ANGLE AND SMALL-CAR IMPACT TESTS OF AN ARTICULATED GORE BARRIER EMPLOYING LIGHTWEIGHT CONCRETE ENERGY-ABSORBING CARTRIDGES

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A crash attenuator for errant vehicles, employing lightweight concrete energy-absorbing cartridges, has been further tested to demonstrate its capabilities to decelerate lightweight cars without excessive loads and to deflect standard-sized automobiles in side impact at high speeds and angles. Favorable test results were experienced in all phases of the testing. A Volkswagen sedan that impacted the attenuator at 58 mph (93 km/h) was driven away with 9½ in. (241 mm) of maximum front-end crush. Fendering tests involving standard-sized cars traveling at speeds up to 68 mph (109 km/h) were successfully performed, without seriously deteriorating the residual head-on capability of the attenuator. Analyses of the results of these and previous tests show that the attenuator stroke is very nearly independent of vehicle mass, causing about the same average deceleration in 60-mph head-on impacts of the 1,800-lbm (817-kg) Volkswagen and a 3,700-lbm (1678-kg) Rambler. For impacts of the same weight vehicle at different velocities, the average deceleration is roughly proportional to the 1.6 power of impact velocity.

•HIGHWAY CRASH ATTENUATORS are proving themselves as effective lifesaving systems in installations across the nation. This paper reports tests of an improved attenuator system that evolved from concepts originally applied in the water cell attenuator, coupled with sophisticated use of vermiculite concrete as an energy absorber. Prototype tests reported earlier (1) compared the system with its water cell predecessor for head-on impacts and showed improvements in deceleration profile, as compared to the water cell performance, which had been documented earlier (3, 4). This paper reports tests of an improved system involving a low-speed, lightweight car and angle impact performance and results of field trials on maintenance and refurbishment. The system demonstrated very good performance in all tests, matching or exceeding the performance of all competitive systems known to the authors and improving on the constant-stroke characteristics of the water cushion attenuator. Notable improvements in both fendering and light-car head-on performance are possible because of large attenuator weight reductions, as compared to the water cushion system.

A significant part of the total cost of crash attenuation systems results from corrective maintenance following impact. A recent California study, comparing real-world performance of three different prototype crash attenuator systems, is cited to give preliminary quantification to this problem (5).

DESCRIPTION OF ATTENUATOR SYSTEM

The basic features of the attenuator are shown in Figure 1. The construction of the device has been discussed in previous papers and will only be briefly treated here (1,2). The energy-absorbing mechanism employed involves the controlled fracture of a concrete matrix and controlled crushing of vermiculite aggregate particles. Control is provided by geometric and structural constraints: Cells are designed to resist axial forces. The center void produces a gradual force buildup over the initial part of the stroke of each cell, allowing accommodation of inertial loads in high-speed impacts.

After the void fills by crushing, the concrete matrix is thrust through the orifice between the wires. Debris is contained within the pleated aluminum sheath and is further crushed when a sufficiently broad area is reached. The cells are glued to light, stiff plates to form cartridges and are sealed inside waterproof plastic or fiber packages. These packages are inserted into the "sandwich" hardware developed for the Hi-Dro Cell attenuator (3).

The vermiculite aggregate and wire-helix orifice built into the basic cells provide a velocity-sensitive system that is similar to, but superior in performance to, the water system originally used (4). The concrete cartridges are much lighter than the water system, so that initial deceleration in high-speed tests may be more readily controlled. The overall system exhibits constant-stroke behavior over the range of speeds and vehicle weights normally encountered, as is seen below.

Figure 2 shows details of attenuator construction.

DESCRIPTION OF TESTS

The tests reported in this paper were performed on leased facilities at the Lincoln, California, airport. Cars were either cable-guided and towed or driven by live drivers using special safety equipment.

Photographic data were obtained by two high-speed (~1000 pps) movie cameras and two standard-speed movie cameras. Documentary still photographs were also taken. Electronic acceleration data were recorded by a biaxial accelerometer pack mounted in the passenger compartment behind the driver's seat. A 500-ft (152-m) hard line connected the accelerometer pack with stationary readout equipment. Longitudinal and lateral accelerations were recorded. Figures 3, 4, and 5 show acceleration histories for the various tests.

