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Midwest Guardrail System with Round Timber Posts

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A modified Midwest Guardrail System (MGS) was developed by using small-diameter round wood posts. The barrier system was configured with three timber species: Douglas fir (DF), ponderosa pine (PP), and southern yellow pine (SYP). Barrier VII computer simulation, combined with cantilever post testing in a rigid sleeve and soil, was used to determine the required post diameter for each species. The recommended nominal sizes were 184 mm (7.25 in.) for DF, 203 mm (8 in.) for PP, and 190 mm (7.5 in.) for SYP. A grading criterion limiting knot size and ring density was established for each species. The recommended knot sizes were limited to 38 mm (1.5 in.) or smaller for DF, 89 mm (3.5 in.) or smaller for PP, and 64 mm (2.5 in.) or smaller for SYP. The minimum ring densities equaled or exceeded 6 rings per inch (rpi) for DF, 6 rpi for PP, and 4 rpi for SYP. Two guardrail systems—one using DF posts and another using PP posts—were crash tested according to the Test Level 3 requirements specified in *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* Crash testing was not conducted on the SYP system because of the adequacy of previous testing on 184-mm (7.25-in.) diameter SYP posts in a standard W-beam guardrail system and post design strength comparable to that in the other two species. Both crash tests showed that the modified MGS functioned adequately for both wood species. Three round wood post alternatives were recommended as an acceptable substitute for the standard W152×13.4 (W6×9) steel post used in the MGS.

Prompted by the devastating forest fire season of 2000, President William J. Clinton initiated the development of what would become the National Fire Plan. It established four main goals: improve fire prevention and suppression, reduce the amount of hazardous fuels, restore fire-adapted ecosystems, and promote community assistance (*1*).

One of the most commonly used fire-prevention techniques is fuel management, an idea that has been around for many years. In the 1960s, the Forest Service of the U.S. Department of Agriculture began managing fuels with controlled burn techniques (*2*); fires were initiated in areas where they could be contained to consume the small-diameter forest thinnings (SDTs) that might serve as fuel for future fires. These thinnings were most commonly made up of various pine and fir species. Although this controlled burn technique has generally been effective, it has been stated to offer no economic benefits while carrying many risks.

There are many uses for the small-diameter trees that make up most of the forest thinnings—including lumber, structural round wood, wood composites, wood fiber products, compost, mulch, energy, and fuels (*3*). One proposal is to remove the forest thinnings and sell them for use in various products, hopefully recovering the cost of removing the material. A large number of end products have the potential to recover the costs associated with removing SDTs. Therefore, more uses for SDTs must be developed (*4*).

Guardrail post production was a possible application under consideration for using SDTs. SDTs used in guardrail systems would provide a new application for thinnings and also reduce the cost of the barrier system. However, further research was deemed necessary to determine the structural properties of SDT material so that the use of round wood in new value-added markets (i.e., longitudinal barrier systems) can be expanded.

LONGITUDINAL BARRIER SYSTEMS

For more than 50 years, longitudinal barrier systems have been constructed along the nation's highways and roadways to prevent errant motorists from colliding with dangerous fixed objects or traversing hazardous roadside geometries beyond the edge of the traveled way. Although several different longitudinal barrier systems can be found throughout the United States, strong-post W-beam guardrail systems historically have been the most common. Typical design details for these common barrier systems can be found in AASHTO's *Roadside Design Guide* (*5*) as well as in AASHTO's *Task Force 13 Report, A Guide to Standardized Highway Barrier Hardware* (*6*).

Longitudinal, W-beam barrier systems generally consist of a W-beam guardrail element, evenly spaced support posts, and blockouts or post spacers. The W-beam rail is available in two thicknesses—2.66 mm (12 gauge) and 3.42 mm (10 gauge)—although most installations have used 2.66-mm (12-gauge) rail sections. Guardrail posts have been manufactured from both wood and steel materials. For the steel alternative, both the W152×12.6 (W6×8.5) and W152×13.4 (W6×9) wide-flange post sections have been used. For the wood alternative, 152- × 203-mm (6- × 8-in.) rectangular and 184-mm (7.25-in.) diameter round-post cross sections have been successfully used and generally manufactured from Grade 1 or better southern yellow pine (SYP) material. Although several post options

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have been available throughout the United States, rectangular wood and wide-flange steel posts traditionally have been used. Blockouts have been incorporated into barriers to position the W-beam rail away from the traffic-side face of posts. This rail offset reduces the propensity for vehicles to snag on the posts, raises the rail section during post rotation, and decreases the potential for vehicular instabilities and rollover. Over the last two decades, most post spacers were manufactured from wood materials and were generally the same size as the rectangular post. However, over the last 15 years, several companies have also developed blockouts manufactured from recycled polymer materials to promote the positive environmental aspects of keeping used tires out of landfills.

Three post types have been commonly used in strong-post, W-beam guardrail systems: W152×13.4 (W6×9) steel posts, 152- × 203-mm (6- × 8-in.) rectangular wood posts, and 184-mm (7.25-in.) diameter round wood posts. Round timber posts traditionally have been the least costly. Although round SYP posts have been the most economic ones, large-scale implementation of round-post, W-beam barrier systems has been mostly limited to the state of Texas, with most of the research and development of these barrier systems conducted at the Texas Transportation Institute (*7–10*). As such, significant opportunities exist for increased use of round posts of multiple timber species in crashworthy, strong-post, W-beam guardrail systems.

In 2000, the Midwest Roadside Safety Facility (MwRSF), in cooperation with the Midwest States Pooled Fund Program, developed a guardrail system that would improve barrier performance for higher center-of-mass vehicles, provide reasonable barrier height tolerances, and reduce the potential for W-beam rupture (*11–14*). This W-beam guardrail system later became known as the Midwest Guardrail System (MGS). Design changes incorporated into the W-beam barrier system included a nominal W-beam rail top mounting height of 787 mm (31 in.), a reduced guardrail post-embedment depth of 1,016 mm (40 in.), an increased blockout depth from 203 to 305 mm (8 to 12 in.), and a repositioning of the guardrail splice from post to midspan locations. Prior crash testing has demonstrated that the MGS was capable of containing and redirecting both 0.75-ton pickup trucks and small cars according to current impact safety standards. On the basis of these successes, the researchers decided to use the MGS for this study.

RESEARCH OBJECTIVES

Several objectives were identified for this research project. The first objective was to determine the structural properties of round wood posts manufactured from Douglas fir (DF), ponderosa pine (PP), and SYP when subjected to impact loading conditions. A second objective was to determine an acceptable diameter, grading specification, and embedment depth for each wood species to allow its use as a substitute for the rectangular SYP and wide-flange steel posts used in guardrail applications, including the MGS. Nonlinear, dynamic vehicle-to-barrier impact analysis was used to investigate MGS failure criteria and to evaluate barrier performance. The final research objective was to conduct a safety performance evaluation of the MGS with round wood posts according to guidelines in *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features* (*15*). Upon project completion, an installation manual and standard computer-aided drafting plans were prepared for the round-post MGS using PP, DF, and SYP posts.

