Crash-Test Evaluation of Barriers Installed on a Curved Off Ramp

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

Although much has been learned about a relatively large number and variety of barrier systems installed on straight and level alignments, there has been a total lack of information on vehicle and barrier behavior and curved-superelevated-sloped alignments. Some recent catastrophic accidents on freeway off ramps have suggested that a better understanding of barriers mounted on these types of alignments was in order. Accordingly, a test program was designed to evaluate the performance of three barrier configurations mounted on a curved, superelevated structure with a downgrade. The objective of this project was to evaluate the performance of the three barrier configurations by using three vehicle types for comparison. The project included full-scale tests of three basic barrier installations: (a) concrete safety shape with vertical orientation, (b) concrete safety shape installed perpendicular to the superelevated roadway, and (c) tubular Thrie-beam and collapsing tube retrofit. Crash tests were conducted by using three vehicle types impacting a 40 mph (65 km/h) and a 15° angle (as measured from curve tangent). The three vehicle types were (a) 1800-lb (820-kg) mini-compact car (Honda Civic), (b) 2250-lb (1020-kg) subcompact (Vega), and (c) 20 000-lb (9070-kg) school bus (1970 66-passenger Ford/Wayne). All three barrier systems contained and redirected the full range of test vehicles. In terms of vehicle stability and acceleration, the tubular Thrie-beam retrofit was superior. However, there was some barrier damage in the bus test of this system.

For the past two decades, extensive crash-test evaluations have been conducted on longitudinal traffic barriers (i.e., guardrails, median barriers, and bridge-railing systems). In addition, many investigations have also included the use of computer simulations to predict vehicle and barrier behavior during the collision event. Although much is known about the performance of a relatively large number and variety of barrier systems installed on straight and level alignments, there has been a total lack of information on vehicle and barrier behavior on curved-superelevated-sloped alignments. Some recent catastrophic accidents on freeway off ramps have suggested that a better understanding of barriers mounted on these types of alignments was in order. Accordingly, a test program was designed to evaluate the performance of three barrier configurations mounted on a curved, superelevated structure with a downgrade.

The objective of this project was to evaluate the performance of three barrier configurations by using three vehicle types for comparison. In addition, two indirectly related tasks were also structured to provide information on vehicle mass and crush properties.

The project included full-scale tests of three basic barrier installations:

1. Concrete safety shape with vertical orientation,
2. Concrete safety shape installed perpendicular to the superelevated roadway, and
3. Tubular Thrie-beam and collapsing tube retrofit.

These barriers are shown in Figure 1.

Crash tests were conducted by using three vehicle types impacting at 40 mph (65 km/h) and a 15° angle (as measured from curve tangent). The three vehicle types were as follows:

1. 1800-lb (820-kg) mini-compact car (Honda Civic),
2. 2250-lb (1020-kg) subcompact (Vega), and
3. 20 000-lb (9070-kg) school bus (1970 66-passenger Ford/Wayne).

Each of the test vehicles contained two uninstrumented part 572 anthropometric dummies (50th percentile males). The dummies were positioned in the driver (restrained) and right front seat (unrestrained) occupant positions for the car tests. In the bus tests, the dummies were positioned to represent a restrained driver (lap belt) and an unrestrained passenger. The remaining payload of the bus was composed of three loose 100-lb (45-kg) sandbags per seat. An on-board camera recorded the motion of the dummies during the tests.

FINDINGS

In order to conduct the full-scale tests, a test installation that had the selected off-ramp geometry was excavated at the end of a paved airport runway. This excavation was paved with asphalt to simulate an off-ramp deck. The installation as shown in Figure 2 is essentially a curved ramp with the following characteristics:

1. 160-ft (48.8-m) outside radius,
2. 25-ft (7.6-m) roadway width,
3. 4.5 percent downgrade, and
4. 12 percent superelevation.

The crash tests were conducted on the three different barrier configurations by using the same test conditions. Sequential test photographs are arranged by vehicle type in Figures 3, 4, and 5. Figures 6, 7, and 8 contain after-test photographs arranged by vehicle type. The results of the crash tests are summarized in Table 1.

