Development of Retrofit Railings for Through Truss Bridges

M.E. BRONSTAD, L.R. CALCOTE, C.E. KIMBALL, JR., AND C.F. McDEVITT

The design and development of bridge railing systems for through truss structures are described in this paper. The unique design of these structures makes rigid railings mandatory to exclude the errant vehicles from the truss members located behind the railing. The two systems were designed to meet different performance conditions. The high-performance system contained and redirected a 20,000-lb (9000-kg) bus impacting at 55 mph (90 km/h) and a 15-degree angle. The low-service-level system contained and redirected a 4,500-lb (2000-kg) car impacting at 60 mph (95 km/h) and a 15-degree angle. In addition, 2,250-lb (1000-kg) and 1,800-lb (800-kg) cars were used to evaluate the systems, including the bridge approach railing, for the high-performance system. The two systems meet the design criteria and are recommended for immediate implementation.

The focus of this paper is on a particular type of bridge that has unique problems. The superstructure of these bridges is mostly above the bridge deck, thus critical structural members are exposed to contact with out-of-control vehicles. Furthermore, because many of the older through truss structures are narrow, the clearances for bridge railing protection of the truss members are restrictive and little space is available for barriers and barrier deflection under impact.

Catastrophic failures of these structures occur periodically, and some gain nationwide attention (see Figure 1). Structurally adequate bridges can collapse because of inadequate protection for bridge railings. Many of the older through truss structures have relatively long spans and would require large expenditures to replace them with more modern structures. For this reason FHWA considers the development of protective bridge railing systems for these unique structures as a cost-effective way to keep these otherwise structurally sound bridges in service and also to minimize the potential for catastrophic events.

OBJECTIVE AND SCOPE

The objectives of the research effort were to identify the important characteristics of through truss structures and to design and develop retrofit designs to protect vital structural members from impact by out-of-control vehicles.

Figure 1. Through truss failure.

This project involved background studies, structural analyses, laboratory experiments, computer simulation, and full-scale crash tests. Vehicles used in the crash tests ranged from 1,800-lb (800-kg) subcompact cars to 20,000-lb (9000-kg) school buses.

Design drawings were prepared for bridge railings according to two levels of service. The higher-level railing was designed to contain and redirect a 20,000-lb (9000-kg) bus impacting at 55 mph (90 km/h) and a 15-degree angle without subsequent damage to a truss member behind the barrier. The lower-level railing was designed to contain and redirect a 4,500-lb (2000-kg) sedan impacting at 60 mph (95 km/h) and a 15-degree impact angle.

DESIGN CRITERIA

Design criteria were formulated for both the high-performance and the lower-service systems.

High-Performance Retrofit

Based on considerations detailed in the project report (1) a high-performance retrofit was to be essentially a rigid railing for a 55-mph (90-km/h), 15-degree angle impact with a 20,000-lb (9000-kg) school bus. In addition, the roll of the vehicle was to be limited to keep the bus out of the truss member zone.

Movies of school bus tests conducted at Texas Transportation Institute were reviewed to evaluate vehicle roll. Sequential test photographs showed the maximum roll of the vehicle during the nominal 60-mph (95-km/h), 15-degree angle tests. The rigid 27-in. (0.7-m) railing produced roll that could not be tolerated in this project (i.e., the truss members would be struck). Even with a flexible collapsing ring bridge rail (2) the maximum roll angle would be sufficient to involve the truss members. Therefore, an upper railing element was thought necessary to prevent such contact.

Low-Service Retrofit

A low-service retrofit is for use on bridges that, by virtue of geometry, vehicle mix, or other considerations, would not require the protection of the high-performance railing system. Selection of the structural adequacy test for this system was based, in part, on a recently completed NCHRP research project at the Southwest Research Institute (3). This project developed a multiple-service-level approach for the placement of bridge railings based on need. The lowest service level from this project has a strength test requirement characterized by a 4,500-lb (2000-kg) car impact at 60 mph (95 km/h) and a 15-degree angle. A summary of the design criteria for the two bridge railing systems is presented in Table 1.

PRELIMINARY DESIGNS AND ANALYSES

Preliminary designs and analyses were conducted that led to prototype barrier crash tests. The results of these preliminary investigations are available in the project report (1).

BARRIER DEVELOPMENT

High-Performance Retrofit

Based on results of preliminary tests TTR-1 and TTR-2, a self-restoring 3-in. (75-mm) stroke was incorporated into the lower beam-mounting detail, as shown in Figure 2. This was done to temper the abrupt redirection of the bus caused by more rigid designs. Installation photographs are shown in Figure 3.

The bus impacted the barrier at 53.9 mph (86.7 km/h) and a 15.3-degree angle. As shown in Figure 4, the bus rolled a maximum of 10.7 degrees toward the barrier as it was redirected. The right front wheel was pushed rearward by the lower rail, which caused suspension failure and forced the entire front axle to rotate. After losing contact with the barrier the vehicle dropped onto the now horizontal front right wheel and slid to a stop essentially parallel to the barrier (see Figure 5). The maximum deflections were such that the 3-in. (75-mm) en-

Table 1. Summary of design criteria.

Item	Low-Service Retrofit	High-Performance Retrofit
Structural adequacy test		
Vehicle weight (lb)	4,500	20,000
Impact speed (mph)	60	55
Impact angle (degree)	15	15
Deflection permitted (in.)[a]	6	
Vehicle roll considerations	NA	-[b]
Impact Severity[c]		
Vehicle weight (lb)	1,800	1,800
Impact speed (mph)	60	60
Impact angle (degree)	15	15

[a] Deflection is measured from behind the bridge post.
[b] Vehicle roll over the barrier should be limited to keeping the vehicle within maximum deflection limit.
[c] The barrier is rigid so the usual acceleration criteria are not applied; however, smooth redirection with no snagging is required.

Figure 2. Modified self-restoring through truss retrofit.

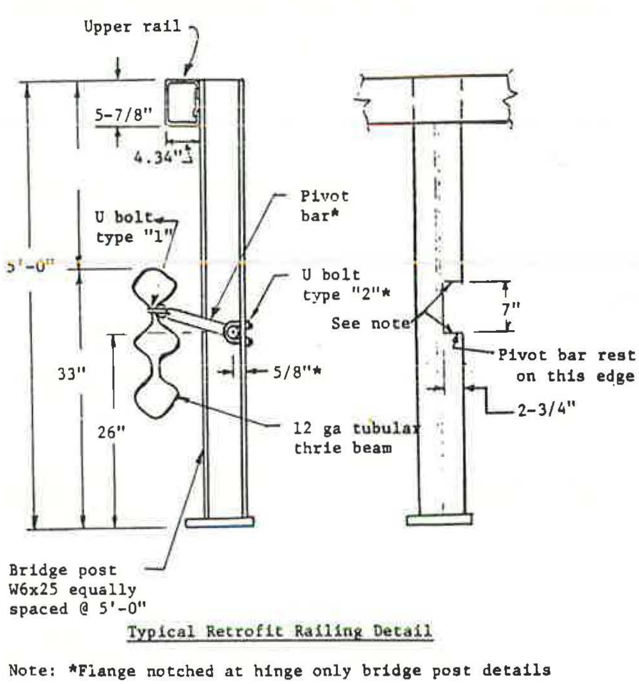


Figure 3. Self-restoring high-performance retrofit photographs.

