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Thrie-Beam Guardrails for School and Intercity Buses

DON L. IVEY, CHARLES F. McDEVITT, RICHARD ROBERTSON, C. EUGENE BUTH, AND ARTHUR J. STOCKER

The results of full-scale tests that were conducted to establish the upper performance limits of conventional W-beam guardrail and Thrie-beam guardrail systems are described. The tests showed that these conventional guardrail systems cannot safely redirect a 9070-kg (20 000-lb) school bus in a 15° angle impact at 96.5 km/h (60 mph). The development and evaluation of a modified Thrie-beam guardrail are also described. A series of full-scale tests has demonstrated that the unique feature of this guardrail system, a special 0.36-m (14-in) deep blockout, not only prevents the wheels of mini-compact cars from snagging on the posts but also raises the rail during impact to stably redirect heavier vehicles such as school and intercity buses.

In order to provide safer highway appurtenances for the public, there is an increasing emphasis on designing traffic barriers such as guardrails and bridge rails for a wider spectrum of highway vehicles. Witness the growing emphasis on designing guardrail terminals for mini-compact cars as they become a more significant part of the vehicle fleet and also recent efforts to design bridge rails for both school and intercity buses (1,2).

This report describes work that was aimed at investigating the feasibility of enlarging the spectrum of vehicles considered in the guardrail design process. Until recently, guardrails have been designed to accommodate a 2041-kg (4500-lb) automobile at 96.5 km/h (60 mph) and 25° as the most critical test. The goal of this study was to determine if a relatively conventional guardrail design is suitable to safely redirect a 9072-kg (20 000-lb) school bus moving at 96.5 km/h and at an impact angle of 15°. If this proved not to be the case, the objective was to see if reasonably economical guardrails can be designed to accomplish this task.

To reach these objectives, the tests described in Table 1 were conducted. The cross sections of the guardrail for each test are shown in Figures 1, 2, and 3.

The tests were conducted in the order given in Table 1. The Thrie-beam guardrail shown in Figure 1 was selected for the first test. Because it was a choice between the conventional W-beam guardrail and the conventional Thrie-beam guardrail, the following reasoning dictated the choice of the Thrie-beam. If the Thrie-beam (G9) guardrail failed to redirect a school bus, there was no reason to test the W-beam, since it would certainly be of lower capacity. This might save one test that could be used to evaluate a modified Thrie-beam rail. If the Thrie-beam functioned reasonably well, there was a chance that the W-beam (G4-1S) guardrail would also perform adequately. The W-beam guardrail then would be selected for the second test. The testing program would prove the latter situation to be the one encountered. Although detailed accounts of these individual tests are given in subsequent parts of this report, a brief description of each test is presented here.

DISCUSSION OF TEST RESULTS

In the first test, which was conducted on the Thrie-beam guardrail shown in Figure 1, the 9081-kg (20 020-lb) bus at 89.5 km/h (55.6 mph) and 13.5° was contained and redirected; the bus then went through a slow 90° counterclockwise roll before falling onto its left side and sliding to a stop. Although the 90° roll was not an ideal reaction, it was a fairly smooth roll, which should not be extremely hazardous to passengers if the integrity of the left-side windows is maintained. The performance of the rail was therefore considered marginal. The guardrail exhibited enough strength and maintained continuity so that the bus was contained and redirected. Accelerations on the bus during the event were low, while permanent deflection of the rail was about 0.41 m (1.33 ft).

Based on the results of the first test, it was decided that the conventional W-beam guardrail has a reasonable chance of containing and redirecting a school bus. The W-beam had about as much post support as the Thrie-beam. After impact deflection, it has about the same point of resistance height as the Thrie-beam. This is true as the rail begins to deflect, at least up to the time that the bus rolls enough to make contact with the top part of the deflecting and rotating W-beam or Thrie-beam. To counter the argument that the W-beam guardrail had a chance of containing and redirecting a bus were the facts that the barrier height would be reduced 13.3 cm (5.25 in) and the bending stiffness of the W-beam would be much lower than the Thrie-beam, a factor that results in the transmission of lateral load to fewer support posts during an impact. The full-scale test resolved this question by demonstrating that the factors against a successful containment were dominant.

