Modeling and Simulations of Vehicular Impacts on W-Beam Rail with Raised Blockouts

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Abstract

With recent changes about appropriate height for beam guardrail, there are more locations where rail height is below the recommended heights. Raising blockout on posts is a cost effective means to adjust rail height, however there is not any known analysis of how this might affects rail performance. The information compiled from this simulation study will enable the DOTs to decide whether raising wood blockouts on wood posts can be chosen as a cost effective mean to adjust rail height when below recommended value, without compromising the rail system performance. Researchers made use of pendulum testing facility to test raised 8-inch wood blockouts on wood posts embedded in soil. Force-displacement data was recorded and evaluated to understand the strength of raised blockout on wood post system and its capability to transmit impact forces into the soil. Results from pendulum testing were also employed to calibrate the behavior of a finite element model of a post and raised blockout system embedded in soil.

The researchers detected real-world configurations of W-beam guardrail installations with wood blockouts on wood posts and identified those configurations for which the practice of raising wood blockouts on wood posts would need some additional investigation to assess system crashworthiness according to roadside safety standards. Three cases were identified for further evaluation through FEA analyses: 1) 31-inch MGS system, 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts; 2) 27¾-inch rail system, 4-inch increased post embedment due to possible rail deficiency or posts settlement, and 4-inch raised blockouts on posts; 3) 27¾-inch rail system, 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts. All cases indicate that the practice of raising wood blockouts on wood posts to maintain minimum rail height requirements appear to likely pass required roadside safety evaluation criteria.

Background

On May 17, 2010, the Federal Highway Administration (FHWA) issued a technical memorandum to provide guidance to State Departments of Transportation (DOTs) and FHWA Division Offices on height of guardrail for new installations on the National Highway System (NHS) (Nicol, 2010). The technical memorandum details the minimum mounting heights of systems successfully crash tested per the NCHRP Report 350 "Recommended Procedures for the Safety Performance Evaluation of Highway Features" and the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) (Ross et al., 1993; AASHTO, 2009). In regard to MASH, the memorandum recognized performance issues with modified G4(1S) guardrail and recommended adoption of 31-inch high guardrail designs for new installations.

The FHWA Office of Safety Design and the FHWA Resource Center gives suggestions on how to adjust rail height when pavement work is needed. In the case the barrier does not need to be moved, it is a common practice to raise the blockout on the post up to three inches, as a cost effective means to adjust rail height. This requires field drilling or punching of a new hole in the guardrail post. There is not, however, any known analysis of how raising beam guardrail blockout might affects rail performance. In fact, a moment is also applied to the system, when subjecting the blockout-post system to an impact after the blockout is raised on the post. Tensile and compressive stresses increase proportionally with bending moment. Failure in bending might occurs when the bending moment is sufficient to induce tensile stresses greater than the yield stress of the material throughout the entire cross-section. Thus, the bending moment to which the raised blockout on post is subjected might play a significant role in the performance of the overall rail system.

Multiple states have guidelines regarding the maintenance and updating of existing guardrails that do not comply with the current recommended mounting height. Many states recommend replacing or resetting the post to adjust rail height. Few other states have documentation on adjusting rail height by raising blockouts in certain situations. The criteria of the situations include guardrail post material and slope configuration.

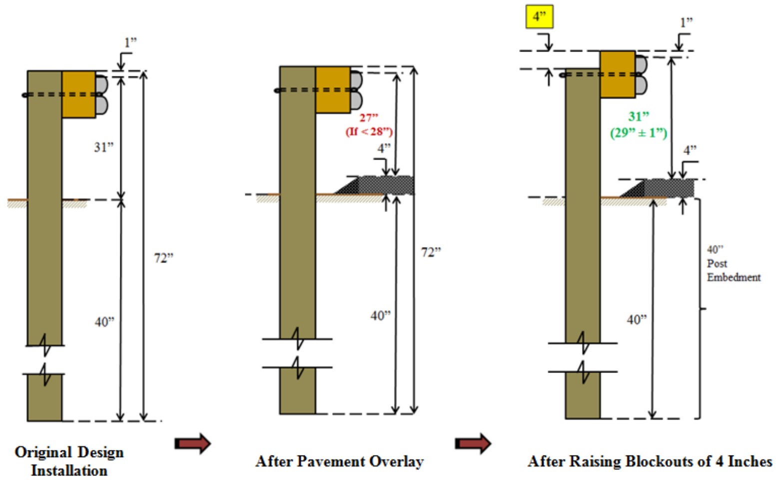
The purpose of this research is to analyze the rail performance when wood blockouts are raised on wood posts as a mean for adjusting rail height, and to use computer simulations to determine the articles crashworthiness according to applicable evaluation criteria.

