

Bridge and Other Highway Structures (2) should be amended by adding a tabulation of allowable stresses for fillet welds loaded transversely in which the allowables are increased by a factor of 1.36. Thus, the allowable stress of 30 MPa specified for 4043 fillets on 6063-T6 parent metal shown would be increased to 41 MPa (footnoted to allow a further increase by a factor of 1.17 to 48 MPa if the fillet is joining round or near-round members subject to bending). The allowable of 41 MPa (6.0 ksi) is consistent with the factor of safety of 2.64. When it is intended that another factor of safety be used [for example, 2.34 in the Aluminum Association Specifications for Aluminum Structures (9)], this allowable could be modified accordingly if care is taken to assure that the shear strength of the parent metal is not exceeded.

REFERENCES

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Crash Tests of Light-Post Thrie-Beam Traffic Barriers

JAMES E. BRYDEN AND KENNETH C. HAHN

Thrie-beam corrugated steel rail (a W-beam that has a third corrugation) was tested as a single-rail upgrading for discontinuous bridge-rail panels and on S3x5.7 posts as a guiderail and double-faced median barrier. Tests were performed to determine rail deflection characteristics, structural adequacy, vehicle decelerations, and vehicle damage. Ten-gage Thrie beam was used for all tests. As a bridge-rail upgrading, the Thrie beam is suitable for 60-mph, 25° impacts by 4500-lb vehicles. As a guiderail or median barrier on S3x5.7 posts, it appears suitable as a longitudinal barrier, based on tests with 2250-lb and 3500-lb vehicles. Proposed design deflections for Thrie-beam guiderails and median barriers are close to those for box-beam guiderails and median barriers. Further testing of these guiderail and median-barrier designs would yield better definition of impact and redirection characteristics and would better indicate what actions could be taken to reduce the impact between the vehicle's wheel and the posts.

New York's most frequently used longitudinal traffic barrier systems consist of steel rail elements—cable, W-beam, or box beam—mounted on S3x5.7 steel posts. These light-post barriers depend primarily on rail tension or beam bending to redirect impacting vehicles because the posts yield on impact to prevent snagging of vehicles. Traffic accident studies confirm that their performance has generally been very good (1,2).

A new rail element called a Thrie beam was developed several years ago. It is a W-beam that has a third corrugation added. Tests reported by Southwest Research Institute (3) claim good performance for this rail element in strong-post designs, and other tests (4) indicate that tubular Thrie-beam bridge rail performs well as a bridge-rail upgrading system. However, before the work reported here was done, the Thrie beam had not been tested on S3x5.7 posts.

Despite the generally good performance of New York's light-post barriers, the Thrie-beam rail element seems to offer distinct advantages over current designs. The standard height of W-beam rail on

S3x5.7 posts in New York State is now 33 in to the rail top. Less height increases the chances that large cars may penetrate the barrier (1). However, at the 33-in mounting height, small cars may tend to lodge beneath the rail.

To protect vehicles from snagging on rigid elements behind the 6-in vertical face of the box beam when there is a transition to a bridge parapet, a second rail element must be introduced before the transition. This second rail requires special hardware and must be terminated safely upstream well behind the main rail. Downstream, the box beam must be terminated flush with the concrete face to eliminate snag points. Very often the approach guiderail is a W-beam element that requires a complicated transition to box beam upstream of the bridge before the transition to the bridge parapet or rail.

Finally, a box-beam median barrier is troublesome to maintain. To replace any damaged posts, rail sections either 18 or 36 ft long that weigh 400 or 800 lb must be removed by using heavy mechanized equipment. Proper alignment of post paddles and rail slots and reassembly of the internal tube splices are difficult. Also, an impacted box-beam median barrier may bend at the mounting slots. Straightening damaged rails is very difficult and reassembly is impossible unless the rail elements are perfectly straight.

Because it is 20 in deep, Thrie-beam performance is much less sensitive to mounting height, and its resistance to penetration is greater for both small and large cars. At bridge parapets, the need for a transition from W-beam to box beam is eliminated. Neither the W-beam nor the Thrie beam need be terminated at concrete anchors. Instead, a commercially available transition of W-beam to Thrie beam is bolted in place to maintain rail tension. Beam

depth reduces the snag potential at bridge-rail parapets.

A 10-gage Thrie-beam rail on S3x5.7 posts could result in a median barrier or guiderail that has sufficient bending resistance and tension to produce deflections similar to those of box-beam median barriers or guiderails. Mounting details are similar to those for the W-beam and simpler than those for the box beam. Maintenance problems would be eliminated if the Thrie beam could be substituted for the box beam. By using S3x5.7 posts, the cushioning effect of the light-post systems would be maintained.

The overall aim of this study was to develop Thrie-beam traffic barriers and upgraded bridge rails that would result in improved motorist safety and lower maintenance costs. The safety aim would be realized through impact performance superior to that of current barrier designs (greater resistance to penetration), smoother transitions to bridge rails and parapets, and stronger and more forgiving bridge rails. The economic aims would be realized by eliminating special transitions and hardware and by easing median-barrier maintenance procedures as compared with those for box beams.

METHODOLOGY AND DESCRIPTION OF SYSTEMS

This study consisted of eight full-scale crash tests to determine the performance of Thrie beam for bridge-rail upgrading, guiderails, and double-rail median barriers. Testing details were taken from Transportation Research Circular 191 (5), and two major variations were used. For the bridge-rail tests, the standard impact conditions of 60 mph and 25° with a 4500-lb vehicle were the target conditions. For the guiderail and median-barrier tests, however, a 3500-lb vehicle weight was used because New York's light-post rail systems were developed by using 3500-lb vehicles and standard design deflections are based on that weight. Tests were also performed with 2250-lb sedans to evaluate impact severity.

Bridge-Rail Upgrading

The first Thrie-beam application tested was an upgrading of discontinuous-panel bridge railings. Such railings, designed to meet the 1957 American Association of State Highway Officials (AASHO) specifications (6), were installed in New York State through the mid-1960s. A three-post railing panel 34 in high, which is common on New York bridges, was chosen for testing.

A concrete footing 3 ft wide and 3 ft deep was used to anchor the bridge rail for these tests. It protruded 6 in above grade to present a 6-in curb height, which is common to almost all New York bridges; the remainder was below ground. For the transition tests, a firmly anchored timber curb, also 6 in high, was added to simulate the granite curb normally used on bridge approaches.

