The Modular Crash Cushion—Research Findings and Field Experience

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The modular crash cushion is an arrangement of 55-gal tight-head barrels positioned to protect motorists from inadvertently driving into rigid obstacles. A crash cushion should be capable of stopping a moving vehicle over a distance sufficient to allow a relatively low deceleration rate. The modular crash cushion has been subjected to 6 full-scale vehicle crash tests. Three of these tests were head-on impacts, 2 were at an impact angle of 30 deg, and 1 was at an impact angle of 20 deg. The photographs and data reported in this paper show that the modular crash cushion was highly effective in stopping vehicles with acceptable levels of deceleration. As a result of these tests, modular crash cushions have been installed at 4 locations in Houston and 2 locations in Dallas; contracts are being let for additional installations in Texas and other states. Since the cushions were installed in Houston, 5 vehicles have collided with them with very minor damage to the vehicles. Only 1 of the 5 drivers received even minor injuries.

•THE MODULAR CRASH CUSHION, in its first-generation form, is an arrangement of 55-gal tight-head barrels positioned to cushion or reduce the severity of vehicle collisions with rigid highway obstacles. This protective device is crashworthy and economical. It has been subjected to 6 full-scale vehicle crash tests that are reported in this paper. A typical arrangement is shown in Figure 1.

The occurrence of several single-vehicle accidents at elevated exit ramps on the Interstate Highway System pointed out the need for such a crash-cushion system. This type of accident has occurred when motorists were traveling on the main freeway lanes and decided too late to try to turn onto an off ramp. The gore separating the off ramp from the main lanes usually terminates in a reinforced concrete wall that anchors the bridge railing (Fig. 2). This railing prevents motorists from inadvertently driving over the side of the freeway. Misjudgment on the part of the motorist when attempting the exit turn can result in a collision with the concrete retaining wall in the gore, even though these retaining walls have been heavily delineated as danger zones. The recurrence of accidents with this general pattern demonstrated the need for a protective impact-attenuation system at these points.

The purpose of the modular crash cushion is to stop a moving vehicle over a distance sufficient to allow a relatively low deceleration rate (approximately 12 to 18 ft for a 60-mph vehicle velocity). The proposed protective system was subjected to 6 full-scale vehicle crash tests; 3 of these tests were head-on, 2 were at an impact angle of 30 deg, and 1 was at an impact angle of 20 deg.

As a result of these tests, modular crash cushions have been installed at 4 locations in Houston and 2 locations in Dallas; contracts are being let for additional installations in Texas and other states. Figure 2 shows one of the Houston locations

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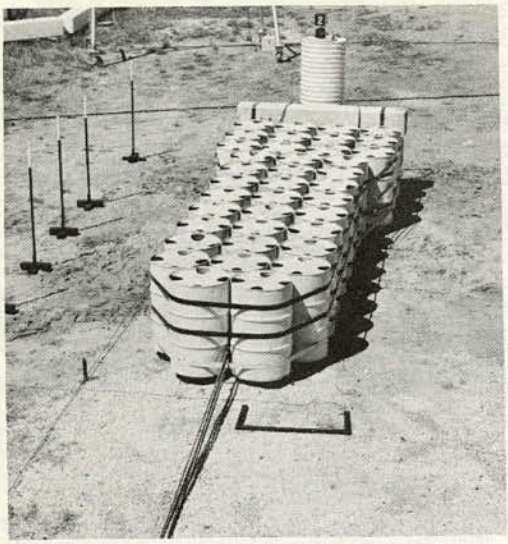

Figure 1. Modular crash cushion.

