Background
Barriers are designed and tested to specific design parameters and variations from the design requirements can influence their performance. For this reason, there are tolerances set for the installation and maintenance of w-beam guardrails. These installation guidelines call for a rail height of 27.5 inches plus or minus 3 inches. Despite the efforts to comply with the guidelines, a myriad of factors pose challenges to keeping barriers at the designated height. Factors that influence the effective height of a guardrail include incorrect installation, ground settlement, damage from nuisance hits, and roadway resurfacing. Recent research has shown that guardrails even an inch lower than the guideline height result in a greater propensity for vaulting by the larger vehicles on the road (e.g., 2000 kg pick-up trucks) [1].

Since safety is a primary concern of public agencies, many have sought economical options to correct guardrail height problems. One option that has been proposed (and even used in some agencies) is to simply raise the blockout and rail to a higher height without lifting the post. This allows the blockout to extend above the top of the post. Since this “fix” has not been crash tested, there are concerns that it may represent an unacceptable option.

Objectives & Approach
The objective of this study was to investigate the performance of the G4(2W) w-beam guardrail with 3” vertically raised blockouts, for varying terrain profiles. This was done by using computer models to represent the G4(2W) system with blockouts in standard configuration, raised three inches vertically, and connected to the posted using one or two bolts. The simulation analysis was undertaken using previously developed and validated finite element models of the C2500 pick-up truck and the w-beam guardrail systems. Various validations of the model previously conducted involved comparison of simulation results to the results of full-scale tests. In the various validations the computer models were found to provide stable results, and are sensitive to variations in design over a variety of crash conditions. Since these models had been previously validated quite rigorously, no further validations were undertaken for this effort. There was high confidence that the model would provide viable results.

The option to raise the blockout was subject to the basic “strength” test for longitudinal barriers outlined in NCHRP Report 350. Test 3-11 involves a crash of a 2000 kg pick-up truck (2000P vehicle) at a velocity of 100 km/h (62 mph) at an impact angle of 25 degrees (see Figure 1). Crash simulation runs were set up to replicate this crash test condition.

The simulation replicated all of the other conditions for the test, including level surface, critical impact point, and installation tolerances.

Conditions
Crashes were simulated at a speed of 100 km/h and impact angle of 25 degrees with a 2000kg pick-up for installations on flat terrain and sloped (2:1) terrain. Four cases for the study were defined based upon design drawings provided by the agency (see Figure 2). These were:
• Case 1 – Standard w-beam guardrail installation G4(2W) with the blockout in a “normal” position. This was considered to be the benchmark condition for the comparison of results.
• Case 2 – Standard w-beam guardrail installation with blockout in “normal” position, but the post at a side slope break point.
• Case 3 – Similar to Case 2, but with the blockout and rail raised 3 inches and attached to the posts with a single bolt.
• Case 4 – Similar to Case 3 but with the blockout and were attached to the posts using two bolts.

Variations of the basic finite element model for the w-beam guardrail were made to provide an exact replication of these designs.

The cross-sectional forces in the rail were measured using data that was taken from the various positions noted in Figure 4. These forces for Case 1 served as the benchmark for determining if the proposed redesign leads to significant additional forces in the rail. Excessive rail forces might lead to failure or rupture of the rail. If the barrier system redesign caused these forces to approach or exceed the strength of the rail, then there would be reason to question the viability of the redesign.

The simulations were also used to generate measures of rail deflection for each of the sections previously noted. The maximum deflection represents an important area of concern in evaluating the viability of the redesign options.

 Forces on the bolts attaching the guardrail to the posts were extracted from the simulations and compared to analyze the effect of change in blockout position on the bolt forces and release of the rail from the posts. Figure 4 shows the location of the two bolts used in the comparison.

Several measures of vehicle performance were captured to fully understand the implications on vehicle stability. Vehicle behavior analysis considered tendencies to vault or roll over the barrier, as well as the propensity for ride-down accelerations that might cause injury to the occupant. The change in bumper height was used as a metric of whether the vehicle was rising to a height that might lead to vaulting. A point in the left corner of the bumper was tracked through each case in the simulations (Figure 5).

Finally, four measures of occupant risk typically reported for NCHRP Report 350 Test 3-11 were also compared for all four cases to predict probable

**FIGURE 2 – Simulated Cases**

**FIGURE 3 – Rail Cross-Sections**

**Analyses**

This study involved an analysis of the forces on the guardrail and assessment of vehicle behavior. For each aspect, several measures were tracked in the simulations to fully understand the implications of the current and proposed designs.

First, the animations derived from the simulation of the test cases were visually examined to ensure proper overall behavior of all components of the guardrail system. This was done to avoid unrealistic interactions between the vehicle and guardrail.

Second, various metrics based upon the physical response of the barrier when impacted were analyzed. The analysis considered the effects across multiple sections of the barrier, not just at the impact location. Figure 3 illustrates the sections that were defined and monitored in the simulations.

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injuries. These included occupant longitudinal and lateral ride-down accelerations, as well as occupant longitudinal and lateral impact velocities.