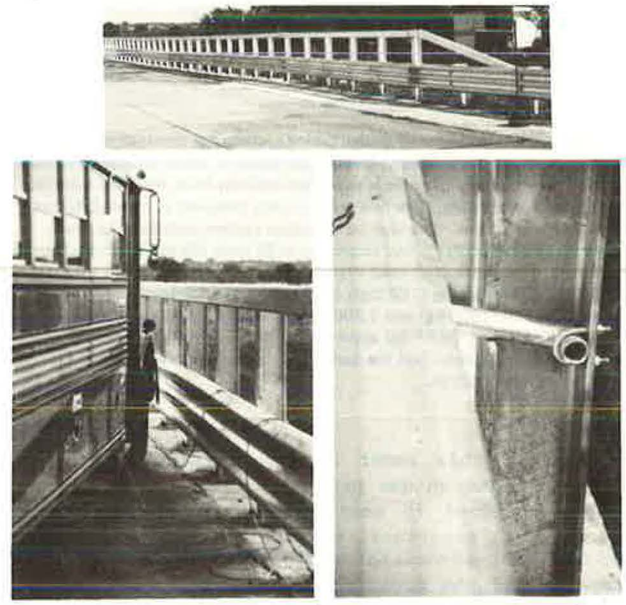
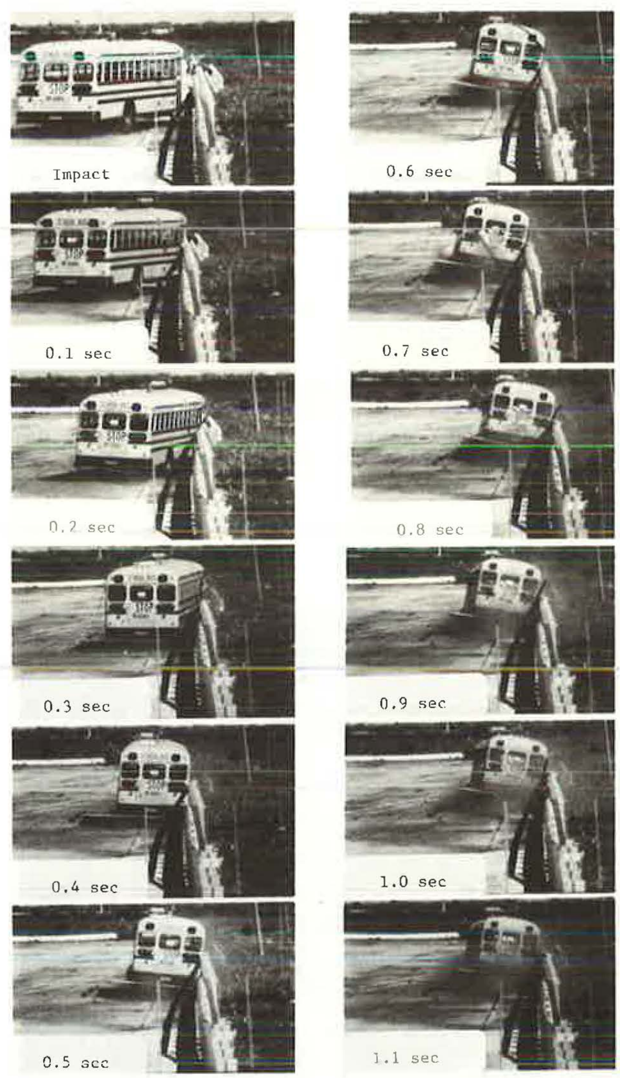


Figure 4. TTR-3 impact sequence.



croachment goal beyond the rear post line was met. The roll of the vehicle and the exit conditions were also considered favorable. Some sheet metal snagged on posts at the opening between upper and lower rails (see Figure 5).

Figure 5. Photographs after test TTR-3.

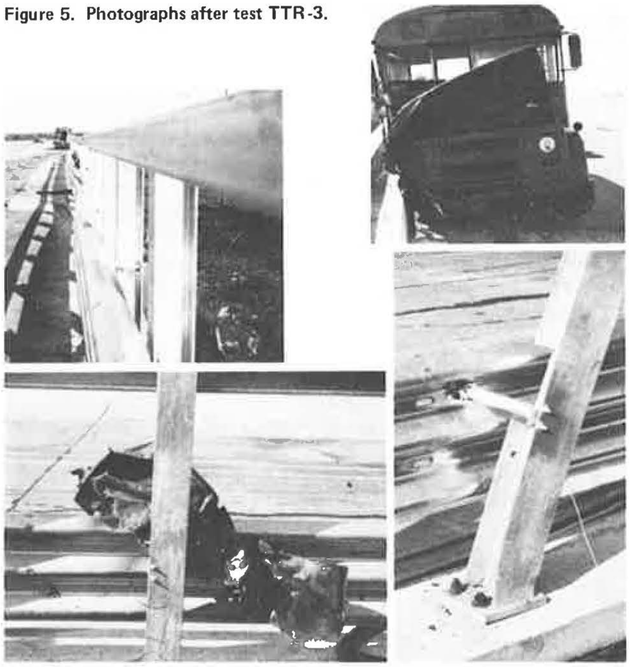
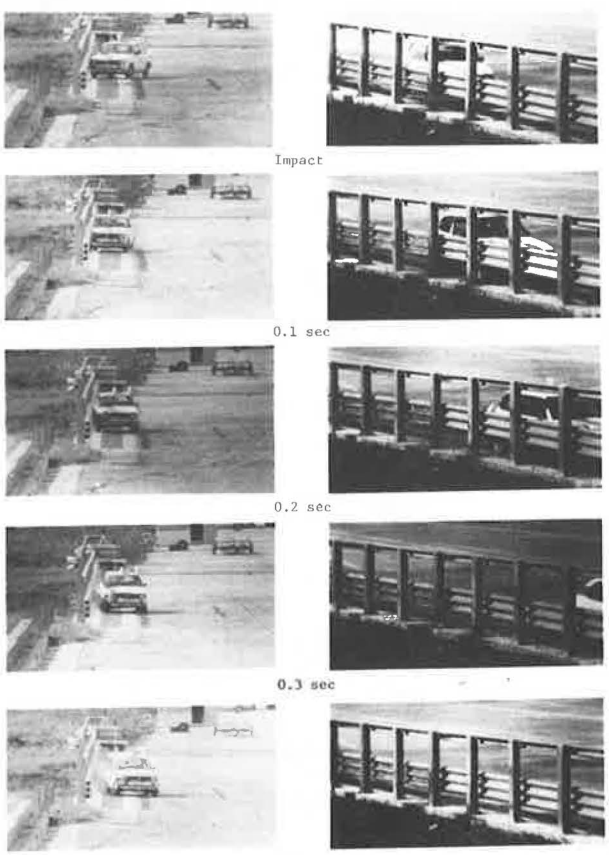


Figure 6. Test TTR-4 impact sequence.