Case Investigation

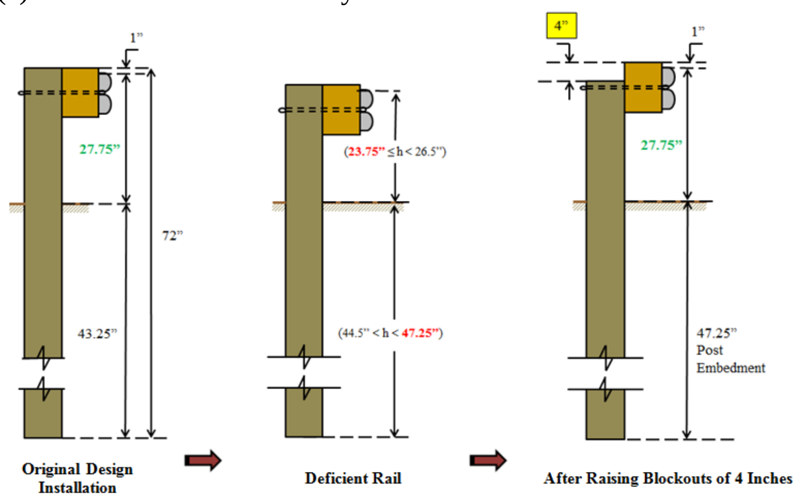
The researchers detected real-world configurations of W-beam guardrail installations with wood blockouts on wood posts. The researchers then worked with DOT representatives to identify those configurations for which the practice of raising wood blockouts on wood posts would need some additional investigation to assess system crashworthiness according to roadside safety standards (Figure 1).

Case 1. Pavement Overlay Without Soil Backfill – on an MGS System

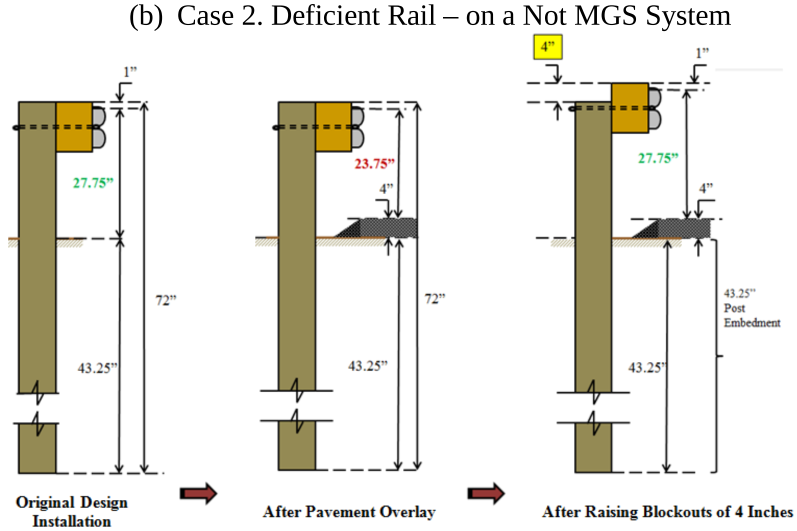
Researchers considered the case of a Midwest Guardrail System (MGS) initially installed as a 31 inches rail height with post embedment depth of 40 inches. As consequence of a pavement overlay, the height of the W-beam rail with respect to level ground has decreased to a value less than 31 inches. Post embedment remained the same, since soil backfill was not considered. With 4 inches pavement overlay, the height of the top of the W-beam would become 27 inches from the top of the newly added pavement overlay. The MGS system rail height would now need to be increased to comply with FHWA requirements. For this specific case, it was agreed in increasing the rail height back to the original value, 31 inches (Figure 1(a)). A 72-inch long wood posts and 12-inch wood blockouts were considered for evaluation according to MASH TL-3 standards.



(a) Case 1. Pavement Overlay Without Soil Backfill – on an MGS System



(b) Case 2. Deficient Rail – on a Not MGS System



(c) Case 3. Pavement Overlay Without Soil Backfill – on a Not MGS System

Figure 1. Case Investigation (Not in Scale).

Case 2. Deficient Rail – on a Not MGS System
The researchers refer to a "deficient rail" as a W-beam guardrail system whose rail height is less than 26½ inches from ground level. The system was initially installed as a 27¾ inches rail height with post embedment depth of 43¾ inches. Various causes might have brought the post to settle in the ground (for example, soil material might have settled around the post with time). With post settlement, the total post embedment has increased, lowering the height of the W-beam rail with respect to level ground. When the rail height reaches a value less than 26½ inches from the ground, the rail system is considered deficient and the rail needs to be raised to a minimum value of 27¾ inches to comply with FHWA requirements (Figure 1(b)). A 72-inch long wood posts and 8-inch wood blockouts were considered for evaluation according to NCHRP Report 350 TL3 standards.

Case 3. Pavement Overlay Without Soil Backfill – on a Not MGS System
Researchers considered the case of a system initially installed as 27¾ inches rail height with post embedment depth of 43¾ inches. As consequence of a pavement overlay, the height of the W beam rail with respect to level ground has decreased to a value less than the original one. Post embedment has remained the same, since soil backfill was not considered given the fact that it does not seem to be a common practice for DOTs. With a 4-inch pavement overlay, for example, the height of the top of the W-beam would become 23¾ inches from the top of the newly added pavement overlay. The height of the rail system would now need to be raised to a minimum value of 27¾ inches to comply with FHWA requirements (Figure 1(c)). A 72-inch long wood posts and 8-inch wood blockouts were considered for evaluation according to NCHRP Report 350 TL-3 standards.

