

to the 40- and 30-fps threshold velocities to arrive at design values of 30 and 20 fps for longitudinal and lateral impacts, respectively.

One of the objectives of this research program was to explore the relationship assumed in NCHRP Report 230 between lateral occupant impact velocity and injury in real-world accidents. As shown graphically in Figure 5, there were no occupant injuries during the first vehicle impact that were greater than AIS 3 even for occupant risk values of nearly 50 fps. From these data points, it appears to the authors that the lateral impact threshold limit of 30 fps may be too conservative and could be increased to 35 or 38 fps without adversely affecting occupant injury level. Simply stated, the design value of 20 fps may be unnecessarily restrictive, especially for more rigid longitudinal barrier systems, and could be relaxed to a design value of 25 or 30 fps.

CONCLUSION

The development of roadside safety hardware has been an active field of research for more than 25 years. Many of the attitudes and assumptions of the earlier years have become solidly cast into our present thinking about occupant protection with little regard to the validity of those assumptions today. The taxonomist Steven J. Gould has said that "Good science

is self-correcting" (4); good engineering should also be self-correcting.

This study has suggested that the current 20-fps design limit for the lateral occupant impact velocity is not as crucial in mitigating injuries in redirection collisions as was once believed. The effort spent by hardware developers in meeting this overly restrictive measure might better be spent in effecting improvements in other phases of the collision, namely the postimpact trajectory.

REFERENCES

1. J.D. Michie. Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances. NCHRP Report 230. TRB, National Research Council, Washington, D.C., March 1981.
2. J.D. Michie. Collision Risk Assessment Based on Occupant Flail-Space Model. *In* Transportation Research Record 796, TRB, National Research Council, Washington, D.C., 1981, pp. 1-9.
3. The Abbreviated Injury Scale (AIS-80). American Association for Automotive Medicine, Morton Grove, Ill., 1980.
4. S.J. Gould. The Flamingo's Smile: Reflections in Natural History. W.W. Norton Inc., New York, 1985.

Low-Maintenance End Treatment for Concrete Barriers

DEAN L. SICKING and HAYES E. ROSS, Jr.

ABSTRACT

The development of a low-maintenance crash cushion end treatment for concrete barriers is described. Features of the cushion include (a) no sacrificial energy-absorbing elements, (b) sufficient strength to withstand most impacts without damage to any components, (c) width approximately the same as that of the standard concrete safety shaped barrier, and (d) compliance with NCHRP Report 230 safety standards after only minor modifications. Results of six full-scale crash tests on the cushion are described.

Maintenance activities on heavily traveled urban freeways have become a major problem for most transportation agencies. Metal beam barriers on these freeways are frequently struck and must be repaired after most accidents. In recognition of these problems, highway engineers have begun to replace metal beam barriers with the almost maintenance-free concrete safety shaped barrier. However, the ends of these rigid concrete barriers pose both safety and maintenance problems. When left exposed or sloped to

the ground, the rigid barrier end is a severe hazard. Efforts to mitigate this hazard include the use of crash cushion end treatments, flared ends, ends buried in earth berms or back slopes, and transition to a W-beam that is then terminated with a guardrail terminal. All of these safety treatments present some safety or maintenance problems, or both.

The crash cushion is probably the safest concrete barrier end treatment in use. However, crash cushion maintenance can be costly. All existing crash cushions use expendable energy-absorbing elements to attenuate head-on impacts, which destroy one or more of these energy-absorbing elements. Replacement of the damaged elements is costly, and for those end

treatments that are struck frequently, repair costs during the life of an end treatment can be greater than initial costs. In an effort to reduce maintenance requirements associated with the use of concrete barriers on the roadside, a study was undertaken to develop a low-maintenance crash cushion end treatment for the concrete safety shaped barrier.

In this paper are described the findings of a research study funded by the Texas State Department of Highways and Public Transportation (1). The reader should refer to the cited report for more information about this study.

DESIGN CONSIDERATIONS

A large portion of crash cushion repair costs is associated with the repair or replacement of damaged components. The most effective method of cutting repair costs is to limit component damage by eliminating sacrificial energy-absorbing elements and strengthening other components. Maintenance costs can be cut further by reducing the size of the end treatment to cut the number of impacts.

