# Performance of Guardrail Systems Encased in Pavement Mow Strips

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**Abstract:** Pavement mow strips are being used to combat growth of vegetation around guardrail posts. However, the effect of pavement post encasement on crashworthiness of strong post guardrail systems has not been investigated. In this paper, performance of these systems is examined using experimental testing and numerical simulation. Mow strip dimensions, materials, and depths are considered in addition to the presence "leave-out" sections around posts. Seventeen configurations using wood and steel posts embedded in various mow strip configurations and confinement conditions were subjected to dynamic impact testing with a bogie vehicle. Dynamic impact tests were numerically simulated and full-scale mow strip system models were assembled using the subcomponent models. A concrete mow strip with grout leave-outs was designed based on predictive numerical simulations. This design was subsequently constructed and subjected to full-scale crash testing. With reference to nationally accepted criteria, crash tests of a strong post steel guardrail system and a wood post guardrail system encased in the selected mow strip configuration were considered to be successful. Recommendations for implementation are provided.

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#### Introduction

Unchecked, roadside vegetation growth can impede motorist vision and degrade the appearance of a roadside facility. Amid environmental concerns regarding the use of herbicides and safety concerns regarding the manual mowing practice to control growth of roadside vegetation, there is a nationwide trend toward encasing guardrail posts in pavement. This pavement layer prevents growth of vegetation within several meters of guardrail installations and thereby reduces the need for hand mowing or herbicide use. However, by increasing the rigidity of the confining material around the guardrail post, the pavement "mow strip" impedes rigid-body rotation and deformation of the post. This confinement induced by the pavement mow strip can lead to premature post fracture of a wood post or severe snagging of a vehicle on a steel post that can negatively affect performance of the guardrail system.

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Note. Discussion open until April 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 19, 2004; approved on May 19, 2005. This paper is part of the *Journal of Transportation Engineering*, Vol. 131, No. 11, November 1, 2005. ©ASCE, ISSN 0733-947X/2005/11-851–860/\$25.00. Previous research related to guardrail encased in pavement mowing strips is virtually nonexistent. However, a number of papers have addressed the use of simulation in roadside safety applications. The performance of several roadside safety features has been analyzed using nonlinear finite element analyses. Some of these features include an end terminal design (Reid et al. 1996), a generic guardrail (Plaxico et al. 2000; Tabiei and Jin 2000), a guardrail with recycled posts (Atahan and Ross 2004), a crash cushion (Miller and Carney 1997), and a breakaway sign support (Reid and Paulsen 1998). Several assumptions were made in each of the aforementioned papers regarding material properties, boundary conditions, and meshing depending on the particular scope investigated.

This research examines current mow strip configurations used in Texas in an effort to develop a standard mow strip system that meets National Cooperative Highway Research Program (NCHRP) *Report 350* criteria for roadside appurtenances (Ross et al. 1993). Mow strip systems are investigated using subcomponent impact testing; the nonlinear, dynamic, finite-element analysis code *LS-DYNA* (2001); and full-scale crash testing. Parametric variation inherent in various mow strip designs makes computer simulation an ideal analysis tool for the design process.

In order to quantify the extent of mow strip usage and to develop a matrix of mow strip design configurations for dynamic testing and numerical simulation of subcomponents, a state of practice survey was distributed to each of the 25 Texas Department of Transportation (TxDOT) districts. Standard mow strip specifications and engineering drawings were acquired. The survey indicated that 65% of participating TxDOT districts currently utilize vegetation control mow strips. With a majority of districts using some form of mow strip, it is important to establish a standard design that meets the criteria of *Report 350*.

Table	1.	Test	Matrix	of	Mow	Strip	Configura	tions
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Case	Mow strip material	Post type	Leave-out material	Leave-out size	Leave-out depth	Peak force (kN)
1	None	Wood	Not applicable	Not applicable	Not applicable	74.2
2	None	Steel	Not applicable	Not applicable	Not applicable	69.8
3	Asphalt	Wood	Asphalt	305 mm (1 ft) diameter	200 mm (7.87 in.)	75.3
4	Asphalt	Wood	Asphalt	457 mm (18 in.) diameter	200 mm (7.87 in.)	106.8
5	Asphalt	Steel	Asphalt	305 mm (1 ft) diameter	200 mm (7.87 in.)	101.7
6	Asphalt	Steel	Asphalt	457 mm (18 in.) diameter	200 mm (7.87 in.)	86.3
7	Concrete	Wood	Not applicable	Not applicable	Not applicable	93.7
8	Concrete	Wood	Grout	457×457 mm (18×18 in.)	100 mm (3.94 in.)	68.2
9	Concrete	Wood	Grout	457×607 mm (18×24 in.)	100 mm (3.94 in.)	56.7
10	Concrete	Steel	Not applicable	Not applicable	Not applicable	91.8
11	Concrete	Steel	Grout	457×457 mm (18×18 in.)	100 mm (3.94 in.)	68.7
12	Concrete	Steel	Grout	457×607 mm (18×24 in.)	100 mm (3.94 in.)	59.6
13	Asphalt	Wood	Grout	457 mm (18 in.) diameter	100 mm (3.94 in.)	62.0
14	Asphalt	Steel	Grout	457 mm (18 in.) diameter	100 mm (3.94 in.)	74.6
15	Asphalt	Wood	Asphalt	457 mm (18 in.) diameter	100 mm (3.94 in.)	98.6
16	Asphalt	Steel	Asphalt	457 mm (18 in.) diameter	100 mm (3.94 in.)	99.7
17	Asphalt	Steel	Rubber mat	457 mm (18 in.) diameter	Not applicable	69.6