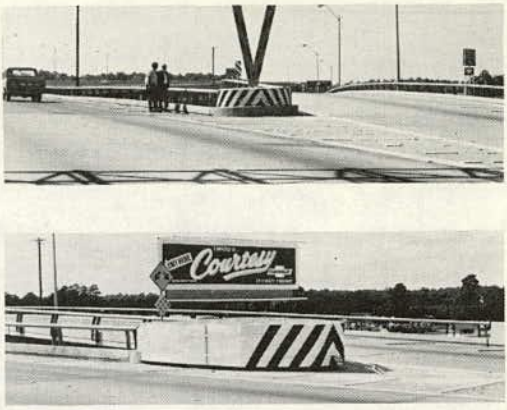

Figure 2. Elevated gore in Houston before and after installation of modular crash cushion.

before and after the installation of the modular crash cushion. Since the installation at 4 sites in Houston, 5 vehicles have collided with the crash cushions. Only 1 of the 5 drivers received even minor injuries. The minor injury occurred when the vehicle impacted a bridge rail after the collision with the modular crash cushion. The early field experience with the modular crash cushions has been very good.

DETAILS OF MODULAR CRASH CUSHIONS

A typical modular crash cushion configuration is shown in Figure 3. Protecting a simulated rigid bridge pier, the cushion is composed of 38 barrels that are welded together at top and bottom at every point where their rims meet. Portions of the tops and bottoms of the barrels were cut out to reduce the crushing strength to the desired

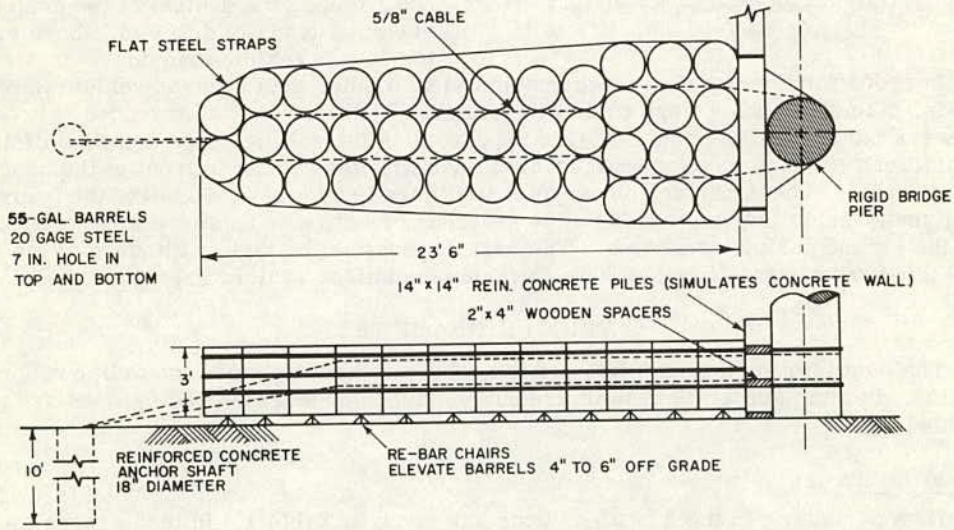

Figure 3. Typical configuration of modular crash cushion.