Many concrete barrier end treatments must be placed very close to the traveled way. If a cushion is to have application at such sites, it must be narrow--ideally no wider than the standard concrete barrier. Narrow crash cushion end treatments must perform as a crash cushion when struck head-on and as a longitudinal barrier when struck downstream. Therefore the objective of this research was to design a low-maintenance crash cushion end treatment for concrete barriers that would (a) not have any sacrificial energy-absorbing elements, (b) have sufficient strength to withstand most impacts without damage to any components, (c) be approximately the same width as the standard concrete safety shaped barrier, and (d) meet nationally recognized safety standards (2).

ENERGY-ABSORBING ELEMENTS

The initial phase of crash cushion development involved a search for a material or device that could absorb large amounts of energy at high strain rates without sustaining any damage. Numerous chemical, plastic, and rubber companies were contacted during the search, and a large number of potential energy-absorbing materials were located. Samples were obtained of all materials that had the basic properties of interest, including Norsorex, Sorbothane, open- and closed-cell polyurethane and polyethylene foams, and several natural and synthetic rubber compounds. Spring manufacturers were also contacted regarding the potential use of steel springs as energy-absorbing devices.

Each of the candidate materials was evaluated to determine durability, response to static and dynamic loading, and cost and energy absorption per unit weight. Ultraviolet radiation and freeze-thaw tests were conducted to determine material durability, and high-speed (75-fps) and low-speed compression tests at several different temperatures were conducted to determine response to loading. Several rubber compounds were found to have the necessary durability and loading response for use in a crash cushion end treatment. The rubber cylinder, when used as ship and dock fenders, has been shown to absorb large amounts of energy and to be resistant to damage during impact loadings (3,4). Therefore a cylindrical rubber element was chosen for the energy-absorbing cartridge in the low-maintenance crash cushion end treatment.

The response of rubber cylinders to static trans-

verse loadings has been thoroughly studied both empirically and theoretically (3-5). These studies have shown that for any particular rubber compound the static stiffness of a rubber cylinder is a function of the ratio between the outer diameter (D) and the wall thickness (t). Therefore the static stiffness of large-scale rubber cylinders can be determined by measuring the stiffness of scale-model cylinders with similar D/t ratios.

However, study of the dynamic response of rubber cylinders to transverse compression has been quite limited. The nonlinear characteristics of rubber and the large strains associated with the collapse of a cylinder make dynamic analysis virtually impossible. Therefore an empirical study of the dynamic force deflection characteristics of rubber cylinders was undertaken. One-fifth-scale-model cylinders, made from several different rubber compounds, were obtained in a variety of wall thicknesses. The scale-model cylinders were then tested statically and at three different impact speeds (5, 30, and 75 fps) to determine their force deflection characteristics. Figure 1 shows a sketch of the test setup used in the dynamic tests. Note that the test configuration allowed the sample to be compressed fully at a constant velocity.

The energy absorbed during a dynamic test has three sources: (a) inertia, (b) elastic stiffness, and (c) damping. As shown in Figure 1, when the bore

