PERFORMANCE OF THE HI-DRO CUSHION CELL BARRIER VEHICLE-IMPACT ATTENUATOR

Gordon G. Hayes, Don L. Ivey, and T. J. Hirsch, Texas Transportation Institute, Texas A&M University

The Hi-Dro Cushion Cell Barrier vehicle-impact attenuator consists basically of water-filled plastic tubes with orifices in the caps. A colliding vehicle forces the water out the orifices, thereby experiencing a restraining force that depends on orifice size and number, number of tubes being compressed, amount of water in the tubes, and other design considerations. Six full-scale crash tests were conducted to evaluate the effectiveness of the barrier as a vehicle-impact attenuator. The resulting test decelerations were substantially lower than those from a rigid wall test included for comparison purposes. Other full-scale tests have been conducted elsewhere. Data from a computer simulation model of the crash cushion developed at Brigham Young University showed excellent agreement with data from selected tests performed in this series.

•AS PART of its 4S program (Structural Systems in Support of Highway Safety), the Federal Highway Administration sponsored a series of vehicle crash tests to help evaluate the Hi-Dro Cushion Cell Barrier vehicle-impact attenuator. The testing was conducted in September, October, and November of 1969.

The impact attenuator has been analyzed and simulated by digital computer under another portion of the 4S program (1). This system is now handled by Energy Absorption Systems, Inc., of Chicago.

The crash cushion consists of an assembly of plastic, water-filled tubes with orifices in the caps. When the Hi-Dro Cushion Cell Barrier is struck by a vehicle, the water in the tubes is forced out the orifices. This reaction of individual tubes results in a predictable barrier deformation-force characteristic. Augmenting the vehicle-stopping force is the barrier inertia.

DESCRIPTION OF SYSTEM

The basic unit of the crash cushion is the Hi-Dro Cushion Cell, which is a hollow cylinder or envelope made of plastic material (Fig. 1). The cap contains orifices through which the water in the cell can be expelled. The stiffness of the cell is determined by the orifice areas. These cells were assembled as shown in Figure 2 for the first three tests.

The 138 cells were divided among eight "bays" separated by diaphragms as shown in Figure 2. The third bay from the front was void of cells due to design factors concerning the profile of the acceleration pulse produced during impact (1). The diaphragms separating the bays were made of 1½ in. fiberglass-coated plywood. The three diaphragms closest to the rigid barrier each had two ¼ in. steel plates attached. The rows of cells in each bay were separated by ¼ in. Duraply interior panels.

The fish-scale fender panels were designed to provide redirectional ability during angled impacts, while providing minimum interference during head-on crashes. These panels were hinged to the transverse diaphragms and were made of 1¼ in. fiberglass-coated plywood in the first three tests. The last three fender panels on the "off" side of the cushion were left off in order to avoid modification of the existing backup wall.

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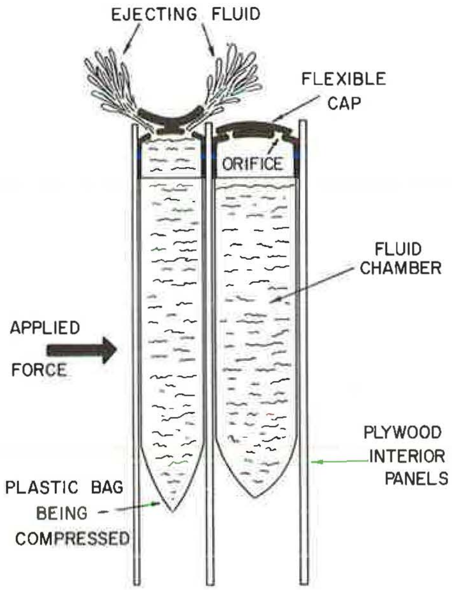

Figure 1. Function of Hi-Dro Cushion Cell.

