HYBRID BARRIER FOR USE AT BRIDGE PIERS IN MEDIANS (MODULAR CRASH CUSHION PLUS CONCRETE MEDIAN BARRIER)

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A traffic safety barrier for use at bridge piers in roadway medians has been designed and crash-tested. The hybrid system consists of steel drum crash cushions that have smooth transitions to concrete median barriers. The system is narrow enough to allow installation in relatively restricted median areas under highway overpasses. The crash cushions, which are located in front of the outermost bridge piers, act as energy absorbers for frontal impacts and as redirection barriers for angle impacts. The concrete median barrier serves as a redirection barrier for "interior" angle impacts. Two vehicles were directed into the side of the crash cushion at 10 and 20 deg to test the system in the crash cushion median barrier transition area. The vehicles were redirected smoothly and showed no spin-out or overturning tendency. Without structural repairs to the barrier after the 10-deg test, a lightweight vehicle was directed head on into the crash cushion and was brought to a stop in an acceptable manner.

•BRIDGE piers in roadway medians at highway overpass structures present a rigid-object hazard to passing motorists. The probability of injury to occupants of a vehicle that violates the median in the overpass area can be greatly reduced by adding an energy-absorbing device to the front of the outermost bridge piers.

The use of guardrails at such locations is not a wholly satisfactory solution because a substantial portion of the length of these median installations are end-treatments, and all currently available guardrail end-treatments are quite hazardous themselves (1). The hybrid crash cushion and concrete median barrier discussed in this report is one possible alternative to current treatments at these locations.

An impact attenuator that has a compatible transition to a concrete median barrier system was designed, constructed, and tested under a contract with the Federal Highway Administration (FHWA). These evaluation tests consisted of crashing two vehicles at angles of 10 and 20 deg into the side of the system and one vehicle head on into the crash cushion.

DESCRIPTION OF BARRIER SYSTEM

Two simulated concrete bridge piers were installed for the tests. The protective installation shown in Figure 1 is a combination of a shaped concrete median barrier (2) and a variation of the modular crash cushion (3, 4). This cushion was designed by the Structures and Applied Mechanics Division of FHWA with the assistance of the Texas Transportation Institute (TTI).

The crash cushion was composed of 55-gallon steel drums with holes in the tops and bottoms to reduce the crush strength. Plywood panels (2 ft high and 4 ft long) covered with sheet metal were attached to the side of the crash cushion adjacent to oncoming traffic to provide a redirection capability for vehicles that strike a glancing blow. These redirection panels are attached to the drums in a fish-scale fashion and telescope in a head-on collision without altering barrier crush characteristics.

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These 2- by 4-ft panels were chosen in preference to the 3- by 8-ft panel scheme used in earlier development tests (4) and in the demonstration conducted by U. S. Steel to minimize the ramping of the vehicle that was noted in these impacts. The 2- by 4-ft panel was inspired by Hensen's (5) use of 2- by 3-ft panels in the design of a barrier for use in Denver, Colorado. It was felt that the 2-ft high panels, centered on the 34¾-in. drums, would decrease ramping by offering a smaller smooth surface. It was anticipated that the tops and bottoms of the drum would probably lip over the panel edges during impact and retard any ramping tendency. Also, it was felt that the lower trailing corners of these 2- by 4-ft panels were not as likely to scrape against the ground and cause a tendency toward ramping in this fashion.

Steel cables gave the cushion and redirection panels lateral stability for side impacts. The cables were passed through eyebolts in the support posts so that the drums, support posts, and redirection panels could slide along the cables during a head-on collision. The ¾-in. wire rope cables were located at the top rolling hoop of the steel drum to encourage a slight downward wedging action (again to decrease ramping tendencies) of the panels during side impacts. This feature was suggested by the U. S. Steel demonstration tests conducted by TTI.

As shown in Figure 1, the support cables on the left (looking from the front of the crash cushion) were arranged differently. The two ¾-in. cables were located between the first and second columns of drums to eliminate vehicle snagging at the cable anchorage in the event a "reverse" impact occurred from traffic in the other lanes. No plywood redirection panels were used on the left side in this installation. If panels had been used on the left side, they would have had to be hinged at their rearward edge to redirect vehicles moving from the rear to the front. The outside top edge of the concrete median barrier was aligned with the side face of the steel drums (adjacent to front-to-rear traffic) so that unnecessary contact with the drums would be avoided.