Thrie beam that was 10-gage rather than 12-gage was used because the added stiffness would help distribute impact loads over more bridge-rail posts, which reduced the chance of pocketing at panel ends and helped in the transition from guiderail to bridge rail. The first design (Figures 1 and 2) was tested by impacting on the bridge and on the approach guiderail. It consisted of spliced sections of 10-gage Thrie beam mounted directly onto the bridge rail; the rail top was 33 in above the pavement. The rail was held in place at each bridge-rail post by four 3/4-in bolts--two in each corrugation valley--around the post and through the 5/8-in backup plates. The approach rail was W-beam 33 in high that transitioned to the Thrie beam 53 ft

upstream of the bridge and was mounted directly onto S3x5.7 steel posts on 6-ft 3-in centers. Near the bridge, post spacing narrowed to 4 ft 2 in (three spaces) and 3 ft 1-1/2 in (six spaces). The connection between post and rail was a single 5/16-in bolt at each post, except for the unconnected backup posts. An expansion splice, which consisted of a piece of Thrie beam 6 ft 3 in long that had the splice bolt holes elongated to 2-1/2 in, was installed at the bridge's upstream end. The 5/8-in splice bolts and the 5/16-in mounting bolt used in the expansion splice were installed handtight to permit longitudinal rail movement when the bridge expanded and contracted. Such a splice was used in each of these upgrading tests to determine whether splice slippage would adversely affect impact performance.

The first test was to confirm the system's adequacy to redirect vehicles that impacted on the bridge at standard conditions (4500 lb, 60 mph, 25°). The second test, which had an impact 10 ft upstream of the bridge rail, was conducted to determine whether the transition from guiderail to bridge rail that used S3x5.7 posts was strong enough to prevent rail pocketing and vehicle snagging on the end of the bridge rail.

After unsatisfactory performance in the second test, the transition was redesigned for the third (Figures 2 and 3). Five W6x8.5 posts on 3-ft centers were added just upstream of the bridge, and an S3x5.7 post pattern similar to that used in the previous two tests was installed upstream of the W6x8.5 posts. The transition was further strengthened by doubling the rail element for one and one-half rail lengths. The double rail extended 3 ft onto the bridge and 16 ft back onto the guiderail. The second rail element was simply placed over the first, and the splice bolt holes were adjusted as necessary to provide bolt clearance. The Thrie-beam approach rail was not tested at the change from light to heavy posts. Unlike the box beam, the wide bearing area of the Thrie beam does not cut into the vehicle sheet metal and thus keeps the vehicle's wheels relatively far from the heavy posts.

Impacts that used small cars at 15° were not included in the bridge-rail tests. Earlier tests by others (3,4) had already confirmed that Thrie-beam railing systems resulted in satisfactory redirection of small cars. Thus, as long as the strength of the bridge-rail upgrading proved adequate, redirection of small vehicles would not be a problem.

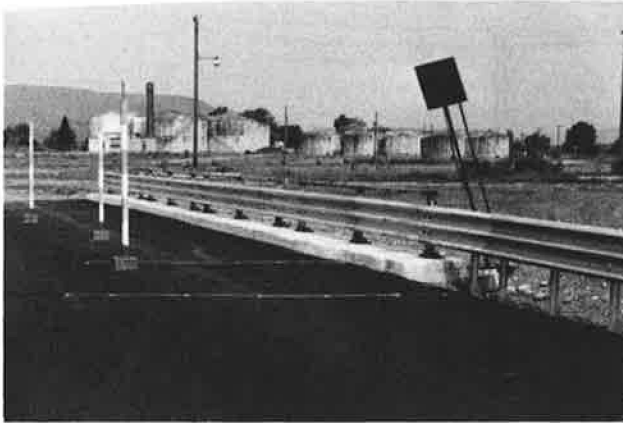
Guiderail and Median-Barrier

Bridge-railing upgrading tests were followed by two tests of guiderails (Figures 4 and 5). Ten-gage Thrie-beam rail mounted 33 in high on S3x5.7 posts at 6-ft 3-in centers was impacted by intermediate and compact cars.

Three tests of a median barrier were performed (Figures 5 and 6). Back-to-back 10-gage Thrie beam was bolted directly to S3x5.7 posts by using one 5/16-in bolt per rail at each post. Because of a possible wheel-snag problem detected in the two guiderail tests, rail height was reduced to 30 in. A post spacing of 6 ft 3 in was tested by using both an intermediate and a compact car, and a post spacing of 12 ft 6 in was tested with an intermediate-weight vehicle.

Ten-gage Thrie beam was used for the guiderail and median-barrier designs because it permitted duplication of deflection properties of box-beam barriers without the use of close post spacings and it eliminated the need to change beam thickness at bridge-rail transitions. Also, a single rail thickness for guiderail and bridge rail simplifies main-

Figure 1. Bridge-rail upgrading (tests 22 and 23).

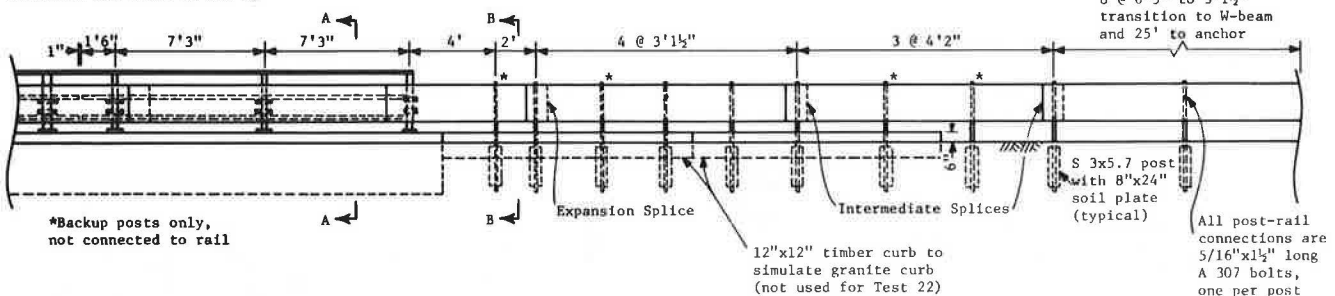


tenance inventory requirements and prevents the incorrect rail thickness from being used during repairs.