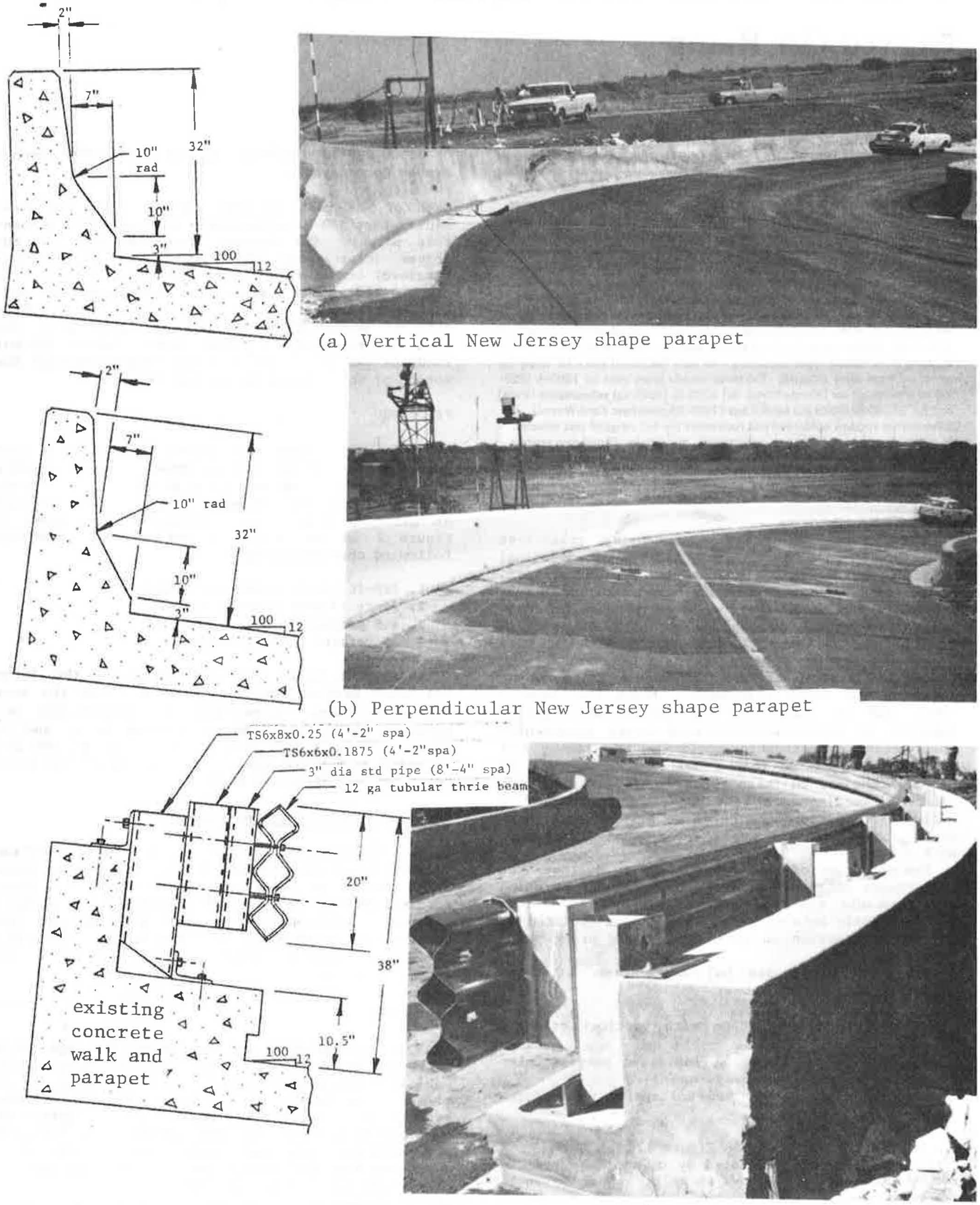
Vertical Safety Shape Test Series

A New Jersey-shape bridge parapet was installed vertically as the outside bridge rail on the simulated deck. The cross-section dimensions and reinforcing of the barrier were selected from a state standard, although the barrier strength was not expected to be critical for the 40-mph (65-km/h), 15° angle impacts. Findings from the tests are described below.

Test CB-1

A 1974 Vega impacted the barrier at 37.2 mph (59.8 km/h) and an 18.7° angle. As shown in Figure 3, the vehicle front wheels turned into the barrier as it climbed the lower sloped face. Rolling of the vehicle away from the barrier, which is typical of the interaction between New Jersey-shape barriers and vehicles, continued until the vehicle front wheel was near the top of the barrier. The maximum tire climb was 1.6 ft (0.5 m). The vehicle wheels then returned to grade with a continuous cyclic scrubbing of the outside barrier (with less climb at each cycle) until the vehicle left the barrier. The vehicle came to rest 4.5 ft (1.6 m) from the downstream end.

Figure 1. Barrier test installations.