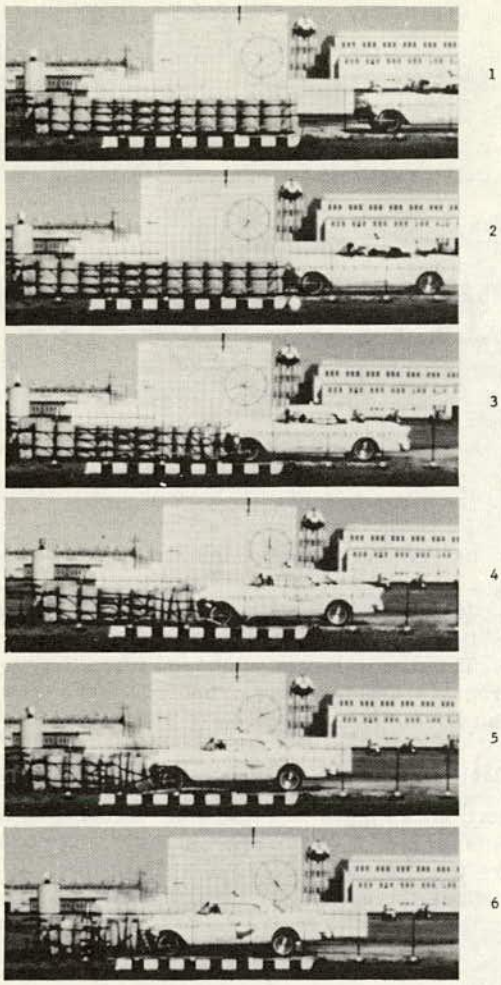

Figure 4. Sequential photographs during test 2.

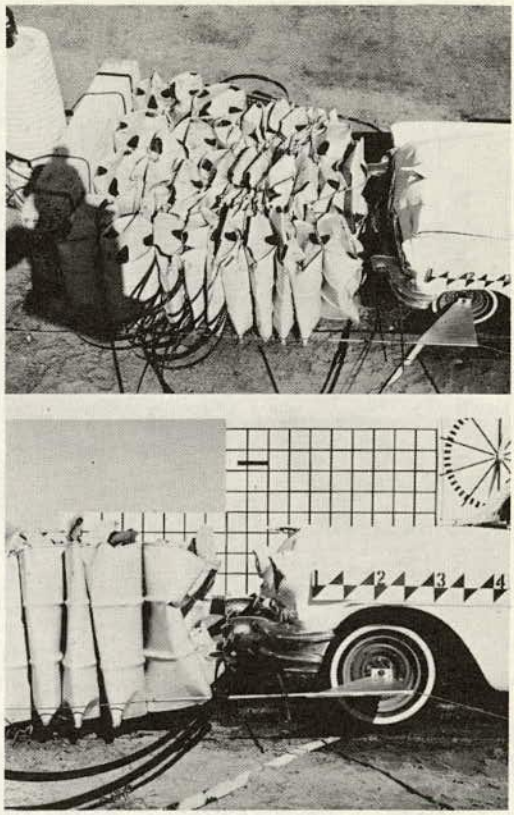

Figure 5. Crash cushion and vehicle after test 2.

level. The barrel system is surrounded by 3 steel banding strips and is supported by reinforcing bar chairs. These re-bar chairs place the system at the desired elevation (usually 4 to 6 in. above grade) to prevent vehicle ramping.

In order for the modular crash cushion to take other than head-on vehicle impacts, $^5/_8$-in. diameter cables were tied to the simulated bridge pier and threaded between the rows of barrels. These cables were supported on the rolling hoops and tied off at a reinforced concrete anchor shaft located flush with the ground in front of the nose of the barrier. These cables, shown as dotted lines in Figure 3, stabilize the barrel system under angle impacts and have the secondary function of holding the barrels close to the ground during a collision. The barrels must not be rigidly attached to the cable, but must remain free to slide down the cable during the vehicle impact.

VEHICLE CRASH TESTS

The details of instrumentation and data analysis are explained in earlier reports (1, 2). In this paper, the results are summarized and selected photographs are presented.

Head-On Tests

Data pertaining to the 3 head-on tests are given in Table 1. In test 1 there was almost negligible damage to the vehicle. The 1964 Dodge, traveling at 60 mph, was

TABLE 1

CHARACTERISTICS OF HEAD-ON TESTS

Characteristic	Test 1	Test 2	Test 3
Vehicle weight, lb	3,200	4,460	3,360
Vehicle velocity, fps	88.3	81.7	77.1
Stopping distance, ft	13.3	16.0	12.1
Maximum longitudinal deceleration, g			
Electronic accelerometer	12.7	8.0	–
Impact-O-Graph	–	13.0	12.0
Average longitudinal deceleration, g			
Electronic accelerometer	–	5.2	–
Calculated[a]	9.1	6.5	7.6
Impact-O-Graph	–	6.8	6.4
Attenuation index			
$AI_{(max)} = \frac{G(\text{max barrels})}{G(\text{max rigid})^b}$	0.23	0.27	0.25
$AI_{(avg)} = \frac{G(\text{avg barrels})}{G(\text{avg rigid})^b}$	0.27	0.22	0.26

[a]Calculated from stopping distance (Table 2).