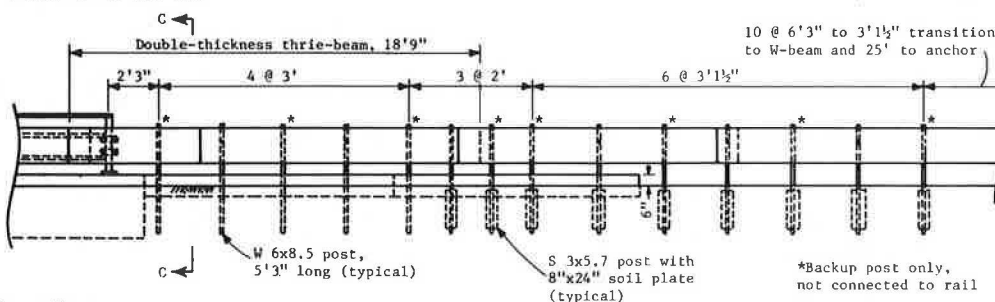
The guiderail and median barrier for these tests was installed on an asphalt pavement constructed over compacted gravel. This represents typical practice in New York State, where guiderail on new construction is installed on paved shoulders and medians. This condition may offer slightly greater post resistance than direct embedment in soil. However, New York's standard S3x5.7 posts include a soil plate 8x24 in, shown in past tests (7) to develop the full strength of the post even in weak soils. Thus, although the typical New York State post embedment tested may appear stiffer than direct soil embedment does, post reactions would probably be similar for both cases.

Figure 2. Details of bridge-rail upgrading (tests 22, 23, and 23A).

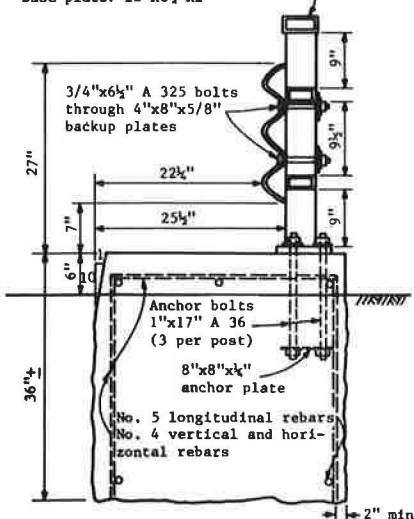
ELEVATION FOR TESTS 22 AND 23



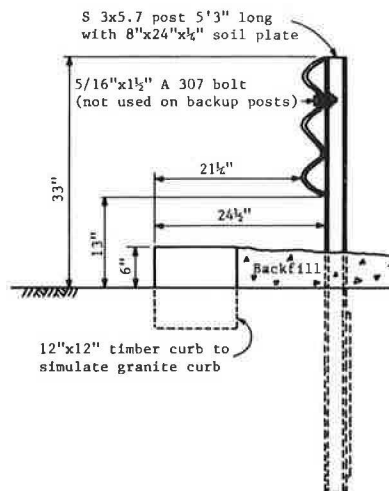
ELEVATION FOR TEST 23A



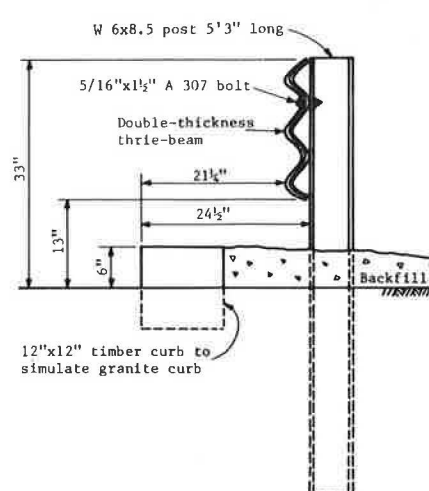
Top rail: 5"x2"x0.156" tube
Post: 4"x4"x0.156" tube
Lower rails: 4"x1 1/2"x0.180" tubes
Base plate: 12"x8 1/2"x1"



SECTION A-A (Test 22)



SECTION B-B (Test 23)

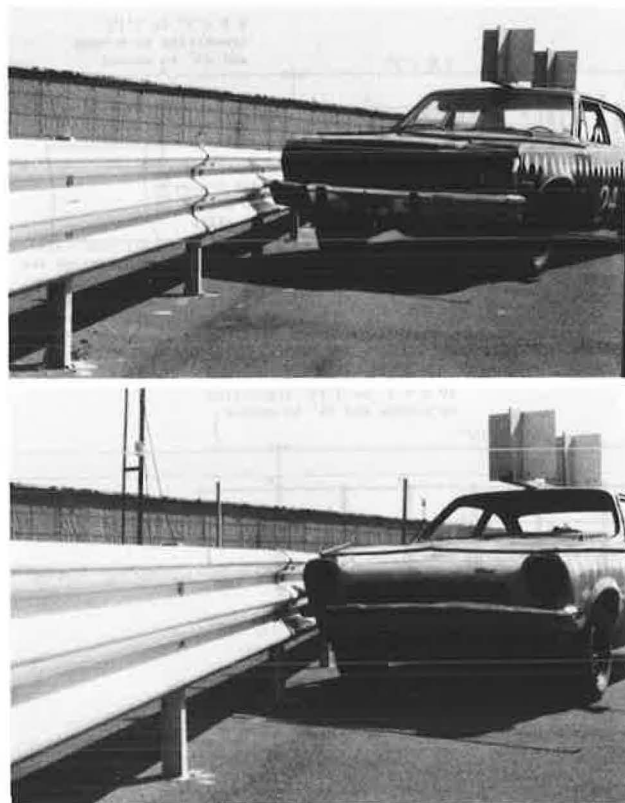


SECTION C-C (Test 23A)

Figure 3. Bridge-rail upgrading (test 23A).



Figure 4. Guiderrail with large car (test 24, top) and small car (test 25, bottom).



RESULTS

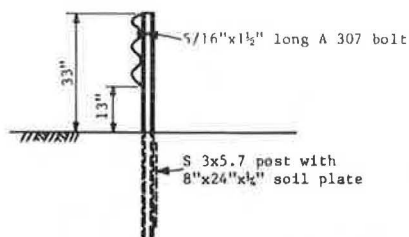
Bridge-Rail Upgrading Tests

Three full-scale crash tests of the Thrie-beam bridge-rail upgrading are summarized in Table 1. For the three tests of this upgrading, target impact conditions were 4500 lb, 60 mph, and 25°, although actual impact conditions varied somewhat.