Lightweight-Car Head-On Impacts

Two tests were performed on the Hi-Dri attenuator to evaluate lightweight car performance. A preliminary test with a Karmann Ghia VW was conducted to evaluate test conditions. The vehicle impacted at slightly more than 50 mph (80 km/h) with minimal damage. Acceleration loads were light, and the total stopping distance was approximately 10 ft (3.05 m).

A standard 1962 Volkswagen sedan impacted at 58 mph (93 km/h). Total stopping distance was 13 ft (3.96 m). The front-end crush was only 9½ in. (241 mm). (The spare tire was in place in the front truck compartment.) Following the test, the engine was started, and the VW was backed from the Hi-Dri attenuator on its own power and driven from the site, with the front fenders rubbing the wheels. Had the impact occurred on the freeway, the car could have been driven a few miles to get help. After the fenders were pulled away from the tires, the test vehicle was driven a distance of 40 miles (64 km) at freeway speeds. The front wheels were still in alignment. Figure 6 shows photographs of these tests.

Occupants of the VW could easily have survived the impact. Occupants wearing lap and shoulder belts could have escaped without injury (7).

Angle Impacts Into the Side of the Attenuator

Two high-speed angle impacts were performed with a standard-sized car on a nominal 20-ft (6.1-m) long standard eight-bay unit protecting a rigid 3.5-ft (1.07-m) wide barrier. The vehicles weighed approximately 4,000 lbm (1800 kg) and impacted at 60 mph (97 km/h) or greater. The impact angle relative to the axis of the unit was 15 deg. This, added to the 5-deg half-wedge divergence of the attenuator, resulted in a 20-deg impact angle with the face.

The impact point on the unit was nominally 6 ft (1.83 m) ahead of the rigid corner. It was selected to provide a severe test for the attenuator. The highest impact loading

Figure 1. Hi-Dri cartridge vehicle attenuator.

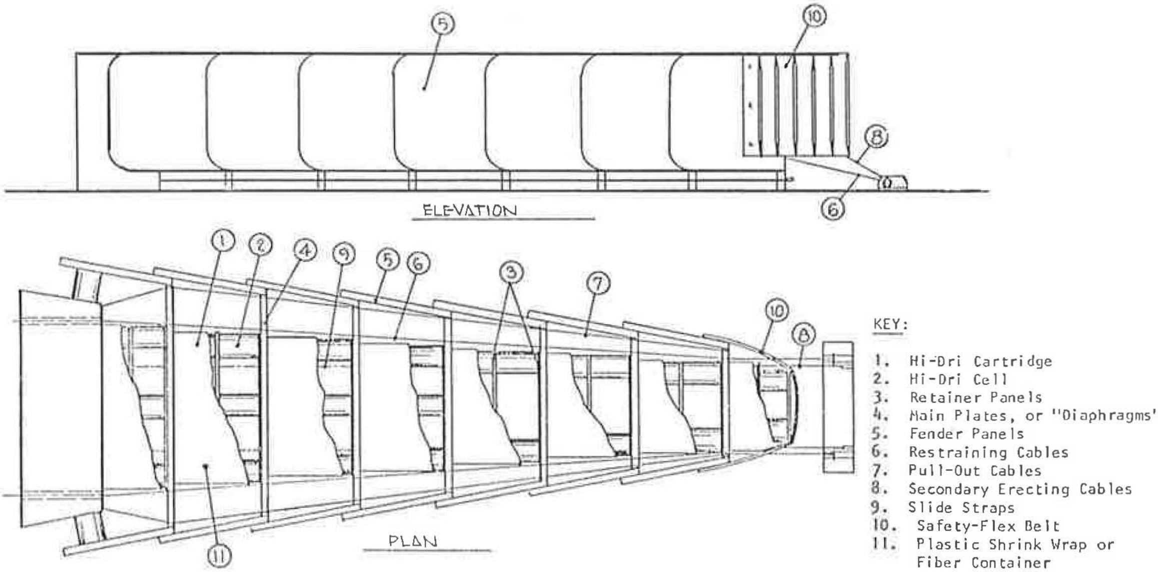


Figure 2. Hi-Dri cartridge.