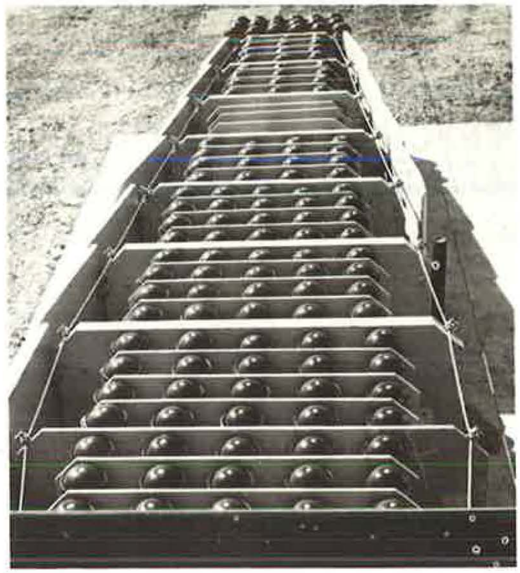

Figure 2. Top view of barrier.

In the final two tests, the five front fender panels on the impacted side were made of fiberglass-coated Hexcel, which is a lightweight, high-strength paper material resembling a honeycomb. In addition, the wood portions of the second and third diaphragms from the rear of the attenuator were removed and the 12-gage steel plate in the last diaphragm was eliminated in order to maintain the previous weight distribution after the modified fender panels had been installed. The $\frac{7}{8}$-in. diameter restraining cables were increased to 1 in., and the last diaphragm was increased in width to provide a constant diverging side slope.

TEST PROGRAM

The test conditions for the series are given in Table 1. For the angled tests, the impact point was approximately the rear edge of the first fender panel. The side of the unit diverged from the centerline by 6 deg 9 min, making an impact angle with the side of the cushion of about 26 deg.

Four accelerometers were used in each test vehicle, two on each longitudinal frame member. For head-on tests, all were mounted longitudinally, while in the angled tests, one on each side was mounted transversely. In addition, a mechanical Impactograph was mounted in the vehicle trunk as a secondary source of acceleration data.

TABLE 1
TEST CONDITIONS

Test	Vehicle	Weight (lb)	Initial Speed (mph)	Initial Angle With Barrier Centerline (deg)	Propulsion
A	1964 VW sedan	1,820	42	0	Self-powered
B	1961 Pontiac sedan	4,650	64	0	Self-powered
C	1963 Pontiac sedan	4,410	54	20	Self-powered
D	1962 Renault sedan	1,680	59	0	Towed
E	1964 Dodge sedan	3,710	59	20	Self-powered

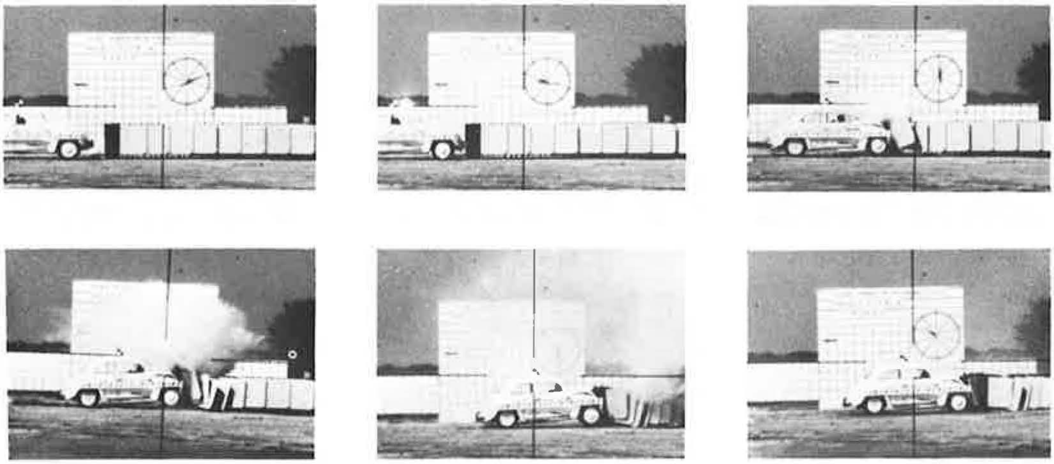

Figure 3. Sequential photographs of Test A.