The concepts for this barrier called for as narrow a barrier as possible to allow its use where space is restricted as well as to offer a smaller target to an errant vehicle in order to reduce the number of collisions with the barrier. For this reason, the shaped concrete median barrier was selected as an element of the hybrid barrier.

The number of drums per row toward the rear of the barrier was increased in previous designs for steel drum crash cushion tests to stop 2,000- to 4,500-lb impacting vehicles with acceptable decelerations and to avoid the use of an unnecessarily long barrier. This resulted in barrier designs that had four to six drums per row at the rear of the barrier. In those tests, all of the drums had the same crushing strength (same gauge and hole cutout pattern). This could be referred to as a monomodular design concept. The crash cushion used in these tests consisted of three columns of drums with relatively "soft" drums on the crash-cushion nose, "medium stiff" drums in the center, and "stiff" drums in the rear of the crash cushion.

The crush characteristics of these drums and the corrugated metal pipe segments used in this design are given elsewhere (6). It was recognized that the use of two or more different gauge drums with identical hole cutout patterns could result in confusion in the field. To minimize the possibility of such field problems occurring, we used the same gauge drums with varying hole cutout patterns. Data on crush resistances for various hole cutout patterns are given elsewhere (6).

The resulting design had the same number of drums in each row, which permitted the cables to be kept straight in plan view, as is desirable, and the side of the crash cushion to be aligned parallel to the roadway. This had the advantage of reducing the angle of impact with the side of the barrier in a given collision as compared with the previously discussed design.

The concrete median portion of this barrier is an adaptation of the GM shaped concrete section. In an earlier test (a 63-mph, 25-deg impact into a 32-in. high New Jersey shaped concrete median barrier) reported by Nordlin (2), portions of the sheet metal of the vehicle lipped over the top of the barrier. Because the concept of the hybrid barrier discussed in this report called for a design in which the concrete median section of the barrier could be placed as close as possible to the bridge piers, the concrete median barrier height was increased to 40 in. as shown in Figure 1. This modified GM shape had an upper face that was 25 in. high with a 3⅞-in. offset as compared to the 16⅞-in.

height and $2\frac{7}{8}$-in. offset of the standard GM shape. The purpose of this change was primarily to improve barrier performance for collisions involving pickup trucks and heavier vehicles. Evaluation of this aspect of the barrier design was beyond the scope of this investigation.

PHOTOGRAPHIC INSTRUMENTATION

Four high-speed cameras were used in Tests A and B. One camera was located perpendicular to the initial path of the vehicle, one parallel to the crash-cushion centerline, one perpendicular to the crash-cushion centerline, and one overhead. In Test C, a head-on impact, two cameras were located perpendicular to the crash-cushion centerline (and vehicle path), and one was mounted overhead. Three documentary cameras were used in all tests.

The high-speed motion pictures of the tests had timing marks on the edge of the film from which film speed, and therefore elapsed time, could be computed. Each test vehicle had a stadia board and several targets on it to facilitate the measurement of vehicle movement. The average speed of the vehicle over a desired interval could then be obtained from time-displacement determinations. These measurements were made along the path of the vehicle. The lateral motion of the vehicle (perpendicular to the crash cushion) was determined from the overhead or end-view cameras.

ELECTROMECHANICAL INSTRUMENTATION

In Tests A and B, transverse and longitudinal accelerometers were mounted on short flanges welded to each longitudinal frame member just behind the front seat. In Test C, only longitudinal accelerometers were included on the vehicle. Throughout this report, longitudinal decelerations indicate accelerations toward the rear of the vehicle, and transverse decelerations indicate accelerations toward the right of the vehicle (deceleration = negative acceleration). In all tests, an anthropometric dummy was secured in the driver's seat by a lap belt connected to a load cell that sensed lap belt force. In Test C, a head-on impact, biaxial accelerometers were mounted in the head of the dummy. The signals from the various transducers were transmitted by telemetry to a ground station and recorded on magnetic tape. The accelerometer data were passed through an 80-Hz low-pass active filter to reduce the effects of "ringing."

