# Upgrading Safety Performance by Retrofitting Bridge-Railing Systems

E. O. Wiles, C. E. Kimball, and J. D. Michie, Southwest Research Institute, San Antonio

The inadequate performance of many current bridge-railing systems in vehicle collisions has resulted in a large number of injuries and fatal accidents. An analysis of representative bridge-railing designs submitted by 44 highway agencies in 1974 showed that most did not fully conform to the 1973 American Association of State Highway Officials specifications. Most of these bridge-railing installations have been in service for more than 10 years and were designed to less restrictive requirements. An alternative to replacing inadequate installations with conforming systems is to upgrade the existing installation with a modification or retrofit design. To reduce the number of potential retrofit designs, existing bridge-railing systems can be grouped in four categories according to their profile geometries and features. Each category has its own constraints for retrofit modification (i.e., curbs, parapets, and such), but a properly conceived retrofit design for a category can be adapted to any bridge-railing system in that category. About 82 percent of the existing systems reported in the survey can be placed in Southwest Research Institute categories II and III. Five retrofit designs for these categories were developed and evaluated by a 22-vehicle crash-test program. These five designs are judged suitable for carefully monitored in-service use to upgrade the safety performance of substandard systems.

Olson (1) has shown that about one-third of all fatal accidents on freeways during the period of 1965 to 1967 involved a vehicle that ran off the road and hit a fixed object and that about 22 percent of those fixed objects were the barrier-railing systems of bridges. A bridge-railing system includes the approach guardrail, the transition, and the railing itself. Hosea (2) has reported that an element of a bridge-railing system was the first object struck in 18 percent of the fatal accidents at fixed objects on completed sections of the Interstate highway system in 1968. An analysis of accidents at bridge railings by location has shown that 73 percent of the vehicles impacted the approach guardrail and bridge end and 27 percent collided with the bridge railing (1). The performance of the barrier systems in these accidents was judged inadequate because 16 percent of the vehicles either vaulted or penetrated the installation and 52 percent pocketed or snagged.

In 1967, the American Association of State Highway Officials (AASHO) published a study of design and operational practices related to highway safety (3) that emphasized the need for a structurally sound transition between guardrails on bridge approaches and the bridge railings themselves, and in several states, intensive programs to upgrade existing bridge-railing systems were initiated. Accident statistics from California (4), shown in Table 1, indicate that those programs have been most successful. The rate of fatal accidents on freeways per 100 million vehicle kilometers of travel (MVKT) for bridge railing decreased in the period from 1965 to 1973 by about 50 percent and even more significantly in 1974 and 1975 when the 24.6-m/s (55-mph) speed limit was set. This improvement in highway safety, which has been confirmed by observations in other states, may be partially attributed to improvements in vehicle crashworthiness and occupant restraint systems. Nevertheless, the California statistics indicate that upgrading bridge-railing systems has helped to reduce the number of fatal accidents.

An approach that promises further reductions in highway fatalities is that of upgrading substandard bridge-railing systems with cost-effective devices that can be easily retrofitted to existing bridges. Such devices should be readily adaptable to a majority of existing bridges and quickly and economically adjustable in the field.

## ANALYSIS OF EXISTING BRIDGE-RAILING SYSTEMS

A letter survey of 51 highway agencies was carried out in September 1974. The purpose of the survey was to determine (a) the types of bridge-railing systems that are in current use, (b) the types of approach guardrails that are in use, and (c) the accident experience of different bridge-railing designs. A total of 44 state highway agencies responded to at least a part of the survey. These responses reported on 3940 km (2450 miles) of bridge railing, which is about 15 to 20 percent of the estimated total [20 600 to 24 780 km (12 800 to 15 400 miles)] in the United States. This is considered a significant and meaningful sample.

From the information assembled in this survey, 14 representative designs for bridge-railing systems were selected and analyzed with respect to their conformance to the 1973 AASHO specifications (5) and their predicted (or observed) performance during vehicle crash tests. The selection of the 14 examples was based on two factors: (a) a minimum of 56 km (35 miles) of reported installation and (b) sufficient design information. The combined length of the 14 examples is 2665 km (1656 miles) or 67 percent of the total reported in the survey.

All of these systems were designed before the adoption of the 1973 specifications and should not be expected to conform. However, these specifications can be used as a safety-performance reference. The analysis showed that only 1 design fully conformed, 1 design could be considered marginally conforming, and 12 out of the 14 designs did not conform with one or more provisions of the specifications. On the basis of length, 68 percent of the systems analyzed did not conform, and 27 percent conformed marginally. A more detailed analysis of existing systems is given in the program report (6).