## **Test Matrix Development**

A test matrix of mow strip layouts (see Table 1) was created using data from the state of practice survey. The layouts represent mow strip materials and dimensions deemed most critical to performance of the system. Mow strip and leave-out materials and geometries were considered when establishing the test matrix. As the most commonly used mow strip materials, PG64-22 Type D hot mix asphalt and TxDOT Class B riprap concrete were selected for dynamic impact tests. The hot mix asphalt mow strip constructed for dynamic testing was compacted with the same process and equipment used in the construction of the road. Using either a 305 mm (12 in.) or 458 mm (18 in.) diameter auger, postholes were then drilled through the asphalt into the soil. Posts were set into the holes, and the void around the posts was backfilled with hand-tamped soil meeting the specifications of standard soil specified in Report 350. The top several centimeters of backfill around the post were formed with various materials (hand-tamped hot mix asphalt, grout, etc.) intended to prevent growth of vegetation.

Concrete made with Portland cement is another material that is often used in both roadway and mow strip construction. TxDOT Class B concrete is the most commonly used grade of concrete for mow strip construction. Often referred to as riprap, Class B is required to have a minimum 28-day compressive strength of 14 MPa (2,031 psi). To avoid shrinkage, cracking, and separation from the adjacent roadway, mild steel reinforcement is sometimes used in concrete mow strips. Reinforcement often consists of No. 3 bars at 305 mm (12 in.) center-to-center or welded wire fabric W6×W6 or W3×W3. In some instances, mow strip concrete is placed without reinforcement. Unlike construction of an asphalt mow strip, guardrail posts are typically installed prior to placing concrete in a mow strip. An auger cannot be used to drill through cured concrete in the same manner as it can asphalt and, therefore, posts are set into the soil and concrete is placed around them.

To minimize the number of tests required, the most severe (i.e., most stiff) mow strip systems were examined. To this end, a maximum practical thickness for both mow strip materials was selected. A 127 mm (5 in.) thick concrete mow strip and a 200 mm (8 in.) thick asphalt mow strip were chosen for dynamic impact testing. Furthermore, in order to satisfy maintenance requirements, provide room for leave-out sections around the posts, and encase the full depth of guardrail in the mow strip material, a practical mow strip width of 1.1 m (3.6 ft) was selected. To prevent growth of vegetation along the entire length of guardrail, all posts were encased in the mow strip.

Some highway design engineers have recognized negative implications of fully encasing guardrail posts in a stiff material such as asphalt or concrete and follow a practice of installing "leave-out" sections around the posts. A leave-out section is a rectangular or circular section around a post containing material that is weaker than the mow strip material. This section is intended to allow for some degree of post rotation by deforming or crushing prior to failure of the post.

Wood posts and steel posts have vastly different failure mechanisms, and geometric differences between the two types of posts can effect the interaction between the post, the guard-rail system, and a vehicle. Therefore each mow strip material was investigated using both wood and steel posts. Based on equipment typically available for use in the field, 305 mm (12 in.) and 457 mm (18 in.) diameter augers were used to create leave-outs in the asphalt mow strips. In the concrete mow strips,  $457 \times 457$  mm ( $18 \times 18$  in.) and  $457 \times 607$  mm ( $18 \times 24$  in.) leave-out sections were formed around the posts. As a baseline, direct soil embedment and concrete embedment without a leave-out section around the post were chosen for testing to develop a range of post responses.

# **Dynamic Testing of Subcomponents**

After a test matrix had been developed, mow strip installations were constructed for dynamic impact testing. Each post was impacted head on at a speed of 35 km/h (21.7 mph) using a 839-kg (1,850-lb) bogie impact vehicle equipped with a calibrated crushable nose assembly and staged honeycomb construction (Albertson et al., unpublished report, 1994). The

bogie vehicle provides an inexpensive method for performing multiple dynamic impact tests. The bogie vehicle also allows for flexibility in the location of the test installation.