[b]G(max rigid) = 0.9V; G(avg rigid) = 0.574V; V in mph (4).

stopped in 13.3 ft at an average deceleration of 9.1 g (Table 2 gives the calculation for average deceleration from stopping distance). In test 2, the test vehicle was stopped in 16 ft at an average deceleration of only 6.5 g (Figs. 4 and 5). This test was conducted on a 23.5-ft protective system. A shorter, more compact attenuation device was used in test 3. This system stopped the test vehicle in only 12.1 ft at an average deceleration of 7.6 g.

A comparison of the severity of these crashes is given in Table 1 by the attenuation index. The maximum and average decelerations that would have been experienced by the vehicle had it struck a rigid barrier, such as a concrete retaining wall, are calculated using accepted theory. The attenuation index is the ratio of the test maximum or average deceleration divided by the rigid barrier maximum or average deceleration respectively. In these two tests the decelerations are approximately a fourth as severe as they would have been had the vehicle struck an unyielding rigid object.

Angle Tests

A comparison of the 3 angle vehicle crash tests is given in Table 2. Test 4 gave the longest stopping distance and correspondingly the smallest values of vehicle decelerations. Undue emphasis should not be placed on this test because of the occurrence of a structural failure of the cable anchorage system. When the vehicle collided with the barrels, the cable support that was in front of the nose of the barrel system was torn loose. The failure of the cable support allowed the barrel system to rotate laterally away from the vehicle, and this produced a significantly smaller resistance to the movement of the vehicle. If the vehicle had been traveling at a higher speed (velocity at impact was 41 mph), the secondary impact of the vehicle with the bridge abutment could have been severe.

TABLE 2

CHARACTERISTICS OF ANGLE TESTS

Characteristic	Test 4	Test 5	Test 6
Angle of impact, deg	30	30	20
Longitudinal stopping distance, ft	16.2	13.2	13.7
Vehicle weight, lb	3,640	3,540	3,860
Vehicle velocity, fps	60.6	73.2	59.7
Maximum longitudinal deceleration, g			
Electronic accelerometer	4.7	6.8	–
Impact-O-Graph	–	–	9.0
Maximum transverse acceleration, g			
Electronic accelerometer	–	6.4	7.4
Impact-O-Graph	–	–	11.0
Average longitudinal deceleration, g			
Electronic accelerometer	2.5	3.9	–
Calculated[a]	3.5	6.3	4.0
Impact-O-Graph	–	–	4.6
Average transverse acceleration, g			
Electronic accelerometer	–	0.8	3.5
Impact-O-Graph	–	–	6.4

[a]Calculated from stopping distance. The most reliable deceleration measurement is the one calculated from the stopping distance and the vehicle initial velocity by the equation, $G_{avg} = (V^2/2gS)$, in which V is the initial velocity in fps; S is the movement of the vehicle's center of gravity in ft from its position at first contact to its position when the vehicle has a longitudinal velocity of zero; and g is the acceleration of gravity, 32.2 ft/sec^2.

In test 5, the barrel system was surrounded with 12-gage W-guardrail, which was not rigidly attached to the barrels and could slip through the supports as the barrels crushed. It was intended that the guardrail would help provide the necessary lateral stability and redirect the vehicle. The necessary lateral stability was achieved, but at the high impact angle of 30 deg the vehicle pocketed in the barrel-guardrail system. Because of the increased rigidity provided by the guardrail, the average deceleration level was higher than it was in either of the other two angle-impact tests.