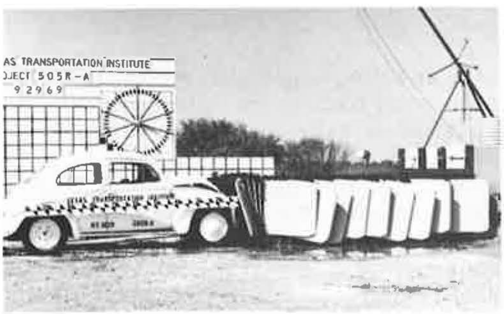

Figure 4. Vehicle and barrier after Test A.

An Alderson anthropometric dummy simulated a driver and was secured by a seat belt attached to a load cell for measuring seat-belt force. Redlakes Hycam cameras, operating at 500 frames per second, recorded the events for time-displacement analysis. A Photosonics camera (500 frames per second) was mounted over the barrier looking vertically downward. Much of the event was obscured in this view by the ejected water. Other cameras covered each test for documentary purposes.

The initial velocity and stopping distance, or distance in contact, can be measured accurately from the high-speed films, and an average deceleration can be calculated from these values. This average deceleration can be compared with that from the electromechanical accelerometers, which also indicate peak g.

DESCRIPTION OF TESTS

Table 2 gives the pertinent test data. In the first test, a Volkswagen sedan weighing 1,820 lb impacted the barrier head-on at 42 mph. The vehicle was stopped in 13.2 ft with an average deceleration of 4.5 g and a peak deceleration of 14.6 g. The vehicle damage was not severe (Figs. 3 and 4).

The second test used a Pontiac sedan weighing 4,650 lb that impacted head-on at an initial speed of 64 mph. The average deceleration over 17.3 ft and 0.34 sec was 7.9 g, while the maximum deceleration of 13.4 g was lower than that of the first test (Figs. 5 and 6).

In the third test, a Pontiac sedan weighing 4,410 lb struck the cushion at 54 mph and at an angle of 20 deg with the barrier centerline. The vehicle had begun to redirect and had rotated approximately 5 deg when the main restraining cables pulled out of their front anchorage connections. The left front of the vehicle went head-on into the rigid barrier, and the vehicle rolled over on its right side (Figs. 7 and 8).

The cables pulled out of their connectors due to an improper installation procedure. A lead filler was used instead of a more desirable babbitt metal. All cushion units in

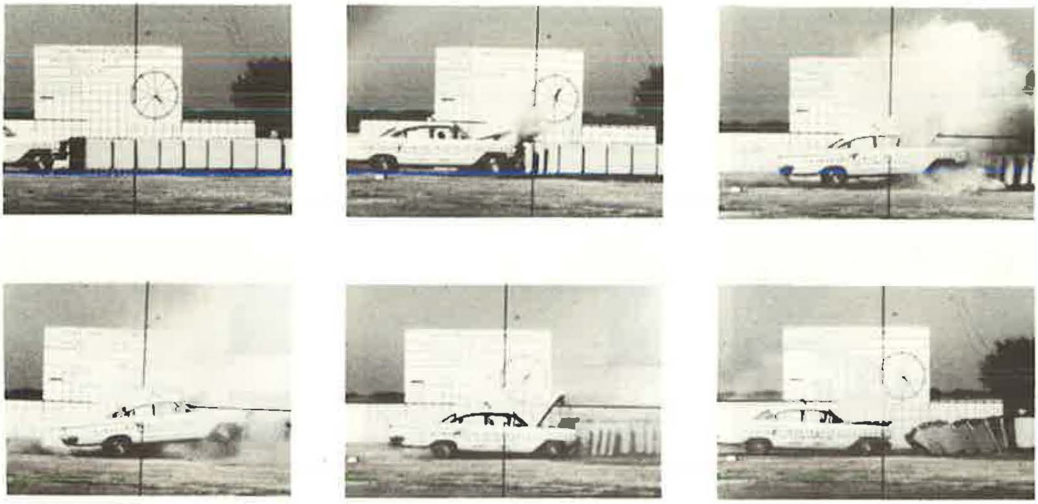

Figure 5. Sequential photographs of Test B.