Finite Element Analysis

Finite element analyses (FEA) were used to evaluate both vehicle components and crashworthiness of safety barriers and hardware for each case. The FEA discussed herein were performed using the LS-DYNA® explicit finite element code (Hallquist, 2014). LS-DYNA is widely used to solve nonlinear, dynamic response of three-dimensional problems and is capable of capturing complex interactions and dynamic load-time history responses that occur when a vehicle impacts a barrier system.

A finite element model of the MGS System with wood posts was developed and successfully validated against test MGSSYP-1 performed at the Midwest Roadside Safety Facility (MwRSF) with the objective to crash test and evaluate the MGS with rectangular Southern Yellow Pine (SYP) posts to MASH (Gutierrez et al., 2013). The same finite element model was then used to replicate the three geometrical cases previously identified fur investigation according to Test Level 3 impacts. When necessary, minor modifications where applied to the model. Simulations were run to determine how the test article would perform after raising the blockouts on the posts to obtain the desired rail height with respect to ground/pavement overlay.

For those cases which included pavement overlay, tapered edge details from Texas Department of Transportation standards were considered for implementation within the computer models (TxDOT, 2011). According to such standards, the pavement overlay should have a tapered edge length of 1.75 * T, where "T" is the total thickness of all overlay layer. It was also assumed that the tapered edge would start at the height of the face of the guardrail, following Washington State Department of transportation standard (WSDOT, 2011).

1. MGS System with 4-inch Pavement Overlay and 4-inch Raised Blockouts

The finite element model of the MGS system with wood posts previously developed and validated was modified so that a 4-inch overlay was added in front of the post. The 4-inch overlay was terminated following the TxDOT guidelines reported in their standards. To maintain the original rail height of the MGS system after the overlay, the wood blockouts were raised 4 inches with respect to the posts. Post embedment remains 40 inches, as in the original MGS system installation. Details of the MGS system with 4-inch pavement overlay and 4-inch raised blockouts are included in Figure 2. Analysis was performed according to MASH Test Level 3-11 criteria. Researchers used the NCAC detailed finite element pickup truck model to complete their simulation (NCAC, 2014). The barrier was impacted 12 ft upstream of a post, with initial nominal speed and angle of 62 mph and 25 degrees, respectively.

The modeled 2270P vehicle remained upright during and after the modeled collision event. Maximum roll, pitch and yaw angles were 2.9, -2.1, and -37.3 degrees respectively. Occupant impact velocities were 15.09 ft/sec and 15.42 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -7.7 g and -7.2 g in the longitudinal and lateral directions, respectively. No phenomenon of snagging or pocketing seemed to occur. The rail did not show regions of high plastic strain that might suggest failure of the steel W-beam. Results suggest that the practice of raising wood blockouts on wood posts for an MGS system to maintain a rail height at 31 inches from the pavement overlay appear to be crashworthy and likely to pass safety evaluation criteria required by MASH. Results are summarized in Figure 3.