In the second test, conducted on the W-beam guardrail shown in Figure 2, the bus was not contained. At a speed slightly higher than in the first test [96.0 km/h (59.6 mph) compared with 89.5 km/h], the bus started to redirect as the left front corner made contact. However, as it rolled left and yawed clockwise, the rear of the bus went over the barrier, penetrating into the zone behind the rail. At one point the bus was sliding upside down along the guardrail, which resulted in a shredding of the bus top. This reaction was obviously unacceptable because it would have resulted in many severe passenger injuries.

Table 1. Description of tests.

Test No.	Vehicle	Impact Velocity[a] (km/h)	Impact Angle[a] (°)	Point of Impact	Rail Type
1	9072-kg school bus	96.5	15	Midstream	Thrie-beam
2	9072-kg school bus	96.5	15	Midstream	W-beam
3	9072-kg school bus	96.5	15	Midstream	Modified Thrie-beam
4	1032-kg 1976 Honda sedan	96.5	15	Midstream	Modified Thrie-beam
5	956-kg 1975 Honda sedan	96.5	20	Midstream	Modified Thrie-beam
6	14 515-kg intercity bus	96.5	15	Midstream	Modified Thrie-beam

Note: 1 kg = 2.24 lb; 1 km/h = 0.62 mph.
[a]Values shown here are the planned test values; actual observed values differed slightly, as shown in Table 2.

Figure 1. Conventional Thrie-beam guardrail (test 1).

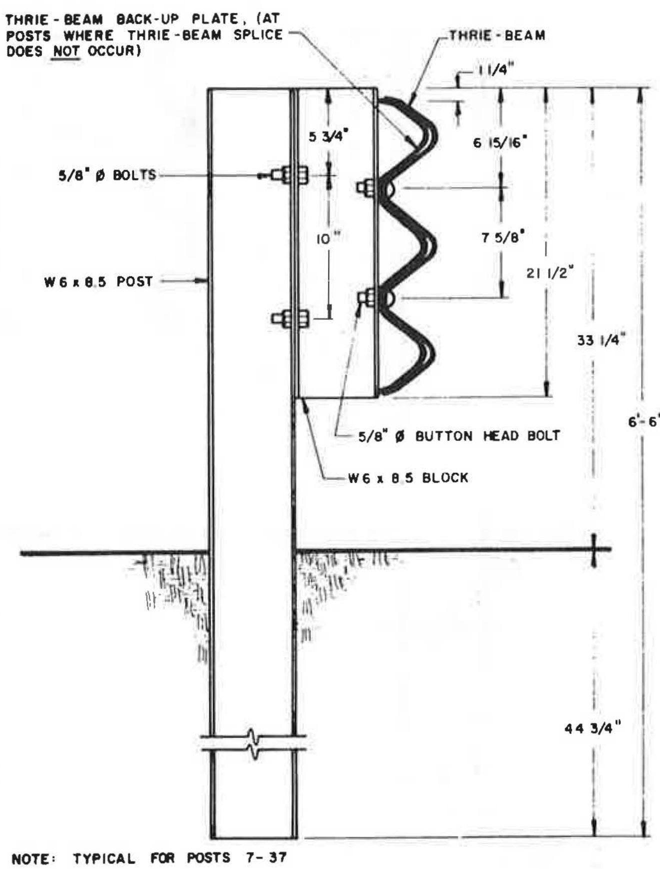


Figure 2. Conventional W-beam guardrail (test 2).