Test TTR-4

In test TTR-4 the 1,840-lb (835-kg) vehicle impacted the barrier at 59.8 mph (96.2 km/h) and a 14.8-degree angle. As shown in Figure 6 the beam displaced up and back during the collision and then returned to the original position. The barrier systems sustained no discernible damage; damage to the vehicle was moderate (see Figure 7).

The basic bridge railing approach and terminal treatment are shown in Figure 8. The upper railing was carried full height beyond the structure for five post spans and tapered down and back behind the lower railing as shown. The self-restoring hinges were installed on intermittent W6 x 15.5 posts.

Test TTR-5

In test TTR-5 the 20,000-lb (9070-kg) bus impacted the transition 15 ft (4.6 m) upstream of the bridge end at 59.6 mph (95.9 km/h) and a 15.9-degree angle. As shown in Figure 9, the bus pitched upward as it rolled toward the barrier (maximum roll angle was 15 degrees) while being redirected, and then returned to an upright position. The right front wheel was pushed rearward by the lower rail, which caused suspension failure and forced the entire front axle to rotate about a vertical axis. As the bus lost contact with the barrier, the front dropped down onto the right front wheel similar to test TTR-3 and slid 90 ft (27 m) past the end of the installation. A secondary collision with another barrier downstream caused additional front-end damage.

Figure 7. Photographs after test TTR-4.

Figure 8. High-performance retrofit approach guardrail.

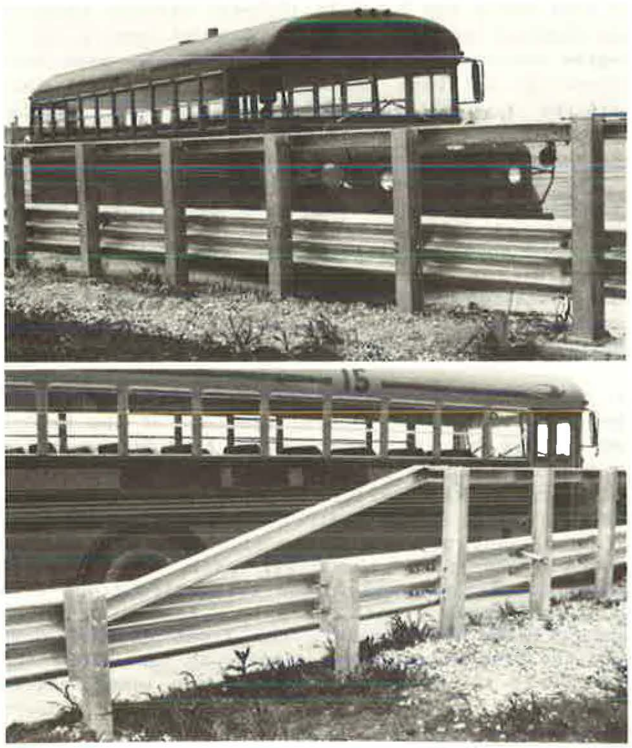
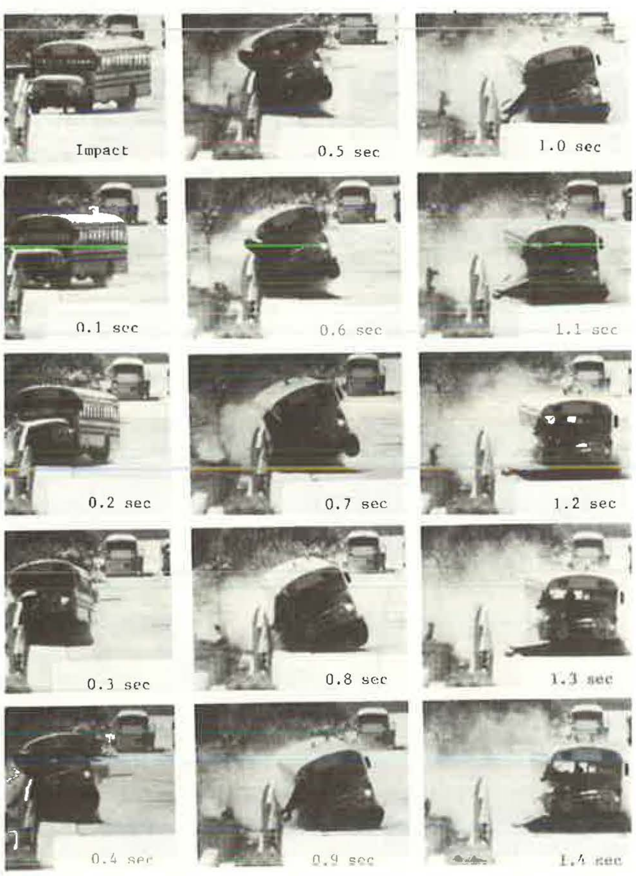


Figure 9. Test TTR-5 impact sequence.



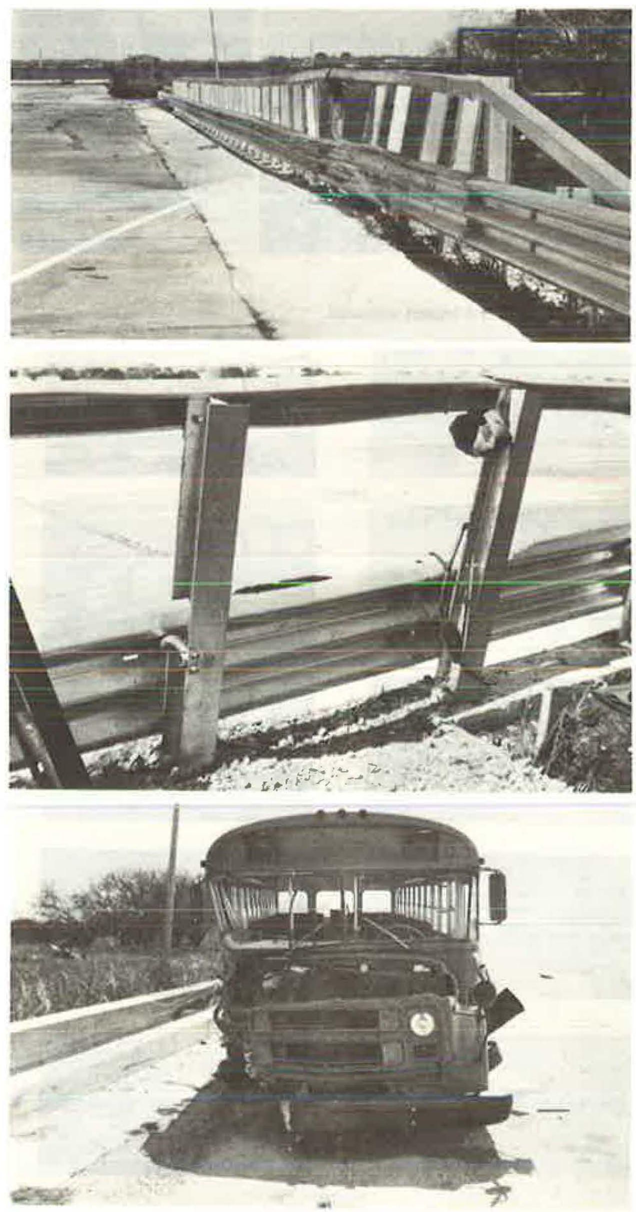
Damage to the barrier consisted of two upper and lower beam sections and two bridge posts. Some concrete fracturing occurred at the two bridge posts. The soil-mounted posts were displaced in the soil but were essentially undamaged. The bus sustained front suspension and steering linkage damage sufficient to dislodge the front axle from is mounting. The barrier deflection was significant, but in an acceptable range regarding intrusion into a leading truss member location. Photographs after the test are shown in Figure 10.

