in current installation and maintenance practices. While this may seem hard to believe, remember that analysis and certification testing focuses only on the standard height installations. There has been no known testing to determine the degree of effect on safety performance for rail height variations until recently. Further, differences even in the manner height is measured makes it difficult to assess the situation.

In this study, the safety performance of w-beam guardrails is evaluated relative to the effect of variations in the rail height on its adequacy in redirecting the striking vehicle, particularly to keep the vehicle from vaulting the barrier. This research was conducted to help DOTs understand the margin of safety associated with various rail heights to be able to make appropriate decisions in routine maintenance and rehabilitation efforts.

Figure 1 – Typical w-beam guardrail hardware.

Approach:
The objective of this study was to investigate the effect of rail height on the safety performance of G4(1s) w-beam guardrail systems. The study involved three steps. In the first step, an existing, detailed finite element model of the G4(1s) guardrail system was adapted for the analysis of rail height. This model incorporated the details of the rail, connections, the post, the blockout, and the soil in which the post was embedded. [1] This w-beam guardrail model had been validated against data from full-scale crash tests. In the second step of the study, the validated model served as the basis for four additional models of the G4(1s) guardrail to reflect varying rail heights. In two of the four models, the rails were raised 40 and 75 mm (1.5 and 3 inches). In the other two models, the rails were...
lowered 40 and 75 mm. Simulations with these four new models were carried out and compared to the first simulation to evaluate the effect of rail height on safety performance. The third step of the study consisted of performing new full-scale crash tests with the guardrail at standard height and 60 mm (2.5 inches) lower to further validate the results. The data from the crash tests validated the simulation results.

**Guardrail Modeling & Validation:**
A finite element model of the w-beam guardrail system for this study was adapted from the developed in a previous study [1]. The previous efforts demonstrated that an accurate representation of w-beam guardrail could be formulated and further that it could be effectively used to analyze design feature impacts on the safety performance of the barrier. All components of the guardrail system were incorporated in the model (Figure 2). This included the w-beams, posts, blockouts, and bolts. This ensured the correct mass, inertia, and stiffness of the different parts of the model. The soil was also explicitly modeled using solid elements in a soil mesh to simulate the post/soil interactions. The geometry of the bolts was found to affect the system behavior and was incorporated in the model.

![W-Beam guardrail model](image)

**Figure 2 – W-Beam guardrail model.**

The guardrail system used in this study is based on the modified G4(1s) design. The rails in this system are made up of standard 12-gauge w-beams with lengths of 3.807 m (12.5ft). The rails are supported using W150x12.6 (W6x9) steel posts. These posts are 1830 mm (72in) length and embedded 1100 mm (43.3in) into the ground. Routed wood blockouts are placed between the posts and the w-beam rails and have dimensions of 150 mm x 200 mm x 360 mm (6 in x 8 in x 14 in). The system level model of the G4(1s) guardrail system is modeled to have a total length of 53.3m (175 ft) and it is anchored at both ends using a standard Breakaway Cable Terminal (BCT). The system consists of 29 posts and 14 w-beams.

Once the adaptations to the guardrail model were completed, it was combined with a vehicle model to simulate the setup for Test 3-11 (i.e., 2000P, 100 km/hr (62 mph), 25 degrees test) as recommended in the NCHRP Report 350.

**Evaluating Guardrail Height:**
Four additional versions of the model were created to reflect varying guardrail heights. The rail heights in these simulations, measured from ground level to the center of the W-Beam rail were as follows: 475, 510, 550, 590, and 620 mm (rounded to 18.5, 20, 21.5, 23, and 24.5 in). The base model reflected the standard height at center (i.e., 550 mm or 21.65 inches). This implied a top of rail height at 706 mm or 27.75 inches. All other features of the model were identical. These models were used to evaluate the performance of the guardrail system for varying heights with a focus on the potential of the vehicle to underride or override the guardrail and its capacity to remain upright during and after collision. These are typically the primary criteria in evaluating guardrail systems. Occupant impact velocity and ridedown acceleration were also derived from the simulations, but were considered less critical since they were below the recommended limits.