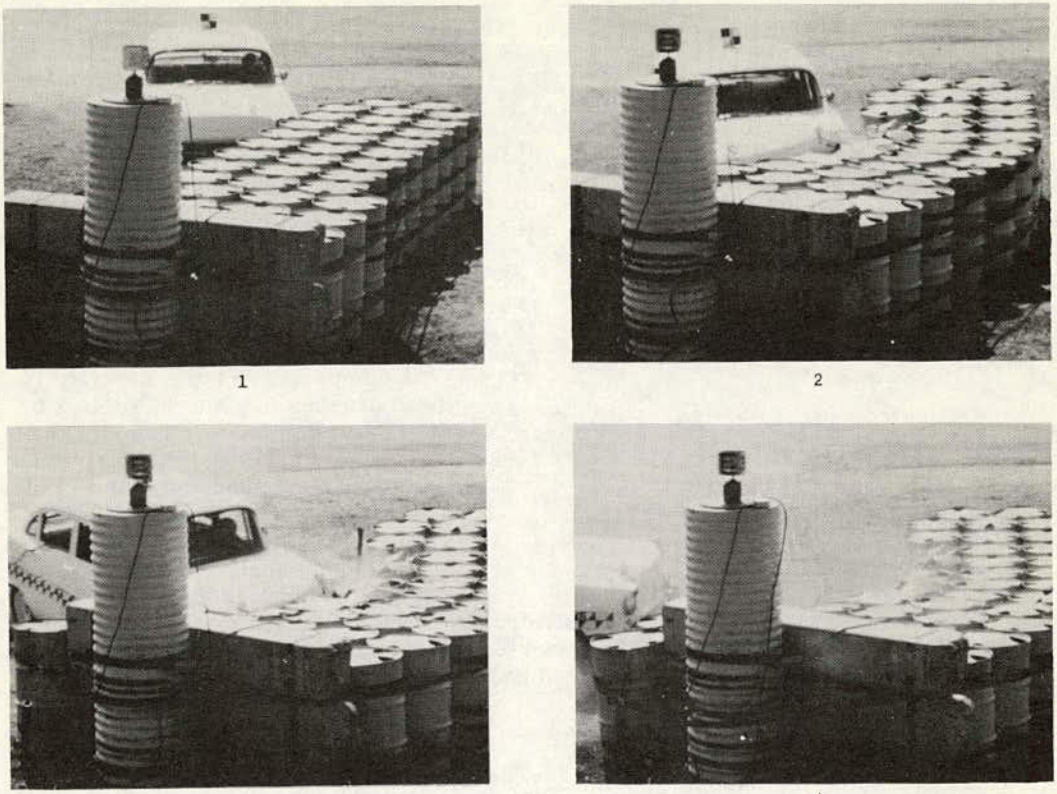

Figure 6. Sequential photographs during test 6.

The final test of an angular collision (test 6) showed an acceptable interaction between the vehicle and the protective system. At an impact angle of 20 deg, the vehicle was stopped with an average longitudinal deceleration of 4.6 g, a level that is not difficult for a restrained passenger to undergo. The only shortcoming of this test was rebound of the system caused by the elastic energy stored in the cables. This caused the vehicle to be pushed out and away from the impact area after the crash (Fig. 6). Provisions were made to reduce this stored energy in the field installations by securing the cables with deformable supports.

Another way of showing the satisfactory performance of these barrel systems is shown in Figure 7 (3). This figure, which is based primarily on the work of Stapp and De Haven, defines the area of severe injury, area of moderate injury, and area of noninjury for human exposure to g-levels of various durations. The tests of the barrel protective devices are shown by the large black dots. The numeral beside each dot designates the particular test. All barrel tests conducted by the Texas Transportation Institute are well within the area of acceptable human tolerance. It should be emphasized that this area was defined on the basis of a restrained passenger subjected to sternumward acceleration. Injury could result at these deceleration levels because of a second collision of the passenger with the interior of the vehicle if the passenger is not restrained.