DESCRIPTION OF TESTS

Test A

A 4,150-lb Ford sedan was directed obliquely into the side of the crash cushion at a speed of 56.7 mph. The vehicle's approach path made a 20-deg angle with the centerline of the crash cushion. The impact point was selected such that the driver's seat was directed at the center of the front bridge pier. With this impact point, it was thought that maximum barrier deflection would occur in the vicinity of the transition between the crash cushion and the shaped concrete barrier and thus provide the most meaningful test for this transition. The left front end of the vehicle contacted the crash cusion at the rear edge of the fifth fender panel from the front, as shown in Figure 2. Both the maximum deformation of the crash cushion and the maximum vehicle decelerations occurred at roughly 0.150 sec after impact. As desired, the front end of the vehicle was near the bridge pier-median barrier transition at this time. Figure 3 shows sequential photographs from an end view. Elapsed times are not shown in Figure 3 because the camera used in the test does not incorporate timing marks on the film.

The vehicle redirected smoothly. The residual lateral deformation of the side of the crash cushion was 16 in. Seven steel drums and eight fender panels were damaged. Figure 4 shows the vehicle after the test. The left front of the vehicle was deformed 18 in. longitudinally and 16 in. transversely. The damage to the left front wheel caused the vehicle to swerve in an arc to the left after loss of contact with the barrier.

The vehicle deceleration data are given in Tables 1 and 2. The average lateral deceleration (from contact until the vehicle was parallel to the barrier centerline) calculated from high-speed film over a period of 0.27 sec was about 4 g. The accelerometers indicated a maximum longitudinal deceleration of 14.4 g and a maximum transverse

Figure 1. Crash cushion median barrier system.

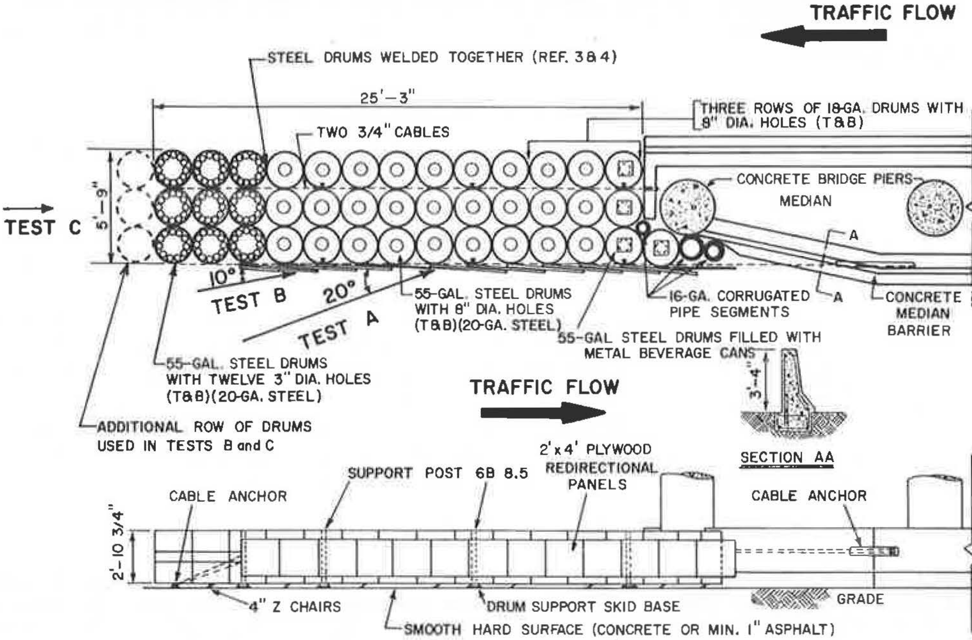


Figure 2. Barriers before and after Test A (oblique view).