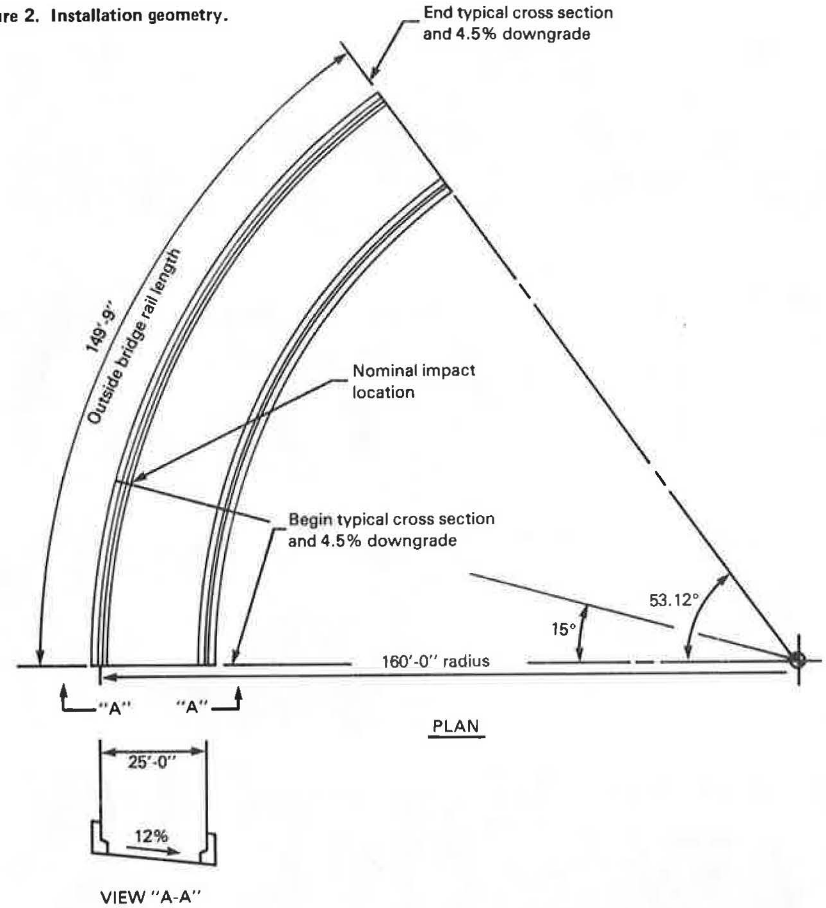


(a) Vertical New Jersey shape parapet

(b) Perpendicular New Jersey shape parapet

(c) Tubular thrie beam retrofit

Figure 2. Installation geometry.



Test CB-2

The school bus impacted the barrier at 41.8 mph (67.3 km/h) and a 15.5° angle. As shown in Figure 4, the bus rolled slightly away from the barrier as the left front tire climbed up the barrier face a maximum of 1.9 ft (0.6 m) and the front of the bus pitched upward. As the front moved downward from the maximum climb, the bus rolled toward the barrier before returning to a stable position near the installation end. After barrier contact was terminated, the bus turned to the right during braking and stopped about 100 ft (30 m) from the end.

Barrier damage consisted of minor scraping. Bus damage included a bent bumper and fender, two of five lug nuts sheared, and two shattered windows, as shown in Figure 7. The window damage was due to driver head intrusion and loose sandbag contact (near the rear end).

Test CB-3

A 1976 Honda Civic impacted the barrier at 40.0 mph (64.4 km/h) and a 13.9° angle. As shown in Figure 5, the vehicle rolled away from the barrier as the left front tire climbed the barrier face a maximum of 1.7 ft (0.5 m) and the vehicle front pitched upward. At 0.3 s after impact, the entire vehicle was airborne (tire contact with upper portion of barrier existed) and remained so for about 0.3 s. At this time the right wheels returned to grade, and the left wheels remained in barrier contact until the vehicle came to rest 8 ft (2.4 m) past the end of the barrier.

Perpendicular Safety Shape Test Series

Findings from the series of tests conducted on the New Jersey safety shape parapet, which was oriented perpendicular to the superelevation, are described below.

