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Performance of a Thrie-Beam Steel-Post Bridge-Rail System

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ABSTRACT

Twelve full-scale crash tests were performed to evaluate the performance of a thrie-beam bridge-rail system. The railing consisted of 10-gauge thrie-beam steel rail attached to W6x9 steel posts spaced at 8 ft 4 in. Posts were attached to the deck by using base plates and anchor bolts. The system was tested both with and without a 6-in. curb with the rail at a height of 33 in. (measured from the deck) for both designs. Also tested were transitions from W-beam guiderail on S3x5.7 posts to thrie-beam guiderail on W6x9 posts and from the thrie-beam guiderail to the bridge rail. Tests with both 4,500- and 1,800-lb vehicles showed that the railing system generally meets the recommended performance standards in NCHRP Report 230.

The reconstruction of older structures to replace existing railings with new ones that meet current standards is prohibitively expensive, so the New York State Department of Transportation (NYSDOT) has initiated efforts to improve performance by installing additional railing components. Called "upgradings" or "retrofits," these designs use existing railing and superstructure components to the greatest extent possible and add only the necessary railings, posts, and connectors to achieve the desired performance. Several bridge-railing retrofits have already been tested and are now in use on bridges with discontinuous-panel railings (1,2).

However, some structures do not permit simple attachment of the retrofit to the existing railing system. One solution developed by the Structures Design and Construction Division is shown on Standard Sheet BDD 81-57F (Details for Attaching Thrie-Beam Railing to Bridge Railing). This design mounts 10-gauge thrie-beam railing on new heavy steel posts that are attached to the deck by using an anchor plate and grouted anchor bolts. Analytical procedures used to develop that design indicated the need for W6x25 posts spaced at 4 ft 6 in. Southwest Research Institute has previously tested a similar design that used 12-gauge tubular thrie-beam rail with good results (3). A 12-gauge thrie-beam on W6x9 post spaced at 5 ft that could redirect a 4,500-lb vehicle at 60 mph and 15 degrees was also developed for use as a low-service-level bridge rail (4). The NYSDOT design, which used a single 10-gauge thrie beam, appeared to offer several advantages:

1. Less complex splices are required,
2. Handling is easier because of its lighter weight,
3. Fewer inventory items are required for repair, and
4. Construction and maintenance costs should be lower.

The principal disadvantage of the proposed New York design was heavy steel posts at close spacing; the necessity of grouting so many bolts into the deck would add substantially to the railing's cost. However, other Texas Transportation Institute tests (5) evaluated a railing system composed of two W-beam rails overlapped to form three corrugations similar to a thrie beam. That railing performed adequately when attached to steel posts spaced at 8 ft 4 in., which indicated that it may be possible to increase the post spacing of the New York design.

METHODOLOGY

A total of 12 full-scale tests were conducted in 1982 and 1983 following the recommendations of NCHRP Report 230 (6). These tests were planned to determine maximum permissible post spacing as well as the level of performance provided by this railing system. In addition, tests of proposed transitions to W-beam approach guiderail were needed to ensure their adequate performance. Concrete footings 3 ft wide by 3 ft deep by 40 ft long simulated bridge decks for these tests. Two footings were used: one providing a 6-in. curb and the other simulating a curbless deck. New York's standard bridge deck designs have provided good performance in service, and deck failure has not been noted in severe railing impacts. Thus, it was possible to simplify these tests by using a rigid footing rather than by constructing a more detailed simulated deck.

DESCRIPTION OF BARRIER SYSTEMS

The railing design developed by the Structures Design and Construction Division consisted of 10-gauge thrie beam attached to W6x25 steel posts. The thrie beams are standard 13.5-ft sections, providing 12.5-ft lay lengths with 1-ft splice overlays. The posts were welded to 1-in.-thick base plates, and 1-in.-diameter threaded steel rods were grouted into the deck 10 in. deep for anchor bolts. The railing face was set flush with the curb face for the first test, which placed the centers of the anchor bolts about 3 in. behind the curb. On the basis of a review of the research just discussed, post spacing was increased to 6 ft 3 in. for the first test rather than the 4.5 ft shown on the BDD sheet. Height to the top of the rail was 33 in. above the deck. Four sections of thrie-beam rail were mounted on the simulated bridge, totaling 50 ft in length, and the thrie beam was transitioned to W-beam guiderail on both ends. The W-beam was then anchored to standard concrete foundations, providing a total barrier length of 132 ft. Post size and spacing on the bridge were varied from test to test on the basis of results of the preceding test. Those details are provided in the next section. In addition, this railing system was tested on a curbless deck to determine performance of that configuration. With no curb, the height of the thrie beam was maintained at 33 in. by increasing the post length. The transitions to W-beam guiderail generally consisted of one length of thrie beam extending off the bridge, a tapered transition from three to two corrugations, and then NYSDOT standard W-beam guiderail on S3x5.7 steel posts. Several designs were tested before performance was considered adequate, and details of those designs are also provided in the next section.

RESULTS

Twelve tests were conducted to evaluate the railing system and transition, including three on the bridge railing with curb, five on the transition from W-beam guiderail to thrie-beam approach rail, and two each on the thrie-beam approach rail and bridge railing without curb. Results are summarized in Tables 1 and 2 and discussed in this section.