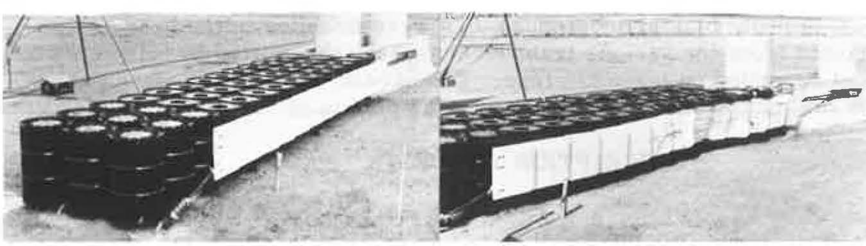


Figure 3. Sequential photographs of Test A (view parallel to barrier).

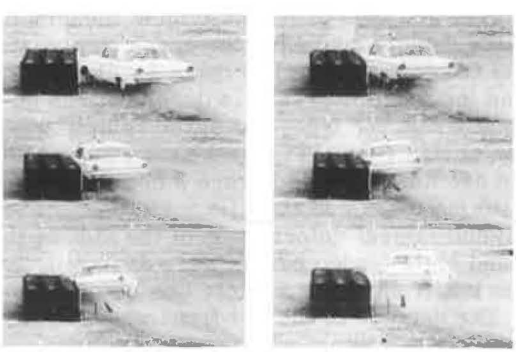


Figure 4. Vehicle after Test A.

deceleration of 10.4 g. The average longitudinal deceleration was 2.6 g over a period of 0.46 sec, and the average transverse deceleration was 2.0 g over a period of 0.46 sec.

Test B

In this test, a 3,990-lb 1964 Dodge sedan struck the barrier 10 deg to the centerline at a speed of 62.3 mph. The purpose of this test was to evaluate the transition between the crash cushion and the shaped concrete barrier under test conditions (60 mph, 10 deg) that have caused vehicle ramping and near overturn in previous tests. The crash cushion had been restored to its original condition with the exception of one corrugated steel pipe at the edge of the concrete backup wall that was not replaced. In addition, another row of steel drums was added to the front of the crash cushion. As in Test A, the impact point was selected such that the driver's seat was aimed at the center of the bridge pier.

Figure 5 shows the barrier after the test, and Figure 6 shows sequential photographs of the test. The damage to the crash cushion was slight. The redirection was very smooth, with only a slight ramping of the left front end of the vehicle observed. The vehicle left the barrier at an angle of about 5 deg to the centerline of the crash cushion; the tracks of the vehicle as it left the barrier can be seen in Figure 5. The damage to the vehicle is shown in Figure 7. The vehicle was driven away from the site after the test, which indicates, along with the small angle of departure, that a driver could have maintained control after the impact.

The accelerometer data showed that the maximum longitudinal deceleration was 3.4 g and the maximum transverse deceleration was 11.0 g. The average longitudinal and transverse decelerations over a period of about 0.4 sec were 0.8 and 2.0 g respectively. The high-speed film showed that the average longitudinal deceleration was 2.5 g and the average deceleration perpendicular to the crash cushion was 3.0 g. Parallelism occurred at 0.19 sec.

Test C

Damage reports from field installations indicate that more than one collision can occur before the damage is discovered and the crash cushion repaired. To evaluate the performance of the crash cushion after an angle impact, we conducted the final test of the series without restoring the crash cushion except for painting and reshaping some of the fender panels. (The shape of these panels does not have a significant effect in head-on impacts.)

A 1965 Simca weighing 1,790 lb struck the crash cushion head on at a speed of 55.8 mph. At test time, the crash cushion had a bow in it from the previous test; the maximum deformation was 9 in. The condition of the crash cushion before and after the test is shown in Figure 8. The damaged fender panels can be seen in Figure 9 (t = 0.000 sec). The front end of the lightweight, rear-engine vehicle was deformed 11 in. at the bumper level, and the hood was pushed back but did not penetrate the windshield.

The vehicle's forward motion stopped in 0.257 sec, after 11.3 ft of travel. The average deceleration over this interval, inferred from the films, was 9.2 g. The vehicle rebounded 1.8 ft. The average deceleration, inferred from the accelerometers, over a period of 0.356 sec was 7.2 g.

In this test, the resultant from the biaxial accelerometers in the dummy's head was plotted and graphically integrated piecemeal to obtain an index to compare to a published injury criterion called the Gadd Severity Index (7). This index is defined as follows:

$$SI = \int_0^t a^n \, dt$$

where

a = acceleration in g,
t = time in seconds, and
n = an exponent greater than unity.