Test TTR-6

Test TTR-6 was performed to evaluate typical bridge rail performance with a 2,250-lb (1020-kg) compact at 60 mph (95 km/h) and 15 degrees, which is the standard impact severity test according to TRB Circular 191 (4).

The 2,250-lb (1020-kg) vehicle impacted the barrier at 58.8 mph (94.7 km/h) and an angle of 15.4

Figure 10. Photographs after test TTR-5.



degrees. As shown in Figure 11, the vehicle was redirected smoothly. Damage to the barrier was negligible, and the vehicle sustained only moderate damage (see Figure 12).

Test TTR-7

Test TTR-7 was performed to evaluate the self-restoring retrofit for the structural adequacy test criteria of TRB Circular 191 (4). The 4,441-lb (2014-kg) vehicle impacted the barrier at 58.3 mph (93.9 km/h) and a 27.1-degree angle. The vehicle was redirected smoothly until the undeformed hood slid over the top of the lower beam and snagged on a post. A portion of the hood penetrated through the windshield before the hood was severed from the hinges.

Except that the hood snagged, the barrier performed in an acceptable manner. The maximum barrier deflection was not sufficient to encroach into the truss member zone.

Test TTR-8

Test TTR-8 was performed to evaluate the bridge approach for the 4,500-lb (2040-kg) car structural adequacy test. The more flexible characteristics of the approach barrier decreased the likelihood that the hood snagging problem would recur. However, as shown in Figure 13, the hood snagging occurred again as the vehicle was redirected after a 57.8-mph (93.1-km/h), 29.6-degree angle impact.

Test TTR-9

As a result of the hood snagging noted previously, 6-in. (0.2-m) spacers were installed between the posts and beams to minimize the likelihood of its occurrence (see Figure 14). A 25-degree angle impact is more likely to occur in a wider approach section than on a narrow bridge; therefore, the spacers were installed in the approach railing segment for this test.

The structural adequacy test of the approach railing system was repeated with this test. The 4,500-lb (2040-kg) vehicle impacted the barrier 26.6 ft (8.1 m) upstream of the bridge at 60.2 mph (96.9 km/h) at an angle of 25.9 degrees. As shown in Figure 15, the vehicle was redirected smoothly and no hood snagging was evident. The same vehicle, a 1978 Ford LTD, was used in tests TTR-7, TTR-8, and TTR-9 to ensure valid comparisons.

Test TTR-10

Test TTR-10 was performed to evaluate the bridge approach design with an 1,800-lb (800-kg) subcompact car at 60 mph (95 km/h) and 15 degrees. The 1,658-lb (752-kg) vehicle was redirected smoothly after striking the barrier at 61.3 mph (98.6 km/h) and a

Figure 11. Test TTR-6 sequential photographs.

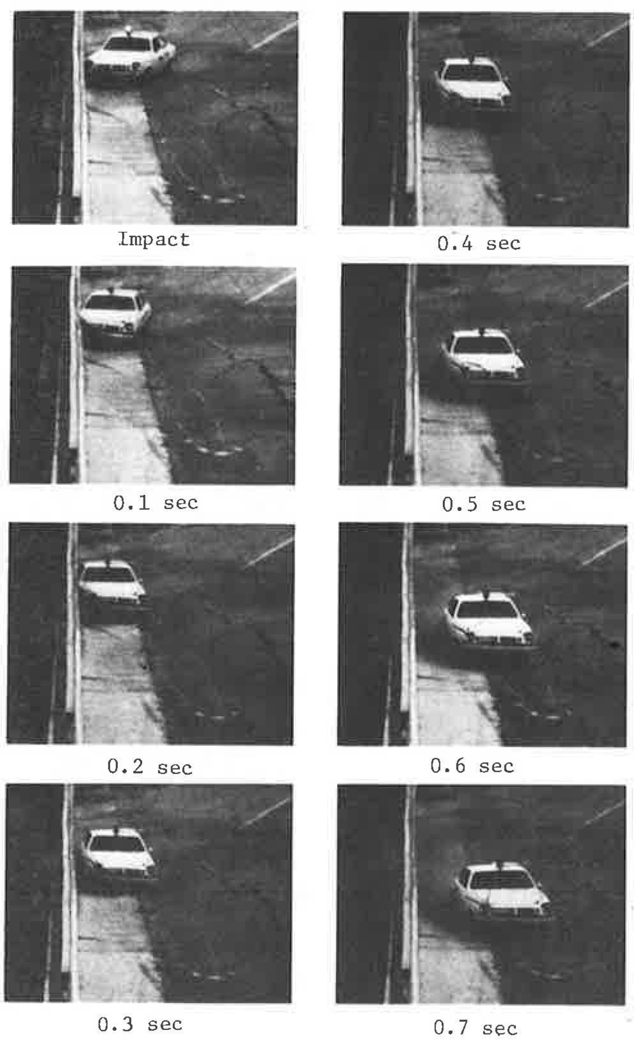


Figure 12. Photographs after test TTR-6.