Railing with Curb

For the first test of the railing with curb, W6x25 steel posts were spaced at 6 ft 3 in. with the face of the thrie beam flush with the curb face (Figure 1). In Test 64, the 4,500-lb Dodge station wagon impacted 1.9 ft downstream from Post 3 at 60.1 mph and 26 degrees. It remained in contact with the barrier for 15.5 ft and was smoothly redirected at an 8-degree exit angle. After departure, the vehicle turned gradually toward the left, achieving an angle of 15 degrees with the barrier. Dynamic barrier deflection was limited to 1.1 ft. The vehicle remained stable throughout the impact, with maximum roll of 15 degrees (clockwise), maximum pitch of 5 degrees (front down), and maximum yaw of 21 degrees (counterclockwise). Peak 50-msec average decelerations were 5.8 g longitudinal and 8.4 g lateral, with occupant impact velocities of 19.4 ft/sec longitudinal and 21.2 ft/sec lateral. Lateral occupant impact velocity thus only slightly exceeded the recommended value of 20 ft/sec 15-degree impacts, and the longitudinal value was well below the recommended limit of 30 ft/sec. Vehicle damage was considered moderate for a 25-degree impact on such a stiff barrier; it included damage to the hood, grill, bumper, right front fender, and right front wheel and suspension, with minor sheet metal damage along the right side. Barrier damage was heavy. Two rail sections were damaged, and four posts--3, 4, 5, and 6--were bent back, with the anchor bolts broken out of the curb. On basis of the results of Test 64, the railing appeared to be stiffer than necessary. Post size thus was reduced to W6x9 with 3/4-in. base plates and post spacing increased to 8 ft 4 in. In addition, the railing was moved back so the face of the thrie beam was 6 in. behind the curb. This provided 9 in. to the center of the anchor bolts and was intended to eliminate the severe anchor-bolt breakout encountered in the first test.

In Test 65, the 4,500-lb Plymouth station wagon impacted 0.8 ft downstream from Post 2 at 58.8 mph and 27 degrees. Contact distance was 17.4 ft, with maximum dynamic deflection of 1.4 ft. The vehicle was again smoothly redirected at a 16-degree exit angle, 4-degree maximum roll, 5-degree pitch, and no measurable yaw. Impact severity was similar to that of the previous test, with peak 50-msec average decelerations of 4.8 g longitudinal and 9.3 g lateral. Occupant impact velocities were 18.2 ft/sec longitudinal and 21.5 ft/sec lateral. Vehicle damage was again moderate and similar to that in Test 64. Barrier damage, however, was significantly less (Figure 2). Two rail sections were again damaged, as well as two posts. However, the posts were bent above the base plates, with no damage to the anchor bolts or curb. Repair thus required simply unbolting and replacing the two damaged posts and no curb repair or anchor-bolt replacement was needed.

Tests 64 and 65 results thus confirmed that post spacing could be increased from the 4 ft 3 in. originally calculated. However, it appeared that the 8-ft 4-in. spacing was about the upper limit with the 10-gauge thrie-beam rail, and wider spacing might permit excessive rail deflection, resulting in pocketing or snagging at posts. To evaluate occupant risk, the barrier was rebuilt with the same design for Test 66. The 1,860-lb Subaru sedan impacted 2.1 ft downstream from Post 2 at 59.6 mph and 14 degrees. Barrier contact was only 8.1 ft, with a maximum dynamic deflection of 0.25 ft. The vehicle was smoothly redirected at a 9-degree exit angle, with maximum roll, pitch, and yaw of 10, 4, and 7 degrees, respectively. Peak 50-msec average decelerations were 3.8 g longitudinal and 11.9 g lateral. Although the lateral 50-msec average value is high compared with TRB Circular 191 criteria (7), lateral occupant impact velocity was 23.4 ft/sec, only slightly exceeding the recommended value in NCHRP Report 230. The 2-ft impact distance was not reached in the longitudinal direction. Barrier damage was superficial, limited to minor dents on the bottom corrugation of the impacted section. Vehicle damage was moderate, including the bumper, grill, hood, right front fender and wheel, and suspension.

W-Beam-to-Thrie-Beam Transition

After completion of the curbed bridge-rail tests, the guiderail-to-bridge-rail transition was tested. It is anticipated that the thrie-beam bridge rail will have maximum application for situations in