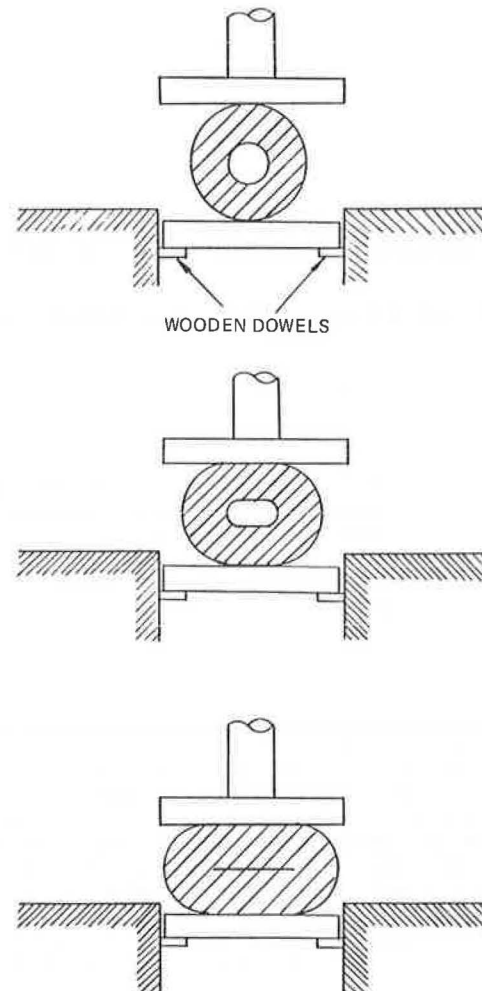


FIGURE 1 Scale-model cylinder dynamic testing configuration.

of a test specimen was completely collapsed, approximately one-half of the specimen had been accelerated to the speed of the impact plate, while the other half was virtually stationary. The energy absorbed by the inertia of the specimen was then estimated from the impact velocity and the mass of the specimen as

$$E_i = 1/2 m V^2$$

where

$$\begin{aligned} E_i &= \text{energy transferred to cylinder due to} \\ &\quad \text{inertia (in.-lb),} \\ m &= \text{mass of cylinder (lb-sec}^2/\text{in.)}, \text{ and} \\ V &= \text{velocity of impact plate (in./sec).} \end{aligned}$$

Energy absorbed due to the elastic stiffness of the specimen was measured from static testing. Energy attributable to internal damping within the specimen was then estimated from results of dynamic tests as

$$E_d = E_t - E_i - E_e$$

where

$$\begin{aligned} E_d &= \text{energy attributable to internal damping} \\ &\quad \text{(in.-lb),} \\ E_t &= \text{total energy absorbed during dynamic test} \\ &\quad \text{(in.-lb), and} \\ E_e &= \text{energy absorbed during static testing} \\ &\quad \text{(in.-lb).} \end{aligned}$$

The energy absorbed by internal damping was found to be approximately the same for the tests at 30 and 75 fps. It can be concluded that damping within the tested rubber materials is of a hysteretic nature. Therefore energy absorbed by the rubber cylinders, with the exception of momentum transfer, is largely independent of impact velocity.

For purposes of estimating the energy absorbed by a full-scale cylinder, it was assumed that the ratio of elastic energy absorbed to damping energy absorbed was constant for each rubber compound and was unrelated to cylinder size or wall thickness. Static force deflection characteristics of large-scale rubber cylinders can be estimated directly from tests of scale-model specimens as mentioned earlier. Analysis of the results of dynamic scale-model tests indicated that thin-walled rubber cylinders do not absorb significant amounts of energy. Therefore the crash cushion design would have to use relatively thick-walled cylinders, which weigh in excess of 300 lb, and the front of the cushion would rely on momentum transfer to slow a colliding vehicle. The hardest rubber compound included in the study was selected for use in the cushion in an effort to reduce the total amount of rubber required. The selected compound is an 80-durometer natural rubber material.

Two 28-in.-diameter rubber cylinders, with wall thicknesses of 1.75 and 4.5 in., made from the

selected compound were then fabricated and tested statically and dynamically to verify the loading response of large cylinders. Table 1 gives the estimated and the measured energy absorption characteristics of the full-scale rubber cylinders. As shown in the table, predicted values based on scale-model testing were quite close to measured values.

The cushion was then designed to attenuate head-on impacts with a single row of rubber cylinder energy-absorbing cartridges. The cushion was modeled for head-on impacts as a series of lumped masses and springs. The principles of conservation of energy and momentum were then employed to determine the impact severity of various sizes of vehicles as discussed in Ivey et al. (6). This analytic procedure is based on the assumption that the rubber cylinders will collapse one at a time such that one cylinder is almost completely collapsed before the next cylinder begins to be crushed. The final cushion design contained six thin-walled (1.75-in.) cylinders at the front of the cushion and seven thick-walled (4.5-in.) cylinders at the rear. Head-on impact severity measures predicted by the conservation of energy and momentum analysis are given in Table 2.