## CATEGORIZATION OF BRIDGE-RAILING DESIGNS

It is estimated that there are more than 200 unique bridge-railing designs in use on the approximately half million bridges in the United States. To develop and evaluate safety modifications for each of these designs would require a formidable expenditure of effort and most certainly would not be cost-effective.

An alternative approach is to place existing bridge-railing designs, regardless of their safety-performance capability, in one of the four Southwest Research Institute (SwRI) categories that are illustrated in Figure 1 and described below.

| Category | Description |
|---|---|
| I | Metal rail and metal posts mounted flush to bridge deck; curb or walk (if present) does not project more than 0.15 m (6 in) above bridge deck |

| Category | Description |
|---|---|
| II | Concrete baluster rail or concrete parapet with up to four metal rails; no curb or walk that projects into traffic lane beyond face of rail |
| IIIN | Concrete parapet with walk less than 0.061 m (24 in) wide and curb; one to three rails may be attached to parapet |
| IIIW | Concrete parapet with walk 0.61 m (24 in) or more wide and curb; one to three metal rails may be attached on top of parapet |
| IV | Concrete safety shape with or without one or two metal rails |

The definitions of these categories are based on the geometries of the bridge-railing profiles and are specifically delineated so that all bridge railings within a category that lack adequate safety-performance capability will be amenable to a common retrofit design. The fact that a specific bridge railing is exactly like or only remotely similar to one of the four categories is not intended to imply its level of safety performance. The purpose of the categorization is to reduce the number of retrofit designs so that a design developed for a given category will be applicable to all of the bridge railings in that category.

## CONSTRAINTS ON RETROFIT DESIGNS

After a review of bridge-railing design drawings and interviews with bridge designers, the following constraints were added to the general bridge-railing service requirements for the retrofit designs.

1. A majority of the bridges of interest are narrow. Although pavements and shoulders have often been widened in recent years, narrow bridges have been retained because of the expense and technical difficulty required for their modification. The high rates of accidents at bridge ends have been attributed to both the narrow roadways on bridges and the funnel effect of the transition from a wide highway to a narrow bridge. Consequently, a large number of bridges that may require retrofitted bridge railings cannot afford further reduction of the bridge-deck width by encroachment of the bridge-railing modification and, thus, bridge-railing retrofit designs must attempt to maintain present bridge-deck widths.
2. Curbs and walks extending out from a bridge railing are only marginally effective in redirecting errant vehicles. Furthermore, vehicles impacting curbs are caused to jump and may strike the backup structure in an unpredictable attitude. The newest design standards minimize the use of curbs in front of longitudinal traffic barriers for this reason. However, the curbs are an integral part of the structure of many bridges and cannot be removed without major reconstruction. Thus, retrofit designs should accommodate the existing curb conditions.

## RETROFIT DESIGNS

In developing the retrofit designs a majority of the effort was directed toward categories II and III for the following reasons:

1. Category I represents fewer than 14 percent of the existing bridge-railing systems. Moreover, these designs can often be upgraded by simple procedures such as the replacement of a rail or may be economically replaced by a conforming design. (While the least common, some category I barriers may be the most hazardous and thus justify a high priority for upgrading if exposure is high.)
2. About 82 percent of the existing bridge-railing systems are either category II (42 percent) or category III (40 percent).
3. Category IV represents fewer than 6 percent of existing bridge-railing systems, and most category IV designs already satisfy the 1973 AASHO requirements and perform satisfactorily during vehicle crash tests.

In this program, a bridge-railing system is defined as including (a) the approach guardrail and terminal, (b) the bridge railing, and (c) the transition from the approach guardrail to the bridge railing, and it is important for safety performance in collisions that these elements behave in an integral manner. Hence, the entire bridge-railing system should be considered during the design phase, although the emphasis in this research was directed toward the bridge-railing and transition elements, and less attention was given to the approach guardrail and terminal. The transition elements in the retrofit designs include a portion of the approach guardrail, but no upstream guardrail terminals were evaluated in the test phase. Suitable terminals have been developed and evaluated in other programs (7).

One retrofit design was developed for the category II bridge railing. The primary element of this R(II)-1 design is a new railing element known as the tubular thrie beam, which is fabricated by welding two thrie (or triple corrugated) beams together as shown in Figure 2a. The beam is joined to and blocked out from the concrete baluster rail by 0.15-m (6-in) diameter collapsing tubes spaced at 2.5-m (8.3-ft) intervals; there was no attempt to space the tube supports to the concrete post in the test system.