For the first test (test 22), a 4500-lb sedan impacted the upgraded system at 25° and 53.3 mph 10 ft downstream from the first bridge-rail post. Impact occurred on the stone shield below the front bumper and on the right front wheel. No appreciable vaulting was apparent, because of the 6-in curb. The vehicle was in contact with the curb for 27 ft

Figure 5. Details of guiderail (tests 24 and 25, top) and median barrier (tests 26, 27, and 26A, bottom).

GUIDERAIL (Tests 24 and 25)



MEDIAN BARRIER (Tests 26, 27, and 26A)

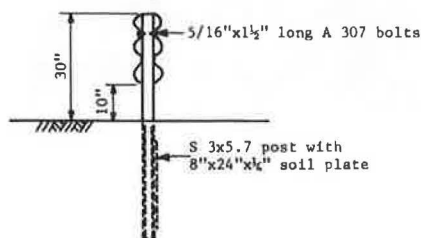


Figure 6. Median barrier that has 6-ft 3-in post spacing.



and with the rail assembly for 12 ft. Maximum dynamic rail deflection was 0.5 ft. On impact, the car rolled -2° (left). The hood latch and right hood hinge broke, which allowed the hood to open and fall back over the windshield. As the car left the rail, it pitched +3° (down) and yawed a maximum of +17° (left) before straightening out along the exit trajectory. Redirection was fairly smooth and the car exited the system at 3°. After having left the barrier, the car traveled an additional 125 ft, turning to the right because of the severe damage to the right front suspension and sheet metal. The highest 50-ms decelerations were 9.8 g longitudinal and 2.8 g lateral. The vehicle suffered extensive front-end sheet-metal and suspension damage.

Rail damage was limited to one bent bridge-rail section and post and one bent Thrie-beam section. Permanent rail deflection was 0.2 ft, but no slip-page occurred in the expansion splice at the end of the bridge. Slight bowing of the bridge-rail base plates resulted at posts on either side of impact, but neither the bridge-rail system nor the anchorage appeared close to failure. Based on this test, the Thrie-beam bridge-rail upgrading appears to have adequate strength to withstand impacts on the rail

Table 1. Results of bridge-rail upgrading tests.

Variable	Test		
	22	23	23A
Point of impact	10 ft onto bridge	10 ft before bridge	10 ft before bridge
Vehicle weight (lb)	4500 ^a	4600 ^a	4570 ^a
Vehicle speed (mph)	53.3	51.7	60.9
Impact angle (°)	25	24	25
Exit angle (°)	3	22	11
Maximum roll (°)	-2	-7	+4
Maximum pitch (°)	+3	+6	-3
Maximum yaw (°)	+17	+19	-22
Contact distance ^b (ft)	27, 12	22, 18	21, 21
Contact time ^c (ms)	273	317	398
Deflection (ft)			
Dynamic	0.5	2.9	3.1
Permanent	0.2	1.8	1.2
Deceleration (g)			
50-ms avg			
Longitudinal	9.8	9.1	NA
Lateral	2.8	3.8	NA
Maximum peak			
Longitudinal	14.5	13.5	NA
Lateral	6.4	6.1	NA
Avg continuous			
Longitudinal	1.9	2.1	NA
Lateral	0.8	0.9	NA

^a 1975 Plymouth used for test 22; 1970 Chrysler, for test 23; and 1967 Chrysler, for test 23A.

^b First distance is on the curb; second, on the rail.

^c Time is for the longer contact distance.

at standard strength-test conditions of 4500 lb, 60 mph, and 25°.

For the second test (test 23), a 4600-lb sedan impacted the approach rail at 24° and 51.7 mph 10 ft upstream of the first bridge-rail post. Impact was on the stone shield and right front wheel, and again no vaulting was seen when the 6-in curb was impacted. The car was in contact with the curb for 22 ft and with the rail for 18 ft. Maximum dynamic barrier deflection was 2.9 ft. On impact, the car began to redirect smoothly, but the Thrie-beam rail on the S3x5.7 posts deflected enough to result in pocketing at the leading end of the bridge rail. The subsequent sharp redirection and exit from the rail caused the car to roll -7° while it pitched +6°. During the exit along a 22° trajectory, the car yawed +19° as it crossed back across the pavement; it finally came to rest about 150 ft from the impact. The highest 50-ms decelerations were 9.1 g longitudinal and 3.8 g lateral. A sharp dropoff at the edge of the test pad caused the vehicle to roll over before coming to rest, but this was not directly attributable to the impact performance of the railing system.

Vehicle damage before the rollover was similar to that incurred in the previous test--bent front fenders, shifted bumper, dents on the right side, and suspension, wheel, and tire damage. Four guiderail posts were bent over on impact, and two others were deflected backward. Two Thrie-beam sections were damaged, as were three bridge-rail posts and one horizontal rail. Maximum permanent deflection of 1.8 ft was recorded on the approach guiderail, and the maximum permanent deflection on the bridge rail was 3 in at the first post. Again, no slippage occurred at the expansion splice. In addition, the base plate of the first bridge-rail post was bowed upward.

Because of the pocketing and steep redirection experienced in test 23, the approach guiderail system was stiffened for the next test as previously described. For test 23A, a 4570-lb vehicle impacted at 25° and 60.9 mph 10 ft upstream from the first bridge-rail post. The right front wheel impacted the 6-in curb with no apparent vaulting, and the right front fender impacted the rail. The car was

in contact with the curb and rail for 21 ft; there was a maximum dynamic deflection of 3.1 ft. The vehicle was smoothly redirected at an exit angle of 11°. Maximum vehicle roll was +14°, and maximum pitch was -3°. The car was airborne about 8 in as it left the curb. There was no measurable vehicle yaw until well after the vehicle left the rail, when the damaged right front suspension resulted in a yaw of -22°. The accelerometer system malfunctioned on impact, so no deceleration data were recorded. However, based on the barrier deflection observed, review of test films, and recorded impact speed, decelerations would probably have been similar to those recorded in the first two tests. The vehicle suffered damage to the front-end sheet metal and bumper, the right-side fenders and doors, the right-side tires and wheels, and the suspension. Also, hood-latch failure caused a cracked front windshield when the open hood fell back onto the glass. None of the guiderail posts were damaged, although five were pushed back. All three bridge-rail posts in the first panel were bent backward; there was a maximum permanent deflection of 6 in. At the first post, the base-plate weld was broken and the plate was bowed upward. The second base plate was bowed, but the weld remained intact. Both thicknesses of Thrie beam were damaged in two rail panels; the result was a total of four damaged pieces. Maximum permanent deflection of the Thrie-beam approach rail was 1.2 ft, and again no slippage occurred at the expansion splice.