Scale-model cylinders of the selected compound were tested dynamically at -20°F and 120°F to determine the effects of temperature variation on the stiffness of the rubber. The variation in the energy absorbed, given in Table 3, was found to be less than 35 percent from the lowest test temperature to the highest. Because the front of the terminal behaves as an inertial cushion, it was possible to design the end treatment to perform acceptably at both temperature extremes.

END TREATMENT DESIGN

The final end treatment design, shown in Figure 2, consists of a single row of rubber cylinder energy-absorbing cartridges separated by steel diaphragms. A rubber cylinder is placed vertically in front of the end treatment to capture colliding vehicles and prevent override or underride of the cushion. The remaining rubber cylinders are placed horizontally to allow unrestrained collapse of the cylinders. Thrie-beam fender panels attached to the diaphragms and four 5/8-in. longitudinal cables provide redirection capabilities. Fender panels are attached to the diaphragms with hinges to allow the thrie-beams to open outward without damaging the panels. Steel springs are used to prevent the fender panels from opening under wind loadings.

The rubber cartridges do not have sufficient elastic stiffness to completely restore the system after it has been struck. Four lightweight cables are attached between the diaphragms to allow the cushion to be pulled back into place after an impact. The end treatment is designed to sustain most impacts without replacement of any parts and to be restored to its original configuration in less than an hour.

TABLE 1 Full-Scale Test Results and Scale-Modeling Predictions

Sample (in.)			Static Energy (in.-lb)		Dynamic Energy (in.-lb)	
Wall Thickness	Outside Diameter	Length	Measured	Predicted	Measured	Predicted
1.75	28	24	23,940	22,510		74,280
1.75	28	24	23,880	22,510		74,280
4.50	28	24	180,360	134,640	231,600	215,400

TABLE 2 Predicted Occupant Impact Velocities for 60-mph Head-On Impacts

Vehicle Weight (lb)	Longitudinal Occupant Impact Velocity (ft/sec)
1,800	32
2,250	31
3,000	30
4,500	28

TABLE 3 Summary of Frozen Sample Testing

Ratio of Wall Diameter to Thickness of Sample	Energy Absorbed (in.-lb)		Change (%)
	Unfrozen	Frozen	
0.06	152	182	19.7
0.09	330	443	34.2
0.13	616	837	35.9

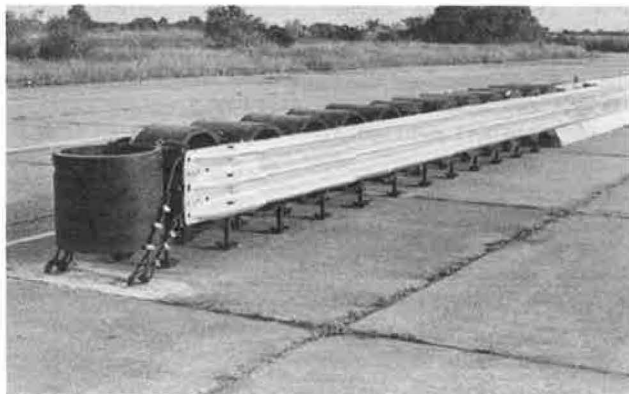


FIGURE 2 Low-maintenance end treatment.

PRELIMINARY TESTS

Three preliminary full-scale crash tests were conducted in an effort to find any design flaws before compliance testing. All three tests involved a 4,390-lb 1975 Ford Torino striking the cushion head-on.

Tests 1 and 2

The first test was conducted at 30 mph with an uninstrumented vehicle. The cushion performed well and stopped the vehicle in approximately 15 ft. The test vehicle exhibited no tendency to vault over or underide the cushion. The vehicle rebounded off the cushion at approximately 5 mph. As shown in Figure 3, the test vehicle was only lightly damaged and cushion damage was limited to minor bending of some of the skid shoes under the steel diaphragms.



FIGURE 3 Test vehicle and low-maintenance end treatment after 30-mph impact.

The cushion was pulled back into place in less than an hour and a second test was conducted at 40 mph. The end treatment smoothly decelerated the test vehicle over a distance of 17.5 ft and vehicle damage was light. The vehicle again rebounded off the cushion at approximately 5 mph. Some of the hinges supporting the three-beam fender panels were damaged and the legs under the leading diaphragm were bent when they contacted the legs under the second diaphragm. Figure 4 shows the end treatment and test vehicle after the second test.