Figure 6. Vehicle after Test B.

service are equipped with factory-fabricated cables and connectors. Because of this installation error, this test cannot be judged to be representative of the performance of the barrier. In spite of this, the films showed a very tolerable average deceleration of 5.8 g over 16.7 ft and 0.34 sec, while the accelerometers detected a peak of only 14.6 g.

Before the fourth test, the modifications mentioned earlier were made. The vehicle was powered by a towing system that disengaged from the vehicle before impact. In this test a 1,680-lb Renault was directed head-on into the cushion at 59 mph. The stopping distance of 16.3 ft gave an average deceleration of 7.1 g (over 0.58 sec), and the maximum deceleration was 15.6 g.

The vehicle apparently struck the front of the barrier about 1 ft off-center and started a yaw and roll motion, finally rolling over on its top after most of the kinetic energy had been absorbed (Figs. 9 and 10).

The final test was another 20 deg impact. A 3,710-lb Dodge sedan traveling at 59 mph was used. This was the only test in which the vehicle left the barrier with significant speed. The average longitudinal deceleration of 4.9 g was calculated over the distance in contact of 19.4 ft by noting the speeds at the beginning and end of this contact. The maximum deceleration was 8.9 g. Figure 11 shows the vehicle after the test.

In this last test, the vehicle began to ramp or climb up the side of the barrier. It became completely airborne by as much as 1.5 ft for about 20 ft and, upon recontacting the ground, rolled over on its left side before coming to rest upright. Examination of vehicle and barrier indicates that a slight contact was made with the upper corner of the rigid steel wall. The path of the vehicle contact up the side panels is shown in Figure 12.

The steel barrier in front of the concrete wall was pulled away from the concrete about 6 in. at the bottom and about 2 in. at the top. The restraining cables were fastened to this steel barrier so this could allow as much as 2 ft of additional localized lateral movement to the cushion.

Figure 7. Sequential photographs of Test C.

Figure 8. Vehicle after Test C.

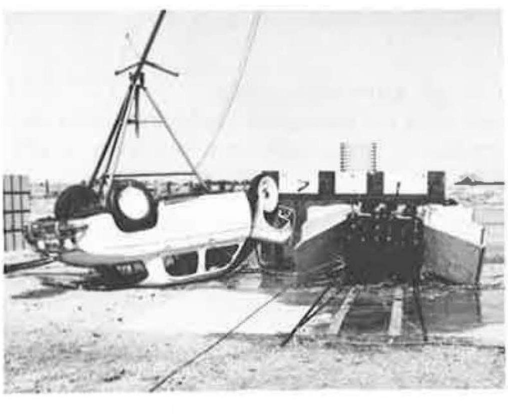

Figure 9. Vehicle and barrier after Test D.

Figure 10. Vehicle after Test D (righted).

Figure 11. Vehicle after Test E.

Figure 12. Barrier after Test E.

TABLE 2

SUMMARY OF DATA

Factor	Test A	Test B	Test C	Test D	Test E	Test Rigid Wall
Vehicle weight, lb	1,820	4,650	4,410	1,680	3,710	3,270
Angle of impact, deg	0	0	20	0	20	0
Film data						
Initial speed, mph	42	64	54	59	59	53
Initial speed, fps	61.6	93.6	79.3	86.3	86.6	78.3
Average longitudinal deceleration, g	4.5	7.9	5.8	7.1	4.9	25.0
Stopping distance, ft	13.2	17.3	16.7	16.3	19.4[a]	3.8
Time in contact, sec	0.74	0.34	0.34	0.58	0.34	0.10
Longitudinal accelerometer data						
Maximum deceleration, g	14.6	13.4	14.6	15.6	8.9	35.0
Average deceleration, g	3.1	6.8	5.6	7.3	4.6	18.0
Time, sec	0.46	0.47	0.42	0.29	0.33	0.13
Transverse accelerometer data						
Maximum deceleration, g	—	—	5.7	—	9[b]	—
Average deceleration, g	—	—	1.1	—	2	—
Time, sec	—	—	0.42	—	0.33	—
Attenuation index[c]						
$AI_{(max)} = \frac{G_{max}\text{ (test)}}{G_{max}\text{ (rigid wall)}}$	0.4	0.2	0.3	0.3	0.2	0.7
$AI_{(avg)} = \frac{G_{avg}\text{ (test)}}{G_{avg}\text{ (rigid wall)}}$	0.2	0.2	0.2	0.2	0.1	0.7
Vehicle deformation, ft	1.04	1.83	3.33	2.33	0.83	3.82