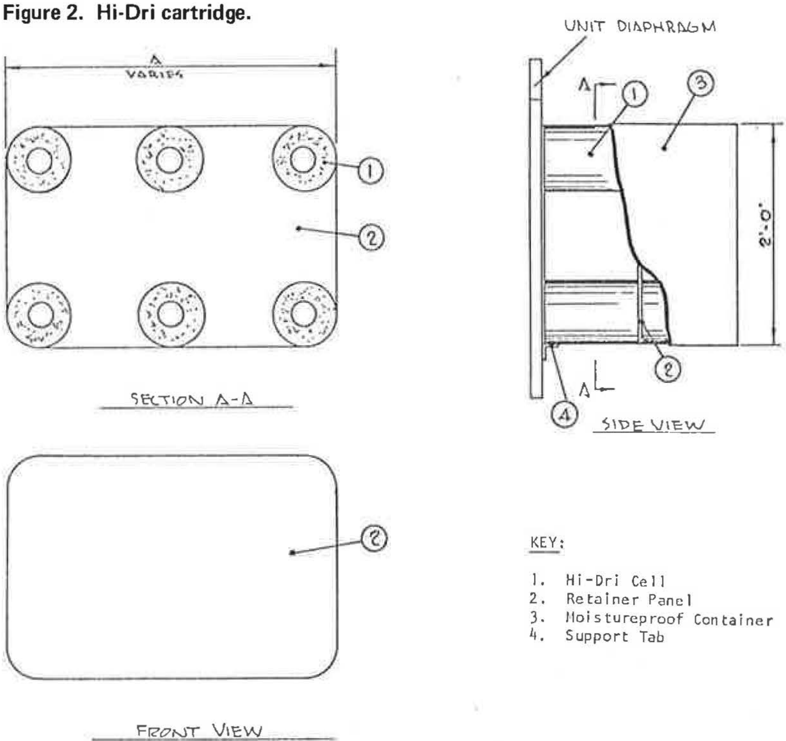


Figure 3. Acceleration trace of head-on impact following high-speed angle impact.

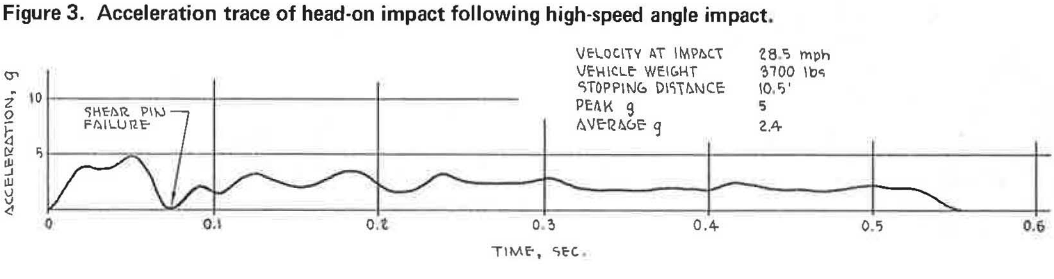


Figure 4. Longitudinal acceleration of head-on impact with Volkswagen sedan.

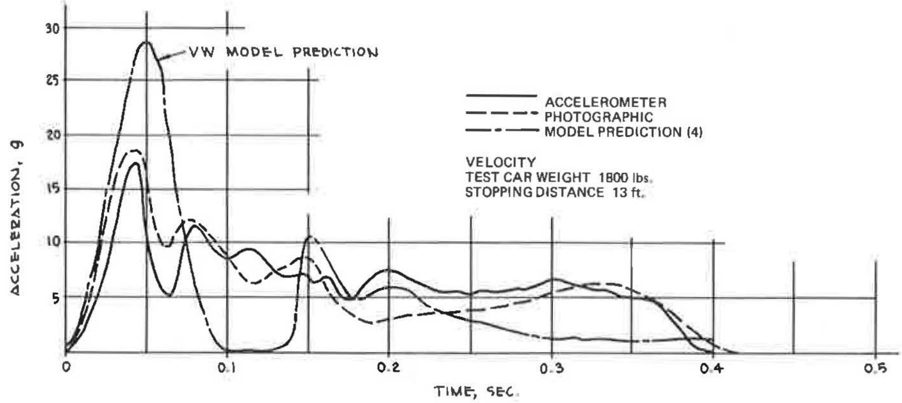


Figure 5. 20-deg angle impacts with standard-sized cars: (a) lateral and (b) longitudinal accelerations of 4,000-lbm vehicle traveling at 60 mph and (c) longitudinal acceleration of 3,700-lbm vehicle traveling at 68 mph.