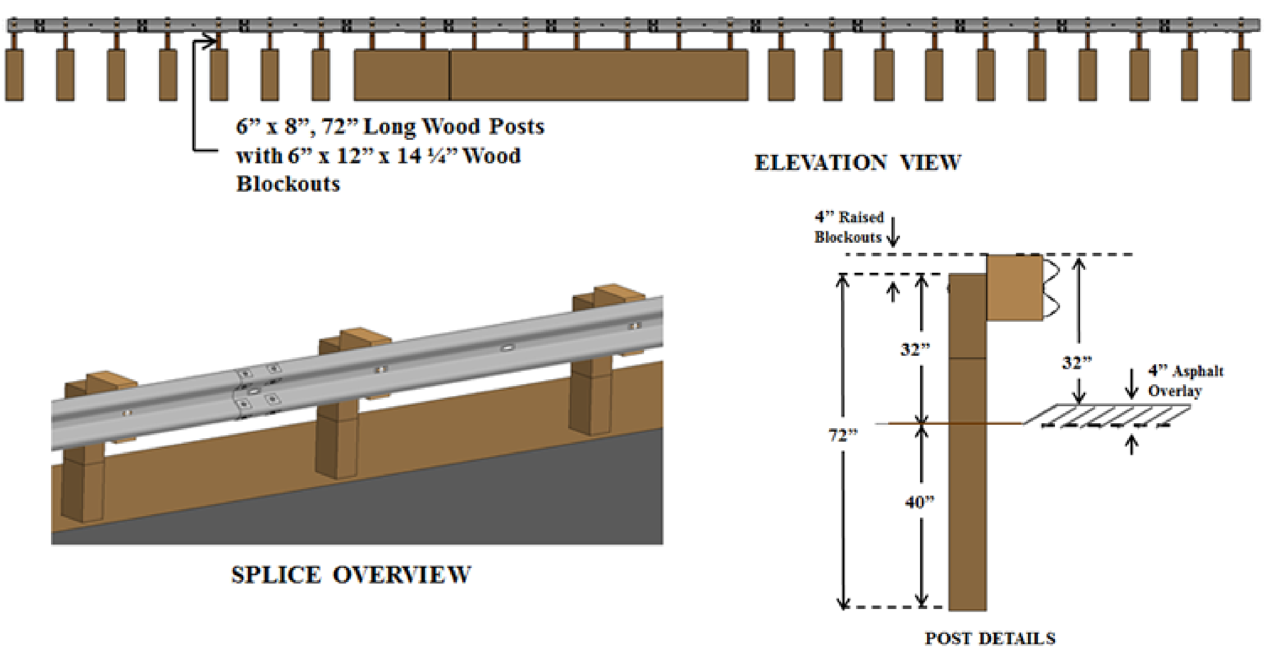
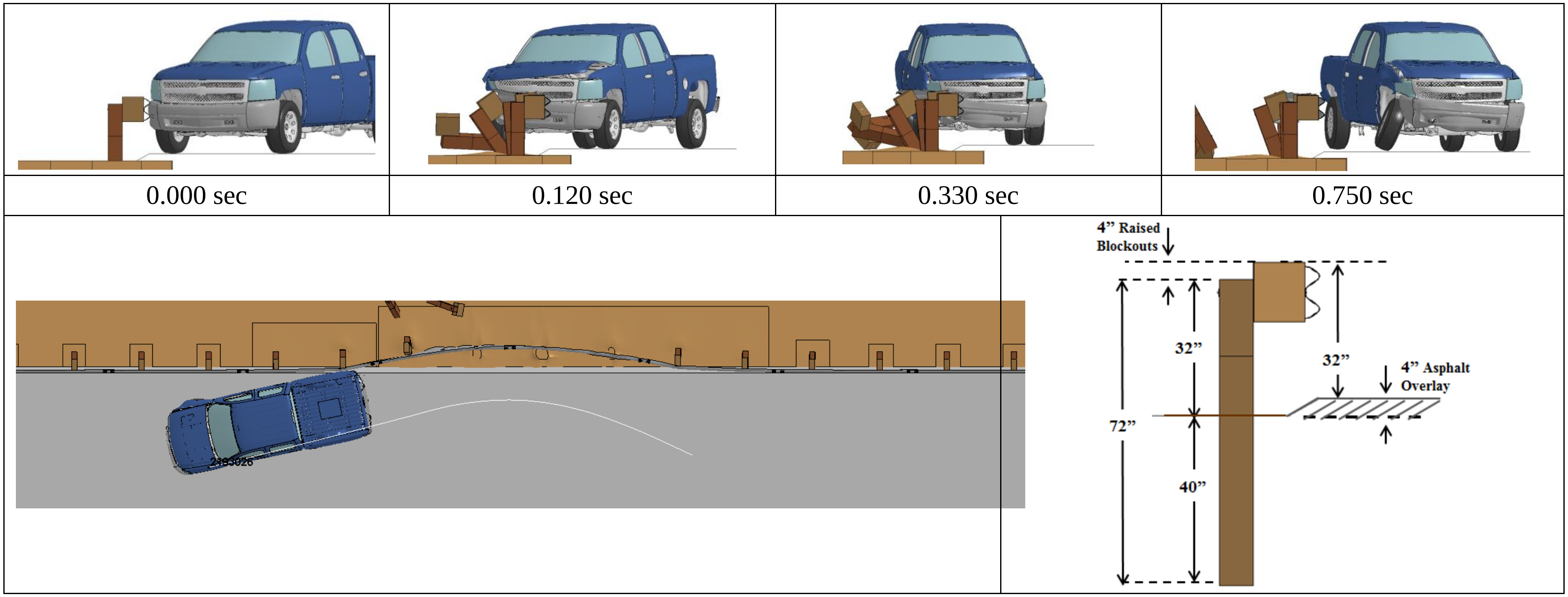


Figure 2. MGS Test Article Installation with 4-inch Pavement Overlay and 4-inch Raised Blockouts.



General Information
- Test Agency .... Texas A&M Transportation Institute (TTI)
- Test Standard Test No. .... *MASH* Test 3-11
- Date .... N/A

Test Article
- Type .... MGS with Wood Posts, 4-inch Pavement Overlay, 4-inch Raised Blockouts
- Installation Length .... 150 ft
- Material or Key Elements..... W-Beam, MGS, Wood Posts, Wood Blockouts, Pavement Overlay, Raised Blockouts

Test Vehicle
- Type/Designation 2270P
- Weight................................. 5000 lbs
- Dummy .... No Dummy

Impact Conditions
- Speed ....62.0 mi/h
- Angle ....25 degrees
- Location/Orientation ....12 ft upstream of post

Post-Impact Trajectory
- Stopping Distance............ N/A

Occupant Risk Values

Impact Velocity (ft/sec)
- x-direction...................... 15.09
- y-direction...................... 15.42

Ridedown Acceleration (g)
- x-direction..............................-7.7
- y-direction..............................-7.2

Vehicle Stability
- Maximum Yaw Angle................... -37.3 degree
- Maximum Pitch Angle.................. -2.1 degree
- Maximum Roll Angle .... 2.9 degree
- Vehicle Snagging.......................... No

Vehicle Damage
- VDS .... N/A
- CDC... N/A
- Max. Exterior Deformation............ N/A
- OCD... N/A

Max. Occupant Compartment Deformation .... N/A

Figure 3. MASH Test 3-11 Simulation Results (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).