[a]Distance in contact.
[b]From Impactograph (accelerometers malfunctioned).
[c]G (maximum rigid) = 0.9V, G (average rigid) = 0.574V, V in mph (2).

Pertinent data from a rigid wall test (3) conducted in March of 1969 are given in Table 2 and shown in Figure 13 for comparison purposes. This vehicle was a 1963 Plymouth sedan weighing 3,270 that was directed head-on into a rigid concrete wall at 53 mph. The vehicle stopped in 3.8 ft (vehicle deformation) with an average deceleration of 25 g and a peak deceleration of 35 g.

Figure 13. Rigid wall crash test.

The damage to the cushion in the head-on tests was relatively minor, usually in the form of torn plastic cells that were easily replaced. The following listing of parts replaced gives an idea of the severity of damage to the barrier in each test:

Test A—No parts were replaced.

Test B—25 cartridges were replaced, 19 of which were repairable.

Test C—Failure of anchorages caused damage that necessitated replacement of several fender panels, diaphragms, and interior panels. (Some replacements were made in the course of the previously mentioned modification of the barrier structure.)

Test D—No parts were replaced.

Test E—Damage occurred to fender panels only. No replacements were made because no further tests were planned.

FIELD EXPERIENCE

One severe collision with a Hi-Dro Cushion Cell Barrier located in New Orleans, Louisiana, has been reported recently (4). On April 2, 1970, a vehicle skidded sideways into the barrier on rain-slick pavement at an estimated speed of 70 mph. The driver's side of the vehicle impacted the barrier nose. The driver, who was unrestrained, suffered cuts and bruises but was treated and released. The vehicle was towed to a garage, and then driven inside. The authors of the report feel that the collision would have undoubtedly been fatal if the impact attenuator had not been there.

DISCUSSION OF RESULTS

Table 2 gives a comparison of attenuation indexes, which are defined as the ratios of decelerations experienced in the cushioned impacts to those calculated for rigid barrier impacts. The values experienced in a rigid wall crash will depend in part on the crush characteristics of the impacting vehicle. For this reason the index for the rigid wall test is not unity. The more attenuation caused by the inclusion of a crash cushion, the smaller will be the attenuation index.

The predictions of the mathematical model developed at Brigham Young University showed very good agreement with the test data for the head-on tests (1). No predictions were made for the angled tests.

Great design flexibility is possible by varying orifice size and number, arrangement of cells, size of cells used, and amount of fluid in the cells.

The 4S program of the Federal Highway Administration uses the following criteria for development and testing of protective barriers (5):

Vehicle weight range—2,000 to 4,500 lb.

Vehicle speed—60 mph.

Impact angle—Up to 25 deg as measured from the direction of the roadway.

Average permissible vehicle deceleration—12 g maximum while preventing actual impacting or penetration of the roadside hazard.

Maximum occupant deceleration onset rate—500 g per sec.

The observed average deceleration levels were significantly below the 12-g level in all tests. The accelerometer traces showed that the 12-g level was exceeded by peak decelerations no longer than 0.03 sec except in Test D, which was a head-on test of a vehicle weighing less than the minimum weight specifications.

Other tests on this type of barrier have been conducted by Rich Enterprises, the California Division of Highways, and Brigham Young University. The results of these tests have, in general, shown acceptable performance of this vehicle-impact attenuator.

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Federal Highway Administration.

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