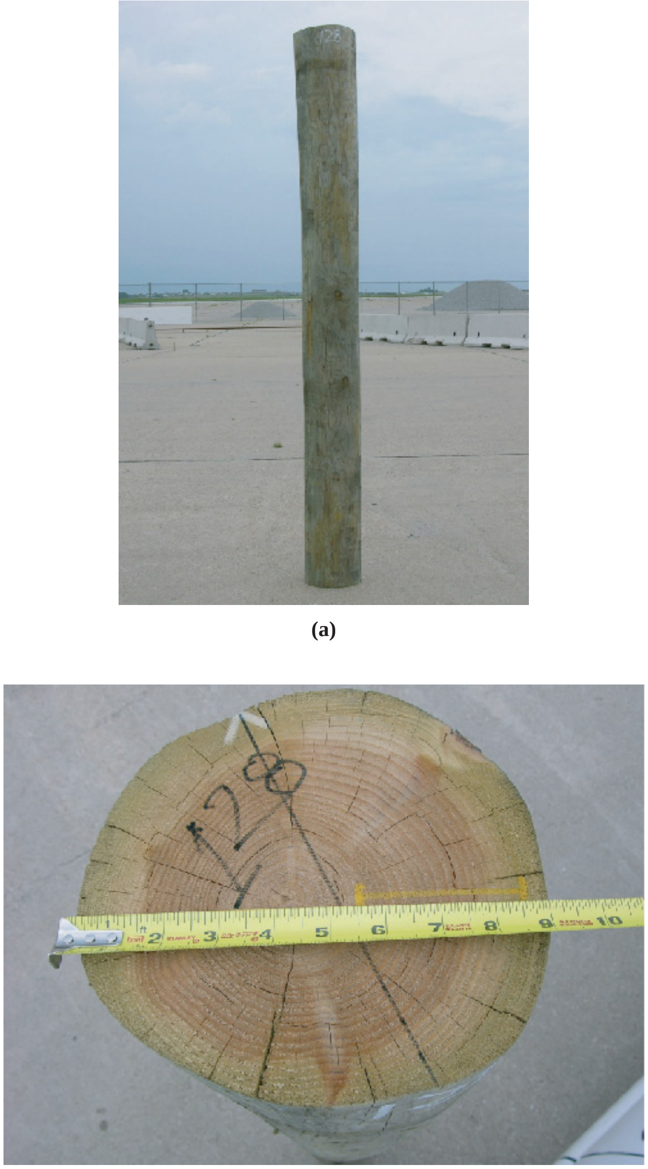
WOOD SAMPLING AND PREPARATION OF SPECIMENS

Initially, a post diameter was selected for the three species based on the success of 184-mm (7.25-in.) diameter, SYP guardrail posts from full-scale crash tests conducted by Texas Transportation Institute researchers (*7–10*). Preliminary sizes for the two species were determined by using tabulated strength values for DF and PP to carry a bending moment equivalent to that of the SYP posts. These sizes were 216 mm (8.5 in.) for PP and 190 mm (7.5 in.) for DF. The diameter for SYP was maintained at 184 mm (7.25 in.). The 1,981-mm (78-in.) length was arbitrarily selected to ensure sufficient length to increase the post-embedment depth, if needed.

Unlike some materials, wood is highly variable. Its strength can change drastically with variation in species, ring density, knot size and density, moisture content, and even region of origin. As such, three categories of posts were defined to investigate the effects of the two most influential variables—knots and ring density. The selected categories were low ring density (LRD) without knots or with small knots (SKN), LRD with big knots (BKN), and high ring density (HRD) SKN. Posts were categorized according to ring density, knot frequency, and knots. Posts with four or fewer rings per inch (rpi) were defined as LRD and those with six or more rpi were defined as HRD. Posts with any knots larger than 64 mm (2.5 in.) in diameter were classified in the BKN category, and posts with knots that were less than 38 mm (1.5 in.) in diameter were classified in the SKN category and were considered to be without knots. A portion of the testing was intended to isolate the properties of posts in these three categories, and a portion was intended to determine the properties of the random population. Additional details about the post population, sampling methodology, and preservative treatments have been previously reported (*16–19*).

Each round post was weighed, measured, documented, and knot mapped. A typical round timber post is shown in Figure 1. The stress wave modulus of elasticity (SWMOE) for each post was estimated with a standard stress wave technique (*20*); each post was tapped once with a hammer, sending a stress wave through the post. At the same time, a sensor determined the time for the stress wave to travel to the other end of the post and return. According to the time and the post length, the wave velocity was calculated and used with the mass density to determine the SWMOE. Posts were ranked in each category by the estimated SWMOE values. The posts for static and dynamic testing were sorted by SWMOE and randomly assigned to the Forest Service's Forest Products Laboratory for static testing or to MwRSF for dynamic testing.

Moisture contents were measured with a pin-type moisture meter at three locations from the post bottom: 533 mm (21 in.), 991 mm (39 in.), and 1,448 mm (57 in.). The area within this region was defined as the critical zone—the zone where fracture was likely to occur. Circumference was also measured in the three critical zone locations and at the top and bottom of the post. Weights and lengths were measured to determine an approximate density. Ring counts were taken over a 3-in. length, and knots were carefully documented. Each post was also photographed during documentation. As the moisture content of a wood post increases up to 23%, the strength of the wood fibers within the post decreases. Beyond 23%, the wood strength is fairly constant. In actual use in the ground, the moisture content may exceed 23%, and therefore the posts would be saturated. Upon completion of post documentation, the timber posts were placed in a 1,219-mm (48-in.) deep tank of water in an effort to sat-



(a)

(b)

FIGURE 1 Typical round timber post.

urate the critical zone of the posts, replicating the worst-case scenario that the posts may encounter when used in a guardrail system. The moisture content and weight of the posts were measured again on test day to give a more accurate representation of the posts after they had been soaked in water.