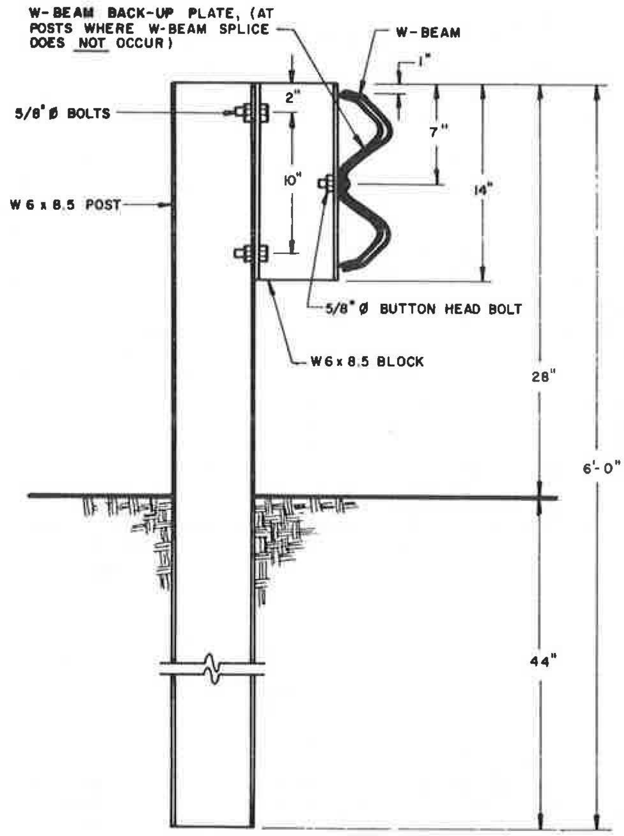
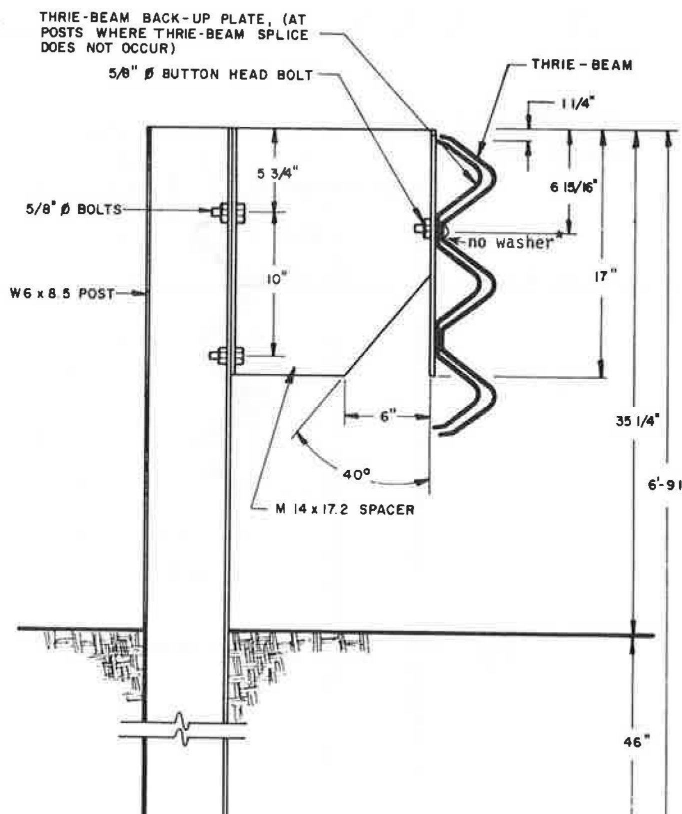


Figure 3. Modified Thrie-beam guardrail (tests 3-6).



NOTE: TYPICAL FOR POSTS NO. 7-37.

*Washers were not used at this connection point so that the posts would easily come free of the rail during large lateral deflections.

By using the experience gained from the first two tests, it was apparent that significant design changes would have to be made if a guardrail was to safely contain and redirect a bus after a 96.5-km/h (60-mph) collision. The Thrie-beam guardrail used in test 1 proved strong enough, but it exerted its resisting force at a point too low to prevent the bus from rolling. It was considered the prime candidate for redesign. The emphasis would be to make design changes that would elevate the point of resistance during a collision. The guardrail shown in Figure 3 is the result of those efforts. The following design changes were established during design meetings between Texas Transportation Institute (TTI) and Federal Highway Administration (FHWA) engineers:

1. The overall height of the barrier was increased by 0.05 m (2 in), from 0.84 m (33.25 in) (Figure 1) to 0.90 m (35.25 in) (Figure 3).
2. The blockout depth was increased by 0.20 m (8 in), from 0.15 m (6 in) to 0.36 m (14 in). This results in the rail moving upwards as the support post rotates.
3. A triangular-shaped segment was cut from the web of the M14x17.2 spacer as shown in Figure 3. This notch allows the lower portion of the Thrie-beam and the adjacent spacer block flange to bend in during a collision. This keeps the rail face vertical in the impact zone. It also reduces the contact forces between an impacting vehicle and the lower part of the Thrie-beam, thereby requiring the centroid of the resisting loads to move up onto the fully supported part of the rail. The net effect is that the resultant resisting force of the rail is raised to a higher position, which produces a smaller roll moment on the vehicle.
4. Embedment length of the guardrail posts was incresased slightly from 1.14 m (44.75 in) to 1.17 m (46 in). Consideration was given to welding bearing plates on the support posts to significantly increase post capacity. This option was not taken, since it was not determined that additional post capacity was necessary and the addition of the plates would significantly increase fabrication costs.