Four retrofit designs were developed for the category IIIN bridge railing, and one was developed for the category IIIW bridge railing. A sectional view of the R(IIIN)-1 design is shown in Figure 2b. The essential features of the design are the tubular thrie beam that is blocked out from the concrete parapet by brackets spaced at 2.5-m (8.3-ft) intervals. The bracket is made of a relatively stiff 15 by 15 by 4.8-mm (6 by 6 by $^3/_{16}$-in) transverse section (TS) and a 0.15-m (6-in) diameter tube section with a 3.2-mm ($^1/_8$-in) wall. The traffic face of the tubular thrie beam aligns with the curb and does not encroach on the bridge deck. Obviously, the retrofit design eliminates use of the walkway. The collapsing tubes provide 0.15 m (6 in) of dynamic deflection, which attenuates the lateral redirection forces on the car.

The R(IIIN)-2 design shown in Figure 2c has two 0.18-m (6.87-in) deep, semielliptical aluminum rails at mounting heights of 0.38 and 0.68 m (15 and 27 in). The rails are blocked out from the concrete parapet with rigid brackets spaced at 2.4-m (8-ft) intervals. The traffic face of the rail is about on the curb line; for walks of other widths, the bracket geometry would require adjustment to maintain the approximate alignment of the rails and curb. The brackets are attached to the category IIIN system by six 19-mm ($^3/_4$-in) diameter anchor bolts embedded 0.15 m (6 in) deep into the concrete parapet and walk. The transition from the approach guardrail to the bridge railing is effected by a stepped reduction in spacing of the soil-mounted posts from 2.4 to 0.9 m (8 to 3 ft) and the use of posts with soil-bearing plates.

The R(IIIN)-3 design shown in Figure 2d has beams of 20.7-MPa (3000-lb/in$^2$), 28-d compressive strength concrete cast at the test site. The reinforcing consists of No. 4 bars in each corner that are continuous for the length of the 8.50-m (27.9-ft) beam, and the tie bars are No. 4 size and spaced 0.66 m (26 in) apart along the beam. The 25-mm (1-in) diameter anchor bolts are cast into the rear side of the beams, 76 mm (3 in) from the base, on typical 2.4-m (8.0-ft)

**Table 1. Fatal accidents involving bridge railings on California freeways.**

| Statistic | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974[a] | 1975[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Accidents at bridge railings | 23 | 26 | 29 | 29 | 30 | 17 | 15 | 27 | 25 | 9 | 5 |
| Accidents at bridge end posts at gore[b] | 3 | 10 | 5 | 3 | 5 | 6 | 2 | 8 | 5 | 6 | 3 |
| Accidents at guardrail at fixed objects[c] | 14 | 16 | 14 | 11 | 13 | 7 | 9 | 13 | 16 | 12 | 5 |
| Total possible bridge-railing accidents | 40 | 52 | 48 | 43 | 48 | 30 | 26 | 48 | 46 | 27 | 13 |
| Travel MVKT | 37 000 | 41 785 | 46 450 | 54 244 | 59 498 | 63 500 | 68 452 | 74 444 | 79 308 | 78 753 | 84 421 |
| Total freeway completed by end of year, km | 2 877 | 3 313 | 3 839 | 4 188 | 4 402 | 4 846 | 5 139 | 5 514 | 5 754 | 5 910 | 5 997 |
| Rate of fatal accidents per bridge railing (per 100 MVKT) | 0.17 | 0.20 | 0.17 | 0.13 | 0.13 | 0.08 | 0.06 | 0.10 | 0.09 | 0.06 | 0.02 |

Note: 1 km = 0.62 mile.

[a]Maximum speed limit = 24.6 m/s (55 mph).

[b]This item is actually not a bridge-railing problem that can be solved by a retrofit design but rather is a head-on impact situation that is best handled by a crash cushion; it is included to permit comparison to Olson's data (1).

[c]Estimated to be 39 percent of the guardrail adjacent to fixed objects.