DESIGN

The application of very simple principles of structural behavior allow the design and analysis of modular crash cushions. These procedures are given in detail in an earlier report (2) and are only briefly summarized here.

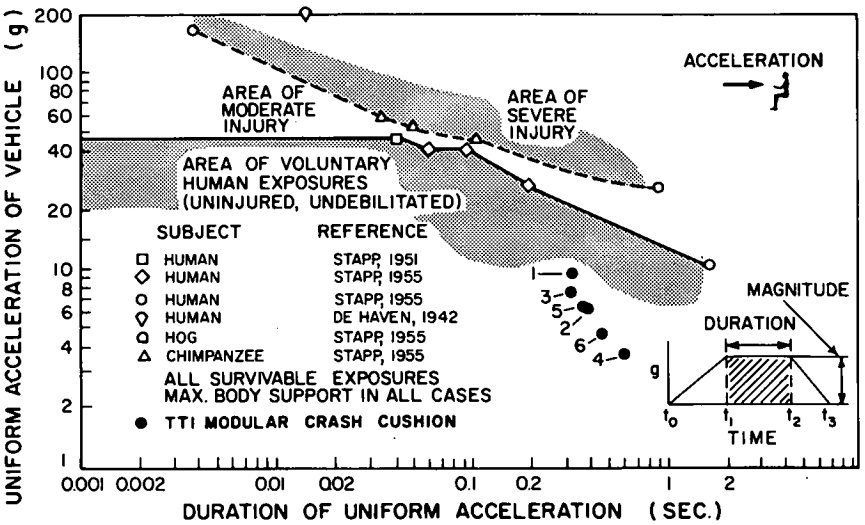

Figure 7. Maximum human tolerance limits to transverse acceleration (sternumward g).

Failure Mode

Figure 8 shows the successive crushing of rows of barrels when the system is impacted head on by a speeding vehicle. As the vehicle penetrates and deforms the modular crash cushion, a stopping force is applied to the vehicle. In Figure 8-2 the first row of barrels has been crushed. The force necessary to crush a single barrel, f_b, has been determined from laboratory static tests. The inertia of the barrels was not taken into consideration. Therefore, the force necessary to crush the first row of barrels (2 abreast) will be 2 times f_b. Similarly, after the next 8 rows of barrels have been crushed (at 3 times f_b), the total necessary crushing force will be 4 times f_b during the crushing of the last 3 rows (4 abreast).

The crash tests have shown that the average deformation of each barrel, among those that are crushed, is 75 percent of its original diameter. Thus a barrel that was originally 24 in. in diameter can be expected to crush approximately 18 in. Measurements of the area under the static force-deformation curve for each particular type of barrel can be used to determine the energy necessary to crush the barrel, e_s.

Analysis of full-scale vehicle crash test data, however, has indicated that the average energy consumed by each barrel in a modular

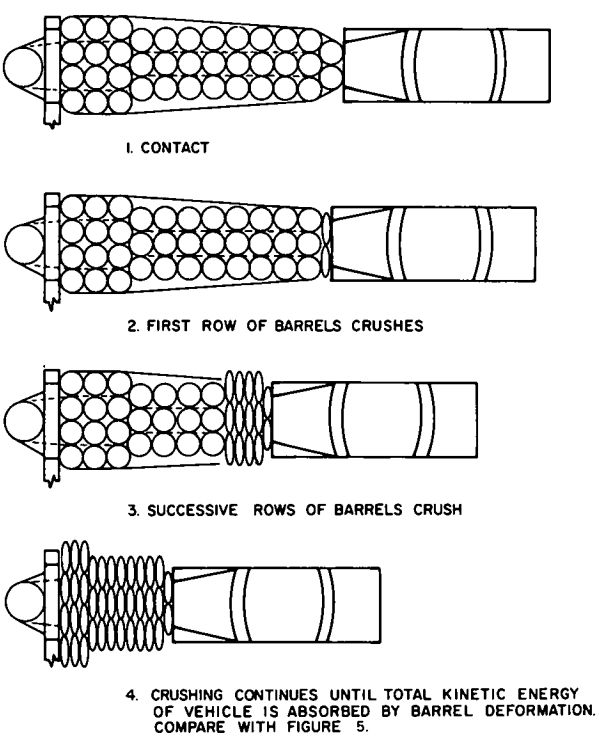

Figure 8. Successive crushing of modular crash cushion.