Guiderail Tests

Two full-scale crash tests of the Thrie-beam guiderail are summarized in Table 2. For both tests, 10-gage Thrie-beam rail was mounted at a height of 33 in and post spacing of 6 ft 3 in was used.

In test 24, a 3600-lb sedan impacted at 56.0 mph and 26°. Before impact, the car snagged momentarily on the guidance-system release post; the result was a +5° vehicle pitch at impact. Initial vehicle-rail contact was on the right end of the front bumper and right front fender. As the rail deflected, the bottom twisted under slightly, and a maximum dynamic deflection of 3.6 ft was observed. The right front

Table 2. Results of guiderail tests.

Variable	Test	
	24	25
Vehicle weight (lb)	3600 ^a	2300 ^a
Vehicle speed (mph)	56.0	60.9
Impact angle (°)	26	25
Exit angle (°)	11	6
Maximum roll (°)	-13	-3
Maximum pitch (°)	+5	+15
Maximum yaw (°)	-7	-90
Contact distance (ft)	30	50
Contact time (ms)	555	821
Deflection (ft)		
Dynamic	3.6	2.1
Permanent	1.3	0.8
Deceleration (g)		
50-ms avg		
Longitudinal	7.3	3.8
Lateral	9.4	5.2
Maximum peak		
Longitudinal	27.7	27.0
Lateral	29.1	23.7
Avg continuous		
Longitudinal	0.9	1.1
Lateral	0.1	0.6

^a1974 Matador used for test 24; 1973 Vega, for test 25.

Table 3. Results of median-barrier tests.

Variable	Test		
	26	27	26A
Vehicle weight (lb)	3500 ^a	2240 ^a	3500 ^a
Vehicle speed (mph)	60.9	68.9	63.3
Impact angle (°)	25	25	25
Exit angle (°)	11	13	11
Maximum roll (°)	+10	+16	+16
Maximum pitch (°)	+5	+8	+4
Maximum yaw (°)	-8	-22	-13
Contact distance (ft)	20	25	46
Contact time (ms)	394	332	542
Deflection (ft)			
Dynamic	2.2	1.2	3.9
Permanent	1.0	0.8	2.5
Deceleration (g)			
50-ms avg			
Longitudinal	11.2	9.8	2.8
Lateral	6.6	4.9	8.0
Maximum peak			
Longitudinal	23.7	31.8	12.8
Lateral	24.3	27.7	17.6
Avg continuous			
Longitudinal	3.6	1.9	0.7
Lateral	3.3	1.3	2.9

^a1973 Matador used for test 26; 1973 Vega, for test 27; and 1972 Ford, for test 26A.

wheel contacted the exposed posts and bent them to the ground. The force of these impacts on the wheel was so great that the wheel was torn completely off the car. After about 30 ft of contact, the vehicle left the rail at an angle of 11°. Due to the missing right front wheel, the vehicle rolled a maximum -13°, yawed -7°, and pitched +5°. Vehicle containment and redirection appeared acceptable, in spite of the wheel contact with the exposed posts. A total of six posts were damaged--the first was pushed back by the rail but not hit by the car; the next four were deflected by the rail and then bent completely down by the right front wheel; and the last was deflected slightly by the rail and impacted by the right front wheel, at which point the wheel separated from the car. Decelerations were not very high if the wheel snag is taken into account. Maxi-

mum 50-ms averages were 7.3 g longitudinal and 9.4 g lateral.

Vehicle damage included a bent front bumper, crushed right front fender, flattened right rear tire, and dented right-side doors and right rear fender. The right front tire and wheel were torn completely off the car. Three sections of Thrie beam were dented and six S3x5.7 posts were bent over, the middle four completely to the ground. Permanent barrier deflection was 1.3 ft.

For test 25, a 2300-lb sedan impacted the barrier at 60.9 mph and 25°. Initial redirection was smooth; the maximum dynamic deflection was 2.1 ft. Again, the right front wheel impacted the exposed posts and was driven back into the wheel well. After about 15 ft of contact, the car rolled -3°, pitched +15°, and then spun out, but the right front corner remained in contact with the rail. After sliding along the rail about 35 ft further, the car exited at an angle of 6° but yawed -90°. Maximum 50-ms average decelerations were quite low for the high speed and angle impact--3.8 g longitudinal and 5.2 g lateral. Containment and redirection were generally quite acceptable, in spite of the impact of the wheel on the exposed posts. Vehicle damage included both front fenders crushed, the hood sprung and driven back to the windshield, the right side dented, and the right front wheel broken from its suspension and driven back under the chassis. Barrier damage was limited to two bent Thrie-beam sections and four damaged S3x5.7 posts. The first was deflected back, but the other three were bent nearly to the ground by the wheel impact. Permanent rail deflection was 0.8 ft.

Median-Barrier Tests

Results of three full-scale crash tests of Thrie-beam median barriers are summarized in Table 3. Because the two previous guiderail tests resulted in contact of the wheel with the exposed posts, the mounting height of the Thrie-beam rail was reduced to 30 in. Post spacing was 6 ft 3 in for the first two tests, but for the third it was increased to 12 ft 6 in to permit greater dynamic deflections. It was hoped that this would reduce deceleration and wheel-post impact problems but still hold dynamic deflections similar to those experienced with the box-beam barrier systems.

In test 26, a 3500-lb sedan impacted the rail at 60.9 mph and 25°; there was contact between the vehicle's right corner and the rail. Redirection was generally smooth and resulted in a maximum dynamic deflection of only 2.2 ft. Again, the exposed posts were impacted by the right front wheel, which was driven back against the wheel well and firewall. Maximum vehicle roll was +10° about 10 ft after initial barrier contact. This roll was caused partly by the damage to the right front wheel and partly by the barrier's tipping out slightly at the top. After 20 ft of contact, the vehicle exited at 11°, pitched +5°, and yawed -8°. Peak 50-ms decelerations were 11.2 g longitudinal and 6.6 g lateral. Vehicle damage included bent front bumper and headlight assembly, crushed right front fender, sprung hood and right front door, dented right-side doors and rear fender, mangled right suspension, and right front wheel and tire torn from the suspension and driven back against the inside fender and firewall. Six Thrie-beam sections were bent--three each on the front and back of the posts--and six S3x5.7 posts were bent at the ground line; their tops were deflected from 3 to 12 in. Permanent barrier deflection was 1.0 ft.