2. 27¾-inch Rail System with Height Deficiency and 4-inch Raised Blockouts

An FE model of 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include 4 inches of additional post embedment, which, in real life, could be the result of post settlement, accumulation of soil and/or debris around the post installation. To maintain the original rail height after the additional soil embedment, the wood blockouts were raised 4 inches on the posts. Details of the rail system with rail height deficiency and 4-inch raised blockouts are included in Figure 4.

The FE test installation consisted of 150 ft of standard 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6 inch × 8 inch × 72 inch long with wood properties and a soil embedment depth of 47¼ inches. Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12 ft-6 inch long 12-gauge W beam rails were modeled. The W-beam top rail height was 27¾ inches with a 21⅞-inch center mounting height. The rail splices were placed at post locations. Researchers used the NCAC detailed finite element pickup truck model to complete their simulation (NCAC, 2014). The barrier was impacted 12.3 ft upstream of a post, with initial nominal speed and angle of 62 mph and 25 degrees, respectively. This system was evaluated according to NCHRP Report 350 Test 3-11 impact conditions and evaluation criteria.

The modeled 2000P vehicle remained upright during and after the modeled collision event. Maximum roll, pitch and yaw angles were 3.8, 1.8, and 32.0 degrees respectively. Occupant impact velocities were 18.37 ft/sec and −17.72 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were −10.6 g and 10.2 g in the longitudinal and lateral directions, respectively. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W beam. Results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain a rail height at 27¾-inch from ground appears to be crashworthy and likely to pass safety evaluation criteria required by NCHRP Report 350. Results are summarized in Figure 5.

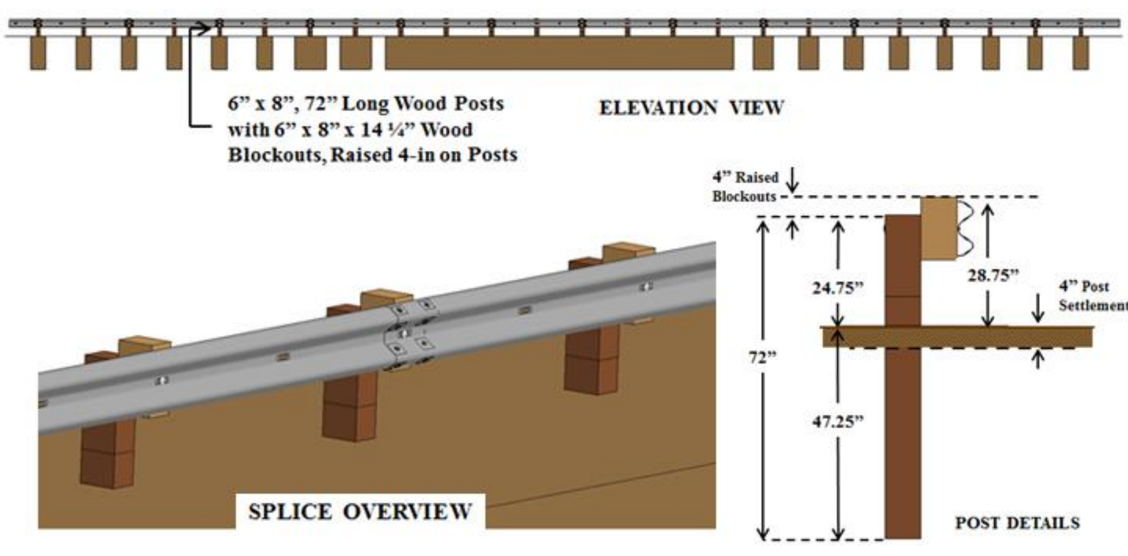
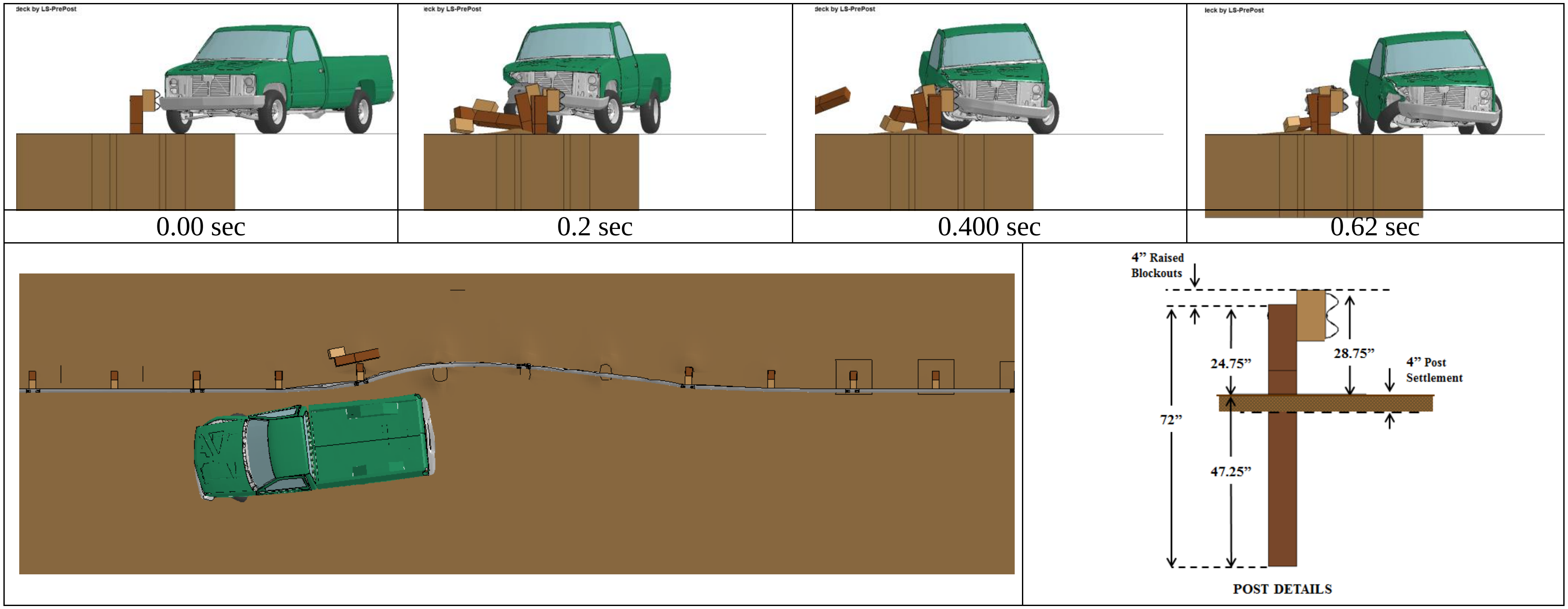