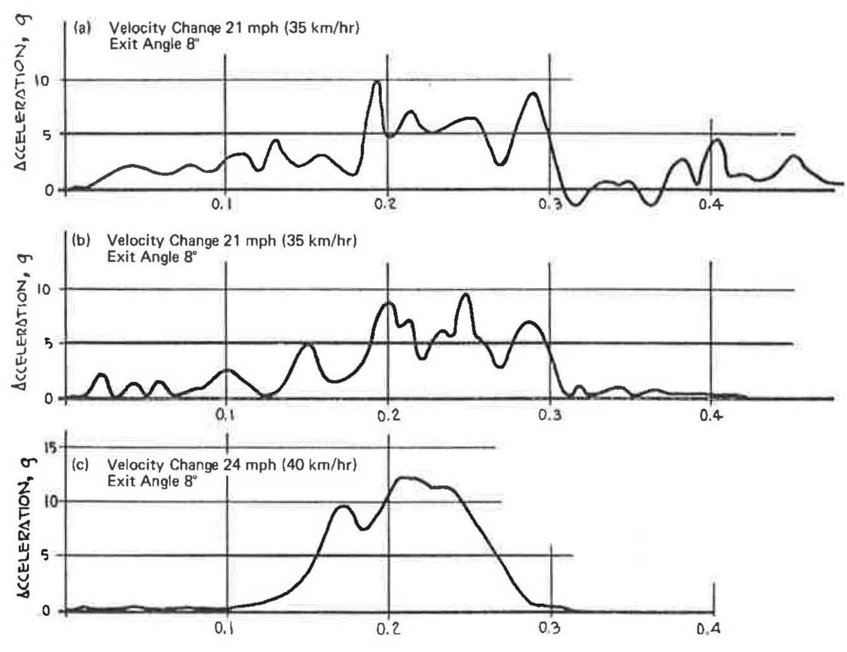
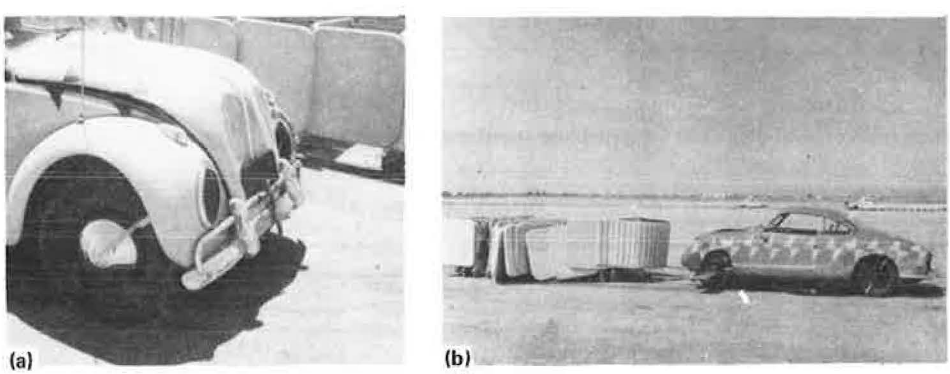


Figure 6. Subcompact cars after (a) 58-mph impact and (b) 50-mph impact.



occurred in the two to three bays just ahead of the rigid barrier (commonly referred to as the coffin corner area). Impacts at this point ensure high loads on the vehicle and attenuator.

In the first test, a 1960 Chevrolet Bel Air four-door sedan impacted at 68 mph (109 km/h) and 20 deg. The exit angle was 8 deg with the face of the unit, resulting in a 28-deg total change of direction. After impact the test vehicle followed a curving path back to the side of the road and came to rest 165 ft (50 m) from the point of impact. The left front quarter panel of the vehicle was severely damaged. The left front wheel was torn loose from the lower control arm. The change of velocity during impact was 24 mph (38 km/h). Unfortunately, electronic acceleration data were lost during this test.

Photographic data indicated a smooth redirection of the vehicle with a roll about the longitudinal axis of only 15 deg away from the barrier. The left side of the car rose approximately 1 ft (0.3 m) from the ground, but the right wheels remained on the ground throughout the test. Three side panels on the attenuator were moderately damaged, but they remained in place and were judged capable to resist further side impacts until replaced. Approximately 10 percent of the head-on energy-absorbing capability of the unit was destroyed during this angle impact, but the shear pins remained intact and kept the unit erect, thus preserving its capability to sustain another head-on or angle impact without maintenance.