Impact testing allows researchers to quantify post behavior (e.g., force-deflection response, failure mode, etc.) for different confinement conditions and also provides the basis for development of finite element models. Results of the subcomponent tests were used to calibrate subcomponent finite element models before their implementation in a full-scale guardrail model. Peak force calculated from accelerometer readings and known mass of the bogie are listed in Table 1 for each impact test.

# **Baseline Tests of Soil**

To compare performance of posts embedded in mow strips to post configurations that have been successful in crash tests, standard soil embedment (Plaxico et al. 2000; LS-DYNA 2001) was used as the baseline test configuration. Two baseline impact tests were performed. A steel W150×13 (W6×9) post was embedded to a depth of 1.1 m (3.6 ft). A 457 mm (18 in.) diameter hole was made in the soil to the embedment depth, and the post was placed into the hole. The void surrounding the post was backfilled with standard soil described in Report 350 and hand-tamped. The same procedure was followed to install a 180 mm (7 in.) diameter wood post to the same embedment depth. TxDOT permits the use of either a 180 mm (7 in.) diameter or  $150 \times 200$  mm (6 × 8 in.) wood post in its strong post W-beam guardrail installations. A 180 mm (7 in.) diameter wood post was selected over the  $150 \times 200 \text{ mm}$  (6×8 in.) wood post because it has a slightly lower flexural strength, thereby making it more critical (i.e., more likely to fail) in a mow strip application.

The bogie vehicle impacted the post at 35 km/h (21.7 mph). Accelerometer data from the bogie for both baseline tests are shown in Fig. 1. The steel post was pushed steadily through the soil as the bogie vehicle progressed forward and eventually rode up onto the post. A similar test was conducted on a wood post during which the bogie was brought to a stop without leaving the ground as the post rotated through the soil. The peak acceleration on the bogie vehicle for both the wood post and the steel post tests was approximately 9 g.

## Asphalt Mow Strip Tests

Two sets of impact tests were performed on posts embedded in the asphalt mow strip. For the first set of asphalt mow strip cases, asphalt filled leave-outs were used. The posts (two steel and two wood) were set in holes, and the void around the posts was backfilled with hand-tamped standard soil from Report 350 to 200 mm (8 in.) below the surface of the asphalt. The top 200 mm (8 in.) volume surrounding the posts was filled with hot mix asphalt. The asphalt was hand-tamped around the posts in an effort to create a weaker layer of material in the leave-out region around the post. The second set of asphalt mow strip test cases used several different leave-out materials. All of the holes that were augered for placement of the post were 457 mm (18 in.) in diameter. This increased the distance between the back of the post and the mow strip providing more room for leave-out material and post rotation before bottoming out on the inside edge of the mow strip layer. Both wood and steel posts were tested with 102 mm (4 in.) thick layers of two-sack grout and hand-tamped hot mix asphalt placed in the 457 mm (18 in.) leave-out region. Posts were set to depth in the augered holes, and voids around posts were filled to 102 mm (4 in.) below the surface with hand-tamped standard soil.



**Fig. 1.** Accelerations of bogie for concrete mow strip impact tests: (a) Steel posts and (b) wood posts

The asphalt mow strip posts were impacted by the bogie vehicle with the same impact conditions as the baseline tests. For both wood and steel post systems, the 200 mm (8 in.) asphalt leave-out layer was too thick to allow the desirable amount of post rotation. Neither 305 mm (12 in.) diameter leave-outs nor 457 mm (18 in.) diameter leave-outs allowed significant post deflection upon impact. The steel posts both yielded at the ground line and allowed the bogie to slide up and over the post. The wood posts fractured at the ground level and failed to bring the bogie vehicle to a stop. Due to this limitation, a second set of five asphalt mow strip bogie tests were performed. One-hundred (100) mm (4 in.) leave-out layers of hot mix asphalt and two-sack grout were used in 457 mm (18 in.) diameter holes surrounding the wood and steel posts. Even when the thickness was reduced from 200 mm (8 in.) to 100 mm (4 in.), the hand-tamped asphalt material in the leave-out did not allow either the wood or steel posts to translate in a substantial manner. Just as in the first set of tests, the wood posts fractured cleanly at the ground line and the steel post yielded at the ground line without significant translation. The grout leave-out material greatly improves performance of the posts under impact by the bogie. The grout broke up as the post was impacted and allowed the post to deflect to the back of the leave-out before yielding or fracturing. Although the grout filled leave-out did not exactly match the performance of



**Fig. 2.** Posts in concrete mow strip after impact: (a) Steel post in concrete; (b) wood post in concrete; (c) steel post in square grout leave-out; (d) steel post in rectangular grout leave-out; (e) wood post in square grout leave-out; and (f) wood post in rectangular grout leave-out

direct soil embedment, grout filled leave-outs greatly enhance performance of the posts over a fixed condition in regard to post displacement and energy dissipation.