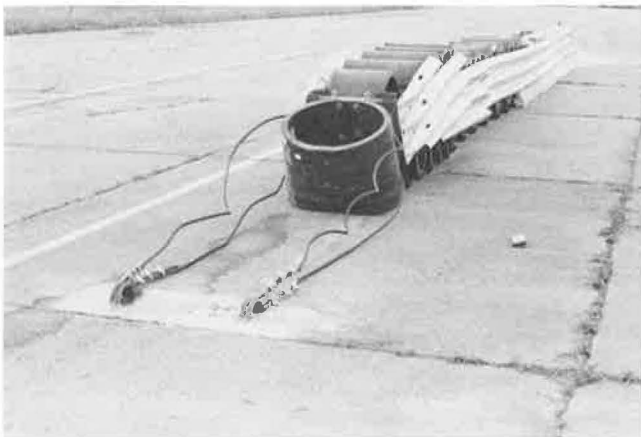


FIGURE 4 Vehicle and end treatment after 40-mph impact.

Test 3

The hinges on the front of the cushion were replaced with larger hinges and the method of attachment to the diaphragms was improved to reduce the possibility of damage. The legs on the first diaphragm were removed and replaced with a single leg in the center such that it would not contact the legs on the second diaphragm during impact. The test vehicle was then instrumented and a third test was conducted at 51 mph. The test vehicle was smoothly decelerated and was pushed back out of the cushion at approximately 7 mph. The vehicle was only moderately damaged, as shown in Figure 5. All occupant risk values, given in Table 4, were well below recommended limits (2). The end treatment was pulled back into place in less



FIGURE 5 Vehicle and end treatment after Test 3.

than an hour and, with the exception of some of the new hinges, was undamaged.

COMPLIANCE TESTING

NCHRP Report 230 (2) calls for four full-scale crash tests of barrier end treatments. One of these tests calls for a 1,800-lb automobile to strike the middle of the end treatment at 60 mph and 15 degrees. Standard three-beam barriers and cable-supported narrow end treatments with three-beam fender panels have performed well under these tests conditions (6,7). It was therefore decided that this test would be eliminated from the matrix and the remaining three crash tests would be conducted.

Test 4

After completion of the third test, the hinges were redesigned to withstand an impact load of more than 200 g's. The new hinges were fabricated from 3/4-in. steel pipe and rod and 1/8-in. steel plate. Compliance testing was then begun with a 1979 Honda that weighed 1,810 lb striking the cushion at 58 mph and zero degrees. The center of the test vehicle was offset 16 in. from the center of the cushion. The small automobile was smoothly decelerated to a stop over a distance of approximately 17 ft. As the front of the vehicle came to a stop, the rear began to spin out. As shown in Figure 6, the vehicle was yawed approximately 90 degrees from its original direction of travel when it stopped.

The modified hinges contacted the next fender panels and prevented the front five cells from col-

TABLE 4 Summary of Crash Test Results

Test No.	Vehicle Weight (lb)	Impact Speed (mph)	Angle of Impact (degrees)	Point of Impact	Vehicle Stopping Distance (ft)	Occupant Impact Velocity (ft/sec)		Occupant Ridedown Accelerations (10 msec avg g's)	
						Longitudinal	Lateral	Longitudinal	Lateral
1	4,390	30	0	Nose	15	- ^a	- ^a	- ^a	- ^a
2	4,390	40	0	Nose	17.5	- ^a	- ^a	- ^a	- ^a
3	4,390	51	0	Nose	22.5	22.0	- ^a	7.7	- ^a
4	1,810	58	0	Nose at 16-in. eccentricity	17.5	35.5	4.2	9.0	1.5
5	4,500	57	0	Nose	23.5	26.4	NA	14.1	NA
6	4,420	61	25	8th fender panel	NA	32.7	18.9	20.9	32.5

Note: NA = occupant did not strike side of vehicle, ^aNot measured.