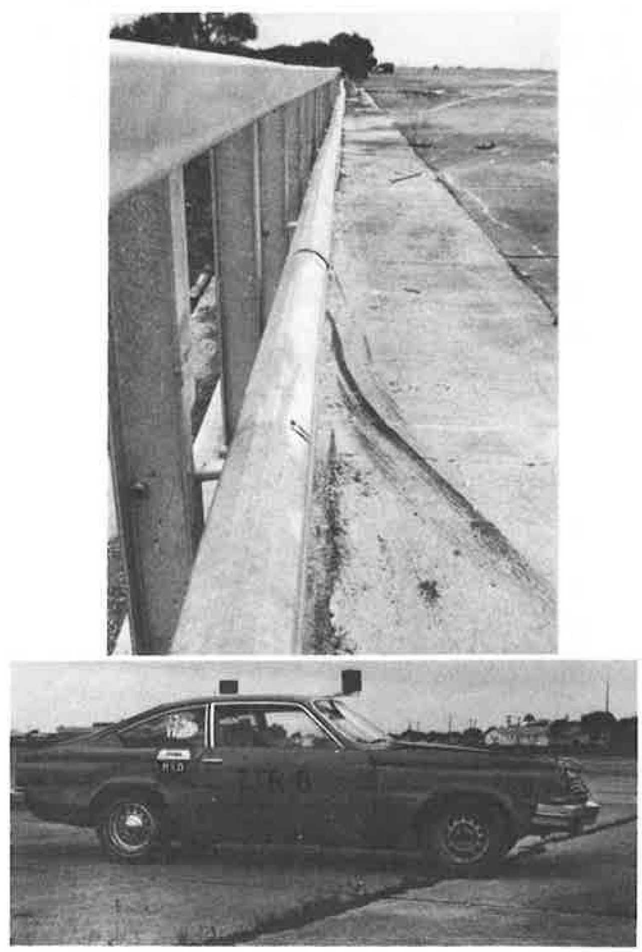


Figure 13. Test TTR-8 sequential photographs.

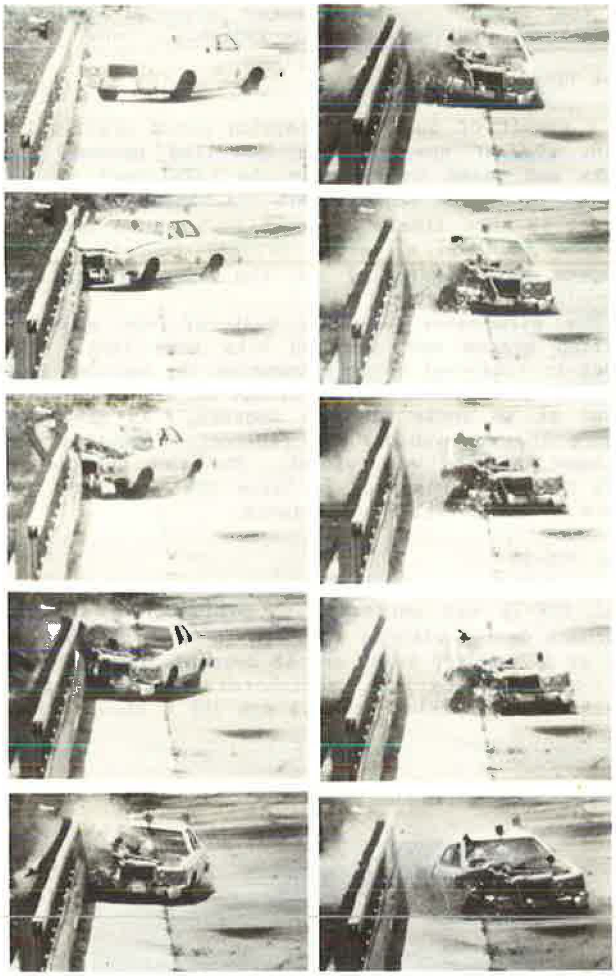


Figure 14. Modified approach guardrail test installation photographs.

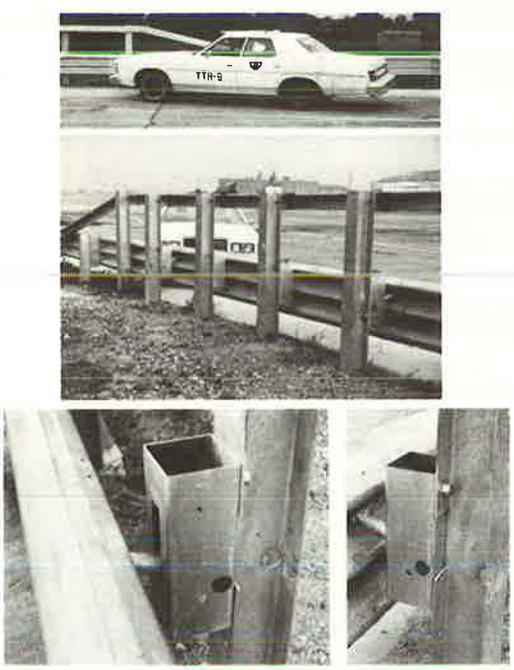


Figure 15. Test TTR-9 impact sequence.

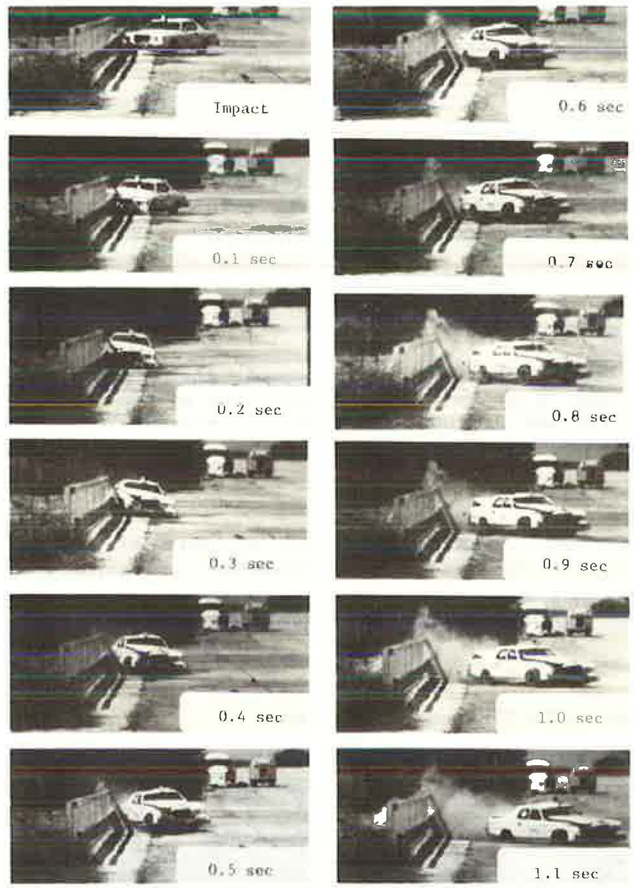
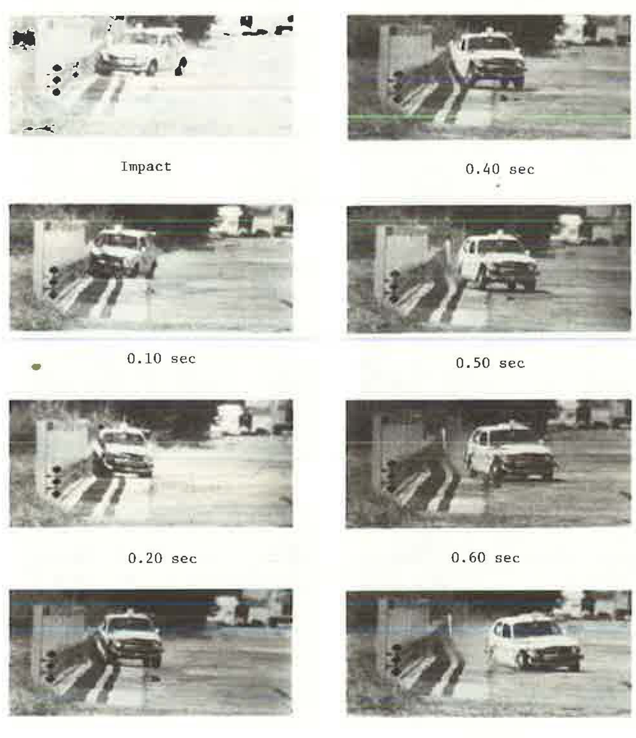