TABLE 1 Test Results: Tests 64-69

Item	Test 64	Test 65	Test 66	Test 67	Test 68	Test 69
Point of impact	1.9' downstream from No. 3 bridge post	.8' downstream from No. 2 bridge post	2.1' downstream from No. 2 bridge post	8.75' upstream from W-beam/ transition conn.	4.65' upstream from W-beam/ transition conn.	6.8'upstream from W-beam/ transition conn.
Barrier Length, ft	132	132	132	132	132	132
Vehicle Weight, lb	4500	4500	1860	4500	4500	4600
Vehicle Speed, mph	60.1	58.8	59.6	58.8	59.5	54.4
Impact Angle, deg	26	27	14	25	24	26
Exit Angle, deg	8	16	9	*	*	17
Exit Speed, mph	46.9	48.9	53.5	*	*	33.4
Max. Roll, deg	15	4	10	-15	-14	6
Max. Pitch, deg	5	5	4	6	7	4
Max. Yaw, deg	21	0	7	-11	4	0
Contact Distance, ft	15.5	17.4	8.1	25	23.4	24.3
Contact Time, ms	272	462	234	N.A.	N.A.	617
Deflection, ft						
Dynamic (from film)	1.1	1.4	.25	4.0	2.5	2.5
Permanent (measured)	.85	1.2	.25	4.0	2.5	2.3
Decelerations, g's						
50 ms avg.						
Longitudinal	5.8	4.8	3.8	9.9	9.2	4.5
Lateral	8.4	9.3	11.9	4.4	4.2	6.0
Max. Peak						
Longitudinal	28.5	9.9	10.3	28.3	14.7	9.7
Lateral	28.6	19.0	17.5	45.0	16.5	11.9
Occupant Ridedown						
Longitudinal	-6.9	2.1	2' not reached	12.9	10.7	6.9
Lateral	10.2	11.3	10.2	11.9	8.6	8.7
Occupant Imp. Vel., fps						
Longitudinal (2.0 ft)	19.4	18.2	2' not reached	30.8	25.6	20.8
Lateral (1.0 ft)	21.2	21.5	23.4	14.8	14.6	13.9
Results and Comments	Good redirection; moderate damage to barrier & car	Good redirection; moderate damage to barrier & car	Good redirection; light damage to car, barrier mod.	*Vehicle did not exit	*Vehicle did not exit	Good redirection; light damage to car, barrier mod.

*did not exit.
**film data indicated 45.3 mph.

TABLE 2 Test Results: Tests 70-75

Item	Test 70	Test 71	Test 72	Test 73	Test 74	Test 75
Point of impact	3.5' upstream from W-beam/ transition conn.	2.3' upstream from W-beam/ transition conn.	thrie-beam/ transition connection	3' downstream from thrie-beam/ transition conn.	5.4' downstream from No. 1 bridge post	No. 2 bridge post
Barrier Length, ft	132	132	132	132	132	132
Vehicle Weight, lb	1980	1800	4380	4500	1900	4500
Vehicle Speed, mph	57.8	60.3	57.0	56.5	58.5	59.3
Impact Angle, deg	20	19	28	29	18	29
Exit Angle, deg	*	11°	*	16	6°	14
Exit Speed, mph	*	44.1	*	34.9**	52.8	44.1
Max. Roll, deg	-180	5	-10	9	12	-36
Max. Pitch, deg	10	1	2	4	3	-8
Max. Yaw, deg	71	5	-5	0	0	0
Contact Distance, ft	19.6	20	12.6	16	11.1	24.7
Contact Time, ms	533	360	477	565	259	400
Deflection, ft						
Dynamic (from film)	.5	.5	1.5	1.25	0	1.75
Permanent (measured)	.35	.5	1.33	1.21	0	1.65
Decelerations, g's						
50 ms avg.						
Longitudinal	8.8	6.3	N.A.	5.2	3.0	6.1
Lateral	4.5	6.0	N.A.	8.9	8.9	7.8
Max. Peak						
Longitudinal	19.6	16.2	N.A.	20.4	5.3	14.8
Lateral	15.5	34.0	N.A.	39.0	15.7	18.4
Occupant Ridedown						
Longitudinal	13.0	4.7	N.A.	6.5	2' not reached	-7.6
Lateral	8.7	10.1	N.A.	13.1	8.8	13.9
Occupant Impact Velocity, fps						
Longitudinal (2.0 ft)	29.2	19.3	N.A.	22.0	2' not reached	22.5
Lateral (1.0 ft)	13.9	17.9	N.A.	20.5	18.7	18.0
Results and Comments	Vehicle snagged on heavy-post; rolled over	Good redirection; light damage to barrier, car mod.	Snagged on No. 1 bridge post; data cable sheared	Moderate damage to car & barrier	No curb; good redirection	No curb; good redirection

*did not exit.
**film data indicated 45.3

FIGURE 1 Thrie beam mounted on W6x25 post for Test 64.

FIGURE 2 Bridge-rail damage from Test 65.

which W-beam guiderail is used. Thus, the next test series examined the transition from W-beam guiderail on S3x5.7 steel posts to the thrie-beam approach rail. Standard mounting height on the W-beam had been 33 in. previously, matching the top of the thrie beam. A transition piece was thus needed that compensated for the depth change of about 8 in. on the bottom of the section. Figure 3 shows the first transition tested. The tapered section was 4 ft 2 in. between post bolt holes, and the lower corrugation terminated in a 12-in. taper. A filler piece was added to the exposed end of the lower corrugation. Post spacing of the S3x5.7 steel posts upstream of the taper was reduced to 3 ft 1.5 in. and then to 2 ft 1 in. Two S3x5.7 posts were installed behind the tapered section, and then three W6x9 posts behind the thrie-beam approach rail spaced at 3 ft 1.5 in. The 6-in. concrete curb on the bridge approach was turned under the tapered section on a 10-ft radius and terminated behind the rail.