crash cushion, e_d, is actually about 50 percent higher than that indicated by the static force-deformation curve. Therefore, for design purposes, an energy consumption of 1.5 times the energy indicated by the simple static barrel tests should be used:

$$e_d = 1.5\, e_s$$

There are several reasons why this should be expected. First, the actual distribution of forces on the barrels in the crash cushion is somewhat different from the force distribution on a single barrel during static laboratory tests. Second, the 2-in. welds that join the barrel rims at contact points contribute to the rigidity of the individual barrels. Third, the interconnection of the barrels in the system contributes to the sum of the individual barrel strengths. This dynamic energy consumption per barrel divided by the deformation distance, 18 in. or 1.5 ft, gives an approximation of the average dynamic crushing force. For a 20-gage steel barrel with a 7-in. hole cut in the center of the top and bottom, this force would be

$$f_d = \frac{e_d}{1.5\text{ ft}} = \frac{1.5\ (9\text{ kip-ft})}{1.5\text{ ft}} = 9\text{ kip}$$

This determination of energy consumption per barrel, e_d, and dynamic crushing force, f_d, is the basic empirical information needed to develop the design procedure for modular crash cushions.

Design Example

An impact-attenuation device must be placed at an elevated gore that will provide an acceptable deceleration level for a 4,000-lb vehicle traveling 60 mph. Twenty-gage, 55-gal steel barrels with a 7-in. diameter hole in the center of each end are available for the construction of a modular crash cushion. The problem is to determine the number and the arrangement of barrels that will fulfill these design criteria.

The vehicle kinetic energy is calculated by the equation

$$KE = \frac{1}{2}\frac{W}{g}V^2$$

in which W is the design vehicle weight, 4,000 lb; g is the acceleration of gravity, 32.2 ft/sec^2; and V is the design vehicle velocity, 60 mph or 88 fps. Thus,

$$KE = \frac{1}{2}\frac{4{,}000}{32.2}(88)^2 = 480{,}000\text{ ft-lb} = 480\text{ kip-ft}$$

It can be assumed that each barrel previously described can absorb 13.5 kip-ft (9 kip-ft x 1.5) of energy. Therefore, the minimum number of barrels needed in the crash cushion is found by the equation

$$N_b = \frac{KE}{e_d} = \frac{480\text{ kip-ft}}{13.5\text{ kip-ft/barrel}} = 35.6\text{ barrels}$$

Use 36 barrels.

It now remains to arrange the barrels in such a way that an acceptable deceleration level will be achieved. If an average deceleration level, G_{avg}, of 6 g is desired for the 4,000-lb vehicle, the total length of the crash cushion can be found as follows:

Minimum stopping distance, L_s, is defined by

$$L_s = \frac{V^2}{2gG_{avg}} = \frac{(88)^2}{2(32.2)6} = 20\text{ ft}$$

Because the total length of the crash cushion, L_t, is defined by the crushing ratio,

0.75, of individual barrels, the total barrier length must be

$$L_t = \frac{L_s}{0.75} = \frac{20}{0.75} = 26.7 \text{ ft}$$

Each barrel is 2 ft in diameter, so that the necessary number of rows of barrels, N_r, is

$$N_r = \frac{26.7 \text{ ft}}{2 \text{ ft/row}} = 13.3 \text{ rows}$$

Try 13 rows of barrels.