Figure 4. 27¾-inch Rail System Installation with Height Deficiency and 4-inch Raised Blockouts.



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No. .... *NCHRP Report 350* Test 3-11
Date .... N/A

Test Article
Type .... , 27¾-inch W-Beam Guardrail, 4-inch Additional Post Embedment, 4-inch Raised Blockouts
Installation Length .... 150 ft
Material or Key Elements.... W-Beam, 27¾-inch Rail Height, Wood Blockout, Wood Post, Raised Blockouts

Test Vehicle
Type/Designation 2000P
Weight................................ 2000 lbs
Dummy .... No Dummy

Impact Conditions
Speed.....................................62.0 mi/h
Angle.....................................25 degrees
Location/Orientation ....12.3 ft Upstream of Post

Post-Impact Trajectory
Stopping Distance............ N/A

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction..................... 18.37
y-direction..................... -17.72
Ridedown Acceleration (g)
x-direction.............................-10.6
y-direction.............................10.2

Vehicle Stability
Maximum Yaw Angle................... 32.0 degrees
Maximum Pitch Angle .... 1.8 degrees
Maximum Roll Angle 3.8degrees
Vehicle Snagging.......................... No

Vehicle Damage
VDS ....N/A
CDC ....N/A
Max. Exterior Deformation ....N/A
OCD...< 150.8 N/m Floorboard Internal Energy

Max. Occupant Compartment Deformation............................N/A

Figure 5. Summary of Results for NCHRP 350 Test 3-11 simulation (27¾-inch Rail Height with Height Deficiency and 4 inch Raised Blockouts.

3. 27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts

An FE model of 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include 4 inches of overlay in front of the post which was terminated following TxDOT guidelines. To maintain the original height of the rail after overlay, the wood blockouts were raised 4 inches on the posts. Post embedment remained 43¼ inches, as in the original rail system installation (Figure 6).

The FE test installation consisted of 150 ft of standard 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6 inch × 8 inch × 72 inch long with wood properties and a soil embedment depth of 43¼ inches. Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12 ft- 6 in long 12-gauge W beam rails were modeled. The W-beam top rail height was 27¾ inches with a 21⅞-inch center mounting height. The rail splices were placed at post locations. Researchers used the NCAC detailed finite element pickup truck model to complete their simulation (NCAC, 2014). The barrier was impacted 13.3 ft upstream of a post, with initial nominal speed and angle of 62 mph and 25 degrees, respectively. This system was evaluated according to NCHRP Report 350 Test 3-11 impact conditions and evaluation criteria.