## **Concrete Mow Strip Tests**

Concrete is the second most commonly used mow strip material in Texas. Six bogie tests were performed on posts embedded in a concrete mow strip (Fig. 2). The concrete mow strip was 1.1 m (3.6 ft) wide and 127 mm (5 in.) deep. The total length of the mow strip was 13.3 m (43.8 ft), which was sufficient to install six guardrail posts separated by a standard 1.9 m (6.3 ft). The mow strip was placed on top of 305 mm (12 in.) of compacted base material. It was constructed using TxDOT Class B riprap concrete with a minimum 28-day compressive strength of 14 MPa (2,031 psi). The concrete was reinforced throughout with weldedwire mesh reinforcement with the exception of the leave-out sections formed around the posts. Both wood and steel posts were tested in direct concrete confinement and with grout-filled leave-outs around the perimeters of the posts.

The posts were installed prior to pouring the mow strip following typical TxDOT installation procedures. The posts were embedded to a depth of 1.1 m (3.6 ft) in 305 mm (12 in.) diameter holes. The holes were backfilled with hand-tamped standard soil. As a baseline, one wood post and one steel post were directly encased in the concrete mow strip. Two sizes of rectangular leave-outs,  $457 \times 457$  mm ( $18 \times 18$  in.) and  $457 \times 607$  mm ( $18 \times 24$  in.), were also included in the test matrix. Due to low cost, ease of installation, and overall effectiveness, a two-sack grout mixture was used as the backfill material in the top 102 mm (4 in.) of the leave-outs.

As expected, direct concrete confinement of the posts represented a severe impact scenario. The bogie impact causes severe damage to the concrete mow strip with little movement of the steel post. By contrast, the wood post fractures rapidly upon impact, thereby reducing damage to the concrete mow strip, but permitting the bogie vehicle to pass through relatively unimpeded. In both cases, the concrete mow strip allows minimal deflection of the post at the ground line and necessitates costly repair.

The second configuration tested within the concrete mow strip involved wood and steel posts surrounded by  $457 \times 457$  mm (18 × 18 in.) grout filled leave-outs. Both the steel and wood posts rotated through the grout to the back of the leave-out and contacted the concrete mow strip. Contact of the wood post with the back of the mow strip caused the post to fracture. Significant reductions in peak acceleration of the bogie and increase in energy dissipation were achieved with the addition of the square leave-outs around the post compared to the concrete confinement condition.

As in the square leave-out case, the rectangular grout leave-out allows significant post deflection with both posts deflecting to the back of the leave-out area. The additional 150 mm (6 in.) of grout behind the posts provided by the rectangular leave-outs results in a substantial decrease in damage to the mow strip system with only minor cracks appearing in the concrete.

# Numerical Simulation of Bogie Tests

Subcomponent modeling allows the research team to gain confidence in the accuracy of smaller-scale models before assembling the full system model for predictive simulations. Posts, soil, mow strip confining layers, W-beam guardrail segments, and other components comprising the guardrail system were studied using subcomponent finite element models. The bogie tests previously described were simulated using a finite element model of the bogie vehicle that is available from the National Crash Analysis Center (NCAC) (Ross et al. 1993; Federal 2002).

Material models available in *LS-DYNA* at the time of the study were used to represent soil (*LS-DYNA* 2001). In order to capture the increase in shear strength under normal stress demonstrated by cohesionless soils, the model proposed by Drucker and Prager was used in this study. Drucker and Prager proposed a modification of the Mohr–Coulomb criterion to take into account the inability of a cohesionless soil to resist tensile loading. The result of this modification is a soil with increased shear strength under normal stress. With the shearing deformation comes volumetric expansion. As illustrated in Fig. 3, soil behind the post expands during compression loading. By comparing results of the simulation to the corresponding bogie tests, input properties of the soil material model were calibrated within published ranges for standard soil in *Report 350*.

Wood is a complex material with different mechanical properties along the grain and perpendicular to the grain. Because failure of a wood post has a significant impact on the behavior of the mow strip system, available *LS-DYNA* (2001) material models were examined in order to adequately represent the



Fig. 3. Test and simulation of bogie impacting a wood post in soil

behavior of wood. In previous research, material 13; *Isotropic Elastic Failure* has been used to model wood posts. Material properties for this model can be calibrated using test data. In order to fully capture the three-dimensional failure mechanism of a wood post in flexure, it is necessary to use an orthotropic material model. *LS-DYNA* has a material model, material 59, which is capable of modeling orthotropic failure of solid elements. While testing the ability of material 59 to model the behavior of a wood post, several numerical instabilities were encountered. Thus material 13 with a strain based failure criterion was calibrated and used in this study.