The modifications described above proved adequate. The third test of a school bus at 89.8 km/h (55.8 mph) and 15° produced a bus reaction that was acceptable. The bus was contained and smoothly redirected and remained upright throughout the event. During the rail contact period, there was approximately 25° of counterclockwise bus roll when viewed from the rear. Overall, it was interpreted as a stable rail collision. Table 2 summarizes data from all of the tests. Sequential photographs from test 3 appear in Figure 4.

Next, two tests of the same modified Thrie-beam guardrail were conducted with Honda Civic sedans in order to see if raising the Thrie-beam rail by 0.05 m (2 in) had compromised its performance for small vehicles. There was concern that the front wheels might get under the rail and snag on the blockout or post. No snagging was observed in either test. In test 4, a 1976 Honda Civic sedan weighing 1032 kg (2276 lb) was redirected with a shallow exit angle and remained upright after a 100.6-km/h (62.5-mph) and 15° impact. The dummy driver's head impacted and broke the side door window. However, the dummy accelerations meet the flail-space criteria in National Cooperative Highway Research Program (NCHRP) Report 230 (3), and the test results are considered satisfactory. Similar results were obtained in test 5, which was conducted with a 1975 Honda Civic sedan at 99.1 km/h (61.6 mph) and an 18° angle. Table 2 summarizes these tests. After tests 4 and 5 had been conducted with the Honda Civic sedans, the bent flange tabs and Thrie-beam rails in the impact zones were restored with a bumper jack and a hammer, as shown in Figure 5.

The final question to be answered was whether the modified Thrie-beam could redirect a 14 515-kg (32 000-lb) intercity bus at 96.5 km/h (60 mph) and 15°. This question was addressed by using several analytical approaches and finally with a full-scale crash test. The analytical approaches attempted were a simple energy balance, a comparative structural analysis, and the Barrier VII program. They all predicted marginal performance of the modified Thrie-beam in an intercity bus test. Barrier VII predicted a deflection of 2.3 m (7.3 ft), but it was noted that this program has on occasion predicted deflections that were somewhat high. We believed that redirection could be achieved if the dynamic deflection could be held under 1.8 m (6 ft).

When the intercity bus test was conducted, the results were excellent. This is evident from Figure 6 and from the test summary given in Table 2. The impact angle was 14.0°. The speed just prior to impact was 95.9 km/h (59.6 mph). Vehicle stability was good, and there was a maximum counterclockwise roll angle of approximately 15° (i.e., roll into the barrier). The dynamic deflection was approximately

Table 2. Summary of data: tests 1-6.

Item	Test 4098-1	Test 4098-2	Test 4098-3	Test 4098-4	Test 4098-5	Test 4098-6
Rail	Thrie-beam	W-beam	Modified Thrie-beam	Modified Thrie-beam	Modified Thrie-beam	Modified Thrie-beam
Blockout	W6x8.5	W6x8.5	M14x17.2	M14x17.2	M14x17.2	M14x17.2
Rail deflection (m)						
Permanent	0.41	1.0	0.71	0.03	0.07	0.9
Dynamic	NA	NA	0.87	0.24	0.31	1.4
Vehicle	1971 school bus	1971 school bus	1971 school bus	1976 Honda Civic	1975 Honda Civic	1962 GMC coach bus
Vehicle weight (kg)	9081	9095	9081	1032	956	14 515
Impact speed (km/h)	89.5	96.0	89.79	100.6	99.1	95.9
Impact angle (°)	13.5	15.0	15.0	15.0	18.0	14.0
Exit speed (km/h)	--[a]	--[a]	--[b]	89.0	79.8	--[b]
Exit angle (°)	--[a]	--[a]	--[b]	2.7	1.0	--[b]
Vehicle acceleration, maximum 0.050-s avg (g)						
Longitudinal	−1.13	−1.84	−1.13	−2.50	−3.10	−0.8
Transverse	−2.95	−2.45	−2.49	−7.35	−7.04	−2.4
Vertical	−1.35	−3.04	−0.85	2.43	1.74	

Notes: 1 m = 3.28 ft, 1 kg = 2.24 lb, 1 km/h = 0.62 mph, NA = not available.
Post = W6x8.5 steel, post spacing = 1.91 m (6.25 ft), and length of installation = 76.2 m (250 ft).
[a]Vehicle rolls.
[b]Undetermined.