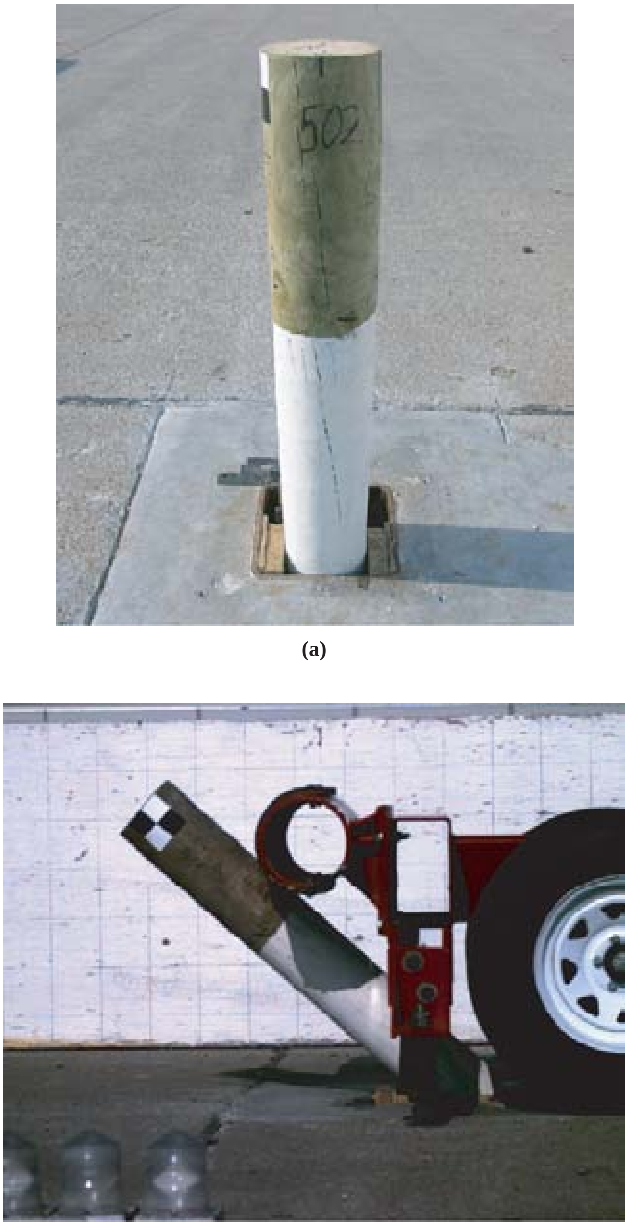
COMPONENT TESTING

The component testing program consisted of two phases. Phase I testing included static and dynamic evaluation of the structural properties for the three wood species when subjected to cantilevered loading. For Phase I, two rounds of testing were conducted to determine the optimum size of the round posts. During Phase II, dynamic testing of posts embedded in soil was performed on each wood species by cantilevered loading while varying the soil embedment depths.

Phase I

The static tests for Phase I were conducted with a million-pound test frame at the Forest Products Laboratory with a loading rate of 0.008 m/min (0.3 in./min). Loads were recorded on a 222.4-kN (50,000-lb) load cell in Round 1 and on a 133.4-kN (30,000-lb) load cell in Round 2. Deflections were recorded with linear variable differential transducers.

The Phase I dynamic tests were conducted at the MwRSF with a 728-kg (1,605-lb) rigid-frame bogie vehicle, as shown in Figure 2. The bogie vehicle traveled at about 32 km/h (20 mph) in Round 1 and 21.7 km/h (13.5 mph) in Round 2. Bogie accelerations were recorded with onboard accelerometers.



(a)

(b)

FIGURE 2 Phase I dynamic test setup with rigid bogie vehicle.

TABLE 1 Test Matrix for Phase I Cantilever Beam Tests

	Number of Static (ST) and Dynamic (DY) Tests in Rounds 1 and 2 for Various Sizes of DF, PP, and SYP posts[a]												
	Round 1						Round 2						
	DF, 190 mm		PP, 216 mm		SYP, 184 mm		DF, 171 mm		PP, 190 mm		SYP, 178 mm		
Variable	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	Total
BKN LRD[b]	5	5	5	5	5	5	5	5	5	5	5	5	60
SKN LRD[b]	5	5	5	5	5	5	5	5	5	5	5	5	60
SKN HRD[c]	5	5	5	5	5	5	5	5	5	5	5	5	60
Population[d]	45		45		45		45		45		45		270
Total tests	60	15	60	15	60	15	60	15	60	15	60	15	450

[a] Static tests were conducted at Forest Products Laboratory, dynamic tests at MwRSF.
[b] ≤4 rpi.
[c] ≥6 rpi.
[d] Random mixture of posts.

For each round of testing, 10 posts for each species and knot–ring category were identified to have the appropriate knot–ring combinations. An additional 45 posts were collected from the larger post population for static testing. The test matrix for the cantilever tests is presented in Table 1. The study was set up so that both static and dynamic tests would be performed on three knot–ring combinations (BKN LRD, SKN LRD, and SKN HRD). The two types of knots—BKN and SKN—varied depending on the species. There were also two rpi categories: low (≤4 rpi) and high (≥6 rpi). Further tests of a larger sample more representative of the expected post population were also tested statically. Grading supervisors from Timber Products Inspection, Inc., assisted in identifying posts with the required diameter knot and rpi categories.

The Round 1 and 2 static and dynamic testing results are presented in Table 2 and include comparisons for SWMOE, modulus of rupture (MOR), and peak load.

After Round 1 testing, the results for peak load and MOR were evaluated to determine whether the post size could be modified. Traditionally, the size of the guardrail post is based on its ability to rotate backward in soil without post fracture as well as its ability to carry the post–soil forces generated along its length as it rotates. On the basis of prior MGS post testing of steel guardrail posts embedded in soil, it was determined that a peak load capacity of 42.3 to 44.5 kN (9.5 to 10 kips) would be adequate for the round wood posts when the load was applied 632 mm (24.875 in.) above the ground.

During Round 1 testing, the targeted post diameters were 190 mm (7.5 in.), 216 mm (8.5 in.), and 184 mm (7.25 in.) for DF, PP, and SYP, respectively. During testing, the peak load capacity of the PP posts was found to be considerably higher than the desired value and the load capacities observed for the DF and SYP posts. As such, the research team determined that the SYP and DF post diameters could be reduced slightly to perform adequately in the MGS, while a larger reduction in post diameter was warranted for the PP posts. After Round 1 testing, new post sizes were ordered with the following targeted diameters: 171 mm (6.75 in.) for DF, 190 mm (7.5 in.) for PP, and 178 mm (7.0 in.) for SYP.

After the first round of dynamic testing and a more detailed investigation, the standard methods used in the dynamic cantilever bogie testing program were found to provide inaccurate test results for peak load. For example, the post strength may have been overestimated by as much as 50% because of the effects of inertia, thus leading to inaccurate diameter calculations. An alternative procedure was investigated in a series of three additional cantilever post bogie tests. These tests confirmed the problem and showed that a reduction in the bogie impact speed would substantially reduce the effects of inertia, thus leading to a more accurate prediction of ultimate fiber stress. Unfortunately, these results were not identified in time to modify the post sizes after Round 1 testing. However, the testing methods were adjusted during Round 2.

After Round 2 testing, the population results suggested that the diameters for the DF and SYP posts were close to the desired peak load range. However, the PP posts appeared to require an increased post diameter. In addition, knot size did not have a consistent impact on the post's load capacity. The knots and rpi data indicated that the most substantial gains in post strength were observed by raising the rpi value. A higher rpi count increased the average MOR and peak loads for all species by 40% and consistently placed the material tested in the upper part of the population distribution. A comparison of the results from the Round 1 and 2 static and dynamic testing programs suggested a dynamic magnification factor from 20% to 30%.

Before conducting the Phase II post–soil embedment tests, it was deemed necessary to determine a modified post diameter for each species. By using a 42.3-kN (9.5-kip) load capacity, a 3% failure rate was established as an acceptable level of risk for the guardrail system to fail due to the fracture of four consecutive posts when subjected to Test Level 3 (TL-3) pickup truck testing according to *NCHRP Report 350* (*15*). A discussion on the failure risk analysis was detailed by Hascall (*16, 18*). The minimum post size was then determined with elastic bending equations and the estimated MOR. Sixty percent of the posts were needed to withstand an impact force of 42.3 kN (9.5 kips) at a height of 632 mm (24.875 in.) or a bending moment capacity of 26.7 kN-m (236 kip-in.). The resulting target post sizes were found to be 165 mm (6.5 in.), 184 mm (7.25 in.), and 171 mm (6.75 in.) for DF, PP, and SYP posts, respectively, and for use in the initial Phase II post–soil embedment testing program.