Table 1. Film analysis data.

Factor	Test A	Test B	Test C
Vehicle weight, lb	4,150	3,990	1,790
Impact angle, deg	20	10	0
Initial speed, fps	83.1	91.4	81.8
Initial speed, mph	56.7	62.3	55.8
Final speed, fps	45.6	75.9	0[a]
Final speed, mph	31.1	51.7	0[a]
Time in contact, sec	0.513	0.414	0.257[a]
Distance in contact, ft	29.2	31.9	11.3[a]
Average longitudinal deceleration, g			
Vehicle parallel to barrier	4.0[b]	2.5[b]	9.2[a,b]
	3.9[c]	2.4[c]	9.9[c]
Loss of contact	2.6[b]	1.3[b]	8.9[b,d]
	2.3[c]	1.2[c]	7.8[c,d]
Average lateral[e] deceleration, g			
Vehicle parallel to barrier	3.9[b]	3.0[b]	–
	3.2[c]	2.6[c]	–

[a]At end of forward motion in Test C.
[b]Calculated by $(V_1^2 - V_2^2/2gD)$; where V_1 = initial speed, V_2 = speed at point of interest, D = distance traveled by vehicle's CG over interval used, and g = 32.2 ft/sec^2.
[c]Calculated by $(1/g)$ $(\Delta V/\Delta t)$, where ΔV = change in speed of vehicle's CG and Δt = time interval.
[d]To end of accelerometer traces (0.5 ft of rebound).
[e]Lateral = perpendicular to barrier centerline.

Table 2. Accelerometer data.

Factor	Test A	Test B	Test C
Vehicle weight, lb	4,150	3,990	1,790
Impact angle, deg	20	10	0
Maximum deceleration,[a] g			
Longitudinal	14.4	3.4	13.8
Transverse	10.4	11.0	–
Average deceleration,[a] g			
Longitudinal	2.6	0.8	7.2
Time interval, sec	0.460	0.411	0.356
Transverse[b]	2.0	2.0	–
Time interval, sec	0.461	0.410	–

[a]Values given are averages of right and left accelerometer outputs.
[b]Transverse to vehicle longitudinal axis.

Figure 5. Barrier after Test B (oblique view).

Figure 6. Sequential photographs of Test B (overhead view).

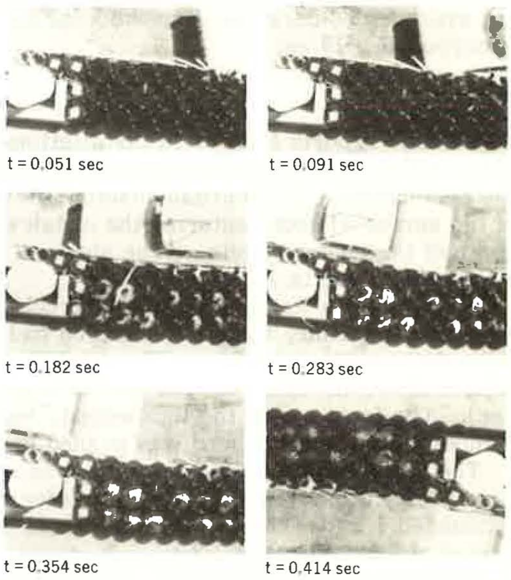


Figure 7. Vehicle before and after Test B.

Figure 8. Barrier before and after Test C (end view).