Test CB-4

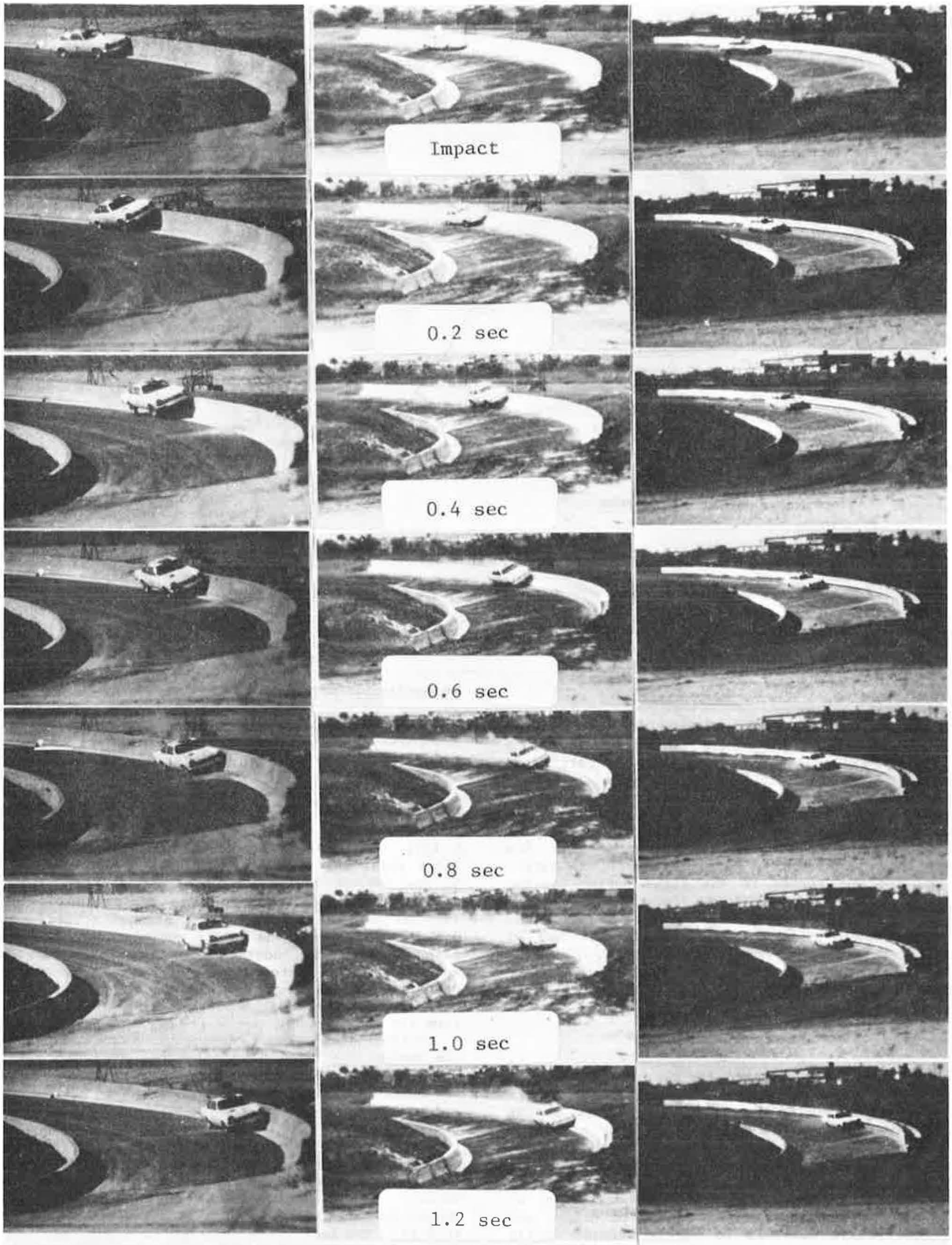
A 1976 Honda Civic impacted the barrier at 38.9 mph (62.6 km/h) and a 13.4° angle. As shown in Figure 5, the vehicle rolled away from the barrier as the left front tire climbed up to a maximum of 1.7 ft (0.5 m) and the vehicle front pitched upward. At 0.3 s after impact, the entire vehicle was airborne, although left tire contact with the upper barrier was maintained. After the right tires returned to grade 0.3 s later, the vehicle remained in contact with the barrier until coming to rest 1 ft (0.3 m) from the barrier end.

Insignificant barrier damage occurred, and vehicle damage consisted of sheet-metal and left front wheel damage. Although the wheel was bent, there was no indication of air leakage.

Test CB-5

A 1975 Vega impacted the barrier at 38.9 mph (62.6 km/h) and a 14.9° angle. As shown in Figure 3, the vehicle rolled away from the barrier as the left wheels climbed the barrier up to a maximum of 1.5 ft (0.5 m). The left tires returned to grade, and then a second and third climb occurred before the vehicle reached the end of the barrier. After losing contact with the barrier, the vehicle went 42 ft (13 m) past the barrier end before coming to rest.

Figure 3. Vega sequential photographs.



NJ Shape - Vertical Axis | NJ Shape - Perpendicular Axis | Tubular Thrie Retrofit

Figure 4. School bus sequential photographs.