TABLE 2 Results for SWMOE, MOR, and Peak Load Average Values for Phase I Cantilever Beam Tests

	Round 1						Round 2					
	DF, 190 mm (7.5 in.)		PP, 216 mm (8.5 in.)		SYP, 184 mm (7.25 in.)		DF, 171 mm (6.75 in.)		PP, 190 mm (7.5 in.)		SYP, 178 mm (7 in.)	
Variable	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY
BKN LRD[a]												
SWMOE (GPa)	9.9	9.6	6.8	6.9	7.6	7.0	9.2	10.1	4.5	4.3	7.4	6.3
(×10^6 lb/in.^{2})	1.43	1.39	0.99	1.00	1.10	1.02	1.34	1.47	0.65	0.63	1.08	0.91
MOR (MPa)	42.4	60.9	26.9	44.8	34.5	48.3	39.9	49.8	35.0	45.9	35.1	38.5
(lb/in.^{2})	6,160	8,830	3,900	6,500	5,000	7,010	5,780	7,220	5,070	6,650	5,090	5,580
Peak load (kN)	41.8	59.6	45.4	73.4	32.0	48.5	28.5	40.9	33.8	39.1	32.0	33.8
(1,000 lb)	9.4	13.4	10.2	16.5	7.2	10.9	6.4	9.2	7.6	8.8	7.2	7.6
SKN LRD[a]												
SWMOE (GPa)	9.7	9.5	5.4	5.4	6.5	4.0	10.5	10.1	4.3	4.6	4.2	4.4
(×10^6 lb/in.^{2})	1.40	1.38	0.78	0.78	0.94	0.58	1.52	1.46	0.62	0.67	0.61	0.64
MOR (MPa)	48.5	51.7	32.4	39.0	54.1	50.6	41.7	52.5	35.0	50.5	38.8	44.3
(lb/in.^{2})	7,040	7,500	4,700	5,660	7,850	7,340	6,050	7,610	5,070	7,320	5,630	6,420
Peak load (kN)	44.0	52.0	50.3	64.5	51.6	53.8	34.3	45.8	33.8	36.9	35.1	41.8
(1,000 lb)	9.9	11.7	11.3	14.5	11.6	12.1	7.7	10.3	7.6	8.3	7.9	9.4
SKN HRD[b]												
SWMOE (GPa)	10.5	10.1	9.6	9.4	13.7	13.7	14.3	10.1	7.8	8.1	11.0	12.0
(×10^6 lb/in.^{2})	1.52	1.47	1.39	1.37	1.98	1.98	2.08	1.47	1.13	1.18	1.59	1.74
MOR (MPa)	50.3	65.5	45.9	63.3	75.3	84.4	62.8	69.2	45.6	52.1	70.8	61.6
(lb/in.^{2})	7,290	9,500	6,650	9,180	10,920	12,240	9,110	10,040	6,610	7,550	10,270	8,940
Peak load (kN)	48.9	64.5	78.7	113.0	68.1	82.3	50.7	59.2	44.0	54.7	65.4	57.4
(1,000 lb)	11.0	14.5	17.7	25.4	15.3	18.5	11.4	13.3	9.9	12.3	14.7	12.9
Population[c]												
SWMOE (GPa)	10.3	—	8.5	—	8.9	—	12.8	—	7.0	—	9.9	—
(×10^6 lb/in.^{2})	1.50		1.23		1.29		1.86		1.02		1.44	
MOR (MPa)	52.5	—	37.5	—	51.9	—	56.3	—	41.0	—	59.1	—
(lb/in.^{2})	7,620		5,440		7,520		8,160		5,950		8,570	
Peak load (kN)	48.5	—	63.2	—	48.9	—	45.4	—	40.0	—	53.4	—
(1,000 lb)	10.9		14.2		11.0		10.2		9.0		12.0	

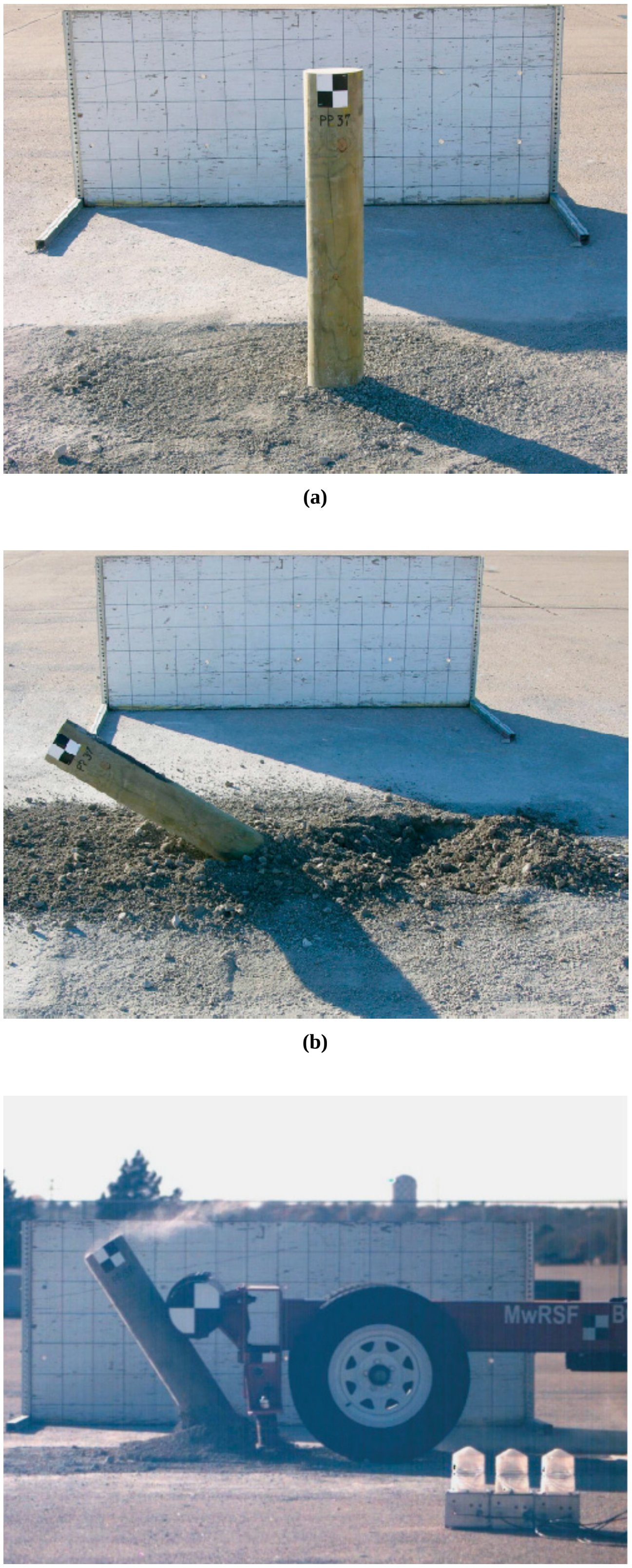
NOTE: ST = static testing, DY = dynamic testing.
[a] ≤4 rpi.
[b] ≥6 rpi.
[c] Random mixture of posts.