Figure 16. Test TTR-10 impact sequence.



20.9-degree angle (see Figure 16). The self-restoring stage deflected a maximum of 3.5 in. (89 mm) before returning, undamaged, to the original position after the vehicle was redirected.

Low-Service Retrofit

Based on computer simulations, a design described in Figure 17 was selected for crash-test evaluation. As part of the installation a readily installed anchor bolt detail was employed. This consisted of drilling into the bridge deck and driving commercially available anchor studs into the holes.

Test TTR-13

The 4,466-lb (2026-kg) vehicle impacted the barrier at 59.3 mph (95.4 km/h) and a 19.1-degree angle. The vehicle was redirected smoothly and continued until contacting another barrier installation inline with the test installation 150 ft (45 m) downstream of the impact (see Figure 18). The design goals of the barrier were met; that is, the maximum deflection beyond the rear post line was 3 in. (75 mm). This maximum deflection at one post was attributed to local buckling due to impact and the pulling of the anchor bolts from the slab for a distance of 0.5 in. (13 mm). A more substantial anchorage (e.g., bolts through the slab) would have prevented much of this deformation.

Two rail sections and three posts of the barrier were damaged. Vehicle and barrier damage are shown in Figure 19. The lower right-hand photograph shows partly pulled anchor studs of post 7.

Figure 17. Low-service retrofit.

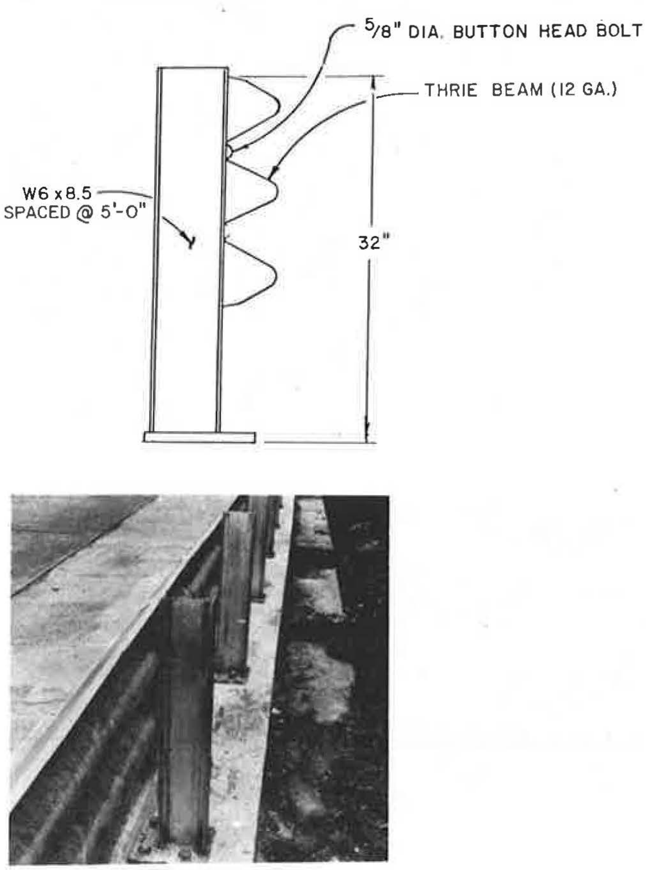


Figure 18. Test TTR-13 impact sequence.

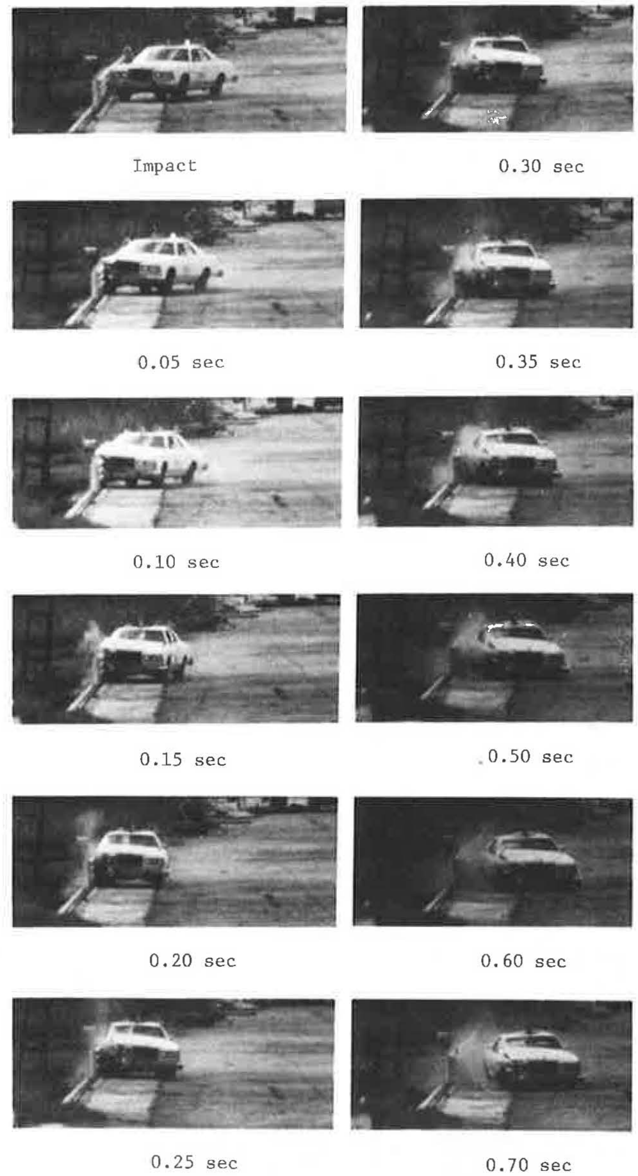
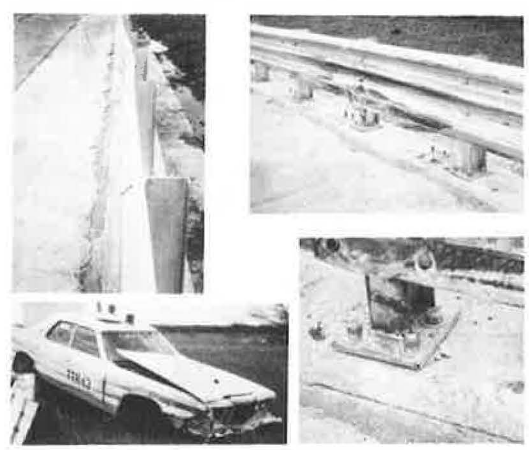


Figure 19. Photographs after test TTR-13.