The tolerances for the guardrail height specified in the Roadside Design Guide (RDG) are ±75mm (±3in). The standard rail height, 550mm (21.5 in) from ground level to center of the guardrail, is specified but little testing has been done to determine the degree of effect on safety performance for these tolerance limits.

Crash simulations were conducted for installation on level terrain with the top edge of the w-beam rail at a 27.5 inch height as the base case with height variations of -3.0, -1.5, and + 1.5 inches. The simulation results clearly indicated that the pick-up would vault the barrier when it was 3 inches low in impacts at 62 mph and 25 degrees. A model of the Chevy C2500 pick-up truck (2000P vehicle) was used in the simulations. A less extreme vaulting occurred when the barrier was only 1.5 inches low for the same impact conditions. No vaulting was noted for impacts at standard heights or above.

The visual results from the simulations are shown in Figures 3 to 5 which depict the sequence of...
events in the crash between the pick-up truck and guardrail. Figure 3 shows the pick-up truck climbing the barrier and vaulting to the opposite side when the rail is at 475 mm or about 3 inches low. Figure 4 shows a similar outcome although the vehicle travels on top of the rail for some distance when the rail is just 40mm or 1.5 inches below standard. In both cases, the guardrail is considered to be within tolerance. Figure 5 shows the results for impacts with the guardrail at standard height. At the standard height and the two cases were an increased height was simulated, the vehicle was effectively redirected and the barrier was able to meet all NCHRP Report 350 recommendations.

The results indicate that reducing the height by as little as 40 mm (1.5 in) could hinder the ability of the barrier to redirect pickup trucks and large SUVs. Summary results from these simulations are given in Table 1.

Table 1: Simulation results summary.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Height to Center of Rail (mm/inches)</th>
<th>475</th>
<th>510</th>
<th>550</th>
<th>590</th>
<th>610</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant Impact Velocity (m/s)</td>
<td>-4.68</td>
<td>-6.12</td>
<td>-7.44</td>
<td>-8.28</td>
<td>-8.47</td>
<td></td>
</tr>
<tr>
<td>Occupant Ridedown Acc. (g)</td>
<td>-3.98</td>
<td>-3.59</td>
<td>-5.27</td>
<td>-8.69</td>
<td>-13.92</td>
<td></td>
</tr>
<tr>
<td>Maximum Barrier Deformation (m)</td>
<td>0.228</td>
<td>0.511</td>
<td>0.637</td>
<td>0.560</td>
<td>0.455</td>
<td></td>
</tr>
<tr>
<td>Max Roll Angle (deg) – 0.5 sec duration</td>
<td>10.82</td>
<td>17.78</td>
<td>8.40</td>
<td>8.37</td>
<td>7.83</td>
<td></td>
</tr>
<tr>
<td>Maximum Yaw Angle (deg) – 0.5 sec duration</td>
<td>8.22</td>
<td>20.71</td>
<td>35.32</td>
<td>37.71</td>
<td>36.82</td>
<td></td>
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</tbody>
</table>

Full-Scale Crash Tests:

To validate the simulation results, two full-scale crash tests were performed at The Federal Highway Administration (FHWA) Federal Outdoor Impact Laboratory (FOIL) [3]. The tests consisted of a 2000P vehicle (Chevrolet C2500 pickup) impacting the w-beam guardrail at 100 km/hr impact speed and 25 degree impact angle. Both tests were identical except for the rail height. In the first test, the rail height relative to the vehicle was similar to the standard rail height simulation. In the second test, the rail was lowered by 60 mm (2.5 in). The effective rail heights for the two tests, from ground level to center of the rail, were 550 mm (21.5 in) for test 04002 and 490 mm (19 in) for test 04003. When measured from ground to the top of the rail, these heights would be equivalent to 700 mm (27.5 in) for test 04002 and 650 mm (25 in) for test 04003. The results from the first test are shown in Figure 6. The results from the second test are shown in Figure 7.