Phase II

For Phase II dynamic testing, 18 post-embedment tests were conducted to determine the response of round posts in compacted soil, as shown in Figure 3. A rigid-frame bogie vehicle was used to strike the posts at about 40 km/h (25 mph) and at a load height of 632 mm (24.875 in.). This velocity was chosen so that the kinetic energy of the bogie vehicle exceeded the energy absorbed in previous MGS post–soil tests. Two post-embedment depths in soil were investigated: 940 and 1,016 mm (37 and 40 in.). Two post diameters were investigated for the PP and DF species, and one diameter was studied for the SYP species. Two of the 18 post–soil tests were performed on rectangular SYP posts to serve as a baseline comparison. Details about the component testing program have been previously reported (*16–19*).

Initially, six soil tests were completed for DF [165 mm (6.5 in.)] and PP [184 mm (7.25 in.)] posts, three for each species. An embedment depth of 1,016 mm (40 in.), the standard for MGS posts, was used as a starting point. From the initial dynamic post–soil tests, the average peak forces observed in the DF and PP posts were 51.7 kN (11.6 kips) and 48.7 kN (11.0 kips), respectively. These results showed that the targeted post load capacity of 42.3 kN (9.5 kips) was about 16% less than the actual soil forces generated through the posts. These results indicated that the post diameters needed to be increased.

A second set of embedment tests was conducted to evaluate the larger posts. The anticipated peak force was increased to 53.4 kN (12 kips) for DF and 57.8 kN (13 kips) for PP. The anticipated force was higher for PP to account for the larger diameter because the post would have to move more soil and a flatter cross section, which would increase resistance to soil rotation. On the basis of these adjustments, the target nominal diameter was increased to 184 mm (7.25 in.) for DF and to 203 mm (8.0 in.) for PP. Testing of 184-mm (7.25-in.) diameter SYP posts with a 940-mm (37-in.) embedment depth showed that a slight increase in post diameter was warranted. As such, the final SYP post diameter of 190 mm (7.5 in.) was chosen for the final design. The embedment depth was decreased to 940 mm (37 in.) to lower peak loads imparted to the posts. An acceptable number of the resized posts passed the second round of soil testing.



(a)

(b)

(c)

FIGURE 3 Phase II dynamic post–soil test setup with rigid bogie vehicle.

COMPUTER SIMULATION

Before full-scale vehicle crash testing, Barrier VII (*21*) computer simulation was used to predict the dynamic behavior of the MGS with the recommended round timber post sizes. Because wood properties vary from post to post, analysis of the round-post MGS included an evaluation of several design variations where different numbers of consecutive weak posts were placed within the system. For each variation, the simulation results were evaluated, including parameters such as maximum dynamic barrier deflection, maximum rail tension, and an analysis to determine the propensity for vehicle pocketing (i.e., rail slope) and wheel snag on the posts. The simulations were performed using the TL-3 pickup truck impact condition of *NCHRP Report 350*, consisting of a 2,000-kg (4,409-lb) pickup truck striking at 100.0 km/h (62.1 mph) and 25°.

For this modeling effort, a representative wood post behavior was developed for round posts rotating in soil. Using an elastic perfectly plastic model for the post, the force–deflection curve for strong axis bending was defined by using an initial stiffness, yield displacement, yield force, yield moment, and failure deflection. For this study, MwRSF researchers selected a post behavior with a yield force and a yield displacement of 28.9 kN (6.49 kips) and 24 mm (0.96 in.), respectively, resulting in an initial stiffness of 1.18 kN/mm (6.76 kips/in.). The yield moment was calculated as 18.24 kN-m (161.44 kip-in.) with a load height of 632 mm (24.875 in.). Failure deflections of 381 mm (15 in.) and 61 mm (2.4 in.) were used for the strong and weak post behaviors, respectively.

Barrier VII simulations were completed for a baseline model as well as with models with one, two, three, and four consecutive weak posts. The results did not show a distinct point where one additional failed post would cause the system to fail drastically. However, a four-consecutive-post failure matched a previous limit where it was believed that a maximum deflection of 1,321 mm (52 in.) was too large based on reasonable engineering judgment. Therefore, the definition of system failure was maintained as the fracture of four consecutive weak posts but subject to change based on later testing. A detailed discussion and tabulation of the Barrier VII results can be found elsewhere, including determination of the critical impact point (CIP) for use in the crash-testing program (*16*, *18*).

POST SIZE AND GRADING CRITERIA

The size and grading criteria were developed after the static and dynamic test results, the population distribution of knots and ring density, and the computer simulation results were reviewed. The criteria were chosen to be tight enough to reduce the diameter of posts as much as possible but relaxed enough to allow a high percentage

TABLE 3 Round Timber Post Criteria for MGS

Species	Diameter at Groundline	Knot Size	Ring Density (rpi)	Slope of Grain
Douglas fir	184 mm 7.25 in.	≤38 mm ≤1.5 in.	≥6	1:10
Ponderosa pine	203 mm 8 in.	≤89 mm ≤3.5 in.	≥6	1:10
Southern yellow pine	190 mm 7.5 in.	≤64 mm ≤2.5 in.	≥4	1:10

of the posts to qualify. The post criteria developed for the MGS are presented in Table 3. The acceptable ranges for post diameters—as measured at the ground line—for DF, PP, and SYP were 178 to 203 mm (7.00 to 8.00 in.), 197 to 222 mm (7.75 to 8.75 in.), and 184 to 210 mm (7.25 to 8.25 in.), respectively. A grading criterion limiting knot size and ring density was established for each species. The final recommended knot sizes were limited to 38 mm (1.5 in.) or smaller for DF, 89 mm (3.5 in.) or smaller for PP, and 64 mm (2.5 in.) or smaller for SYP. The minimum ring densities for each post species were ≥6 rpi for DF, ≥6 rpi for PP, and ≥4 rpi for SYP. Additional grading criteria (i.e., post manufacture, size, scars, shape and straightness, splits and shakes, decay, holes, slope of grain, compression wood, and preservative treatment) as well as a discussion of the 25-mm (1-in.) range in post diameter are provided elsewhere (*16, 18, 19*).

TEST REQUIREMENTS AND EVALUATION CRITERIA

Longitudinal barriers, such as W-beam guardrail systems, must satisfy the requirements provided in *NCHRP Report 350* to be accepted for use on National Highway System construction projects or when out-of-date designs must be replaced. According to TL-3 of *NCHRP Report 350,* the barrier system must be subjected to two full-scale vehicle crash tests. The first test, Test Designation 3-10, consists of an 820-kg (1,808-lb) small car hitting the guardrail system at a nominal speed of 100.0 km/h (62.1 mph) and angle of 20°. The second test, Test Designation 3-11, consists of a 2,000-kg (4,409-lb) pickup truck hitting the guardrail system at a nominal speed of 100.0 km/h (62.1 mph) and angle of 25°. The full-scale vehicle crash tests were conducted and reported in accordance with the procedures recommended in *NCHRP Report 350*.