Test TTR-15

Test TTR-15 was conducted to evaluate the low-service retrofit for the occupant-risk impact conditions of NCHRP Report 230 (5). The 1,750-lb (794-kg) test vehicle impacted the installation at 57.9 mph (93.2 km/h) and an angle of 16.9 degrees (see Figure 20). Redirection of the vehicle was smooth and dynamic deflection was less than 1 in. (25 mm). No repairable damage was sustained by the system. Vehicle damage was moderate (see Figure 21).

DISCUSSION AND APPLICATION OF FINDINGS

A summary of all the tests conducted in the project is given in Table 2. The findings included the systematic design and development of two unique bridge rail retrofit systems for narrow through truss application.

Vehicle Factors

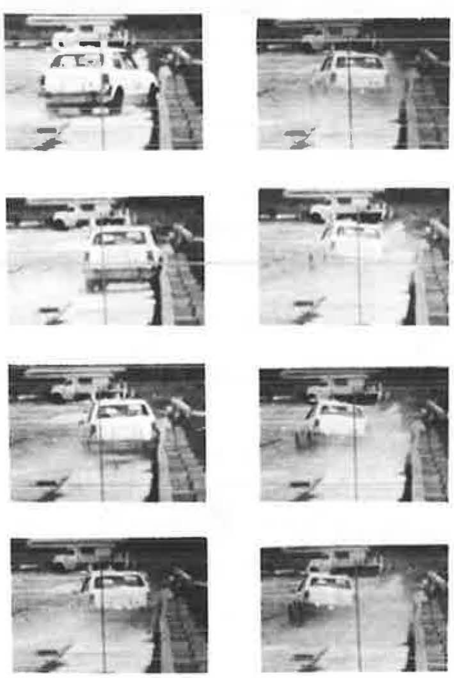
Crashworthiness of school bus suspension and steering assemblies is considered deficient for the severity of impacts in this project. The rigid railing criteria made the destruction of these assemblies during the 55 mph (90 km/h), 15-degree angle impacts unavoidable.

The particular 4,500-lb (2000-kg) sedan selected for crash test in this project had a unique hood design that made snagging of posts more probable than if another design had been used. The problem of hood snagging is discussed in more detail in the final project report (1).

Openings Between Rails

The opening between the upper and lower railings after the lower beam bottoms on the posts is 18-in. (0.5-m) wide. This opening permitted sheet metal portions of the bus and the hood of the 4,500-lb (2000-kg) car to snag on the exposed post flange edges. For wider bridges that will accommodate the 6-in. (150-mm) spacer block, the upper and lower beams should be blocked out accordingly. The higher impact-angle probabilities associated with the snagging problem increase with the width of the bridge; thus, narrower bridges that cannot accommodate the spacer do not have the need of the wider ones that can tolerate the additional 6-in. (150-mm) per side encroachment.

Figure 20. Test TTR-15 sequential photographs.



Application of Findings

Based on the findings of this project, both the high-performance retrofit and the lower-service system are recommended for immediate implementation. Estimated costs for the two systems are shown in Figure 22.

High-Performance Retrofit

The high-performance retrofit system is recommended for use where significant heavy vehicle traffic is present and at sites where impacts with heavy vehicles may occur. For bridges with accommodating width the installation of the blockout spacers between the railings and posts is recommended for reducing the potential for vehicle snagging. Design details for adapting example structures in developing the required post strength are given in the project final report (1).

Low-Service Retrofit

The low-service retrofit system is recommended for use on the following bridges:

Figure 21. Photographs after test TTR-15.

Table 2. Summary of vehicle crash tests.

Test No.	Barrier Description[a]	Vehicle	Vehicle Weight Including Ballast (lb)	Ballast Added (lb)	Impact Speed (mph)	Impact Angle (degree)	Vehicle Accelerations, 50-msec avg (g): Film Latitude	Film Longitude	Electronic Latitude	Electronic Longitude	Maximum Roll Angle (degree): While in Rail Contact	Overall	Maximum Dynamic Deflection (in.)	Maximum Encroachment[b] (in.)	Remarks
TTR-1	HP 1	1966 IH/Wayne, 72-passenger	20,000	6,200	55.2	13.7	3.0	-1.3	NM	NM	20.0	90.0	24.7	20.0	Extensive damage to vehicle front end - vehicle rolled on side after losing rail contact; concrete deck failure contributed to deflection
TTR-2	HP 2	1966 IH/Superior, 72-passenger	20,000	6,600	56.1	17.8	3.3	-3.0	4.0	-1.5	12.5	90.0	8.6	6.2	Extensive damage to front end—vehicle rolled on side after losing barrier contract
TTR-3	HP 3	1969 Chevy/Bluebird, 66-passenger	20,000	6,000	53.9	15.3	2.3	-1.9	3.5	1.3	10.7	10.7	7.8	6.0	Extensive vehicle damage, but design goals met with smooth redirection at shallow exit angle
TTR-4	HP 3	1976 Honda Civic	1,840	–[c]	59.8	14.8	7.8	-3.0	8.1	-2.1	NM	NM	3.0	0	Smooth redirection
TTR-5	HPAR	1969 Chevy/Bluebird, 66-passenger	20,000	6,000	59.6	15.9	1.7	-2.5	5.6	-3.8	15.0	15.0	27.8	5.0	Vehicle redirected with some sheet metal snagging at opening between rails
TTR-6	HP 3	1974 Chevy Vega	2,250	–[c]	58.8	15.4	6.1	-2.5	4.2	-4.1	NM	NM	5.1	0	Vehicle smoothly redirected
TTR-7	HP 3	1978 Ford LTD	4,441	–[c]	58.3	27.1	8.1	-5.1	10.4	-9.5	NM	NM	6.0	0	Vehicle redirected, but hood snagging on post between rail opening caused windshield penetration
TTR-8	HPAR	1978 Ford LTD	4,500	–[c]	57.8	29.6	6.2	-9.3	NM	NM	NM	NM	10.4	10.0	Vehicle hood snagged as in Test TTR-7
TTR-9	HPAR(B.O.)	1978 Ford LTD	4,500	–[c]	60.2	25.9	7.8	-4.8	9.0	-4.2	NM	NM	6.0	2.0	Blocked out rail effective in preventing hood snagging
TTR-10	HPAR(B.O.)	1975 Honda Civic	1,658	–[c]	61.3	20.9	9.4	-4.0	9.5	-3.4	NM	NM	3.5	0	Smooth redirection
TTR-11	LS 1	1975 Ford LTD	4,588	–[c]	61.7	18.4	6.0	-3.5	11.0	-3.5	NM	NM	9.0	5.5	Excessive deformation between posts and at one post
TTR-12	LS2	1978 Ford LTD	4,466	–[c]	49.0	15.0	NM	NM	NM	NM	NM	NM	NM	NM	Inadequate test speed
TTR-13	LS 2	1978 Ford LTD	4,466	–[c]	59.3	19.1	7.2	-4.1	6.6	4.1	NM	NM	3.6	3.0	Vehicle smoothly redirected; design goals met
TTR-14	LS 2	1979 Honda Civic	1,751	–[c]	60.9	19.9	8.7	-6.5	10.9	-5.6	NM	NM	1.0	0.5	Front wheel snagged on posts; otherwise redirected
TTR-15	LS 2	1976 Honda Civic	1,750	–[c]	57.9	16.9	8.3	-2.9	16.7	-2.7	NM	NM	1.0	0.5	Smooth redirection with no wheel snagging