Grout material for the mow strip was modeled using material 12; Isotropic Elastic Failure. This material model allows the user to specify a failure pressure for element erosion. In addition, LS-DYNA has an Add Erosion option that allows the user to simulate material failure by erosion of elements according to seven different failure criteria. The grout material model was validated using a bogie impact simulation of the 457 mm (18 in.) diameter grout-filled leave-out in a 200 mm (8 in.) thick asphalt mow strip (see Fig. 3). The asphalt mow strip impact test was used for validation to avoid complications of concrete fracture that occurred during the concrete mow strip tests. The compressive strength of the grout as tested was 0.83 MPa (120 psi). The Isotropic Elastic Failure material model was used with element erosion to model failure of grout elements. When pressure in an element reaches a specified failure value, the element is eroded. After simulating numerous pressure failure values, a pressure failure of 0.23 MPa (33 psi) allows the grout to fail in a manner that was consistent with the bogie testing. The maximum acceleration placed on the bogie vehicle directly corresponds to failure of the grout. When the grout begins to fail, the reaction force placed on the bogie by the mow strip and post begins to decrease. By calibrating the peak force (or acceleration) placed on the bogie, the most accurate grout pressure failure value can be



**Fig. 4.** Acceleration time history of bogie impacting steel post surrounded by eroding grout elements

found for the simulation. Fig. 4 shows a slight variation between an experimental test and simulation. However, there is good correlation between both the maximum acceleration and the rate of change of acceleration. Future simulations can improve the grout model by implementing a more sophisticated failure criterion; however, by modeling the peak capacity of the grout before failure, an accurate representation of post deflection can be achieved with the existing grout model.

Numerically simulated impact of the bogic vehicle predicts the wood post to deflect through the soil. Soil dilation occurs behind the post both in physical testing and numerical simulation as with the steel post impact. The post deflection pattern is consistent between the experimental test and simulation. In addition, close correlation between test and simulation acceleration histories was obtained (Fig. 4).

#### Numerical Simulation of Full System

Based on the strong post component testing and simulation, full-scale finite element models for several different guardrail configurations were developed (Fig. 5). These configurations include:

- 1. The baseline strong post steel guardrail system [G4 (1S) standard system] with posts embedded in soil;
- 2. The strong steel post guardrail system encased in rigid pavement;
- 3. The strong steel post guardrail system installed in rigid pavement with leave-outs surrounding the posts. The top 152 mm (4 in.) of the leave-outs were backfilled with weak grout material;
- 4. The wood post guardrail system encased in soil;
- 5. The wood post guardrail system encased in a rigid pavement;
- The wood post guardrail system installed in rigid pavement with leave-outs surrounding the posts. The top 152 mm (4 in.) of the leave-outs were backfilled with weak grout material; and
- 7. Steel and wood post guardrail in soil.

The impact scenario case is test 3-11 according to NCHRP *Report 350.* Test 3-11 prescribes an impact condition for which a 2,000 kg truck vehicle impacts the test installation at a velocity of 100 km/h and an impact angle of  $25^{\circ}$ . A full-scale finite element model of a G4 (1S) guardrail system was developed and used in impact simulations as a reference benchmark for the mow-strip configurations and as a means of validating the system models. Numerical simulation shows that the vehicle is smoothly redirected without severe snagging or pocketing, and exits the system in a stable manner without considerable roll. Overall dynamics of the vehicle are consistent between the physical test



**Fig. 5.** Finite element model of steel post guardrail system in soil: (a) Post in soil; (b) blockout bolted to post; and (c) bolted rail splice

and numerical simulation. With numerical simulation of the G4 (1S) guardrail system demonstrating behavior that is typical of full-scale crash tests, this numerical model is used as a baseline model to construct other finite element models of mow strip guardrail system variations. Figs. 6 and 7(a) show simulation of the G4 (1S) guardrail system. Similarly, a full-scale simulation of a round wood post W-beam guardrail system in soil was conducted and validated with previously run crash test results.