Figure 4. Interaction of school bus and barrier at progressive stages of test 3.

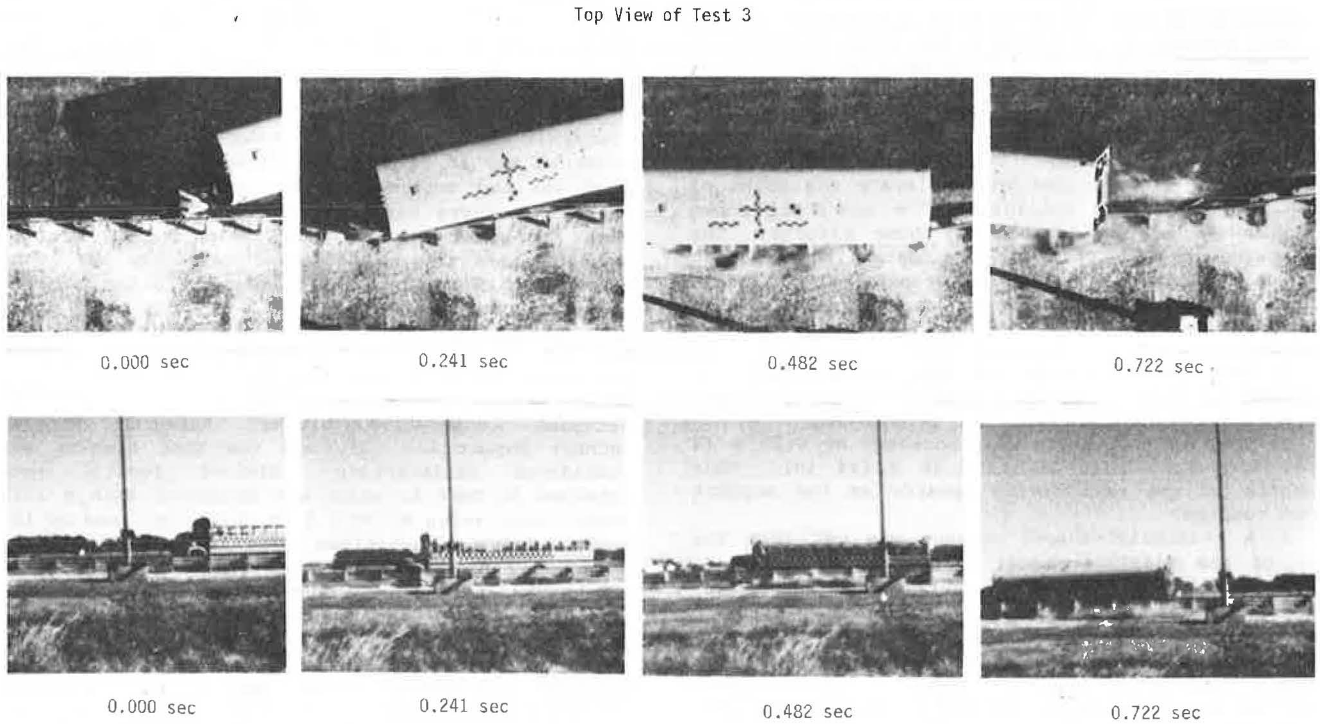
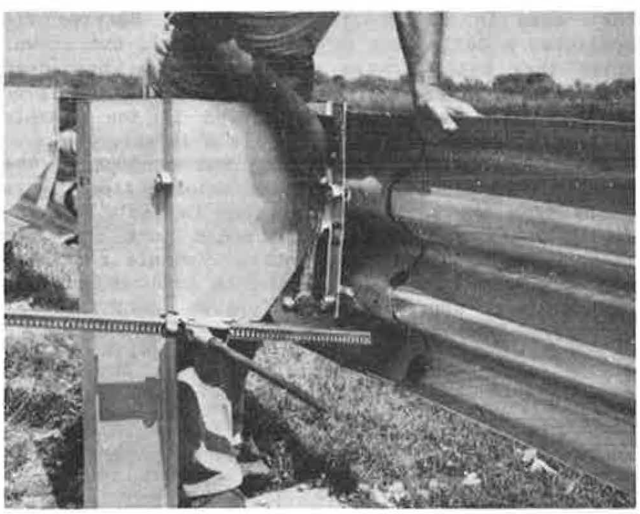


Figure 5. Restoring modified Thrie-beam guardrail after tests 4 and 5 with Honda Civic sedans.