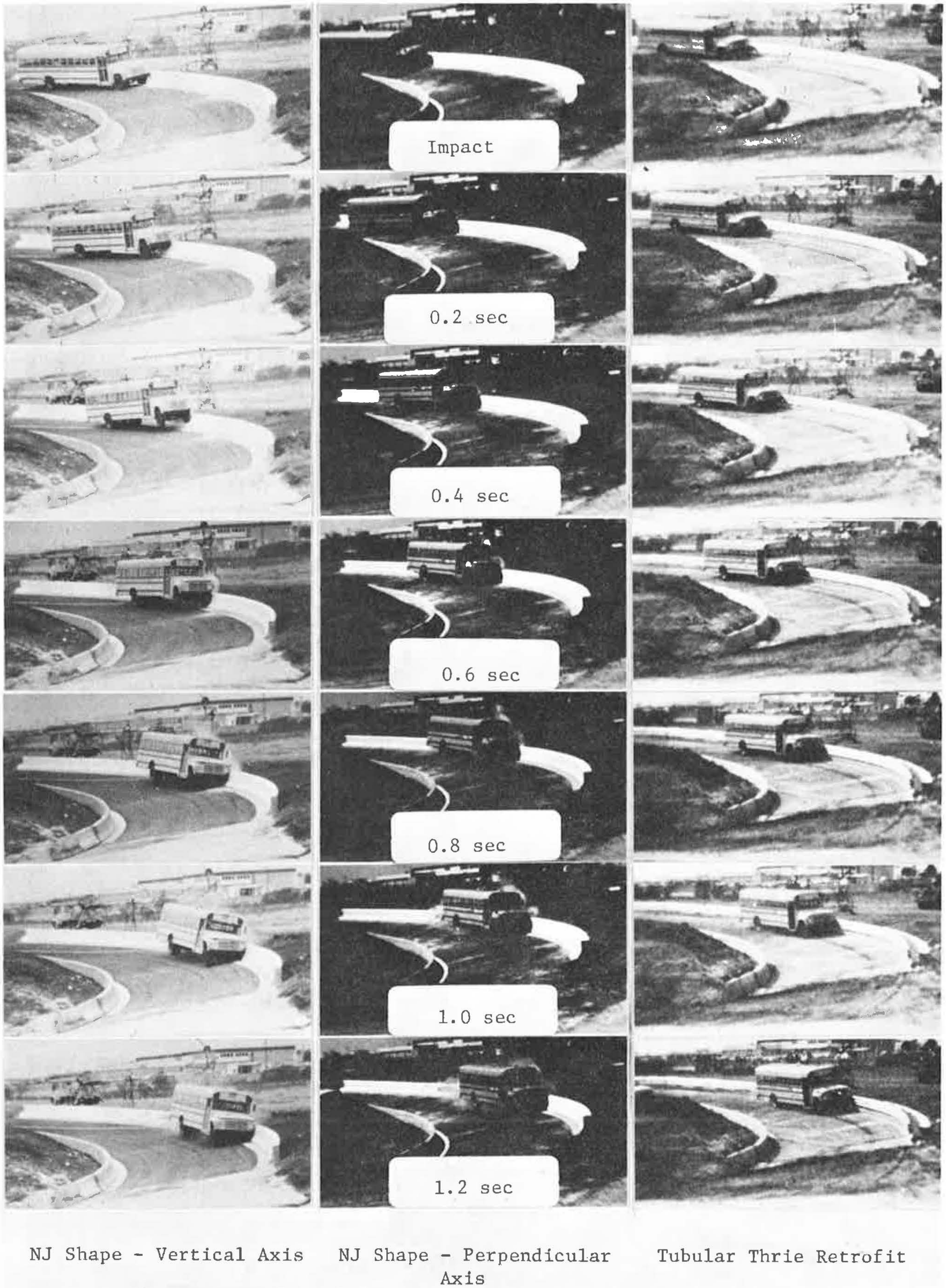


Figure 5. Honda Civic sequential photographs.