In Test 67, the 4,500-lb Plymouth station wagon impacted 8.75 ft upstream from the tapered section at 58.8 mph and 25 degrees. Initially, the vehicle had started to redirect until it encountered the tapered transition. At that point, the right front wheel and suspension snagged against the end of the lower thrie-beam corrugation. Dynamic deflection up

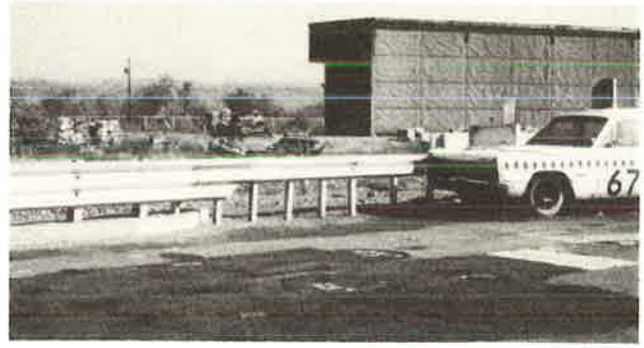


FIGURE 3 W-beam-to-thrie-beam transition evaluated in Test 67.

to that point was about 4 ft, but after the snag the longitudinal load was so great that the W-beam broke in tension at the connection to the tapered section. The W-beam section, tapered transition, and thrie-beam approach section all disconnected from the posts as they were knocked down by the vehicle and rotated back about the first bridge post. The vehicle came to rest against the first bridge post (Figure 4). Peak 50-msec average decelerations were 9.9 g longitudinal and 4.4 g lateral, with occupant impact velocities of 30.8 ft/sec longitudinal and 14.8 ft/sec lateral. The vehicle was heavily damaged, and the entire transition railing was totally destroyed. In addition, the curb was broken and displaced by the impact in the transition area, and the first two bridge posts were bent. Tensile tests were performed on two W-beam samples after the failure. Yield strengths were 59,000 and 62,500 psi with elongations of 23 and 20 percent, both exceeding the specified minimums of 50,000 psi and 12 percent.

For Test 68, the length of the tapered transition was increased to 6 ft 3 in. between mounting bolt holes, with the lower corrugation taper increased to 3 ft (Figure 5). Light posts were again used behind the transition piece spaced at 2 ft 1 in. The increased taper length was intended to reduce the severe snag encountered in Test 67, but it was not successful. The 4,500-lb Ford station wagon impacted at 59.5 mph and 24 degrees 4.6 ft upstream from the tapered section. The vehicle again snagged on the end of the lower corrugation after beginning to redirect. The front wheel and suspension were again trapped between the bottom of the thrie beam and the top of the curb, and the vehicle came to rest against the first bridge post. The rail did not break, but all the posts in the transition area were bent over, and the rail was deflected 2.5 ft. The vehicle traveled 23.4 ft from impact to rest. Peak 50-msec average decelerations were 9.2 g longitudinal and 4.2 g lateral. Occupant impact velocities were 25.6

FIGURE 4 Results of Test 67.

FIGURE 5 W-beam-to-thrie-beam transition evaluated in Test 68.

ft/sec longitudinal and 14.6 ft/sec lateral. The front and right side of the vehicle were heavily damaged.

After Test 68, it became clear that the termination of the lower corrugation presented an insurmountable snag point, and the entire transition was redesigned to include the symmetrical tapered section shown in Figure 6. In this section the middle corrugation drops out and the upper and lower ones continue. This has been adopted as a standard by the American Road and Transportation Builders Association (ARTBA) (8). Because the 8-in. decrease in section depth was split equally between top and bottom, a total height adjustment of 4 in. was required in the top-of-barrier elevation. Sufficient tolerance in the splice bolt holes permitted the tapered section to be tipped up about 1 in., and the remaining 3 in. was gained by lowering the top of the W-beam over one section length. Standard height to the top of the W-beam has since been decreased to 30 in., thus simplifying this connection. As in previous tests, S3x5.7 posts were used with the W-beam and at the beginning of the 6-ft 3-in. tapered section. Mid-length and at the downstream end of the taper, W6x9 posts were substituted to stiffen the transition, and 6-in.-deep blockouts were added to reduce contact with the posts and help maintain rail height during deflection. Finally, the vertical curb radius was replaced with a ramped curb end that terminated the curb 6 ft upstream from the bridge.

FIGURE 6 Symmetrical transition evaluated in Test 69.

In Test 69, the 4,600-lb Cadillac sedan impacted at 54.4 mph and 26 degrees 6.8 ft upstream from the tapered section. This time, the vehicle was smoothly redirected at a 17-degree angle. However, some contact with the heavy posts did occur in spite of the 6-in. blockouts, and exit speed was only 33.4 mph on the basis of accelerometer data. Maximum dynamic deflection was 2.5 ft over the 24.3-ft contact distance. The vehicle turned back toward the rail after exiting and came to rest against the downstream terminal. Maximum roll was 6 degrees, pitch was 4 degrees, and no yaw was observed. Peak 50-msec average decelerations were 4.5 g longitudinal and 6.0 g lateral. Occupant impact velocities were 20.8 ft/sec longitudinal and 13.9 ft/sec lateral. Damage to the vehicle was limited to the right front corner of the grill and bumper, right front fender, and right front wheel. Moderate barrier damage included three light posts and four heavy posts partially bent over, as well as one W-beam, one thrie beam, and the tapered section.