Note: NM = not measured.

[a]Barrier code: HP 1 = high-performance retrofit prototype no. 1, HP 2 = high-performance retrofit prototype no. 1, HP 3 = self-restoring high-performance retrofit, HPAR = bridge approach rail, HPAR(B.O.) = approach rail-blocked out rails, LS 1 = low-service retrofit bridge railing, LS 2 = low-service retrofit bridge railing.

[b]Distance measured behind original bridge post line (rear flange).

[c]Test instrumentation only, some original equipment removed from vehicle.

Figure 22. Estimated costs for through truss retrofit railing.

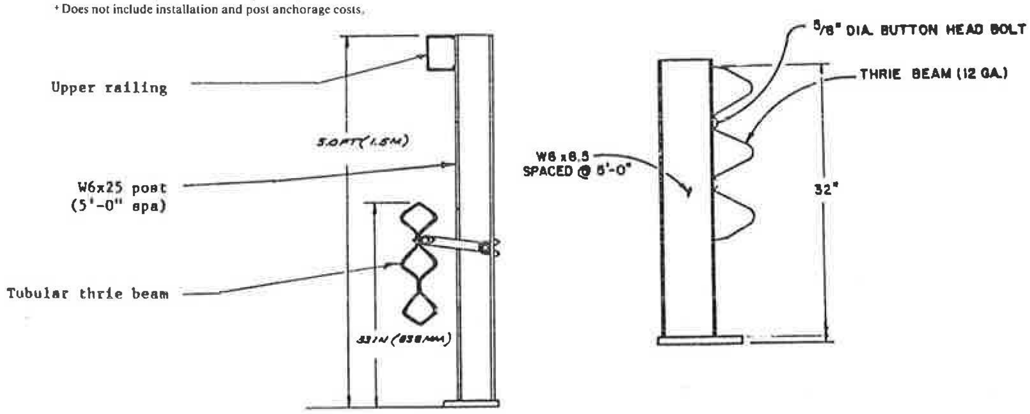
High Performance Retrofit

Item	Est. Cost* ($/lin. ft.)
1. Post — $100 ea.	20.70
2. Upper railing and hardware	4.00
3. Tubular thrie beam and hardware	19.00
4. 'Miscellaneous hardware	1.00
Total estimated cost	$44.70+

Low Service Retrofit

Item	Est. Cost* ($/lin. ft.)
1. Post — $25 ea.	5.00
2. Beam — 12 ga thrie & hardware	5.00
Total estimated cost	$10.00+

*Anderson Safeway Guard Rail Corp., Flint, MI
+Does not include installation and post anchorage costs.



1. One-lane structures,
2. Narrow 20-ft (6-m) wide 2-lane structures,
3. Bridges that have automobile traffic only, and
4. Bridges that have posted speed limits of 35 mph (55 km/h) or less that carry truck and bus traffic.

REFERENCES

1. M.E. Bronstad, L.R. Calcote, and C.E. Kimball, Jr. Retrofit Railings for Narrow Through Truss and Other Obsolete Structures. Final Rpt., FHWA, March 1982.
2. C.E. Kimball et al. Development of a Collapsing Ring Bridge Railing System. FHWA, Rept. FHWA-RD-76-39, 1976.
3. M.E. Bronstad and J.D. Michie. Multiple-Service-Level Highway Bridge Railing Selection Procedures. NCHRP, Rept. 239, Nov. 1981, 155 pp.
4. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. TRB, Transportation Research Circular 191, Feb. 1978.
5. J.D. Michie. Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances. NCHRP, Rept. 230, March 1981, 42 pp.

Publication of this paper sponsored by Committee on Safety Appurtenances.

Bridge Rail to Restrain and Redirect 80,000-lb Trucks

T.J. HIRSCH AND ALTHEA ARNOLD

A standard Texas traffic rail type C202 was modified to increase its height and strength to restrain and redirect an 80,000-lb (36,300-kg) van-type tractor-trailer under 50 mph (80.5 km/h), 15-degree angle impacts. The concrete parapet was increased to 36-in. (91-cm) high, and an elliptical steel rail was mounted on steel posts to increase the rail height to 54 in. (137 cm). One crash test was conducted on the bridge rail. The truck was restrained and redirected smoothly. This test has shown that a simple and economical rail can redirect heavy van-type trucks at speeds up to 50 mph (80.5 km/h) and 15-degree angle impacts. The cost of this rail is estimated at about $80 to $90/ft. Typical passenger car bridge rails in Texas now cost about $25 to $35/ft.

Current bridge rails are designed to restrain and redirect passenger cars. Hirsch (1) presented an analytical evaluation of Texas bridge rails to contain buses and trucks. In another report Hirsch (2) presented the results of crash tests on a modified Texas traffic rail type T202 that successfully redirected a 20,000-lb (9000-kg) school bus and a 32,000-lb (17 400-kg) intercity bus, both at nominally 60 mph (96 km/h) and 15-degree angles. With the increase in the number and size of large trucks the problem of truck-bridge rail collision is becoming more evident. The bridge rail tested here was selected and designed to restrain and redirect an 80,000-lb (36 287-kg) van-type tractor-trailer (3). The design was based on procedures and test data presented by Hirsch (1) and Buth (4).

The basic rail selected was a modification of the concrete parapet, Texas traffic rail type C202. The modified C202 rail consists of a concrete beam ele-