In test 27, the 2240-lb sedan impacted at 68.9 mph and 25°. Despite the severe impact, redirection

was relatively smooth; the maximum dynamic deflection was 1.2 ft. The right front wheel again impacted the exposed posts and was driven back against the inner fender and firewall. During 25 ft of contact with the barrier, the vehicle rolled a maximum of $+5^\circ$ as the barrier top tipped back, but no noticeable yaw or pitch was observed. As the vehicle exited along a 13° trajectory, roll and pitch became more severe ($+16^\circ$ roll and $+8^\circ$ pitch). However, 25 ft after the vehicle's departure, roll was back to 0° , pitch was $+5^\circ$, and yaw was -22° . Peak 50-ms decelerations were 9.8 g longitudinal and 4.9 g lateral.

Vehicle damage included bent bumper, buckled hood, crushed right front fender, dented right-side sheet metal, sprung right-side door, and damaged right front suspension. Also, the right front tire was pulled partly off its wheel and wedged between the bent suspension and the inside fender wall. Barrier damage included four bent and buckled Thrie-beam sections--two each on the front and back of the posts--and five S3x5.7 posts bent back from 3 to 12 in measured at the top of the posts. Permanent barrier deflection was 0.8 ft.

In the final test of Thrie-beam median barrier (test 26A), post spacing was increased to 12 ft 6 in. The 3500-lb sedan impacted at 63.3 mph and 25° . Redirection was smooth; the maximum dynamic deflection was 3.9 ft. Because rail deflection was greater and post spacing was increased, the right front wheel was not damaged by the posts. However, the rail did tip out somewhat at the top, which was reflected in the vehicle trajectory. The vehicle exited at an 11° angle 46 ft after contact. Maximum roll was $+16^\circ$, pitch was $+14^\circ$, and yaw was -13° . Overall, decelerations were less severe than in the first two tests; peak 50-ms averages were 2.8 g longitudinal and 8.0 g lateral.

Vehicle damage was also less severe than in tests 26 and 27. The bumper, right-side fenders, and doors were dented and the right-side tires were flattened, but the wheels and suspension remained intact. Barrier damage was also lighter; four Thrie-beam sections were bent, all on the front of the system, and five posts were bent over from 4 to 18 in at the top of the post. Permanent deflection was 2.5 ft.

DISCUSSION OF RESULTS

The upgraded bridge rail developed during this research performed well and appears to offer a suitable alternative to other upgradings developed elsewhere (4). Its principal advantage is that it uses a single thickness of 10-gage Thrie-beam rail bolted directly to the existing bridge rail, which eliminates the need for the tubular Thrie beam. In the transition from light-post (S3x5.7) guiderail to the bridge rail, however, it was necessary to double the rail element and add heavy posts (W6x8.5) to prevent excessive deflection and pocketing at the first bridge-rail post. Vehicle decelerations experienced in these tests were not excessive and were comparable with those reported for other tests of very stiff bridge-railing systems. Vehicle redirection was good, except for test 23, which resulted in pocketing. That design was then modified and performed well in test 23A. Vehicle damage was moderate if the severity of the impacts is taken into account and compared favorably with other tests of upgraded bridge rails. Although impact speed in test 22 (on the bridge) was less than 60 mph, deflection and rail damage were moderate. Based on the results of that test, the upgraded railing system has strength adequate to withstand 60-mph 25° impacts from 4500-lb vehicles. This bridge-rail

upgrading system thus appears suitable for implementation. Although no test was performed at the transition from light to heavy posts, the other two transition tests provide evidence that this part of the transition will perform satisfactorily. In tests 23 and 23A, the Thrie-beam rail effectively prevented wheel contact with the first bridge-rail post and with the W6x8.5 posts. The 20-in depth of the Thrie-beam rail thus should prevent wheel contact at the change from S3x5.7 to W6x8.5 posts. It must be remembered that the light posts separate from the rail on impact and bend over at the ground line and are thus exposed to wheel impact. The heavy posts, on the other hand, which are rigidly connected to the rail, are deflected back on impact and continue to be protected against wheel impact by the rail.

The guiderail and median-barrier designs also appear to offer acceptable performance; deflection characteristics are similar to those of the box-beam guiderail and median barrier now standard in New York State. Deflection characteristics for all four barriers are given in Table 4. First, standard design deflections for box-beam barriers are given. Based on a 60-mph 25° impact by a 3500-lb vehicle, design deflections for these barriers vary from 2 to 5 ft, depending on the rail element and post spacing selected. Next, actual test deflections for the Thrie-beam barriers are presented, which ranged from about 2 to 4 ft. Finally, proposed design deflections are provided for Thrie-beam guiderail and median barrier at two post spacings each. These design deflections were estimated from actual test results; corrections were added for impact speed, angle, and test-vehicle weights. The deflection for guiderail that has a post spacing of 12 ft 6 in is based on the effects of post spacing observed in the median-barrier tests and in earlier tests of W-beam light-post guiderail (8).