On the basis of the previous test, it appeared that the W-beam-to-thrie-beam transition now performed reasonably well with a large car, although slight post contact was noted. The transition was rebuilt for the small-car test. In Test 70, the 1,980-lb Subaru station wagon impacted at 57.8 mph and 20 degrees 3.5 ft upstream from the tapered section. On impact, the front bumper was under the W-beam, and sheet metal deformation on the front fender was sufficient to allow the front wheel also to protrude under the rail. The S3x5.7 posts collapsed with little resistance when hit by the front of the car, but the bumper and wheel had intruded far enough under the rail that they also contacted the first W6x9 post--in spite of the 6-in. blockout--and a severe snag resulted. On impacting the first heavy post, the car yawed sharply clockwise and rolled over, coming to rest on its roof in front of the barrier. Peak 50-msec average decelerations were 8.8 g longitudinal and 4.5 g lateral, with corresponding occupant impact velocities of 29.2 and 13.9 ft/sec. Damage to the barrier was light, with one light post bent over, three heavy posts dented, and minor scratches on the tapered section. Total barrier contact distance was 19.5 ft, and dynamic deflection was 6 in. The vehicle was heavily damaged.

Although the 6-in. blockout might be adequate in some situations, it did not work well in this case when the bumper and front wheel were able to intrude under the W-beam upstream from the heavy post section. Even though the impact angle was somewhat more severe than the 15 degrees intended, this barrier was considered unacceptable, and design revisions were needed. Testing conducted by the Texas Transportation Institute (9) had shown that a deeper blockout on thrie-beam guiderail performed well in both small sedan and bus tests. Therefore, a welded blockout was added to the heavy posts to increase blockout depth to 14 in. The TTI tests had used an M14x17.2 rolled shape for the blockout. For these tests, 0.25-in. plate was welded to fabricate a blockout closely approximating the rolled shape. In addition, a notch was provided in the lower front of the blockout web. This notch was intended to perform two functions. First, it would provide a collapse mechanism to absorb part of the impact energy, especially with small cars, and second, it would permit the lower corrugation to rotate inward and thus remain more nearly vertical during severe impacts by large vehicles.

In Test 71, the 1,800-lb Honda sedan impacted the barrier 2.8 ft upstream from the tapered section at 60.3 mph and 19 degrees. After 20 ft of barrier contact, the vehicle redirected at an 11-degree exit angle, with maximum 50-degree roll, 1-degree pitch, and 5-degree yaw. Peak 50-msec average decelerations were 6.3 g longitudinal and 6.0 g lateral, with corresponding impact velocities of 19.3 and 17.9 ft/sec. Maximum dynamic barrier deflection was 6 in., and barrier damage was light--two light posts were bent over, one heavy post was dented, and the W-beam and tapered section were scuffed. Even with the 14-in. blockout, the vehicle made slight contact with the second heavy post. Vehicle damage was moderate, confined to the right front corner.

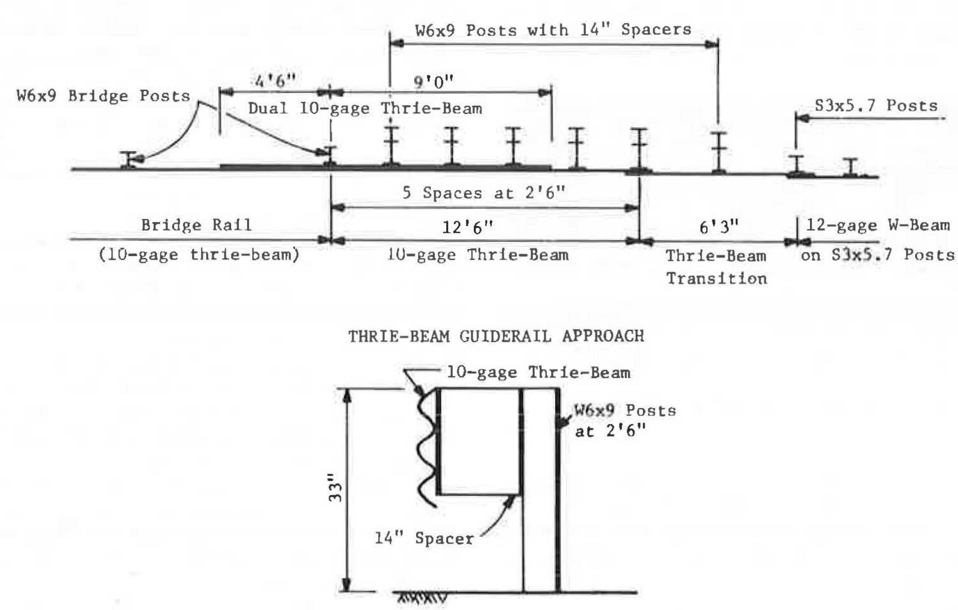
It thus appeared that the symmetrical tapered section combined with the 14-in. blockouts provided adequate performance at the W-beam-to-thrie-beam transition. Because this transition had performed reasonably well with only a 6-in. blockout in the large-car test, it was not considered necessary to retest the deep blockout with a large car. Testing thus proceeded to the thrie-beam bridge approach.