The modeled 2000P vehicle remained upright during and after the modeled collision event. Maximum roll, pitch and yaw angles were 6.4, 3.0, and 26.8 degrees respectively. Occupant impact velocities were 17.06 ft/sec and -16.4 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were –15.4 g and 10.9 g in the longitudinal and lateral directions, respectively. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W-beam. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain the rail height at 27¾ inches from the pavement overlay appears to be crashworthy and likely to pass safety evaluation criteria required by NCHRP Report 350. Results are summarized in Figure 7.

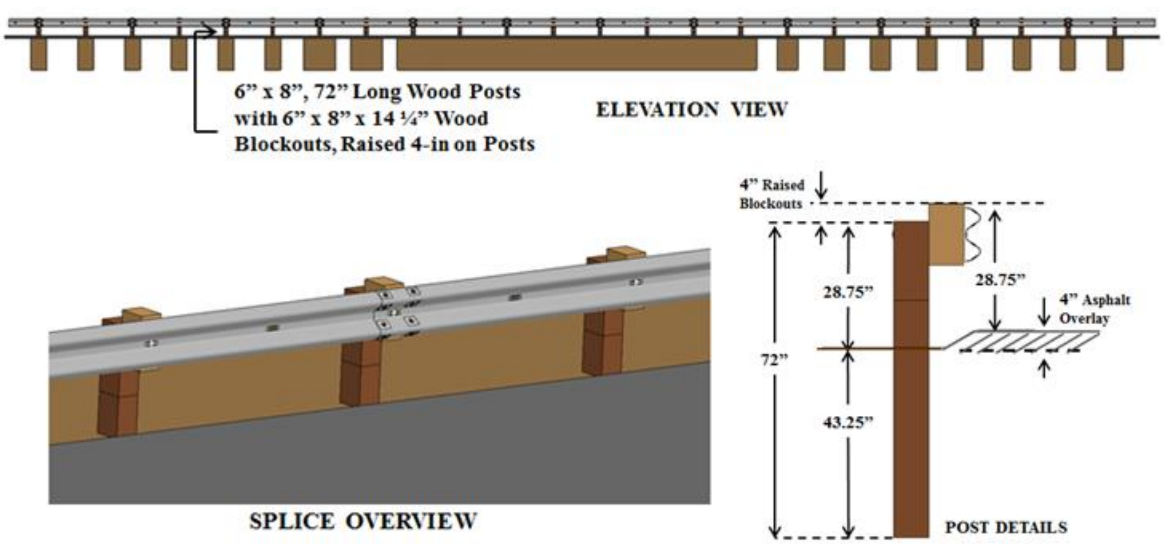
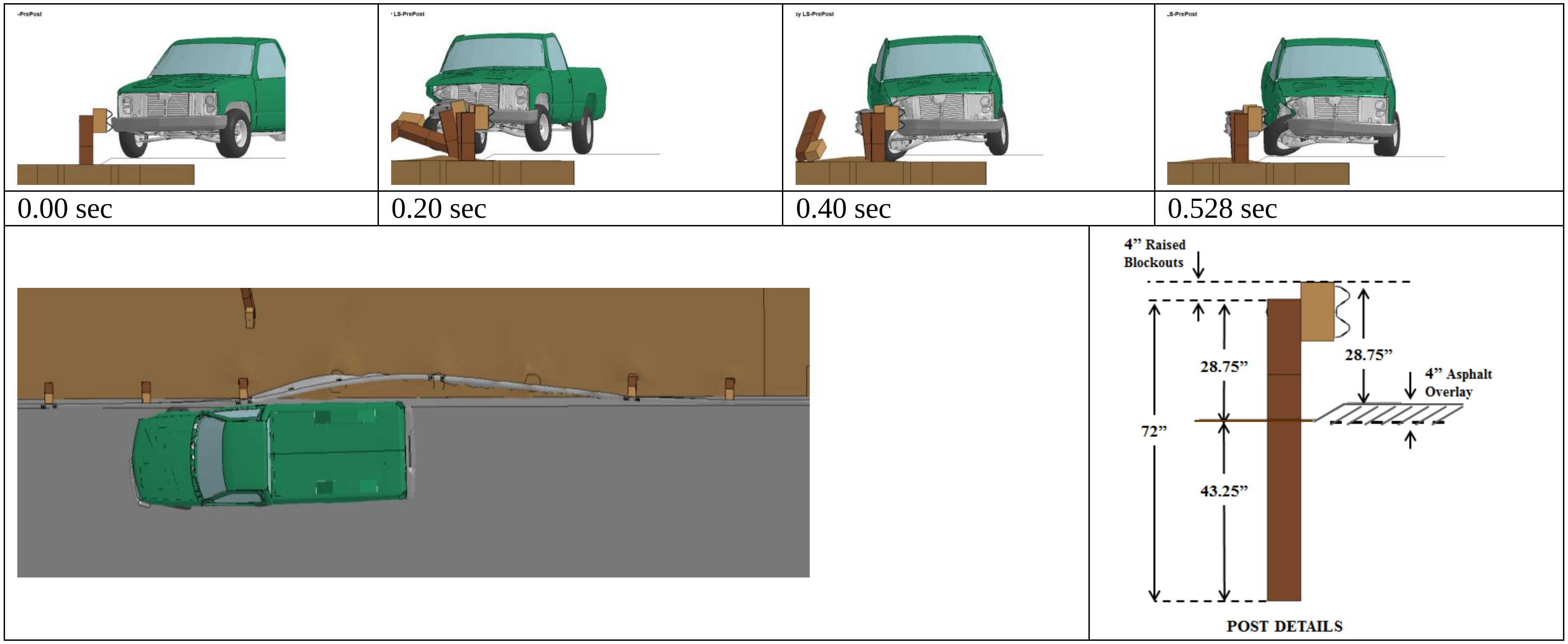


Figure 6. 27¾-inch Guardrail Height Installation with 4-inch Pavement Overlay and 4-inch Raised Blockouts.