The number of barrels in each row, N_w, is

$$N_w = \frac{N_b}{N_r} = \frac{36}{13} = 2.77 \text{ barrels/row}$$

Use 3 barrels in each row.

Thus the basic configuration would be as shown in Figure 9. A more desirable arrangement would be as shown in Figure 10. Placing a smaller number of barrels in the first few rows will decrease the crushing strength in these rows. This is compensated by the fact that, when the velocity is high during crushing of the first few rows, the inertia force necessary to accelerate these barrels is highest. In contrast, placing more barrels in the last few rows increases the crushing strength in these rows. This is compensated by the fact that the vehicle has accumulated the mass of the preceding rows of barrels, and thus the deceleration effect of this higher crushing strength is decreased. The result is a more constant deceleration force on the vehicle.

ECONOMIC CONSIDERATIONS

The extreme economy and effectiveness of this system are apparent. The cost of individual barrels delivered from the factory will range from $6 to $7. Used barrels can be purchased for as little as $2. The modular crash cushion can be fabricated and

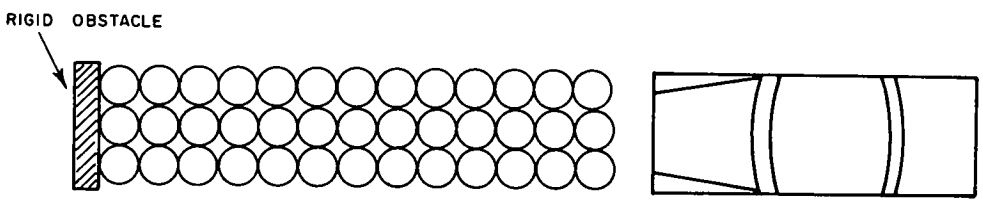

Figure 9. Theoretical barrel arrangement.

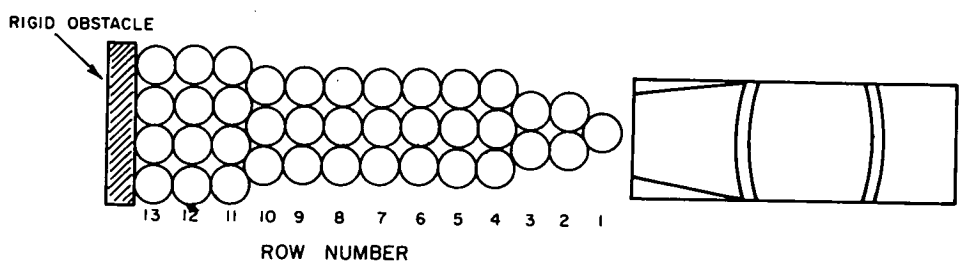

Figure 10. More desirable barrel arrangement.

installed by semiskilled laborers. The system should be painted with a rust preventive and should be inspected periodically so that extensive rusting does not greatly alter the crushing strength of the barrels. The total cost for materials and fabrication of this type of system should range from $300 to $600 depending on whether new or used barrels are available. The cost of installing the barrel system will be highly variable depending on whether freeway modifications are necessary to accommodate the system or whether the freeway was originally built to include these systems.

Replacement should be relatively easy after a barrel system is struck by a vehicle. It may prove feasible to replace the entire system with a spare system that could be stored in a highway department maintenance yard. This could be accomplished quickly during a low-density traffic period. The system that was struck could then be repaired by maintenance personnel if elements of it are still usable.

SUMMARY AND CONCLUSIONS

The modular crash cushion test results indicate that the system should be an effective attenuation device for vehicles traveling less than 60 mph and impacting at angles slightly less than 30 deg. All tests show the deceleration rates to be well within the tolerance limits of restrained humans. Detailed information concerning the determination of the dynamic behavior of the vehicle and the modular crash cushion during a collision is available from the authors (2). The modular crash cushion appears to be a very effective, economical, and practical vehicle crash attenuation device. The early field experience has been very good.

ACKNOWLEDGMENTS

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