FIGURE 6 Vehicle and end treatment after Test 4.

lapsing completely. As a result, the longitudinal occupant impact velocity was somewhat high at 35.7 fps, whereas the recommended value is 30 fps and the maximum allowable impact speed is 40 fps. If the hinges had not prevented the front cells from collapsing completely, the test vehicle would have traveled approximately 2.5 in. further between impacts with each diaphragm and therefore the occupant impact velocity would have been much lower. There would have been little additional speed reduction between diaphragms because the front cells do not absorb a significant amount of energy. The occupant impact velocity can be estimated for this condition by integrating the accelerometer curve from the test and adding 2.5 in. of free travel (no acceleration) after collapsing each cell. The predicted occupant impact velocity from this type of analysis is approximately 31 fps.

As the data in Table 4 indicate, all other severity measures with within recommended limits (2). No components of the crash cushion were damaged, and it was restored with less than 4 man-hours of labor. After the fourth test the hinges were notched to prevent contact between hinges and the downstream fender panels.

Test 5

The fifth test involved a 1978 Mercury Grand Marquis that weighed 4,500 lb striking the cushion head-on at 57 mph. The cushion performed well and brought the vehicle to rest over a distance of approximately 23 ft. All measures of occupant risk were below recommended limits as the data in Table 4 indicate. The vehicle rebounded off the cushion at 10.5 mph.

The cushion and test vehicle were damaged moderately, as shown in Figure 7. One of the redirection cables snagged on a diaphragm and was broken, and one of the lightweight restoration cables between the diaphragms was cut. As a result, the cushion could not be pulled back into position as in previous tests. In addition, there was minor damage to several of the hinges and the legs under the diaphragms. There was still some minor contact between the 3/4-in. rods on the hinges and the fender panels. Therefore it is recommended that the hinges be replaced with a flat plate design. This design should be slightly stronger than those used in the tested design.

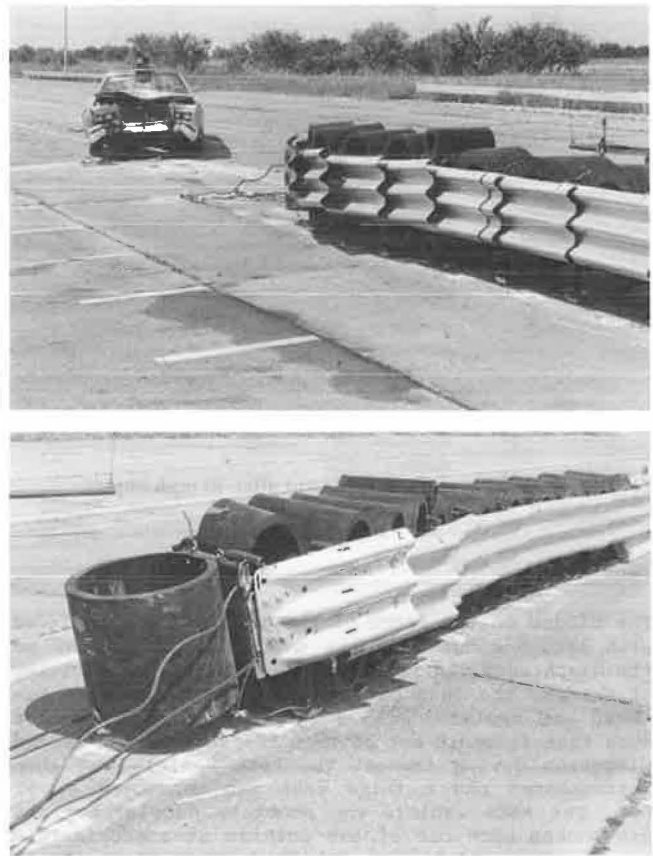


FIGURE 7 Vehicle and end treatment after Test 5.

Cushion repair was accomplished by replacing two 5/8-in.-diameter lateral restraint cables and two 1/4-in.-diameter restoration cables. It should be noted that the damaged lateral restraint cables were old and may have been frayed or damaged during previous research. However, it is recommended that all lateral restraint cables be visually inspected after every accident.

Analysis of test films indicated that all of the energy required to push the vehicle out of the cushion originated from the large-diameter cylinders at the rear of the treatment. If the 10.5-mph exit velocity is a significant concern, vehicle rebound can be virtually eliminated by placing displacement limitation devices on the redirection cables at the sixth diaphragm. These devices would allow the diaphragm to be freely pushed backward but would limit any forward motion of the diaphragm after the vehicle was stopped.