1.4 m (4.6 ft). Eight posts were deformed by the left front wheel, but the rail remained intact and at a level suitable for redirection. The peak 0.050-s average lateral acceleration was 2.5 *g*. The corresponding longitudinal acceleration was only 0.8 *g*, which shows the relatively low forces exerted by the support posts on the left front wheel. Damage to the bus was modest; light sheet-metal damage occurred at the left front and left rear corners.

Even though the performance of the modified Thrie-beam guardrail proved to be a major advance in the performance of conventional rails, cost is always a critical factor when new systems are considered. At this stage, detailed cost-effectiveness analyses have not been conducted, but cost analyses of the three rail systems show a rather modest increase in cost for the modified Thrie-beam guardrail.

Table 3 gives cost estimates for three rail systems (conventional W-section, conventional Thrie-beam, and modified Thrie-beam) for three different installation lengths [less than 304.88 m (1000 ft), between 4573.17 and 9146.34 m (15 000 and 30 000 ft), and between 9146.34 and 30 487.8 m (30 000 and 100 000 ft)]. This comparison, which was based on costs from several prominent suppliers, fabricators, and contractors, shows a 25 percent increase from conventional W-section to modified Thrie-beam [$43.95-$54.78/m ($13.40-$16.70/ft)] and only a 3.4 percent increase from conventional Thrie-beam to modified Thrie-beam [$52.97-$54.78/m ($16.15-$16.70/ft)]. This is for placement of more than 9146.34 m of rail. The comparisons in Table 3 are not as good for smaller jobs but, considering the increased performance spectrum that results from including school and intercity buses, cost-effectiveness is considered likely. It should certainly be cost effective to step up from the conventional Thrie-beam system to the modified.

CONCLUSIONS

Conventional guardrail designs that use standard W-beam rails are not adequate to safely redirect school buses. The W-beam guardrail shown in Figure 2 and subjected to test 2 is representative of the best W-beam systems. Similar rails that have longer post spacings, shorter post-embedment lengths, lower rail heights, or are without blockouts would be expected to perform in an even less-acceptable manner.

The conventional Thrie-beam guardrail will perform marginally to contain and redirect school buses, but it is not likely to keep the bus upright during a collision. Although the 90° roll docu-

Figure 6. Interaction of intercity bus and barrier at progressive stages of test.