**Figure 1. SwRI categories for classification of bridge-railing systems.**

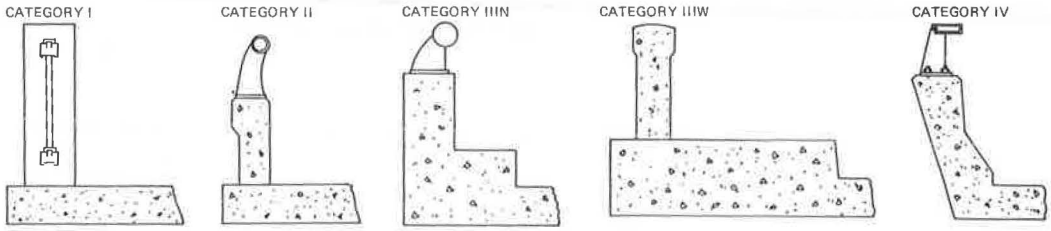
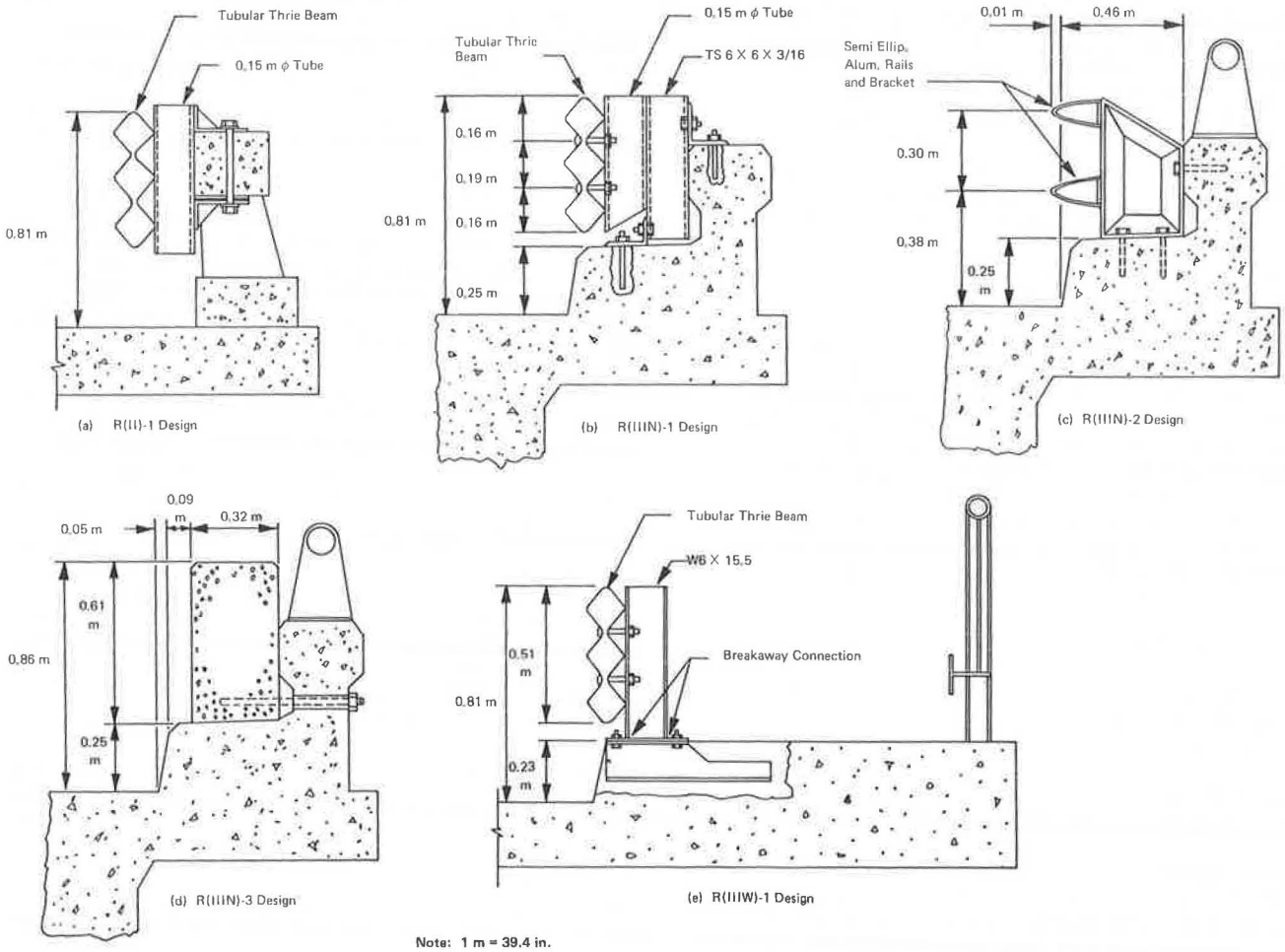



**Figure 2. Retrofit designs.**




Note: 1 m = 39.4 in.