## Steel Post Guardrail Systems

To investigate the effect of having a mow strip made entirely of concrete or asphalt, a finite element model of a full-scale guardrail system encased in a rigid mow strip was constructed. The mow strip was assumed to be rigid in order to represent the case where no movement (rotation) of the post is allowed. This assumption is realistic since relatively thick concrete and asphalt mow strips are used in practice. When simulated, as shown in Fig. 7(d), the bases of the posts do not deflect. This allows the vehicle tire to ride over the post and impact the wood blockout. The vehicle seems to be relatively unstable compared to the base-line simulation because it is riding on the rail. Moreover, the lack of post rotation causes increased stresses in W-beam rail segments in the impact region as well as nonsmooth rail deformation, which causes a larger distribution of relatively high strains (above 30%) in the rail.



**Fig. 6.** Full-scale steel post in soil simulation results: (a) Comparison with crash test and (b) vehicle impacting system

The next logical step was to investigate the placement of leave-out material surrounding the post in the mow strip system model. This was achieved via modeling a grout leave-out section in the rigid mow strip that was previously simulated. The grout material was modeled with solid elements that fail at a certain pressure that corresponds to the material strength of the cement mix. As shown in Figs. 7(b and c), the posts have a better chance of rotating in the mow strip because of the fracture of the weak grout material. The rail deformation pattern does not resemble a pocketing pattern. This results in a much smoother redirection of the vehicle without ride over or potential dynamic



**Fig. 7.** Simulation results for steel post guardrail systems embedded in: (a) Standard soil; (b) rectangular grout leave-outs; (c) square grout leave-outs; and (d) rigid concrete mow strip

instability of the vehicle. Two posts disengaged from the rail and some were rotated in a similar way to post rotation in plain soil. Contours of plastic strain indicate localized concentrations of high strain around bolt slots and moderate plastic strain throughout the rail segment. This indicates that rupture in the rail segment is not likely and only a few tears around the slots are likely to develop.

## Wood Post Guardrail Systems

To investigate the effect of having a mow strip made entirely of concrete or asphalt, a finite element model of a full-scale wood post guardrail system encased in a rigid mow strip was constructed in a similar fashion to a steel post guardrail system. Again, the mow strip was assumed rigid to represent the case where no movement (rotation) of the post was allowed. Four posts were broken and the vehicle sustained damage to the front left area and the driver door. There was no strong indication of the rail developing a pocketing pattern and the vehicle seems to be relatively stable. The rail sustains some high plastic strains along a cross section at a post, which correspond to high stresses and a good probability of rupture of the W-beam at a post.

Similar to the steel post guardrail system, the wood post guardrail system encased in a mow strip with grout leave-outs was modeled. The posts have an increased likelihood of rotating in the mow strip because of the fracture of the weak grout material. The rail deformation pattern does not resemble a pocketing pattern. This resulted in a much smoother redirection of the vehicle without ride over or potential dynamic instability of the vehicle. Two posts disengage from the rail and some were rotated in a similar way to post rotation in plain soil. Plastic strain indicates localized concentrations of high strain around bolt slots and moderate plastic strain throughout the rail segment. This indicates that rupture in the rail segment is not likely and only a few tears around the slots may develop.

Of the three, the system embedded in rigid concrete seems to be the most likely to exhibit vehicular instability. Based on vehicle behavior, the grout leave-outs seem to be a significant improvement over the rigid concrete system; however, the system embedded directly in soil still seems to be the best option. Both leave-out systems redirect the vehicle without causing behavior that induces rolling. In addition, neither system allows the vehicle to overrun the rail during impact.

# **Full-Scale Crash Testing**

Two full-scale crash tests were performed: one on a W-beam guardrail mounted on W6×9 steel posts and 203-mm (8-in.) deep routed wood blockouts, and one on a W-beam guardrail mounted on 178-mm (7-in.) diameter round wood posts with 203-mm (8-in.) deep routed wood blockouts. The 178-mm (7-in.) diameter round wood post was selected over a  $152 \times 203$  mm (6×8 in.) wood post because it has less flexural capacity and, thus, is more likely to fracture when confined within a mow strip.

The concrete mow strip constructed for the crash tests was 1.067 m (3 ft 6 in.) wide and 127 mm (5 in.) thick. A  $457 \times 457 \text{ mm}$  ( $18 \times 18 \text{ in.}$ ) leave out section was formed around the guardrail posts. The traffic face of the posts was offset 76.2 mm (3 in.) from the front edge of the leave out. The posts were set inside 0.457 m (18-in.) diameter augured holes to a depth of 1.1 m (3.75 ft). The void area around each post was backfilled to within 102 mm (4 in.) of the top of the mow strip



(a)



**Fig. 8.** Full-scale mow strip crash test: (a) Full system before impact and (b) comparison of test and simulation after impact

with NCHRP *Report 350* standard soil. The top 102 mm (4 in.) of the leave out was backfilled with a two-sack grout mixture. Details of the test installation are shown in Fig. 8.