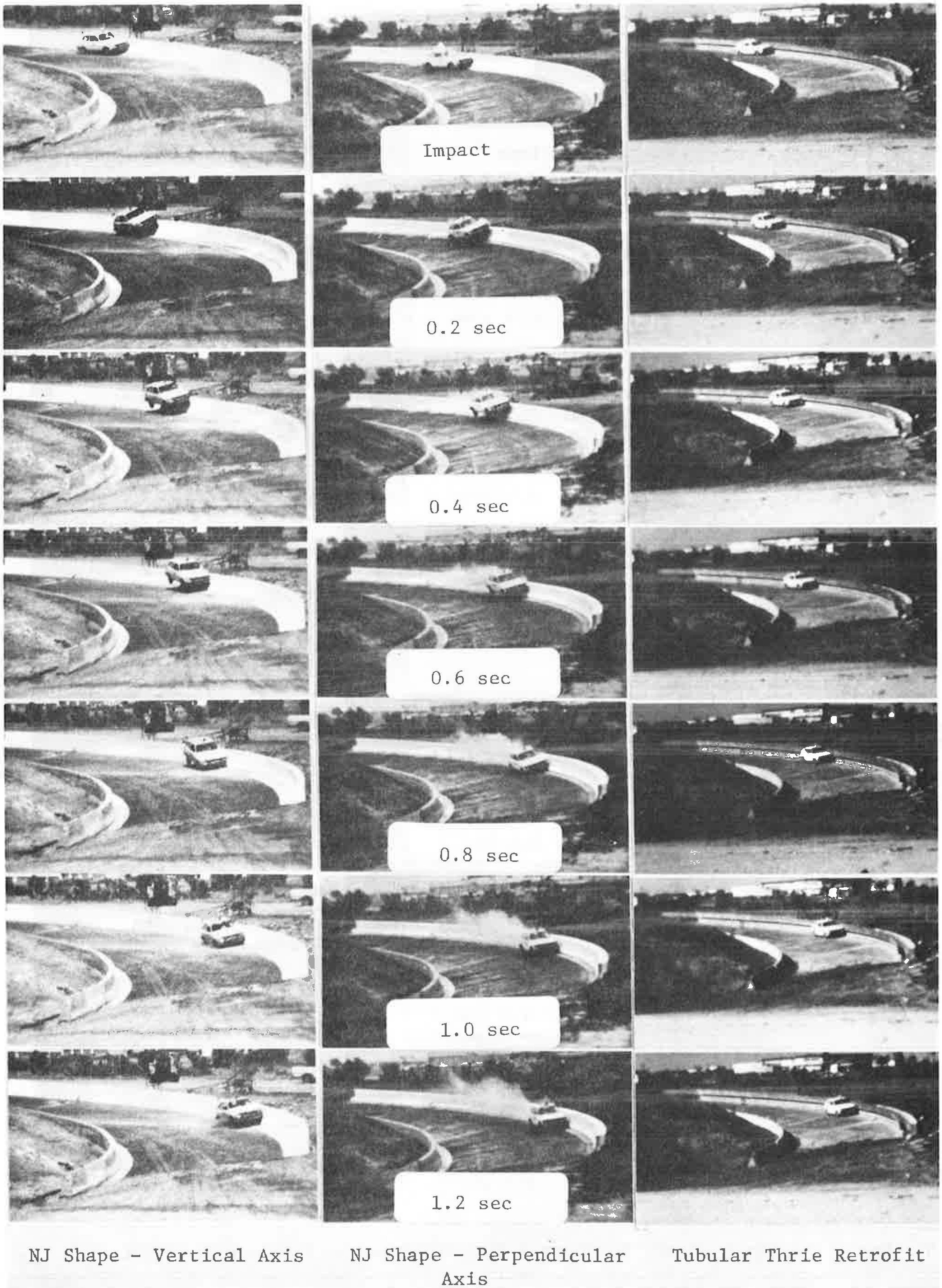
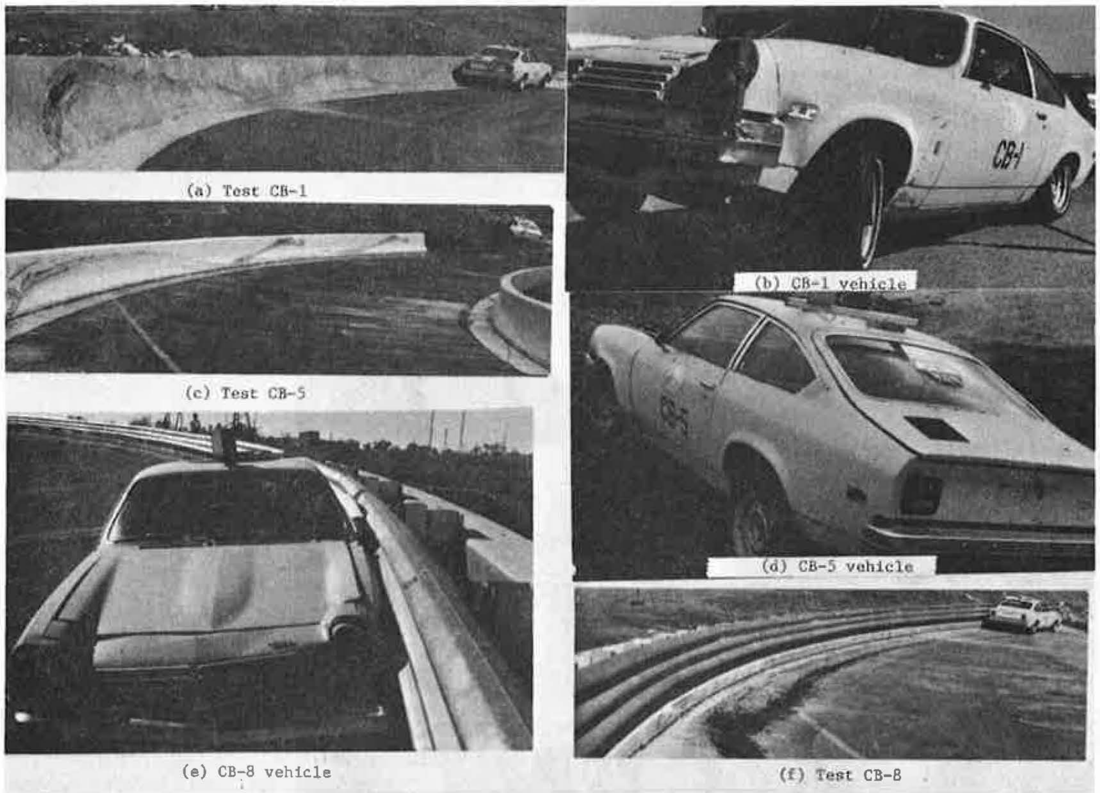
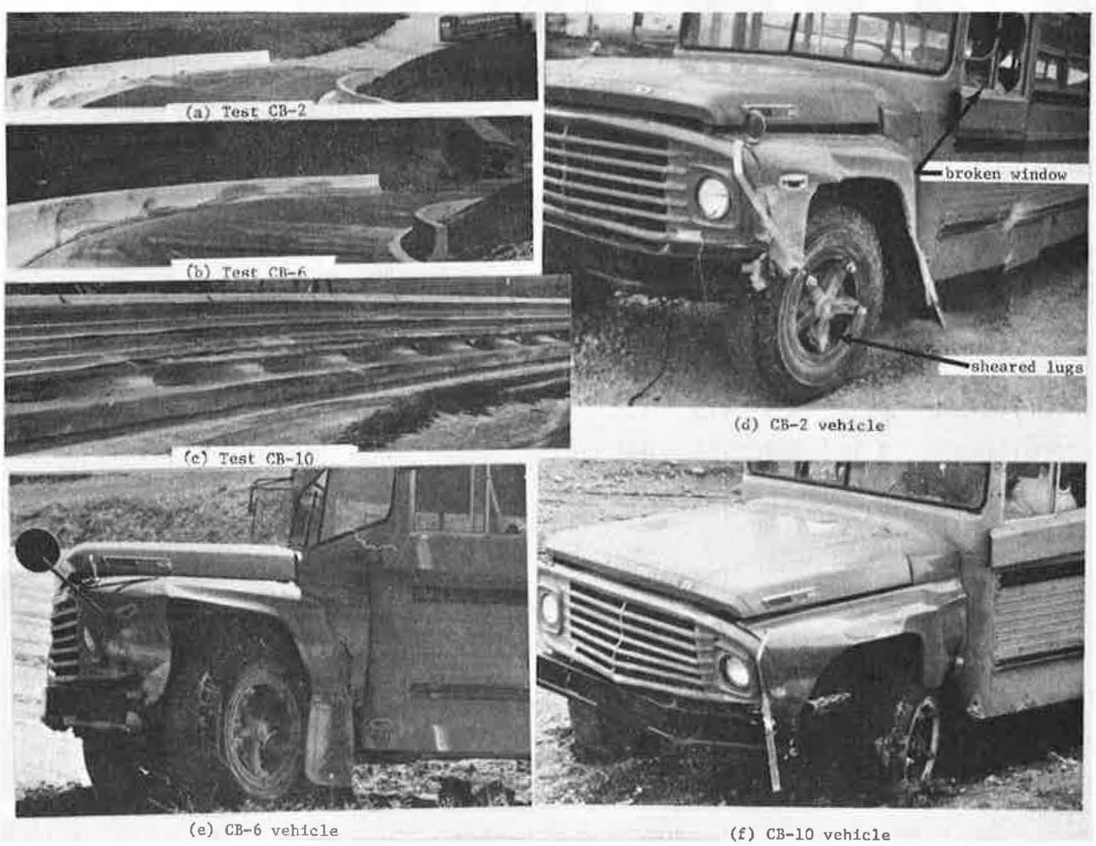