**Figure 3. Test installations.**

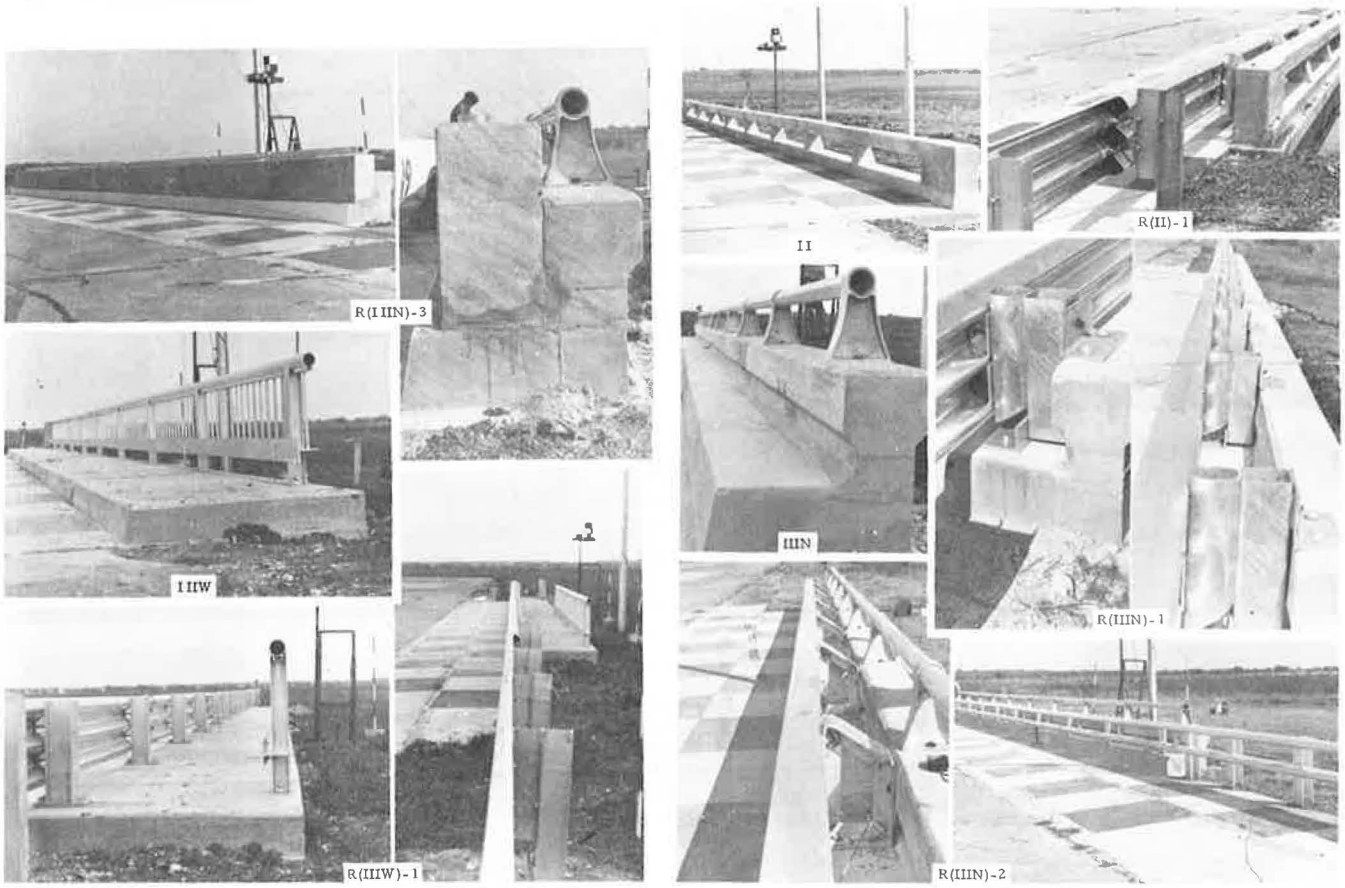


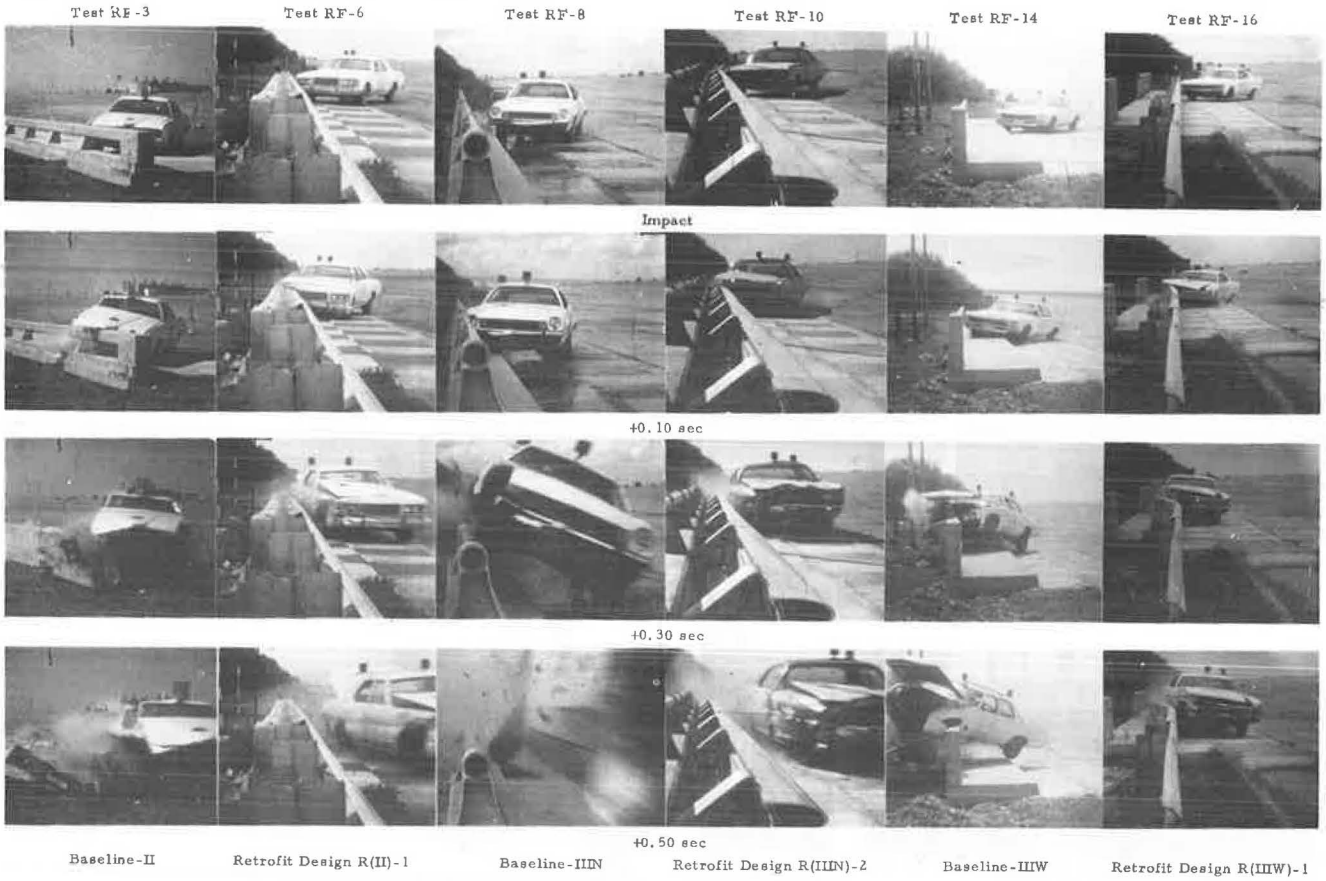

**Table 2. Summary of full-scale crash-test results.**

| Test | Barrier Description | Vehicle Weight (kg) | Impact Speed (m/s) | Impact Angle (°) | Vehicle Exit Conditions: Speed (m/s) | Vehicle Exit Conditions: Angle (°) | Vehicle Acceleration (max over 50-ms duration) (g): Longitudinal | Lateral | Resultant | Max Permanent Rail Deflection (mm) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | II | 2041 | 27.0 | 30.0 | 13.7 | +2.0 | -10.7[a] | -12.3[a] | 16.3[a] | 0 | Vehicle damage severe; barrier damage considerable |
| 4 | II | 966 | 25.5 | 15.5 | 20.6 | -5.8 | -4.1[a] | -7.1[a] | 8.2[a] | 0 | Vehicle frame damage considerable |
| 5 | R(II)-1 | 1021 | 25.9 | 17.1 | 22.3 | -6.8 | -4.1[b] | -8.4[b] | 9.1[b] | 13 | Vehicle smoothly redirected and drivable after test |
| 6 | R(II)-1 | 2041 | 27.1 | 25.0 | 24.4 | -6.0 | -5.9[b] | -11.7[b] | 13.1[b] | 127 | Vehicle smoothly redirected and drivable after test |
| 7[b] | R(II)-1 | 2132 | 26.9 | 25.0 | 21.0 | -10.0 | -4.0[b] | -7.5[b] | 7.6[b] | 549 | Vehicle smoothly redirected and drivable after test |
| 8 | IIIN | 971 | 28.0 | 15.9 | 24.2 | +7.4 | -3.6[a] | -5.3[a] | 5.9[a] | 0 | Vehicle mounted walk during redirection; frame damage considerable |
| 9 | IIIN | 2142 | 26.1 | 29.4 | 17.0 | -11.2 | -9.6[a] | -4.2[a] | 10.4[a] | 0 | Vehicle mounted walk during redirection; frame damage considerable |
| 1 | R(IIIN)-1 | 971 | 28.4 | 16.8 | 24.9 | 0 | -3.7[a] | -6.1[a] | 6.3[a] | 27 | Vehicle smoothly redirected and drivable after test |
| 2 | R(IIIN)-1 | 1950 | 29.8 | 23.9 | 23.5 | -2.9 | -8.2[a] | -8.2[a] | 11.0[a] | 152 | Vehicle smoothly redirected; two tubes on barrier collapsed |