Thrie-Beam Bridge-Approach Section

After the transition from the very flexible W-beam guiderail to the relatively stiff thrie-beam guiderail had been completed, another transition was necessary to the very stiff bridge rail. For the initial design, a single 10-gauge thrie beam spanned from the tapered section to the first bridge post. W6x9 posts with notched 14-in. blockouts were spaced at 3-ft 1.5-in. centers, and one additional W6x9 post was placed at the end of the bridge to provide increased support at that critical point. As in the previous test, the blockout web was notched. In Test 72, the 4,380-lb Plymouth station wagon hit at the downstream end of the tapered section--12.5 ft from the first bridge post--at 57.0 mph and 28 degrees. The barrier deflected 1.5 ft as the vehicle approached the bridge, but this was excessive considering the very stiff railing at the end of the bridge and a pocketing condition developed. In addition to severe pocketing, the right front wheel and suspension snagged on the unblocked post at the end of the curb ramp, and the vehicle stopped very abruptly 20 ft onto the bridge. The car was extensively damaged, including partial collapse of the passenger compartment and roof. Electronic data were lost because of a cable break. In spite of the severe damage to the vehicle, the railing was only moderately damaged, with several posts pushed back, one post bent, and one rail section damaged. In addition, the front flange of the blockouts collapsed against the web notch in the impact area, permitting the lower railing corrugation also to collapse. It appeared that this notch in the blockout contributed to the snag on the post at the end of the ramped curb, because clearance was not maintained between the face of the rail and the posts.

Even if the blockout collapse had not contributed to the snag on the unblocked post, it appeared that with a 1.5-ft deflection, the vehicle would have pocketed at the first bridge post. Thus, it was necessary gradually to increase barrier stiffness in the bridge-approach transition. To accomplish this, a backup section of 10-gauge thrie beam was added behind the thrie-beam approach rail, extending 4.5 ft onto the bridge from the first bridge post and 9 ft upstream into the approach section. Full 12-bolt splices were used at each end to attach it to the front thrie-beam section. The notches in the post blockout were eliminated, and post spacing behind the approach thrie beam was decreased to 2.5 ft. Finally, the last guiderail post at the upper end of the curb ramp was eliminated, because fill conditions at the bridge end would not normally permit it to be installed behind the curb with a blockout. As seen in the previous test, installation on the curb without a blockout presented a potential snag point. Details are shown in Figure 7.

In Test 73, the 4,500-lb Plymouth sedan impacted at 56.5 mph and 29 degrees 3 ft downstream from the tapered section, 9.5 ft from the first bridge post. This time, vehicle redirection was achieved at a 16-degree exit angle after 16 ft of barrier contact and 15-in. dynamic deflection. After exiting, the vehicle turned back toward the rail. Maximum roll was 9 degrees, pitch was 4 degrees, and no yaw was observed. Peak 50-msec average decelerations were 5.2 *g* longitudinal and 8.9 *g* lateral, with corresponding occupant impact velocities of 22.0 and 20.5 ft/sec. The right front corner of the vehicle was extensively damaged, but there was no damage to the passenger compartment. The rail was also extensively damaged, with the posts behind the approach thrie beam pushed back. In addition, the last two guiderail posts twisted 90 degrees, permitting the rail to collapse against the side of the post. Vehicle and barrier damage are shown in Figure 8. Use of heavier bolts to attach the rail to the blockout may have prevented this twisting. In addition, the welds



Note: Spacer used here is similar to spacer detail in Figure 7 of NYSDOT Research Report 118 *(10)*, except 6-in. notch is omitted.

FIGURE 7 Details of final transition design evaluated in Test 73.

FIGURE 8 Vehicle and barrier after impact on guiderail-bridge-rail transition, Test 73.

attaching the first bridge rail to the anchor plate sheared off, permitting that post to deflect back about 1 ft. The welds at the second post cracked but did not separate. There was some concern that this failure at the first post may have helped to reduce the pocketing experienced in the previous test. However, it appears that pocketing would have simply occurred at the second bridge post if deflection of the approach rail had been excessive. It thus appears that the backup rail section and closer post spacing increased transition stiffness enough to prevent pocketing. Performance of the entire bridge-approach rail was now considered satisfactory with both small and large cars.

Tests Without Curb

In Tests 64 and 65, it appeared that part of the impact was absorbed by the 6-in. curb. Eliminating the curb while maintaining rail height at 33 in. thus may result in increased impact forces on the rail. In addition, the 13-in. gap between pavement and rail might permit post snagging, especially by small vehicles with 13-in. wheels. Existing structures where this upgrading system would be used sometimes have no curbs. In addition, it was believed that this rail system might offer good performance on new curbless bridges. Both large- and small-car tests thus were planned to evaluate this design. Other than removing the curb and increasing post length to maintain rail height, the barrier design was the same as that in Tests 65 and 66.

In Test 74, the 1,900-lb Subaru sedan impacted at 58.5 mph and 18 degrees 5.4 ft past the first bridge post. After 11.1 ft of contact, the vehicle exited at 6 degrees with maximum roll of 12 degrees and 3-degree pitch. No measurable vehicle yaw was observed, and no dynamic deflection of the bridge rail. After exiting, the vehicle turned away from the barrier and then continued along essentially a straight line away from the rail. Peak 50-msec average decelerations during impact were 3.0 *g* longitudinal and 8.9 *g* lateral. The lateral occupant impact velocity was 18.7 ft/sec, but the 2-ft longitudinal impact distance was not reached. Damage to the barrier was limited to minor scrapes, and the car sustained only light sheet-metal damage.