On the basis of the success of prior small-car testing on the MGS (*11–13*), the 820-kg (1,808-lb) small-car crash test was deemed unnecessary for this project. Full-scale vehicle crash testing on the MGS with SYP posts was also deemed unnecessary because of the success of prior SYP, round-post, W-beam guardrail systems and the proposed crash testing of two MGSs using both PP and DF round posts.

BARRIER DESIGN DETAILS

Two, full-size barrier installations were constructed for testing and evaluation by using the MGS—one with round DF posts and the other with round PP posts. Each test installation consisted of 55.25 m (181.25 ft) of standard 2.66-mm (12-gauge) thick, W-beam guardrail supported by wood posts, as shown in Figure 4. Anchorage systems similar to those used on tangent guardrail terminals were used on both the upstream and downstream ends of the guardrail system. A photograph of the test installation is shown in Figure 4.

Both systems were constructed with 29 guardrail posts. Posts 3–27 were round timber sections complying with the criteria noted in Table 3. The posts measured 1,753 mm (69 in.) long. Posts 1, 2, 28, and 29 were timber breakaway cable terminal (BCT) posts measuring 140 mm wide × 190 mm deep × 1,080 mm long (5.5 × 7.5 × 42.5 in.) and were placed in 1,829-mm (6-ft) long steel foundation tubes. The timber posts and foundation tubes were part of anchor systems designed to replicate the capacity of a tangent guardrail terminal.

Posts 1–29 were spaced 1,905 mm (75 in.) on center with a soil embedment depth of 940 mm (37 in.), as shown in Figure 4. The posts were placed in a compacted course of crushed limestone material that met Grading B of AASHTO M147-65 (1990) as in *NCHRP Report 350*. For Posts 3–27, 152-mm-wide × 305-mm-deep × 362-mm-long (6- × 12- × 14.25-in.) wood spacer blocks were used to block the rail away from the front face of the wood posts. The spacer blocks were fabricated with two parts—a standard 152-mm-wide × 203-mm-deep × 362-mm-long (6- × 8- × 14.25-in.) block and a special 102-mm (4-in.) curved block to interlock with the round post. A single nail was used to prevent the two blocks from rotating with respect to one another.

The nominal top mounting height of the W-beam rail was 787 mm (31 in.) with a 632-mm (24.875-in.) center height. The rail splices were placed at midspan locations, as shown in Figure 4. All lap-splice connections between the rail sections were configured to reduce vehicle snag at the splice during the crash test. Finally, the round guardrail posts were placed in a water tank and allowed to become saturated before being installed in the soil.

FULL-SCALE CRASH TESTING

Test MGSDF-1 (DF Posts)

Test MGSDF-1 was conducted according to *NCHRP Report 350* Test Designation 3-11. The 2,018-kg (4,450-lb) pickup truck hit the test article at a speed of 100.0 km/h (62.14 mph) and an angle of 25.5°. The target CIP was 953 mm (37.5 in.) downstream of the centerline of Post 12. Actual vehicle impact with the barrier system occurred 152 mm (6 in.) downstream of the target location. About 0.527 s after impact, the vehicle became parallel to the system, and it lost contact with the rail at about 0.671 s. Damage to the barrier system was moderate, consisting mostly of deformed W-beam rail, contact marks on guardrail sections, fractured wood posts, round posts pulled out of the ground, and split or disengaged wood blockouts. Seven round timber posts fractured during the impact event. Maximum dynamic barrier deflection was 1,529 mm (60.2 in.), and the system's working width was 1,531 mm (60.3 in.). Exterior vehicle damage was moderate, consisting mostly of deformation to the left-front corner of the vehicle. The front bumper was crushed from the center region and toward the left side, and the front frame was bent. The left-front quarter panel was crushed backward and inward. The left-front tire was deflated and separated from the steel rim. There were no observable occupant compartment deformations. Test results and sequential photographs are shown in Figure 5. Photographs of the impact location, vehicle damage, and barrier damage are shown in Figure 6.

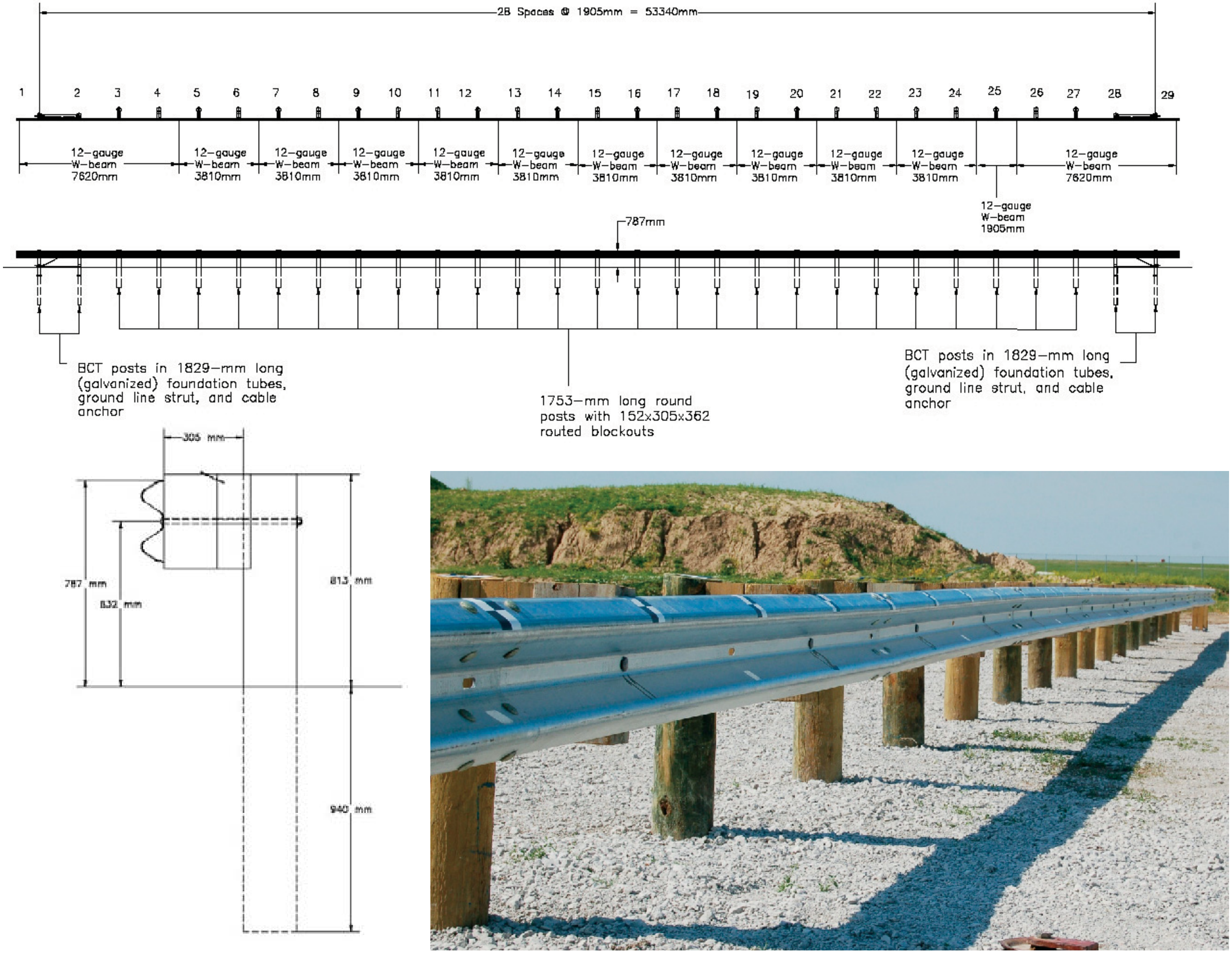
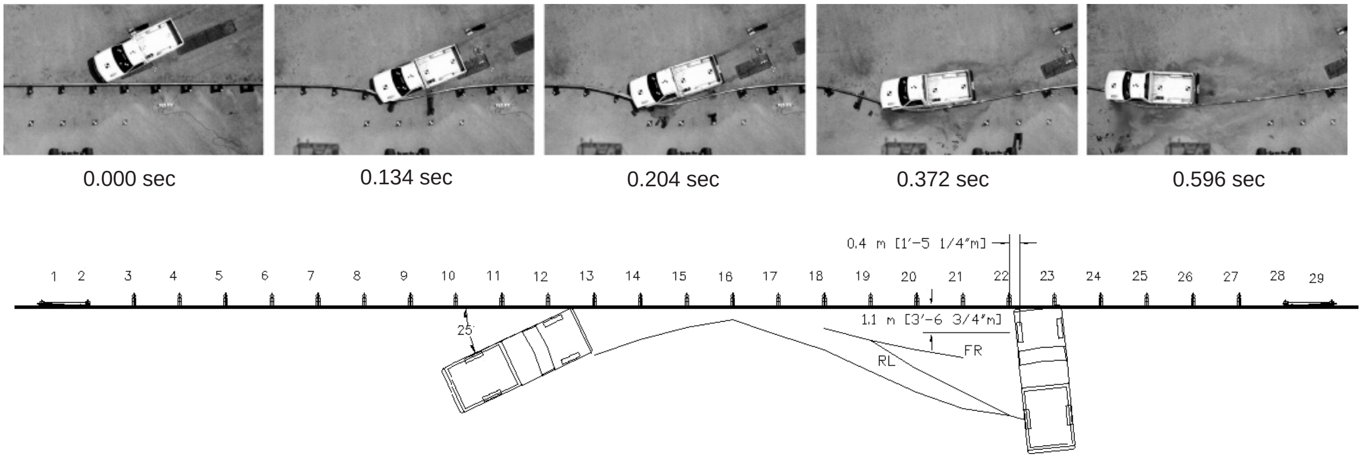