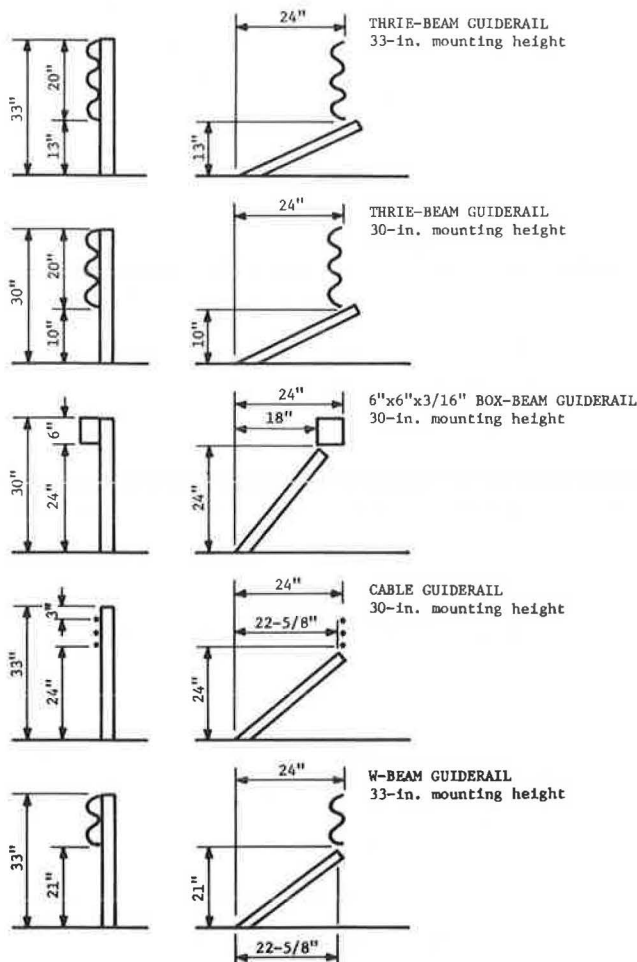
Tests of both guiderail and median barrier generally resulted in acceptable performance. The decelerations recorded in these tests seem reasonable for the severe test conditions. Although some values exceed the guideline recommendations of 10 g longitudinal and 5 g lateral, these impacts were at 25° rather than at 15° . Compared with previous tests of barrier systems (3,9-11) now classified as operational in the American Association of State Highway and Transportation Officials (AASHTO) barrier guide, some of the deceleration values are somewhat higher but are still within reasonable limits for 25° impacts. The two small-car tests, on the other hand, resulted in surprisingly moderate deceleration values, especially if the 25° impact angle and very high speeds (61 and 69 mph) are taken into account. Some vehicle roll was experienced during redirection, but none of the vehicles appeared close to rolling over. Exit angles were all acceptable, although some vehicles did yaw sharply toward the barrier after exit because of steering and suspension damage. Vehicle damage was moderate for all these tests, especially if the high impact speeds and 25° impact angles are considered. No damage to passenger compartments resulted, and damage was generally limited to the right front sheet-metal, grill, bumper, and right front suspension. Vehicle damage appears comparable with that resulting from other tests of Thrie beam and W-beam on heavy posts (3,9-11), which includes damage to the suspension. Because of the high speeds and impact angles for small-car tests, direct comparison with other tests is not possible. However, these results seem favorable if the high severity of these impacts is considered.

The only disappointing aspect of the test was the damage to the front wheel and suspension experienced

Table 4. Summary of barrier deflections.

Barrier Type	Post Spacing (ft)	Impact Conditions		Vehicle Weight (lb)	Deflection (ft)
		Speed (mph)	Angle (°)		
Existing box-beam barrier					
6×6×3/16-in guiderail	3	60	25	3500	4
6×6×3/16-in guiderail	6	60	25	3500	5
6×8×1/4-in median barrier	3	60	25	3500	2
6×8×1/4-in median barrier	6	60	25	3500	4
Tested Thrie-beam barrier					
Guiderail	6¼	56	26	3600	3.6
Median barrier	6¼	61	25	3500	2.2
Median barrier	12½	63	25	3500	3.9
Proposed Thrie-beam barrier					
Guiderail	6¼	60	25	3500	4
Guiderail	12½	60	25	3500	6
Median barrier	6¼	60	25	3500	2
Median barrier	12½	60	25	3500	3.5

Figure 7. Attitudes of several light-post barriers before and after impact.



in four of the five guiderail and median-barrier tests. In spite of this damage, which resulted from contact between the wheel and the posts, vehicle decelerations were within acceptable ranges. Further, this suspension damage generally did not result in unacceptable vehicle trajectories. Such damage is not uncommon for impacts at high angles and high speeds and has been reported in tests of several barriers now in wide use (3,9-11). Several of these earlier tests also resulted in complete removal of the front wheel. Further, several tests

used full-sized cars rather than the intermediate-sized cars used here.

Although this contact between wheel and posts did not appear to result in unacceptable performance, it is desirable to eliminate such damage if possible. Examination of the barriers after impact and close examination of the test films revealed two factors that contributed to the wheel-post impact problem. First, these barriers were all installed on an asphalt pavement; the posts were driven through several inches of asphalt. Combined with the 8x24-in soil-support plates, this resulted in posts that bent at the pavement surface on impact and did not push through the asphalt. This installation condition is typical in New York State, where guiderail and median barrier are frequently installed on asphalt shoulders or medians that are paved over compacted gravel subbases. This very stiff restraint may have increased the severity of the wheel-post impact somewhat. The second contributing factor is the relatively high stiffness of the barriers tested and the greater depth of the Thrie-beam section. As the rail deflected on impact, the rail mounting bolt was snapped, but the posts were bent back by the rail. However, the small amount of post exposed prevented contact of the post with the vehicle bumper or sheet metal. Instead, the main force on the post was imparted by the wheel, which resulted in the suspension damage experienced. For W-beam, cable, or box beam installed on light posts, the shallow rail depth would permit more vehicle sheet-metal contact on the post, which would partly bend it down before it was struck by the wheel. For W-beam and cable, greater deflections would also help eliminate this problem. The relation of several light-post barriers before and after impact is shown in Figure 7, and it can be seen that the Thrie beam is the most critical case for wheel-post impact.

The first effort to reduce contact between wheel and posts was to lower the rail height from 33 to 30 in. However, as seen in Figure 7, this cannot be expected to have much effect, because contact occurs after the rail and post have separated and the post has been bent laterally by the deflecting rail. The second effort, which was successful, was to increase post spacing from 6 ft 3 in to 12 ft 6 in as in the last test (test 26A). By increasing the spacing, greater deflection was permitted, which helped to move the wheel behind many of the posts and to permit the bumper and sheet metal to contact and bend the posts longitudinally. Increasing post spacing also results in fewer posts to contact. Depending on impact conditions, it is much more likely that the vehicle can be redirected without a severe wheel-post impact. Damage to the right front

suspension was successfully eliminated in test 26A, which used the wider post spacing.

Additional tests of the Thrie-beam light-post barriers are needed to provide performance data by using other post spacings and 12-gage rail sections. In addition, 60-mph 15° impacts by small cars will provide confirmation that this barrier system provides very good protection for small cars, although this is already indicated by the 60-mph 25° impacts reported here. Based on these tests, the 10-gage Thrie-beam barrier on S3x5.7 posts spaced at 12 ft 6 in and mounted at a height of 33 in appears suitable for both guiderail and median-barrier use on a trial basis. To reduce front-suspension damage, closer post spacings should be limited to transitions to more-rigid barriers. Limited field installations of this barrier system appear justified at this time, especially used as a bridge-rail upgrading. Because of the wheel-post impact problem, this barrier system does not provide a significant improvement in impact performance over existing barriers but it does provide three distinct advantages over existing systems. It performs well as a bridge-rail upgrading; it can be more readily transitioned to rigid barriers; and its greater depth provides improved vaulting-underride protection. As with any new barrier system, careful documentation of initial field installations is necessary to confirm the good performance indicated by these tests.