In Test 75, the final test in this series, the 4,500-lb Buick sedan impacted at 59.3 mph and 29 degrees at the second bridge post. After 24.7 ft of contact and 21-in. dynamic deflection, the vehicle exited at 14 degrees with a maximum roll of -36 degrees (away from the barrier) and -8-degree pitch, but no measurable yaw. Peak 50-msec average decelerations were 6.1 *g* longitudinal and 7.8 *g* lateral, with corresponding occupant impact velocities of 22.5 and 18.0 ft/sec. Although the vehicle was redirected, it is apparent that this test, which somewhat exceeded the standard 25-degree impact angle, was at the upper limit of performance for this barrier. Post 3 (the first post past impact) was bent back at the base plate, with a permanent deflection of 20 in. at the top of the post. The square plate washers prevented the rail attachment bolts from pulling through, and the rail also bent back and formed a partial ramp. The vehicle was thus pitched up on redirection, with all four wheels in the air as it left the rail. Two rail sections and two posts were damaged, and extensive damage was sustained by the right front corner of the vehicle (Figure 9).

DISCUSSION AND FINDINGS

On the basis of these tests, it appears that the proposed bridge rails essentially meet the recom-

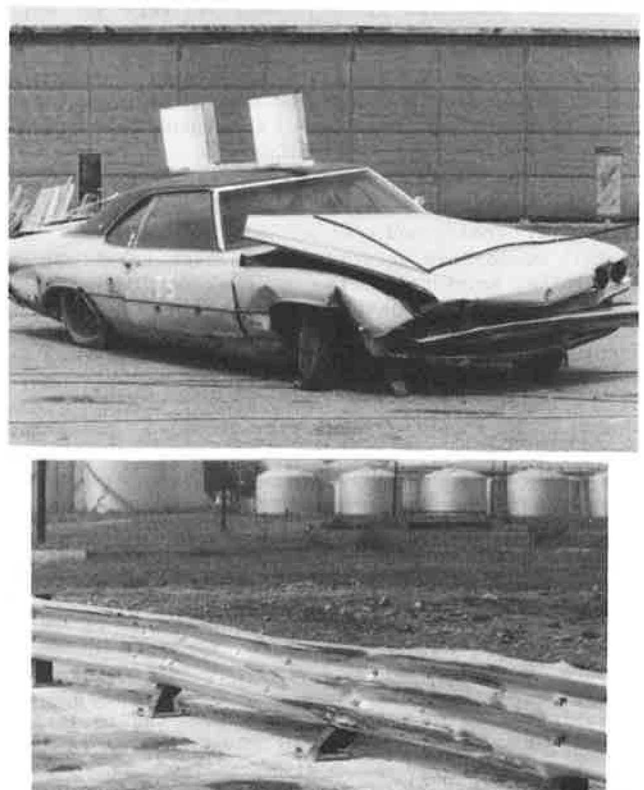


FIGURE 9 Vehicle and barrier after impact on bridge rail, Test 75.

mended evaluation criteria of NCHRP Report 230, both with and without a 6-in. curb. Table 3 of that report recommends tests with 4,500-lb sedans and either a 2,250- or 1,800-lb sedan. For transitions, only a single 4,500-lb test is recommended, but this transition was evaluated at two points with a 4,500-lb sedan and at one with an 1,800-lb sedan.

Test 64 indicated compliance with NCHRP Report 230, but that design was stronger than necessary. Four other tests resulted in clearly unsatisfactory results. The seven remaining tests indicated that the final railing and transition designs were generally in compliance with NCHRP Report 230. All seven tests met Criterion A, which requires smooth redirection. Vehicle trajectory was somewhat marginal in Test 75--the final test of the curbless rail--because of moderate vehicle vaulting. However, considering that the impact angle was 29 degrees rather than the 25 degrees specified, these results appear acceptable. Criteria D and E were easily met in all seven tests.

Criterion F provides suggested values for occupant impact velocities and ridedown accelerations and applies only to the 1,800-lb vehicle. Results of the four successful tests of the 4,500-lb sedan were close to meeting the suggested values, even though impact angles were much more severe. No problem was encountered with the 1,800-lb tests in meeting the suggested longitudinal impact velocity of 30 ft/sec. In fact, in two of three tests, the 2-ft flail space was not reached. Although Tests 71 and 74 were comfortably below the recommended lateral value of 20 ft/sec, it was exceeded slightly in Test 66. However, the 1-ft flail space appears unrealistically large for small sedans, and use of a more realistic number would have reduced this value. Ridedown deceleration values for the three 1,800-lb vehicles were all well below the recommended values. Thus, with two minor exceptions--slight vehicle vaulting in Test 75 and lateral occupant impact velocity slightly exceeding the desired value in Test 66--the bridge-rail and transition designs meet the recommended structural adequacy and occupant risk criteria.

The vehicle trajectory criteria (H and I) are the most difficult to meet. In every test, the vehicle eventually redirected far enough from the barrier that it would have entered the adjacent travel lane, especially considering the narrow shoulders typically found on bridges. However, as pointed out in NCHRP Report 230, this performance factor is difficult to assess. For example, even if redirected at a flat angle such as 7.5 degrees, the vehicle would be 13 ft away from the barrier only 100 ft downstream if no steering input were provided. Thus, the suggested values in Criterion I (exit speed and angle) probably provide a more realistic assessment of performance. The tests generally met the recommended values of no more than 15-mph speed change and exit angle less than 60 percent of impact angle. Two tests were marginal in terms of exit angle (Tests 66 and 69) with Test 66 exceeding the desired value by 0.5 degree and Test 69 by 1.5 degrees. In terms of exit speed, accelerometer data for Test 73 indicated a speed loss of 21.6 mph, but film data, considered more reliable, indicated 11.2 mph, an acceptable value. In Test 71, speed loss was 16.2 mph, slightly exceeding the desired 15-mph value. In Test 69, speed loss was 21 mph, exceeding the desired value by several miles per hour. However, substitution of 14-in. blockouts for the 6-in. blockouts in subsequent tests would help to reduce post contact, and it is expected that a retest at this point on the final design would have resulted in a lesser speed loss.