The tests followed the impact conditions of NCHRP Report 350 test 3-11, which involves a 2,000-kg pickup truck impacting the guardrail at a speed of 100 km/h and an angle of 25°. In both tests, the vehicle was successfully contained and redirected in a stable manner. Fig. 9 shows sequential images of both test and simulation for the steel post guardrail system encased in a mow strip. The grout material in the leave-out sections surrounding the posts failed as designed, permitting the posts in the impact region to rotate in the soil and help dissipate the lateral energy of the vehicle. A partial tear was observed in the W-beam rail after the steel post guardrail test, but the rail maintained its integrity and did not rupture. Two posts fractured during the wood post test, but the vehicle did not pocket into or rupture the rail. Although several of the posts contacted the back edge of the leave-out during testing, there was no damage to the concrete mow strip in either test. The repair would consist of removing the damaged guardrail components and grout and resetting the system within the existing leave-outs.

In summary, both guardrail systems met all the required evaluation criteria of NCHRP *Report 350* and demonstrated low maintenance/repair costs under design impact conditions.

## **Summary and Recommendations**

The successfully tested mow strip systems are considered to be representative of the most severe confinement conditions allowable. Any increase in post confinement beyond that provided by the grout backfill material used in the leave-out sections formed around guardrail posts should undergo additional analysis and/or testing. This applies to systems featuring guardrail posts directly encased in concrete or asphalt. In addition to providing greatly enhanced impact performance, it is believed that mow



Fig. 9. Sequential comparisons of full-scale mow strip test and simulation: (a) 0.0 s; (b) 0.295 s; and (c) 0.595 s

strip configurations featuring leave-outs are also more practical based on ease of repair after an impact. Some recommendations resulting from this research regarding acceptable ranges for some key mow strip parameters, including mow strip material and dimensions, leave-out dimensions, leave-out backfill material, and guardrail post location are provided below.

# Mow Strip Material

One of the objectives of the mow strip research is to develop mow strip configurations that incur minimal damage during an impact and thereby reduce the cost and worker exposure associated with repairs after an impact. Because dynamic bogie testing indicated that a concrete mow strip is more likely to become damaged in an impact, it was chosen for full-scale testing to assess the magnitude and extent of repairs required after a design impact event. In full-scale tests of both the steel and wood post guardrail systems, no posts impacted the concrete mow strip with sufficient force to damage the concrete. Only the sacrificial leaveout material was damaged. Because of this, it is anticipated that little or no repair of the mow strip should be required when either asphalt or concrete is used as the mow strip material. However, to avoid damage to the concrete mow strip layer, the concrete should be at least as strong as the welded wire fabric reinforced TxDOT Class B concrete used in the crash test. Asphalt is also considered to be an acceptable mow strip material.

# Mow Strip Dimensions

The mow strip systems that were crash tested were 1.07 m (3.5 ft) wide. This width is based on two factors. First, this width of mow strip layer provides adequate clearance behind the guard-rail posts to allow for the wheel of a mower deck to ride on the mow strip surface. This allows the mower to cut grass right up to the edge of the paved surface eliminating the need for any roadside hand mowing. Second, the layer of concrete provided behind the grout leave-out is wide enough to prevent significant concrete failure during design impact conditions. If damage to the concrete mow strip layer can be avoided during an impact, repair efforts will be significantly reduced. However, the overall mow strip dimensions can be varied without effecting impact performance, provided a leave-out with dimensions equal to or exceeding those used in the crash test are provided around the guardrail posts.

Depth of the concrete mow strip used in the crash test installations was 127 mm (5 in.). Because the energy dissipating ability of a mow strip system depends primarily on the leave-out material and dimensions, the mow strip depth is not critical to system performance within reasonable bounds. The point of rotation of the post is approximately two-thirds of the post embedment depth and the first point of contact of the post with the mow strip will always be the upper edge. The primary reason for a mow strip depth requirement is the prevention of damage during an impact. Concrete mow strip depths less than 127 mm (5 in.) may result in some damage to the concrete under design impact conditions, but will not adversely affect impact performance. Bogie impacts of posts in asphalt mow strips were conducted using mow strip depths up to 203 mm (8 in.). Acceptable post behavior was observed in these tests. Therefore mow strip depths of 203 mm (8 in.) or less are considered acceptable from an impact performance standpoint. Mow strip depths significantly greater than 203 mm (8 in.) may warrant further investigation since the additional soil confinement may begin to restrict movement of the post.