Findings

Cross-sectional rail forces were monitored at the four sections noted in Figure 3. As might be expected, the forces were the greatest in the simulation results for Section 1. The levels of rail forces in Section 1 for the four cases studied are shown in Figure 6. The maximum forces (at time 0.15 seconds) are slightly higher for Case 4, but they are very close to the benchmark forces represented by Case 1 as well as those for the other cases. The results shown in the graph indicate very similar levels of engagement forces between the Section 1 rail and the vehicle. The maximum forces from all the cases closely match the benchmark. The ride-down force, or force after 0.2 seconds, shows that in the benchmark case the vehicle releases the rail at a faster rate than all the other cases. The slower rate at which force is applied on the rail would mean a lower acceleration change seen in the vehicle.

The maximum deflections from the four cases were monitored at different locations along the barrier. Figure 7 shows the rail deflections for Case 1 over the crash event. A maximum dynamic deflection of 570 mm was noted for this case. The maximum dynamic deflections for Cases 2, 3, and 4 were 620, 615, and 615 mm respectively. It can be noted from comparing these deflections that the 2:1 backslope lead to a small increase in deflection (~50 mm). Comparing Cases 2, 3 and 4 indicates that offsetting the blockouts had minimum effect on barrier deflection. It is important to note that the rail height was kept the same in all four cases.

The last measures taken on the guardrail behavior were the forces on the bolts holding the rail to the posts. Figure 8 shows the bolt forces at Bolt 1 for each of the cases. The benchmark case (Case 1) is depicted by the red line. It can be noted that the forces peak early in the crash and then diminish as the forces are transferred to other parts of the guardrail system or when the rails separate from the post. The bolt force for Case 2, which is the benchmark for the sloped
surface case, is similar to that for Case 1. Cases 3 and 4 (the light and dark blue lines) indicate that the raised blockout cases experience higher forces, but not markedly so.

To analyze vehicle behavior, measures of the yaw angle of the vehicle as it impacts the guardrail were generated. This metric provides an indication of the rate at which the vehicle is redirected by the barrier. Figure 9 shows that the vehicle reaches a maximum yaw of about 38 degrees over the 0.5 sec duration of the Case 1 simulation. The yaw angles experienced in Case 2 (where the barrier is placed at a side slope break point) are also shown in Figure 9 and can be noted to be very similar to Case 1. Since the yaws differ by only 3 degrees, this suggests that there is not much difference between the cases. For Cases 3 and 4 the yaw angle is decreased by almost 10 degrees showing that the vehicle is redirected at a slower rate and the barrier is absorbing more of the impact.

Overall, the simulation results for the various cases are quite similar relative to forces on the guardrail system and vehicle behavior. Table 1 summarizes the metrics generated to evaluate occupant risk under the criteria in NCHRP Report 350 for Test 3-11. The closeness of the data for all aspects suggests that the proposed blockout reset options are viable solutions.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat terrain, no offset, one bolt</td>
<td>11.47</td>
<td>11.28</td>
<td>14.07</td>
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<td>8.08</td>
<td>8.67</td>
<td>8.60</td>
<td>8.12</td>
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<tr>
<td>Sloped terrain, 3”offset, two bolts</td>
<td>4.32</td>
<td>3.46</td>
<td>3.55</td>
<td>3.84</td>
</tr>
</tbody>
</table>
Summary & Conclusions
Using validated finite element models that had been shown to be sensitive to small design differences, crash simulations were used to determine if various redesign options for increasing the height of w-beam guardrails were viable. Four cases were defined for this analysis where Case 1, the standard w-beam guardrail design, served as the benchmark for comparisons.

From simulation data as well as visual review of the video animation, it appears that the response for the four cases were similar. This suggests that the raised blockout design is a viable option for raising the height of w-beam guardrail. Various metrics for the forces on the guardrail, vehicle behavior, and occupant values were compared in the analysis.

Comparisons of maximum values for the metrics of the benchmarks and redesigns showed similar performance in several areas:

- Vehicle yaw – the proposed design did not cause additional yaw and, in fact, seemed to redirect the vehicle at a slower rate.
- Rail section forces – the proposed design had rail forces comparable to the original design.
- Rail lateral deflections – the proposed design showed improved barrier performance when placed at a side slope break point by reducing the deflection by 5 mm.
- Occupant risk measures (NCHRP 350) – the proposed design showed very similar results for all occupant risk aspects that suggest that the proposed design is viable.
- Bumper height – the proposed design showed similar changes in bumper heights as the original design when placed at a side slope break.
- Bolt forces – the proposed design showed that the raised blockout experienced slightly higher forces, but these did not exceed bolt strength.

There is no evidence from this simulation analysis that the raised blockout design would result in an increased likelihood of barrier failure or adverse effects on impacting vehicles. Working on the assumption that the validated models provided adequate sensitivity to the design variations considered here, the results suggest that the raised blockout design will limit the likelihood of vaulting. This ensures a safer ride-down event without the worry of vehicle rolling over. Overall results suggest raising the blockouts is a viable option.

Implications for Current Practice
Complying with installation and maintenance guidelines for w-beam guardrails that call for a height of 27.5 inches plus or minus 3 inches poses challenges to highway agencies. This is particularly true where an agency has a large inventory of deployed guardrail. The proposed method of adjusting guardrail height by raising the rails and blockouts may be a low cost option because no new parts are needed, the rail can be lifted without the need for heavy equipment, and it is easy to drill holes in the posts to accommodate the new blockout position. This approach can help limit guardrail vaulting for deployed guardrail until system upgrades can be made.

References

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