FIGURE 4 Test installation of MGS with round wood posts (BCT = breakaway cable terminal).



- Test Number MGSDF-1 (3-11)
- Date 6/16/06
- Test Article .... Midwest Guardrail System
    - Key Elements .... Round Douglas Fir Posts
    - Impact Location .... 953 mm Downstream of Post 12
- Soil Type .... Grading B AASHTO M147-65 (1990)
- Vehicle Model .... 2000 GMC C2500
    - Curb .... 2,078 kg
    - Test Inertial .... 2,018 kg
    - Gross Static .... 2,018 kg
- Vehicle Speed
    - Impact .... 100.0 km/h
    - Exit .... NA
- Vehicle Angle
    - Impact (trajectory) .... 25.5 deg
    - Exit (trajectory) .... NA
- Vehicle Stability .... Satisfactory
- Vehicle Snagging .... Minor
- Occupant Ridedown Deceleration (10 msec avg.)
    - Longitudinal .... 8.76 g's < 20 g's
    - Lateral .... 5.69 g's < 20 g's
- Occupant Impact Velocity
    - Longitudinal .... 4.03 m/s < 12 m/s
    - Lateral .... 4.03 m/s < 12 m/s
- THIV .... 6.84 m/s < 12 m/s (not req.)
- PHD .... 8.87 g's < 20 g's (not req.)
- Vehicle Damage... Moderate
    - TAD 11-LFQ-4
    - SAE 10LFEW5
    - OCDI LF000000000
- Vehicle Stopping Distance .... 19.2 m downstream of impact
- Test Article Damage .... Moderate
- Maximum Deflection
    - Permanent Set .... 902 mm
    - Dynamic .... 1,529 mm
- Working Width .... 1,531 mm

FIGURE 5 Test results and sequential photographs, Test MGSDF-1 (NA = not applicable, THIV = theoretical head impact velocity, PHD = postimpact head deceleration, TAD = traffic accident deformity, SAE = Society of Automotive Engineers, OCDI = occupant compartment deformation index).

Analysis of the test results for Test MGSDF-1 showed that the MGS with round DF posts adequately contained and redirected the test vehicle with controlled lateral displacement of the guardrail system. Although seven posts fractured during the impact, none of the posts or other detached elements showed potential for penetrating the occupant compartment or presented an undue hazard to other traffic. All other evaluation criteria were also met, including those pertaining to occupant risk, as shown in Figure 5. Test MGSDF-1 was determined to be acceptable according to the TL-3 safety performance criteria in *NCHRP Report 350* when conducted on the MGS with DF posts.

Test MGSPP-1 (PP Posts)

Test MGSPP-1 was conducted according to *NCHRP Report 350* Test Designation 3-11. The 2,025-kg (4,464-lb) pickup truck hit the test article at a speed of 100.2 km/h (62.27 mph) and an angle of 25.5°. Once again, the target CIP was 953 mm (37.5 in.) downstream of the centerline of Post 12. However, actual vehicle impact with the barrier system occurred 229 mm (9 in.) downstream of the target location. At 0.400 s after impact, the truck became parallel to the system. The vehicle exited the system at 0.776 s. Damage to the barrier system was moderate, consisting mostly of deformed W-beam rail, contact marks on guardrail sections, fractured wood posts, round posts pulled out of the ground, and split or disengaged wood blockouts. Four round timber posts fractured during the impact event. Maximum dynamic barrier deflection was 956 mm (37.6 in.), and the system's working width was 1,234 mm (48.6 in.). Exterior vehicle damage was moderate, consisting mostly of deformation to the left-front corner of the vehicle. The front bumper was crushed from the center region and toward the left side, and the front frame was buckled at the left-front corner. The left-front quarter panel was crushed backward and inward. The left-front steel rim was deformed, with damage to the suspension components, and the left-rear tire had abrasions to the outer sidewall. There were no observable occupant compartment deformations. The test results and sequential photographs are shown in Figure 7. Photographs of the impact location, vehicle damage, and barrier damage are shown in Figure 8.

Analysis of the results for Test MGSPP-1 showed that the MGS using round PP posts adequately contained and redirected the test vehicle with controlled lateral displacements of the barrier system. Although four posts fractured, none of the posts or

(a) (b) (c) (d)

FIGURE 6 Impact location, vehicle damage, typical post fracture, and barrier damage, Test MGSDF-1.