| 13[b] | R(IIIN)-1 | 2041 | 29.1 | 26.1 | 19.6 | -0.7 | -7.2[b] | -8.7[b] | 10.7[b] | 457 | Vehicle damage severe; barrier damage considerable |
| 10 | R(IIIN)-2 | 1974 | 26.8 | 21.7 | 21.2 | -3.5 | -4.2[a] | -5.9[a] | 7.2[a] | 0 | Vehicle smoothly redirected; frame damage considerable |
| 11 | R(IIIN)-2 | 930 | 28.8 | 15.1 | 25.0 | -9.0 | -3.8[a] | -5.9[a] | 6.6[a] | 0 | Vehicle smoothly redirected; sheet-metal damage minor |
| 12[b] | R(IIIN)-2 | 2006 | 35.6 | 19.9 | 23.8 | -8.1 | -5.9[a] | -8.2[a] | 9.8[a] | 366 | Vehicle frame damage extensive |
| 18 | R(IIIN)-3 | 2006 | 29.2 | 7.5 | 27.8 | +4.8 | -6.5[a] | -5.6[a] | 7.9[a] | 0 | Vehicle smoothly redirected and drivable after test |
| 19 | R(IIIN)-3 | 2006 | 27.1 | 11.5 | 24.8 | +2.5 | -4.4[b] | -4.9[b] | 6.3[b] | 0 | Vehicle smoothly redirected and drivable after test |
| 20 | R(IIIN)-3 | 971 | 24.8 | 9.2 | 20.9 | -12.0 | -4.3[b] | -8.3[b] | 9.4[b] | 0 | Vehicle smoothly redirected and drivable after test |
| 21 | R(IIIN)-3 | 971 | 19.7 | 16.2 | 16.8 | -1.6 | -5.2[b] | -6.3[b] | 8.1[b] | 0 | Vehicle smoothly redirected; sheet-metal damage minor |
| 22 | R(IIIN)-3 | 971 | 27.7 | 18.3 | 24.5 | +0.7 | -8.2[b] | -16.1[b] | 17.7[b] | 0 | Vehicle smoothly redirected; frame damage considerable |
| 14 | IIIW | 1944 | 27.7 | 25.3 | n/a | n/a | -4.5[a] | -3.3[a] | 4.8[a] | n/a | Vehicle penetrated barrier; damage extremely severe |
| 15 | R(IIIW)-1 | 957 | 29.0 | 13.5 | 26.1 | -5.7 | -1.8[a] | -5.5[a] | 5.8[a] | 12 | Vehicle smoothly redirected and drivable after test |
| 16 | R(IIIW)-1 | 1967 | 28.0 | 25.8 | 22.7 | -3.9 | -4.4[a] | -6.2[a] | 7.6[a] | 61 | Vehicle smoothly redirected; frame damage considerable |
| 17[b] | R(IIIW)-1 | 2021 | 21.5 | 28.6 | 13.9 | -4.8 | -4.6[a] | -4.3[a] | 6.3[a] | 155 | Vehicle damage severe; barrier damage minor |