The results from the first test showed the barrier redirecting the pickup truck vehicle when the rail is set at the standard height. In the second test, the vehicle overrode the barrier and rolled over upon impact with ground surface behind the barrier. These results confirmed the finite element simulation results. Summary results from the two full-scale crash tests are listed in Table 2.

Two full-scale crash tests were undertaken to validate the crash simulation analyses. These crash tests used a C2500 pick-up truck impacting the w-beam guardrail at 62 mph and 25 degrees just as in the simulations. The full-scale tests were noted to be very similar to the vaulting and vehicle stability performance noted in the simulations. These similar results suggest that the crash simulation runs provide a very good approximation of real performance. Further, it suggests the current tolerance limits need to be revised.

Table 2: Test Results Summary

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Test 04002</th>
<th>Test 04003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant Impact Velocity (m/s)</td>
<td>-7.11</td>
<td>-7.52</td>
</tr>
<tr>
<td>Occupant Ridedown Acceleration (g)</td>
<td>-9.16</td>
<td>-10.05</td>
</tr>
<tr>
<td>Maximum Roll Angle (deg)</td>
<td>13.5</td>
<td>23.4</td>
</tr>
<tr>
<td>Maximum Yaw Angle (deg)</td>
<td>40.1</td>
<td>42.8</td>
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</table>

Summary & Conclusions:

Computer simulations were performed to evaluate the effect of guardrail height on the safety performance of G4(1S) barrier systems. First, a finite element model of the guardrail system was created and validated against full-scale crash tests performed by the Texas Transportation Institute. Next, the model of the G4(1s) guardrail system was modified to investigate five different rail heights: a standard height, two lower heights, and two higher heights. Simulations results showed that when the w-beam guardrail is lower than the standard height, there is a high risk of vehicle overriding the guardrail and/or rolling over. A higher guardrail height, on the other hand, would redirect the vehicle and meet all the NCHRP Report 350 evaluation criteria.
Two full-scale crash tests were conducted to validate the simulation results. The first test showed the barrier redirects the vehicle when the rail is set at the standard guardrail height. The second test showed that lowering the height by 60mm (2.5”) caused the vehicle to override the barrier. This is in agreement with the simulation results.

The simulation results indicate that reducing the height by as little as 40 mm (1.5 in) could hinder the ability of the barrier to redirect pickup trucks and large SUVs. Considering the fact that bumper height could also vary among the vehicles, reducing the tolerance on the rail height and setting the minimum height to be equal to the standard height, 550 mm (21.5 in) to center of the rail or 700 mm (27.5 in) to the top of the rail would lead to better barrier performance when impacted by pickup trucks and large SUVs.

**Implications for Current Practice:**
The simulation results indicated that the effectiveness of the barrier to redirect a vehicle is compromised when the rail height is lower than the standard height, but with current tolerance limits. This has come about because there has been an increase of vehicles with higher centers of gravity in the fleet. Such vehicles have been estimated to account for almost 50% of the vehicles on the road. While this increase has been occurring the effective height of guardrail in many instances has compromised due to higher pavements due to resurfacing, normal settlement, and low, but within tolerance, installations.

The results of this research have been shared with the AASHTO Technical Committee on Roadside Safety with the recommendation that they consider modifying the tolerance parameters in the Roadside Design Guide. In the interim, agencies should consider following a more stringent set of guardrail height tolerances in their construction and maintenance practices.

**References:**

**For More Information:**
See the NCAC Website ([www.ncac@gwu.edu](http://www.ncac@gwu.edu)) for more information available for downloading including:
- A powerpoint file providing the crash test results and animations generated from the simulation analyses.
- The reports & technical summaries generated in this research.
- Information on other NCAC efforts

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Figure 3: Simulation results from the 475 mm (3 inches low rail height case.)
Figure 4: Simulation results from the 510 mm (or 1.5 inches low) rail height case.
Figure 5 - Simulation results from the 550 mm (standard Height) rail height case.
Figure 6 - Full-scale crash results from Test 04002 for Standard Height - Isometric View.
Figure 17 - Full-scale crash results from Test 04003 (2.5 inches low) - Isometric View.