Test 6

The final test on the end treatment involved a 4,420-lb Ford LTD striking the cushion at 61 mph and 25 degrees. The center of the test vehicle was directed at the center of the barrier end to maximize the possibility of the vehicle snagging on the end of the barrier. The test vehicle was redirected and exited the barrier at a very low angle.

During the test the lateral support element at the front of the concrete barrier gave way and the front of the barrier deflected 4 in. As the barrier was deflected, it rolled away from the impacting vehicle thereby extending the lower curb face beyond the edge of the treatment. The wheels of the test vehicle snagged somewhat on the exposed lower face and generated relatively high longitudinal and lateral forces on the automobile. Although barrier anchorage for field installations would likely be more substantial and limit this problem, it is recommended that the barrier end be transitioned to a vertical wall to further reduce the likelihood of such an occurrence.

The end treatment was not damaged heavily for a test of this severity, as shown in Figure 8. Repair would have been limited to the replacement of the last diaphragm, two thrie-beam fender panels, one wood block-out on the face of the concrete barrier, and one redirection cable. No rubber cells showed any sign of damage. As in most impacts of this severity, the test vehicle sustained considerable damage.



FIGURE 8 Vehicle and end treatment after Test 6.

CONCLUSIONS

A low-maintenance crash cushion end treatment for concrete barriers has been successfully designed and crash tested. The cushion (a) does not have any sacrificial energy-absorbing elements, (b) has sufficient strength to withstand most impacts without damage to any components, (c) is not significantly wider than the standard concrete safety shaped barrier, and (d) has been shown to meet nationally recognized safety standards (2). Rubber cylinder energy-absorbing cells used in the cushion have withstood six relatively severe crash tests and show no signs of significant damage.

The crash cushion end treatment described here represents a significant step toward reducing maintenance costs associated with such devices. The cushion can withstand relatively severe head-on impacts--small automobiles traveling at speeds of up to 60 mph and large automobiles traveling at speeds of up to 50 mph--without sustaining damage to any components. These impact conditions include more than 95 percent of expected head-on accidents (8). After these accidents the cushion can be repaired in less than an hour and total repair cost should be less than \$100. Further, even high-energy head-on and relatively severe side impacts do not cause a great deal of damage to the system. Finally, the design concepts proven in this study could be easily adapted to other types of cushions with a potential for similar reductions in maintenance costs.

ACKNOWLEDGMENTS

This research study was conducted under a cooperative program between the Texas Transportation Institute, the Texas State Department of Highways and Public Transportation (SDHPT), and the Federal Highway Administration. Harold Cooner of the SDHPT worked closely with the researchers, and his comments and suggestions were appreciated.

REFERENCES

1. D.L. Sicking and H.E. Ross, Jr. A Low Maintenance End Treatment for Concrete Barriers. Research Report 346-1F. Texas Transportation Institute, Texas A&M University System, College Station, Sept. 1985.
2. J.D. Michie. Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances. NCHRP Report 230. TRB, National Research Council, Washington, D.C., March 1981.
3. Marine Dock Fenders. Goodyear Industrial Products Division, Akron, Ohio, undated.
4. Marine Fendering Systems. Uniroyal Inc., Marine Fender Systems, Mishawaka, Ind., undated.
5. P.K. Freakley and A.R. Payne. Theory and Practice of Engineering with Rubber. Applied Science Publishers Ltd, London, England, 1978.
6. D.L. Ivey, R.G. Robertson, and C.E. Buth. Test and Evaluation of W-Beam and Thrie-Beam Guardrails. Texas A&M Research Foundation, Texas A&M University System, College Station, March 1982.
7. D.L. Sicking and H.E. Ross, Jr. Crash Cushion for Narrow Objects. In Transportation Research Record 942, TRB, National Research Council, Washington, D.C., 1983, pp. 16-25.

The contents of this paper reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. This paper does not necessarily reflect the official views or policies of the Texas State Department of Highways and Public Transportation or the Federal Highway Administration.