Note: 1 kg = 2.205 lb; 1 m/s = 2.237 mph; 1 mm = 0.039 in.

[a]Obtained from high-speed cine data. [b]Obtained from accelerometer data. [c]Bridge railing-transition test.

**Figure 4. Dynamic performance of baseline and typical retrofit designs.**




spacings, and project horizontally 0.30 m (12 in). After a 28-d field cure, the beams are lifted into place on the 0.41-m (16-in) wide walk and set in a leveling grout. During the setting of the beams, the anchor bolts are inserted through 38-mm (1.5-in) drilled holes in the parapet and locked into place.

A sectional view of the R(IIIW)-1 design is shown in Figure 2e. A tubular thrie beam at a mounting height of 0.81 m (32 in) is supported on 15 by 22-cm (6 by 8.5-in) W-posts spaced 2.54 m (8.33 ft) apart. To provide lateral flexibility during vehicle collisions, the post-to-baseplate weldments are portioned to break at a loading of 4536 kg (10 000 lb). The foundation beam distributes the impact forces and moments so that no damage is sustained by the concrete during impact, and repairs after an impact will consist of replacing one or more posts.

## TEST PROGRAM

A program of 22 full-scale crash tests with vehicles ranging from 930 to 2142 kg (2050 to 4722 lb) was conducted to examine the dynamic performance of the five retrofit designs in terms of the stated performance goals. The test installations are shown in Figure 3. Visual comparisons of the dynamic performances of baseline and retrofitted systems are shown in Figure 4, and the results of the test series are summarized in Table 2.

A detailed description of the bridge-railing designs and the test procedures and results have been discussed by Michie and others (6).