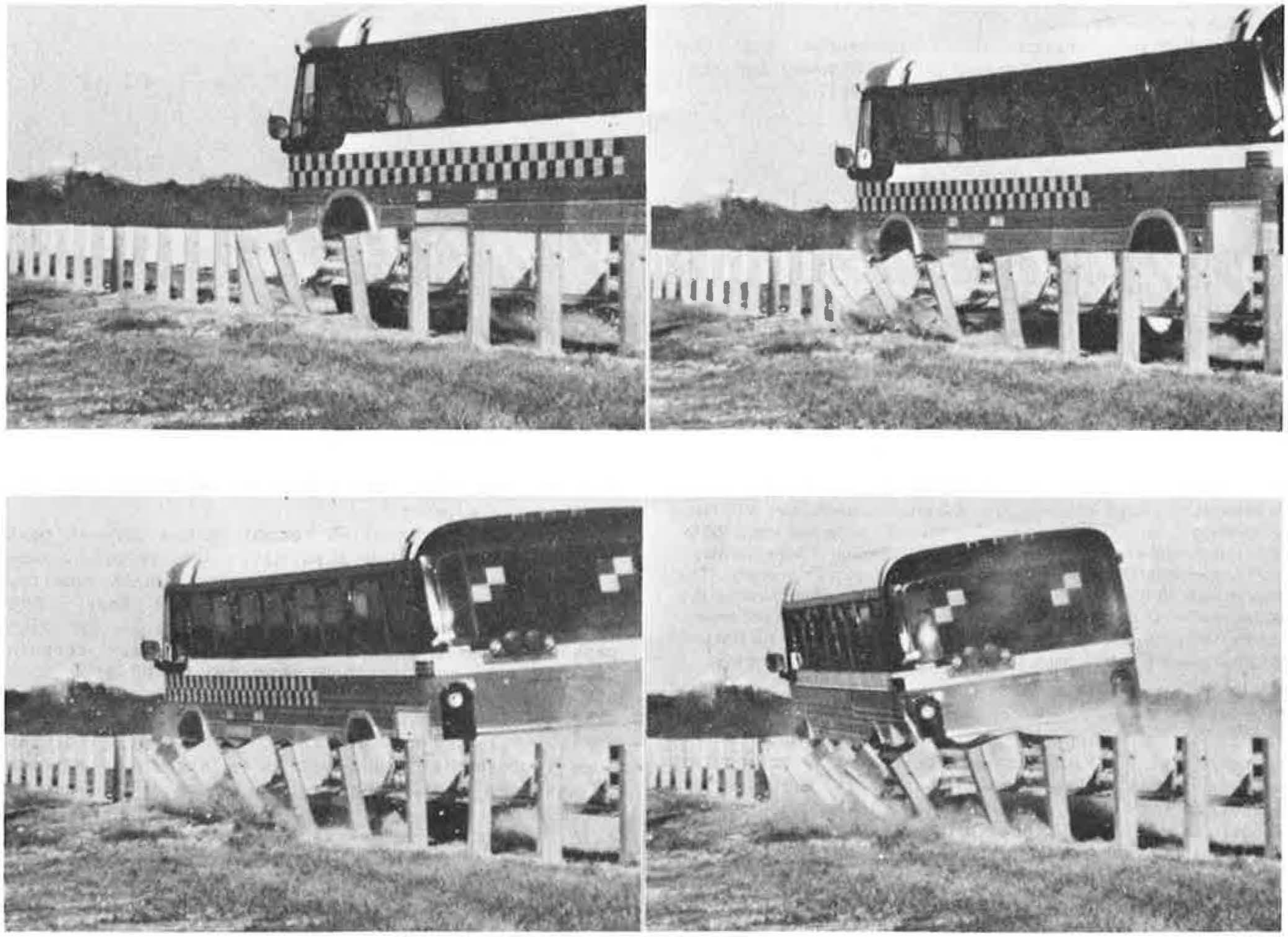


Table 3. Cost analysis for construction of Thrie-beam and W-beam guardrail systems.

Guardrail Type	Cost by Length of Installation ($/m)		
	Less than 304.88 m	4573.17-9146.34 m	9146.34-30 487.8 m
Conventional W-section[a]	54.61	48.88	43.95
Conventional Thrie-beam[a]	63.63	57.73	52.97
Modified Thrie-beam[b]	65.44	59.86	54.78

Note: 1 m = 3.28 ft.
[a]Performance good for automobiles only.
[b]Performance good for automobiles and school and intercity buses.

mented by test 2 was fairly slow and reasonably smooth, any roll that results in the bus ending up on its side is potentially hazardous. The conventional Thrie-beam guardrail does seem to be a significant improvement in performance over the conventional W-beam. If the redirection of heavier vehicles such as school buses becomes an accepted performance criterion, significant modifications of current guardrail systems will be necessary to ensure safe performance.

The modified Thrie-beam guardrail shown in Figure 3 performed well in test 3, the only school bus test to which it has been subjected. The 96.5-km/h (60-mph) tests with Honda Civic sedans at 15° and 18° have demonstrated that the increased rail height and the blockout modification, which allows the lower part of the Thrie-beam to bend inward, will not compromise the rail performance for mini-compact automobiles. No wheel or bumper snagging was observed during these tests.

The fact that the modified Thrie-beam rail functioned well in redirecting a 14 515-kg (32 000-lb) intercity bus illustrates the fact that Thrie-beam guardrails can be designed to accommodate a class of vehicles much larger than automobiles. Although cost-effectiveness has not been demonstrated for the usual highway situation that warrants guardrail, just as in the case of bridge rail there may be special situations where higher-performance guardrails such as the modified Thrie-beam could be justified. The development of warranting criteria for the use of higher-performance guardrail could produce improved highway safety.