Figure 6. Photographs after Vega tests.



(a) Test CB-1
(b) CB-1 vehicle
(c) Test CB-5
(d) CB-5 vehicle
(e) CB-8 vehicle
(f) Test CB-8

Figure 7. Photographs after bus tests.



(a) Test CB-2
(b) Test CB-6
(c) Test CB-10
(d) CB-2 vehicle
(e) CB-6 vehicle
(f) CB-10 vehicle

Test CB-6

The school bus impacted the barrier at 40.0 mph (64.6 km/h) and a 14.8° angle. As shown in Figure 4, the vehicle front pitched upward as the left front wheel climbed the lower barrier slope. The bus rolled toward the barrier as the front wheels turned left. The bus then returned to a stable attitude and remained in constant barrier contact before leaving the barrier with a leftward turn imposed by the direction of the front wheels.

Vehicle damage was confined to the left front fender and bumper. Although the left front wheel and tire contacted the barrier, only tire scuffing was observed and no wheel lug damage was noted.

Figure 8. Photographs after Honda tests.

Table 1. Summary of full-scale crash test.

Test No.	Barrier	Vehicle	Vehicle Weight[a] (lb)	Impact Speed (mph)	Impact Angle (°)	Avg 50-ms Maximum Acceleration (g) Lateral	Avg 50-ms Maximum Acceleration (g) Longitudinal	Maximum Vehicle Climb (ft)	Maximum Roll Angle (°)	Vehicle Damage
CB-1	New Jersey shape, vertical axis	1974 Chevrolet Vega	2 686	37.2	18.7	-5.4[b]	-2.7[b]	1.6	11	Left front fender sheet-metal deformation, bumper displaced, bent left front wheel
CB-2	New Jersey shape, vertical axis	1970 Ford school bus	20 000	41.8	15.5	-5.6[b]	-1.9[b]	1.7	12	Left front fender sheet-metal scraping, damaged left front tire
CB-3	New Jersey shape, vertical axis	1976 Honda Civic	2 170	40.0	13.9	-1.3[b]	-4.5[b]	1.9	11	Left front fender sheet-metal deformation, bumper bent, two lugs sheared on left front wheel
CB-4	New Jersey shape, perpendicular axis	1976 Honda Civic	2 170	38.9	13.4	-2.6[b]	-1.3[b]	1.7	12	Left front fender sheet-metal deformation, damaged left front tire, bent left front wheel
CB-5	New Jersey shape, perpendicular axis	1974 Chevrolet Vega	2 611	38.9	14.9	-5.3[b]	-3.6[b]	1.5	15	Left front fender sheet-metal deformation, bumper displaced
CB-6	New Jersey shape, perpendicular axis	1970 Ford school bus	20 000	40.0	14.8	-2.9[b]	-1.1[b]	0.9	9	Left front fender sheet-metal deformation, bumper bent, left front tire scuffing
CB-7	Tubular Thrie-beam retrofit	1975 Honda Civic	2 170	38.8	15.1	-4.7[b]	-2.8[b]	0	0	Left front fender, scraping of left side
CB-8	Tubular Thrie-beam retrofit	1974 Chevrolet Vega	2 580	39.4	16.8	-3.8[b]	-2.6[b]	0	0	Left front fender, scraping of left side, front wheel suspension
CB-10	Tubular Thrie-beam retrofit	1970 Ford school bus	20 000	39.4	13.9	-1.3[c]	-0.9[c]	0	0	Sheet metal and front suspension