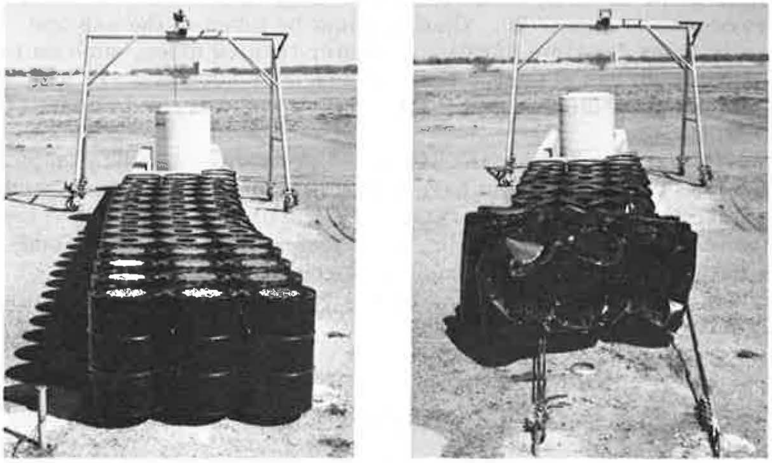
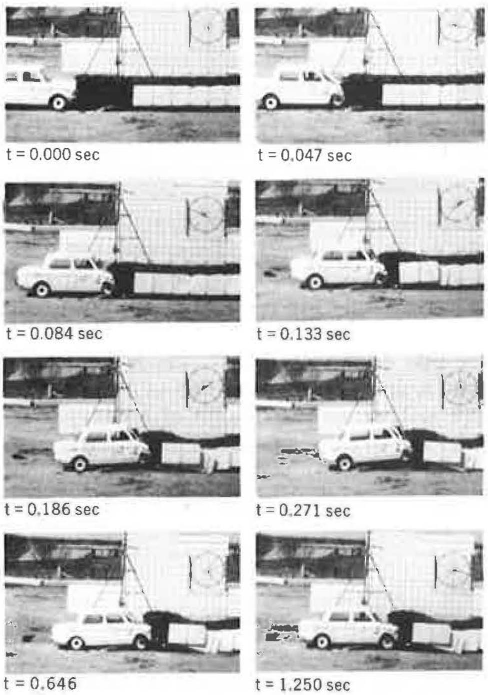


Figure 9. Sequential photographs of Test C (view perpendicular to barrier).



t = 0.000 sec
t = 0.047 sec
t = 0.084 sec
t = 0.133 sec
t = 0.186 sec
t = 0.271 sec
t = 0.646
t = 1.250 sec

For head-face impacts that last between 1 and 60 msec (8), the exponent n has a value of 2.5; the upper limit of the severity index for survival is estimated to be about 1,000, and moderate injury occurs at about 700. Caution must be taken in the use and interpretation of the severity index for time durations greater than 60 msec, such as in this test. For example, Snyder (8) has observed that, although we normally are exposed to 1 g our entire lives, the formula indicates that a fatal injury would occur in about 16 min.

The severity index for this test was 176 for the 540-msec event, which indicates a low probability of head injury. The index would have been lower had it been calculated over the most severe 60-msec interval. The photographs showed that the dummy's face hit the upper portion of the steering wheel; however, the chest, which hit the steering column and lower part of the steering wheel, probably absorbed most of the energy of the torso motion. The dashboard of the vehicle was bent outward by the steering column, and the driver's seat was shifted forward.

CONCLUSIONS

The results of this study allow the following conclusions to be made:

1. The modular crash cushion with compatible transition to a concrete median barrier performed comparable to previous modular crash cushions in attenuating a head-on vehicle impact.
2. The crash cushion used in this test series with a compatible transition to a concrete median barrier had sufficient lateral strength to smoothly redirect 4,000-lb vehicles impacting the side of the cushion at a speed of 60 mph and at angles of 10 and 20 deg.
3. In angle impacts, the vehicles remained relatively stable during and after the redirection process and showed no tendency to ramp, overturn, or spin out. The 2- by 4-ft redirection panels appear far superior to other previously tested redirection panels used on the steel drum crash cushion. Accordingly, adaptation of this panel and cable arrangement to other steel drum crash cushion designs should improve their performance.
4. The vehicle decelerations in all tests indicate that a properly restrained passenger would have survived the impacts with little or no injury (9). This, coupled with the very stable behavior and low departure angles of the vehicles in the angled impacts, suggests that a properly restrained driver might have been able to regain control of the redirected vehicles.
5. This barrier design can also be adopted for use at elevated exit ramps by using the cable and panel arrangement impacted in Tests A and B on both sides of the barrier.
6. Use of the information presented by White (6) will allow the design of a barrier of this type using all 20-gauge drums with different crash strengths (hole cutout patterns) rather than the combination of 18- and 20-gauge drums used in these tests. This should reduce possible confusion in the field because for each selected crush resistance a different hole cutout pattern would be selected.

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