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Abridgment

Crash Tests of Omnidirectional Slip-Base Sign Supports

KENNETH C. HAHN AND JAMES E. BRYDEN

Omnidirectional sign supports with triangular slip bases, which are similar to those successfully tested elsewhere on single-support appurtenances, were tested on multilegged sign installations. Four tests that were performed with 2150-lb vehicles determined compliance with American Association of State Highway and Transportation Officials specifications for vehicle momentum change. The supports were hit from two directions at two speeds, and each test resulted in a momentum change below 750 lb·s. In all the tests, vehicle damage and impact severity were light. The omnidirectional hinge design cannot hold the sign panel upright after one support is removed, but the entire design performs safely.

This study consisted of four full-scale crash tests to determine the impact performance of a triangular omnidirectional slip-base sign support that has an all-direction upper post hinge. [More information about these tests is provided elsewhere (1).] Testing details were taken from Transportation Research Circular 191 (2).

The support design (Figure 1) included base posts set in concrete, intermediate posts bolted to the base, and upper posts spliced to the intermediate posts (all W6x12 sections). The base posts, each topped by a triangular 1.5-in-thick plate, were set in 2-ft-diameter, 4-ft 9-in deep concrete foundations and had the plate top set flush with the ground line. Intermediate 8-ft-long posts that had matching triangular plates were attached to the bases, and three 6-in-long 1-1/8-in-diameter bolts were torqued to 110 lbf•ft. To permit the sign to be erected at 90° and 30° to the direction of vehicle travel, the left base plate was made circular rather than triangular and had two sets of three bolt slots offset by 60°. Two right bases were installed, also offset 60° from each other, so that the sign could thus be erected in either position. The 7-ft 6-in long upper posts were spliced to the intermediate posts with two 0.375-in-thick hinge plates. These plates were bolted to the drilled upper posts through holes and to the drilled intermediate posts through slots in the plates with 5/8-in bolts torqued to 170 lbf•ft for tests 29 and 30 and 190 lbf•ft for tests 31 and 32. An 8.5x16.5-ft (140 ft^2) aluminum sign panel, which had three 2-3/8- by 1-1/4- by 3/16-in Z-bars, was mounted on the upper posts above the splice plates. The bottom of the panel was 7 ft above the ground. The Z-bars were attached to the sign panel with 1/4-in bolts on 16-in centers and to each post with two 1/4-in bolts.

During impact, the triangular plate on the intermediate post slips free of the base and, as the post rotates back, the splice plates bend to form a hinge. As bending continues, the bolts holding the slotted splice plate to the intermediate post pull free and the intermediate post is separated from the rest of the support.

The W6x12 post section tested is the largest post size to be used with this slip-base design. Successful tests of the W6x12 post would qualify smaller post sizes for use with this base. The two-support installation tested is typical for sign panels of up to 147 ft^2 erected on flat terrain and designed to withstand winds up to 80 mph (zone B). All of the bolt torques used initially were determined to be sufficient to withstand the loads developed by 80-mph winds. The hinge-bolt torques were increased for the last two tests in an attempt to keep the sign panel upright on a single support after impact.

All test vehicles were 1973 Chevrolet Vegas weighing approximately 2150 lb and speeds were near the 20- and 60-mph requirements. Vehicle test weights were reduced about 100 lb from the usual 2250 lb, recognizing that future test-weight requirements will be reduced. The actual test weights achieved could not be further reduced by using the vehicles available without extensive alterations. The impact angles were 90° and 30° to the sign face, which corresponds to a car traveling parallel to and at 60° to the pavement, respectively. Based on previous tests of triangular slip bases, these impact angles would produce the maximum vehicle velocity change and a reasonably expected impact condition for the roadway situations previously described.

RESULTS

Results of four full-scale crash tests of the omnidirectional slip-base sign support are summarized in Table 1.

In the first test (test 29), impact was perpendicular to the sign face at 27.7 mph and resulted in a 726-lb•s vehicle momentum. The slip-base bolts, torqued to 110 lbf•ft, separated on impact as designed, but the upper hinge bolts, torqued to 170 lbf•ft, remained in place and pulled the sign panel downward and backward and pitched the car -3° (upward) before the hinge released. The car traveled 11 ft during that period before the hinge released and traveled another 5 ft until the post flew free of the car.

The displaced sign panel then contacted the car roof. This secondary impact, which was directly over the front seat and about 1 ft to the right of center, resulted in a dent about 4 ft long, 3-7 in wide, and less than 1 in deep. This impact was not severe and presented no apparent hazard to vehicle