# Leave-Out Dimensions

Both steel and wood post systems were tested with  $457 \times 457$  mm (18 × 18 in.) square leave-outs. A 457 mm (18 in.) diameter round leave-out provides approximately the same area of leave-out material around the post and is considered to be an acceptable alternative to the square leave-out. Without further testing, these are considered to be the minimum acceptable dimensions for the leave-outs. However, larger leave-out dimensions are considered acceptable from both an impact performance and maintenance/repair standpoint. Under severe impact conditions, larger leave-outs provide more distance for the post to rotate before bottoming out on the mow strip material. If desired, it is considered acceptable to extend the leave-out to the back edge of the mow strip. However, while offering potential improvement in impact performance, this practice may make the leave-out backfill material more subject to cracking or other forms of long-term degradation.

# Leave-Out Backfill Material

The material used to backfill the leave-outs is a standard two-sack grout mixture. Tests indicated a maximum 28-day compressive strength of 0.83 MPa (120 psi) for this material. Other leave-out backfill materials (e.g., foams) may be accepted

as alternatives to the two-sack grout provided their compressive strength does not exceed that of the grout. The strength of an alternative leave-out backfill material can be demonstrated through laboratory and/or dynamic bogie vehicle testing. Alternative leave-out backfill materials should also have a demonstrated ability to resist growth of vegetation. Approval of a backfill material with a compressive strength exceeding that of the twosack grout [i.e., greater than 0.83 MPa (120 psi)] would require a full-scale crash test.

The depth of leave-out backfill material used in the crash tests was 102 mm (4 in.). This depth should be sufficient to resist cracking and growth of vegetation. Shallower depths of leave-out material are acceptable from an impact performance stand-point. However, the long-term durability of a shallow grout layer is not known and any degradation of the leave-out material would likely reduce its resistance to growth of vegetation over time. Backfill depths significantly greater than 102 mm (4 in.) may warrant further investigation through a dynamic bogie vehicle test to assess effects on the force-deflection characteristics of the post.

## Guardrail Post Type

Full-scale crash tests were successfully conducted with both  $W6 \times 9$  steel and 177.8-mm (7-in.) diameter round wood guardrail posts. Both of these post types are considered to be acceptable alternatives for use with the recommended mow strip configurations described above.

A full-scale crash test of the wood post guardrail system was conducted using 177.8 mm (7 in.) diameter round wood posts because it was considered to represent a more critical condition than a  $152.4 \times 203.2$  mm ( $6 \times 8$  in.) rectangular wood post for mow strip applications. For a given grade of wood post, a  $152.4 \times 203.2$  mm ( $6 \times 8$  in.) rectangular cross section has more bending strength than a 177.8 mm (7 in.) diameter round wood post is more likely to fracture under increased confinement and result in vehicular pocketing. Since a 177.8 mm (7 in.) diameter round wood post was successfully crash tested, a  $152.4 \times 203.2$  mm ( $6 \times 8$  in.) rectangular wood post is also considered to be an acceptable post type.

## **Guardrail Post Location**

The front (traffic) face of the guardrail posts should be placed approximately 76 mm (3 in.) from the front edge of the leave-out. This location was selected to maximize the available post deflection distance while providing sufficient room to permit proper tamping of the soil in front of posts installed by drilling and backfilling. If the posts are installed by driving, the 76 mm (3 in.) offset between the front edge of the leave-out and the front face of the post is not required and overall dimensions of the leave-out can be accordingly reduced as long as the distance between the back face of the post and the back edge of the leave-out is maintained.

The offset of the face of the post from the front edge of the leave-out can be increased provided the overall depth of the leave-out is also increased so as to maintain a deflection distance between the back face of the post and the back edge of the leave-out that is equal to or greater than 177.8 mm (7 in.).

 Table 2. Summary of Full-Scale Simulation Results

Guardrail system	Maximum dynamic deflection (mm)	Number of separated posts
Steel posts in soil	862	2
Steel posts in 457×457 leave-outs	795	2
Steel posts in 457×607 leave-outs	780	2
Steel posts in rigid mow strip	627	2
Wood posts in rigid mow strip	868	4
Wood posts in $457 \times 457$ leave-outs	828	3

## Conclusions

Provided that a guardrail is crashworthy, there are other factors that merit consideration such as the cost and related safety concerns associated with routine maintenance (e.g., mowing) and repair operations. Encasing the guardrail in a mow strip can help address some of these issues. However, there are no national standards for this practice and the effect of mow strips on impact performance had not been previously investigated.

The performance of guardrails encased in a pavement mowstrip was researched using component tests, component simulations, predictive full-scale simulations, and full-scale crash testing. Nonlinear finite element analyses were used successfully as a design tool for selecting a working mow strip design for both steel and wood post guardrail systems. Two full-scale crash tests were successfully conducted in accordance with NCHRP *Report 350* to verify impact performance of the recommended designs (see Table 2).

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