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	*NCHRP Report 350* Test 3-11
Date	N/A
Test Article	
Type	27¾-in W-Beam Rail, 4-inch Raised Blockouts, 4-inch Pavement Overlay
Installation Length	150 ft
Material or Key Elements	W-Beam, 27¾-in Rail, Wood Blockout, Raised Blockouts, Pavement Overlay
Test Vehicle	
Type/Designation	2000P
Weight	2000 lbs
Dummy	No Dummy

Impact Conditions	
Speed	62.0 mi/h
Angle	25 degrees
Location/Orientation	13.3 ft from Upstream of Post
Post-Impact Trajectory	
Stopping Distance............	N/A
Occupant Risk Values	
Impact Velocity (ft/sec)	
x-direction…………………	17.06
y-direction…………………	-16.4
Ridedown Acceleration (g)	
x-direction	-15.4
y-direction	10.9

Vehicle Stability	
Yaw Angle	26.8 degrees
Maximum Pitch Angle	3.0 degrees
Maximum Roll Angle	6.4 degrees
Vehicle Snagging	No
Vehicle Damage	
VDS	N/A
CDC	N/A
Max. Exterior Deformation	N/A
OCD.	N/A
Max. Occupant Compartment Deformation	N/A

Figure 7. Summary of Results for NCHRP 350 Test 3-21 simulation (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts.

Summary and Conclusions

With recent changes about appropriate height for W-beam guardrail, there are more and more existing locations identified where rail height is below the recommended heights. Pavement overlays create additional locations where this occurs. Raising blockouts on the posts is a cost effective means to adjust the rail height; however, there was not any known analysis of how this practice might affect rail performance.

The purpose of this research was to analyze wood post W-beam guardrail performance when wood blockouts are raised on the posts to adjust rail height. The researchers made use of pendulum testing to evaluate raised wood blockouts on wood posts. Pendulum tests were performed on 6-inch × 8-inch wood blockouts raised on 6-inch × 8-inch wood posts embedded in soil. Recorded data from the pendulum testing was also used to help validate FE models for use in full-scale impact simulations.

The researchers identified real-world configurations of W-beam guardrail installations with wood blockouts on wood posts. Three cases were identified for further evaluation through FEA analyses:

1) 31-inch MGS system with 4-inches pavement overlay in front of post and 4-inch raised blockouts on posts (MASH, Test 3-11);
2) 27¾-inch rail system with 4-inch increased post embedment due to possible rail deficiency or post settlement, and 4-inch raised blockouts on posts (NCHRP Report 350, Test 3-11);
3) 27¾-inch rail system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (NCHRP Report 350, Test 3-11).

All three investigated cases indicate that the practice of raising wood blockouts on wood posts to maintain minimum rail height requirements appear to be crashworthy and likely to meet applicable NCHRP Report 350 or MASH evaluation criteria.

Acknowledgements

This research project was performed under TPF-5(114) Roadside Safety Research Program Pooled Fund Study. The authors acknowledge and appreciate their assistance and guidance.

References

AASHTO, "Manual for Assessing Safety Hardware", American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

Gutierrez, D.A., Bielenberg, R.W., Reid, J.D., Lechtenberg, K.A., Faller, R.K., and Sicking, D.L., "Midwest Guardrail System (MGS) with Southern Yellow Pine Posts," Midwest Roadside Safety Facility, MwRSF Research Report No. TRP-03-272-13, Lincoln, Nebraska, 2013.

Hallquist J. O., "LS-DYNA Keyword User's Manual, Version 971", Livermore Software Technology Corporation, Livermore, California, 2014.

National Crash Analysis Center (NCAC). Finite Element Model Archive. Accessed July, 2014 http://www.ncac.gwu.edu/.

Nicol D.A. "Memorandum. Roadside Design: Steel Strong Post W-Beam Guardrail." Federal Highway Administration, Washington D.C., May 17th, 2010, http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/policy_memo/memo051710/, retrieved May 2015.

Ross, Jr., H.E., Sicking, D.L., Zimmer, R.A. and Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Features," National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, D.C., 1993.

TxDOT, "Tapered Edge Details HMAC Pavement TE (HMAC) -11," 2011.

WSDOT, "Beam Guardrail Types 1 ~ 4 (W-Beam) Standard Plan C-1," 2011.