Note: 1 lb = 0.45 kg; 1 mph = 1.609 km/h; 1 ft = 0.30 m.

[a]Includes ballast and instrumentation. [b]Electronic transducer data. [c]Film analysis; electronic data unavailable.

Tubular Thrie-Beam Retrofit Series

The tubular Thrie-beam retrofit system tested in this series was developed in a previous Federal Highway Administration (FHWA) contract (1), where it successfully contained and redirected both a 40 000-lb (18 100-kg) intercity bus and an 1800-lb (800-kg) Honda Civic at 60 mph (95 km/h) and a 15° angle. As shown in Figure 1, it was developed for upgrading concrete parapets with or without metal railing on top and was used at narrow safety walks. The retrofit railing is shown attached to the parapet and walk system in Figure 1.

Test CB-7

A 1975 Honda Civic impacted the barrier at 38.8 mph (62.6 km/h) and a 15.1° angle. As shown in Figure 5, the vehicle was smoothly redirected with no measurable roll or wheel climb.

There was no significant barrier damage or deformation. Vehicle damage was limited to the sheet metal at the left fender and along the left side.

Test CB-8

A 1974 Vega impacted the barrier at 39.4 mph (63.4 km/h) and a 16.8° angle. As shown in Figure 3, the vehicle was smoothly redirected with excellent vehicle stability.

No barrier damage or deformation occurred. Damage to the test vehicle included sheet-metal deformation of the left front fender and some suspension damage.

Test CB-10

The school bus impacted the barrier at 39.4 mph (63.4 km/h) and a 13.9° angle. As shown in Figure 4, the bus rolled slightly toward the barrier as the front wheels turned left. The bus remained in a stable attitude throughout contact with the barrier until coming to rest 24 ft (7.3 m) past the downstream end.

Damage to the test vehicle was moderate. The left front fender and bumper were deformed, and the left front wheel was pushed rearward by the impact, fracturing the shaft from the steering box to the pitman arm as well as the u-bolts that connect the spring to the axle on the right side.

Vehicle and Barrier Damage

Figures 6, 7, and 8 contain damage photographs after the Vega, school bus, and Honda tests. Installation damage was significant only in test CB-10, where local crushing of the tubular Thrie-beam and some permanent deflection occurred.

CONCLUSIONS

General Performance

All three barrier systems contained and redirected the full range of test vehicles. In terms of vehicle stability and acceleration, the tubular Thrie-beam retrofit was superior. However, there was some barrier damage in the bus test of this system.

Safety Shape Orientation

There was not a dramatic difference in performance for the two barrier orientations. The preferred orientation from the concrete median barrier research program (2) was perpendicular to the superelevation when the vehicle approach is up the superelevation. Vehicle climb was reduced by this preferred orientation in the car tests, although only in the bus test was this significant. The school bus test was noticeably less severe in terms of vehicle redirection with the preferred perpendicular orientation.

Observations of the Honda test on the vertical barrier (CB-3) indicated that the vehicle was near the threshold of riding on top of the barrier. A slightly larger angle or speed could have produced this performance limit.

Tubular Thrie-Beam Retrofit

The installed Thrie-beam system was clearly more than adequate for the range of impacts tested. The system that was developed to redirect much larger vehicles at 60 mph (95 km/h) and 15° could be substantially reduced in cost by eliminating the intermediate posts that were not needed for the test conditions of this program.

The installed Thrie-beam retrofit was oriented perpendicular to the superelevation, which is preferred. Shimming of the spacers in the field may be required to orient the barrier in this manner.

Vehicle Factors

The shearing of two lugs from the bus wheel during the vertical safety shape test (CB-2) is cause for some concern. This wheel was tracking erratically after leaving the barrier; a loss of this wheel could have dramatically changed the test results.

The unexplained loss of a spindle nut during test CB-5 on the perpendicular safety shape made after-test photographs of the Vega sedan (Figure 6) look much worse than warranted. This spindle nut is a special one used to hold the guide wire flag to the wheel and cannot be considered part of the standard vehicle equipment.

REFERENCES

1. C.E. Kimball, Jr., and others. Heavy Vehicle Tests of Tubular Thrie-Beam Retrofit Bridge Railing. FHWA, Final Rept., Aug. 1980.
2. M.E. Bronstad and others. Concrete Median Barrier Research. FHWA, Rept. FHWA-RD-77-4, March 1976.