## SUMMARY

1. Although recent accident statistics indicate that the safety performance of bridge-railing systems has improved as new designs have been introduced and old installations upgraded, as late as 1968 bridge-railing systems did not perform satisfactorily with respect to today's standards in more than 68 percent of the fatal accidents at bridge railings. An appraisal, according to the 1973 AASHO bridge specifications, of 14 specific bridge-railing designs (representing 67 percent of those surveyed) showed that only 1 system conformed, 1 system marginally conformed, and 12 did not conform with one or more provisions of the specifications. On the basis of lengths of the systems, 68 percent of the existing installations did not conform, and 27 percent of them marginally conformed.

All 14 systems had been designed prior to 1973 to conform to earlier specifications, and the nonconforming deficiencies, which were minor in several instances, were expected.

2. Inadequate safety performance of the approach-guardrail segment can be attributed to inadequate design or improper layout and installation or both. Most states have now adopted improved designs for approach guardrail, but this trend is too recent to be significantly reflected in the field.

3. Although there are more than 200 unique bridge-railing systems in service, these systems can be grouped into four categories, within which all variations are amenable to a common retrofit design. Categories II (parapet but no curb) and III (parapet and curb with as many as four metal rails) represent about 82 percent of all bridge-railing systems in service.

4. Five bridge-railing safety-improvement modifications (for categories II and III systems) have been developed and evaluated. These modifications are judged suitable for carefully monitored in-service use.

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# Evaluation of Concrete Safety Shapes by Crash Tests With Heavy Vehicles

E. O. Wiles, M. E. Bronstad, and C. E. Kimball, Southwest Research Institute, San Antonio

**Three crash tests were made to evaluate concrete median barriers at speeds of approximately 70 and 90 km/h (45 and 55 mph) and angles of approximately 7 and 16° with an 18 000-kg (40 000-lb) intercity bus. The 61.0-m (200-ft) long installation was cast in place and reinforced with one number 4 bar placed 150 mm (6 in) below the barrier top. The freestanding barrier was restrained by a 25-mm (1-in) layer of asphalt placed at the installation bottom on the side opposite the impact. The results of the program include the following: The safety shape performed well at the lower angle impacts with no barrier distress or translation. The severe test [an impact speed of 85.1 km/h (52.9 mph) and an impact angle of 16°] showed that the concrete safety shape with minimum reinforcement and foundation restraint can redirect large vehicles at high impact speeds and angles. In the severe test, the rear-end impact during redirection was the principal cause of the extensive barrier damage and displacement.**

The concrete safety shape is a widely used traffic barrier. Although it was originally used as a median barrier, it is also used on structures and roadway shoulders. This paper is taken from the report (4) of a study of safety shapes that was sponsored by 21 transportation agencies and administered by the Federal Highway Administration Office of Research. One part of this program was a crash-test evaluation that used an 18 000-kg (40 000-lb) intercity bus impacting a concrete median barrier (CMB) under various conditions.

## BACKGROUND

In 1971, 36 states used concrete safety shapes to some extent (1). Of these 36 states, 19 specified the shape first used by New Jersey, which is denoted as MB5 by Michie and Bronstad (2).

In this program, a survey of 25 agencies provided information about CMB accident cases. The following observations were made:

1. The performances of various shapes are comparable except in the prevention of vehicle rollovers, for which the MB5 shape has a definite advantage.
2. A number 4 bar placed 152 mm (6 in) below the top of the barrier is the most common reinforcement used in CMB construction.
3. The CMB is effective in containing and redirecting large vehicles. Only two of the 49 heavy-vehicle accidents reported resulted in penetration of the barrier.
4. The barrier failures that occur are due primarily to heavy-vehicle impacts.

Full-scale, heavy-vehicle crash tests of the CMB have been extremely limited (3). In this program, a series of tests was used to evaluate the performance of a lightly reinforced MB5 barrier with minimal foundation restraint when impacted by an 18 000-kg (40 000-lb) intercity bus. The cast-in-place installation, as shown in Figure 1, was 61.0 m (200 ft) long and was reinforced with one number 4 bar placed 152 mm (6 in) below the barrier top. Restraint of the freestanding barrier was provided by a 25-mm (1-in) layer of asphalt, 1.2 m (4 ft) wide, on the bottom of the installation on the side opposite the impact.

## TEST PROCEDURES

The crash tests were performed with a vehicle controlled by linear actuators attached to the steering linkage, and the linear actuators were remotely controlled through a hard line by the operator in the chase vehicle. The vehicle ignition and brakes were remotely controlled through a tether line that also carried the signals from strain-gauge accelerometers, which were mounted to the vehicle floor pan, 0.30 m (12 in) aft of the front axle