The four unsuccessful tests--67, 68, 70, and 72--also contributed valuable insight into the performance of guiderail-to-bridge-rail transitions. Tests 67 and 68 dramatically pointed out the snagging potential created by terminating the lower thrie-beam corrugation at the W-beam transition. A symmetrical transition carrying through the lower transition was needed to eliminate this snag. These tests further demonstrated the need for deep blockouts to prevent wheel snag during the transition from light-post to heavy-post systems. Even the 20-in.-deep thrie-beam section was unable to prevent snagging without the 14-in. blockout. Finally, the need to increase lateral stiffness gradually to a level close to that of the bridge rail was evident. Even when all the snag points were eliminated, pocketing occurred at the first bridge post in Test 72. Stiffening the approach section by adding a rail backup section eliminated the pocketing problem in the subsequent test.

The bridge railings and transitions developed in the project appear to perform adequately in full-scale tests and with minor exceptions meet or exceed the recommended performance standards in NCHRP Report 230. The railing system can be used either with a 6-in. curb or on curbless decks, and can be attached on existing decks without contact with existing railing or structural members. The transition developed makes it possible to match the railing to light-post W-beam guiderail on the bridge approach, thus providing a complete barrier system. This system simplifies maintenance inventory problems by using components common to other systems to the greatest extent possible. The 10-gauge thrie beam is used on other NYSDOT railings. By avoiding the use of tubular thrie beam, the splice is simplified and inventory requirements are reduced. With the exception of the bridge posts, 14-in. blockouts, and tapered transition piece, the remaining hardware is common to current guiderail and bridge-rail systems.

Based on the 12 tests performed in this project, the following findings can be stated:

1. Bridge rail consisting of 10-gauge thrie-beam rail mounted on W6x9 steel posts spaced at 8 ft 4 in. generally met NCHRP Report 230 recommended evaluation criteria with or without a 6-in. curb.
2. A W-beam-to-thrie-beam guiderail transition on the bridge approach, including a symmetrical tapered transition piece and 14-in.-deep blockouts, performed satisfactorily.
3. W-beam-to-thrie-beam transitions in which the lower thrie-beam corrugation was dropped resulted in severe snagging.
4. A blockout depth of 14 in. was required in the W-beam-to-thrie-beam transitions and throughout the bridge approach to prevent snagging on the W6x9 posts.
5. Notching the lower front corner of the 14-in. blockout web appeared to reduce performance in the 4,500-lb vehicle test by permitting the lower thrie-beam corrugation to collapse toward the posts. This contributed to the vehicle's snagging on an unblocked post in Test 72.
6. A double layer of 10-gauge thrie beam was required in the bridge approach to provide adequate lateral stiffness at the first bridge post.

For a full explanation of testing procedures, data analysis, and test results, the reader is referred to NYSDOT Research Report 118 (10).

ACKNOWLEDGMENTS

Data recording and analysis were performed by Jan S. Fortuniewicz. Bureau technicians who worked in full-scale testing and data analysis include James W. Reilly, Wayne R. Shrome, Alan W. Rowley, and Robert P. Murray. David R. Kinerson and Wilfred J. Deschamps of the Special Projects Section performed the electronics work for this project. The authors also wish to thank maintenance personnel of the Department's Region 1 and the New York State Thruway Authority for their assistance in site preparation and barrier erection on several occasions. The technical contributions of Larry N. Johanson, Daniel E. Feeser, and Frank Naret II of the Structures Design and Construction Division and of William E. Hopkins of the Facilities Design Division are also gratefully acknowledged. Research reported in this paper was conducted in cooperation with FHWA, U.S. Department of Transportation.

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Bridge Rail to Contain and Redirect 80,000-lb Tank Trucks

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ABSTRACT

A standard Texas Type T5 traffic rail was modified to increase its height and strength to contain and redirect an 80,000-lb (36 297-kg) tank-type tractor-trailer at 50-mph (80.5-km/hr), 15-degree impacts. The height of the concrete parapet was increased to 48 in. (122 cm), and a concrete beam was mounted on concrete posts on the top of the parapet to achieve a total rail height of 90 in. (229 cm). One crash test was conducted on the bridge rail. The truck was contained and smoothly redirected. This test has shown that a bridge rail can redirect heavy tank-type trucks at speeds up to 50 mph and 15-degree impacts. The cost of this rail is estimated at about $125 per foot. Typical passenger car bridge rails in Texas now cost about $35 per foot.

Current bridge rails are designed to restrain and redirect passenger cars only. Collisions of large trucks with these bridge rails have in the past led to catastrophic accidents. Concern for the reduction of the severity of these accidents has led highway designers to devote more attention to the containment and redirection of large trucks at selected locations.

The factors involved in the design of bridge rails to contain and redirect large trucks are not nearly so well understood or researched as those involved in the design of passenger car rails.