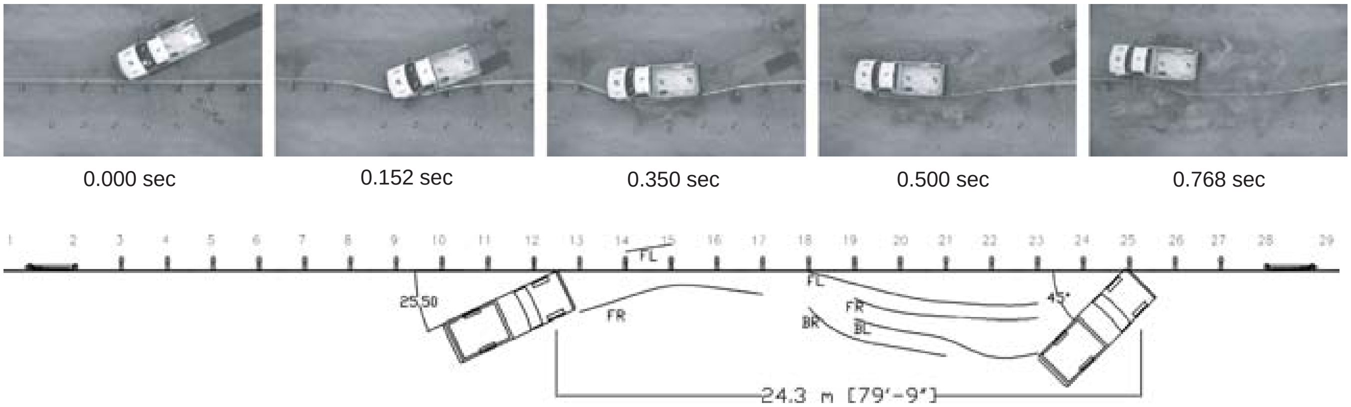
detached elements showed potential for penetrating the occupant compartment or presented an undue hazard to other traffic. All other evaluation criteria were also met, including those pertaining to occupant risk, as shown in Figure 7. Test MGSPP-1 was determined to be acceptable according to the TL-3 safety performance criteria in *NCHRP Report 350* when performed on the MGS with PP posts.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Round, DF, PP, and SYP timber posts were developed for use in the MGS. The wood post option for the MGS provides an additional market for SDTs, helps to reduce the risk of devastating forest fires across the country, increases the U.S. and individual state timber industries, and reduces the cost of the MGS for state departments of transportation, national parks, and other local and county governments. The modified MGS, using a 940-mm (37-in.) post-embedment depth, was successfully crash-tested according to the TL-3 criteria in *NCHRP Report 350*. On the basis of the research results described here, the round-post MGS designs have been accepted by the FHWA for use on the National Highway System (*22*).

Although the initial research and post size determinations were based on a barrier system that was predicted to fail with the fracture of four consecutive posts, full-scale crash testing demonstrated that the failure criteria exceeded this prediction. In Test MGSDF-1, seven consecutive posts failed, yet the system effectively redirected the colliding vehicle. This result indicates that the round-post MGS has the capability to perform in an acceptable manner when more than four consecutive posts fracture.

These research results have demonstrated the capability for the MGS to be installed with alternative posts. At this time, only three timber alternatives have been investigated. However, the research team believes that other post alternatives would perform in an accept-



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- Test Number MGSPP-1 (3-11)
- Date 6/1/06
- Test Article .... Midwest Guardrail System
    - Key Elements.......................Round Ponderosa Pine Posts
    - Impact Location .... 953 mm Downstream of Post 12
- Soil Type ....Grading B AASHTO M147-65 (1990)
- Vehicle Model .... 2000 GMC C2500
    - Curb ....1,959 kg
    - Test Inertial ....2,025 kg
    - Gross Static..2,025 kg
- Vehicle Speed
    - Impact ....100.2 km/h
    - Exit ....37.4 km/h
- Vehicle Angle
    - Impact (trajectory) ....25.5 deg
    - Exit (trajectory) ....19.9 deg
- Vehicle Stability ....Satisfactory
- Vehicle Snagging ....Minor
- Occupant Ridedown Deceleration (10 msec avg.)
    - Longitudinal .... 5.90 g's < 20 g's
    - Lateral .... 4.09 g's < 20 g's
- Occupant Impact Velocity
    - Longitudinal ....6.85 m/s < 12 m/s
    - Lateral ....7.18 m/s < 12 m/s
- THIV .... 6.12 m/s < 12 m/s (not req.)
- PHD .... 8.47 g's < 20 g's (not req.)
- Vehicle Damage.. Moderate
    - TAD 11-LFQ-4
    - SAE 10LFEW5
    - OCDI LF000000000
- Vehicle Stopping Distance......... 24.3 m downstream of impact
- Test Article Damage .... Moderate
- Maximum Deflection
    - Permanent Set...705 mm
    - Dynamic ....956 mm
- Working Width ....1,234 mm

FIGURE 7 Test results and sequential photographs, Test MGSPP-1.

able manner with the MGS, including posts with differences in size, shape, strength, or material. All these alternatives would need to be tested and approved before installation.

The MGS was modified by using round wood posts and subjected to two full-scale vehicle crash tests. Successful barrier performance was obtained with either DF or PP posts. System details were also developed for a round-post, SYP barrier system, even though an additional crash test was not performed. For the DF and PP post systems, dynamic barrier deflections were found to be 1,529 mm (60.2 in.) and 956 mm (37.6 in.), respectively. In comparison, the steel-post MGS was evaluated in Test NPG-4 under similar impact conditions and resulted in a dynamic deflection equal to 1,094 mm (43.1 in.) (*12, 13*). As such, it is apparent that the PP post MGS has lateral barrier stiffness similar to that of the steel-post MGS. Therefore, the PP post MGS should be capable of being attached to existing thrie-beam approach guardrail transition designs in a manner similar to that already used for the steel-post MGS. However, the DF post MGS resulted in a 435-mm (17.1-in.) increase in dynamic rail deflection compared with that observed for the steel-post MGS. Therefore, the DF post MGS should not be directly attached to existing thrie-beam approach guardrail transitions until additional research is completed. Further research is needed to develop an intermediate stiffened guardrail section used to connect the DF post MGS to existing thrie-beam approach guardrail transition systems. As an alternative, future research could be used to determine a slightly larger DF post diameter that would provide MGS barrier deflections similar to those observed with the PP and steel-post MGS.

Several guardrail end terminals exist for use in treating the ends of longitudinal W-beam guardrail systems, such as the MGS. These end terminal systems were developed for standard-height, strong-post, W-beam guardrail systems, but they were later adapted to the MGS, which used steel posts. As such, it is the researchers' opinion that the existing, crashworthy guardrail end terminals would be applicable for use as long as the round-post MGS is not significantly stiffer than the steel-post MGS. However, the use of round wood posts in the terminal would need to be verified through full-scale crash testing.

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(a) (b)

(c) (d)

FIGURE 8 Impact location, vehicle damage, typical post fracture, and barrier damage, Test MGSPP-1.

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