CONCLUSIONS

Based on eight crash tests of Thrie-beam bridge-rail upgrading, guiderail, and median barrier, the following findings can be stated:

1. A bridge-rail upgrading that consists of 10-gage Thrie beam bolted directly to discontinuous-panel bridge rail performed well during a full-scale test. This upgrading system is suitable for 60-mph 25° impacts by 4500-lb vehicles.
2. A 10-gage Thrie-beam transition from guiderail to bridge rail mounted on S3x5.7 posts was not stiff enough to prevent pocketing at the end of the bridge rail.
3. A redesigned transition to bridge rail that used a double layer of 10-gage Thrie beam mounted on W6x8.5 posts performed well and is suitable for 60-mph 25° impacts by 4500-lb vehicles.
4. Five tests of guiderail and median barrier that consisted of 10-gage Thrie beam mounted on S3x5.7 posts resulted in satisfactory vehicle containment, redirection, and deceleration.
5. Damage to the front wheel and suspension occurred in four of these five tests; it was caused by impact between wheels and posts. This damage was no more severe than that reported in many earlier tests of operational barriers, and the total vehicle damage in many cases was less.
6. Lowering the rail-mounting height from 33 to 30 in intensified the wheel-post contact problem because it reduced the chances that the post would be bent longitudinally by the bumper, sheet metal, and frame.
7. Increasing post spacing from 6 ft 3 in to 12 ft 6 in reduced conflict between wheels and posts by increasing barrier deflection and reducing the number of posts available for impact.
8. Guiderail and median barrier that consist of 10-gage Thrie beam mounted at 33 in on S3x5.7 steel posts appear to be suitable longitudinal barriers. They offer several distinct advantages compared with barriers now in use, which includes excellent properties as a bridge-rail upgrading system, simple transition to rigid barriers, and lower suscepti-

bility to vaulting or underride problems compared with narrower rail elements.

9. Testing should continue to determine barrier characteristics at other post spacings and mounting heights and under less-severe impact conditions. Efforts should also continue to reduce conflict between wheel and posts, especially when the need for low dynamic deflections requires use of relatively close post spacings.

10. Design deflections are presented for this barrier system that are very close to those for box-beam guiderail and median-barrier systems.

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SERB: A New High-Performance Self-Restoring Traffic Barrier

M.E. BRONSTAD, C.E. KIMBALL, JR., AND C.F. McDEVITT

This paper describes the development and evaluation of a unique guardrail system. Features of this barrier include a simple gravity-dependent self-restoring stage for automobile impacts that bottoms at a second stage that is capable of redirecting large vehicles. Screening of preliminary designs was accomplished by computer simulation and cost analyses. The prototype barrier design was revised into a final configuration based on crash test results. The self-restoring barrier (SERB) guardrail has successfully redirected vehicles that range from a 950-kg (2100-lb) mini automobile to a 18 000-kg (40 000-lb) intercity bus at 95 km/h (60 mph) and a 15° angle. A unique feature of the new system is the self-restoring elastic 0.3-m (11-in) deflection of the rail, which provides forgiving redirection for most passenger car impacts without damage or permanent deformation of the system.

This paper describes the development and evaluation of a unique high-performance guardrail system. Features of this barrier include a simple gravity-dependent self-restoring stage for automobile impacts that bottoms at a second stage that is capable of redirecting large vehicles. The finalized design is a product of an in-depth investigation conducted by Southwest Research Institute for the Federal Highway Administration. Design criteria were developed first and conceptual designs were subsequently screened by computer simulation and cost analyses. The barrier system selected for crash test evaluation is considered the best of all design concepts investigated during the course of the project. A total of seven crash tests were conducted on prototype and finalized design installations. Included in the evaluations were mini, subcompact, and full-sized cars as well as school and intercity buses.

BACKGROUND

In the early 1970s, crash test evaluations in the United States began to use heavy vehicles to evaluate high-performance barriers. The collapsing ring bridge rail (1) and the concrete median barrier were subjected to impacts by intercity buses (2) and tractor trailers (3). The conditions of impact varied considerably, since there was no recognized standard impact condition for these heavy vehicles. Indeed, there were no standard heavy vehicles specified for crash testing.

The objective of this study was to design high-performance guardrail and median-barrier concepts. It was recognized that many agencies were replacing flexible metal barriers with concrete in urban areas due to frequent requirements for damage repair. A goal of this design study was to provide the agen-

cies with a forgiving flexible barrier that would not require significant maintenance and at the same time would provide containment and redirection of infrequent impacts by heavy buses and trucks. A survey of selected states that were known to have significant heavy-vehicle traffic was conducted to determine deflection limits for the systems. Selection of design vehicles was also a consideration. The final product of the investigations was the set of design criteria for the high-performance self-restoring barrier (SERB) system given below:

1. Impact severity: Provide forgiving redirection for subcompact car for impacts up to 95 km/h (60 mph) and 15° angle,
2. Strength: Contain and redirect an 18 000-kg (40 000-lb) intercity bus impacting at 95 km/h and 15° angle,
3. Damage repair: Allow no significant damage during typical shallow-angle impacts with cars, and
4. Cost: Minimize installation cost.

SERB BARRIER

The SERB barrier is a staged system designed to be self-restoring for most impacts that occur at shallow angles. The tubular Thrie beam is mounted on alternate posts by using a double-hinged pivot bar and cable assembly (Figure 1a). When impacted by a vehicle, the beam deflects up and backward, providing 0.3 m (11 in) of stroke before bottoming on the posts (Figure 1d). As the beam is displaced, the vehicle follows the upward motion, which provides a banking effect that enhances smooth redirection. After bottoming, the SERB guardrail is a very strong barrier 1.0 m (38 in) high capable of redirecting heavy vehicles that impact at 95 km/h and a 15° angle.

FINDINGS

The first three crash tests were conducted on the prototype design shown in Figure 2 (all tests are summarized in Table 1). In this design, the tubular Thrie-beam rail is bolted directly to the single-hinged pivot bar. The rail 0.8 m (30 in) high became 0.9 m (35 in) high when it bottomed against the wood posts. Tests SRB-1 and SRB-2, which used passenger vehicles, were successful. Rollover of the school bus in test SRB-3 (Figure 3) led to the de-