A second test was run at 60 mph (97 km/h) to further demonstrate fendering capability. A 1962 Dodge four-door sedan weighing approximately 4,000 lbm (1800 kg) impacted the side of the unit at the same point and angle as before. The results were almost identical except that there was less damage to the attenuator and car. The exit angle of the second test car was 9 deg, compared with 8 deg for the first car. There was no roll about the longitudinal axis of the second test vehicle. The change of velocity during impact was 21 mph (34 km/h). The peak longitudinal acceleration was 10 g, with an average of less than 4 g during the 150-msec duration of highest deceleration. The peak recorded lateral acceleration was 10 g with 4.5 g average during the highest 150 msec.

Low-Speed Impact of Standard-Weight Vehicle

Immediately following the 60-mph angle impact, a low-speed head-on test was run to demonstrate the capability of the attenuator to sustain repeated impacts without maintenance. A test truck weighing 3,700 lbm (1678 kg) with driver impacted the attenuator at 28.5 mph (46 km/h), without exhausting unit capacity.

The acceleration trace shown in Figure 3 demonstrates the velocity-sensitive characteristic of the cells compared with much higher g loads when impacted at higher speeds. Following the peak loading of 5 g, which parted the shear pins, the acceleration was 2.4 g for 400 msec. The driver reported no discomfort. Total stopping distance was 10.5 ft (3.2 m). Figure 7 shows photographs taken during and after this test.

REDIRECTION IN ANGLE IMPACTS

The lightweight concrete system offers improved performance in angle impacts as compared to the water cell attenuator. The vermiculite cells provide an initial compression resistance to the "diaphragms" as impact load is transferred from the side panels to the diaphragms. This keeps them vertical, which in turn maintains a vertical face for each of the side panels. The initial low-force yield of the energy-absorbing cartridges reduces loads on the attenuator structure. After initial yield, the firm resistance of the cells prevents tipping of the side panels, to the degree seen in the water tube attenuator. Concrete cells are positioned near the top of the 40-in. (1.02-m) high diaphragms at the back of the unit. This is done primarily to prevent head-on impacting vehicles from leaving the ground. The high position of the cells also helps to maintain a firm vertical face to resist the force of a vehicle impacting at an angle.

The fendering performance of the Hi-Dri sandwich is somewhat better than that of the same system using water cells, primarily because the decreased weight of the attenuator allows the use of more tension in the erecting cables without excessive light-car loads in head-on impacts. The energy-absorption capability of the unit at the rear corner was enhanced by positioning two small cartridges facing the side of the rear side panel.

Side panel damage was moderate during the fendering impacts. The units could probably have sustained repeated fendering impacts without service.

CONSTANT-STROKE CHARACTERISTICS

A constant-stroke attenuator offers performance and cost advantages over a constant-force system. Performance advantages accrue because vehicle decelerations are essentially the same for a given impact velocity, regardless of vehicle weight and because vehicle deceleration decreases as velocity decreases. Cost advantages accrue in situations where space is limited, inasmuch as large and small cars are decelerated in about the same distance.

A precisely constant-stroke device would provide a resisting force given by

$$\overline{F} = W\overline{G} = kWV_o^2 \qquad (1)$$

where $\overline{F}$ = average attenuator force, W = vehicle weight, $\overline{G}$ = average deceleration of the vehicle, V_o = impact velocity, and k = a proportionality constant.

The actual characteristics of the Hi-Dri attenuator are shown in Figure 8 for three head-on test conditions, representing standard car near design speed and two other impacts at roughly half weight and half speed. A reasonable fit to this data is provided by the equation

$$\overline{F} = W\overline{G} = 0.0231W^{0.92}\ V_o1.6 \qquad (2)$$

Figure 9 shows a comparison of the ideal constant-stroke performance of Eq. 1, referenced to the standard-car high-speed impact, and the actual performace with an approximation of Eq. 2. As can be seen, the attenuator approaches constant-stroke behavior very closely for vehicles of different weights, at least over the range tested.

It should be noted that these equations reflect the average forces and decelerations. Peak forces will be higher in every case and will be accentuated in the case of the small car because even small inertias will cause large forces on initial impact. One of the most significant advantages of the lightweight concrete attenuator system is demonstrated in Figure 5. Because of its low mass, the small car is particularly sensitive to momentum exchange with heavy barrier components. This is shown by comparison of the predicted vehicle deceleration for the Hi-Dro Cell attenuator with those measured on the lightweight concrete system. The difference is even more dramatic when comparison is made with the 40-mph Hi-Dro cushion Volkswagen test performed by TTI (4). The TTI test indicated a peak vehicle deceleration of about 15 g at 40 mph—roughly the same as that seen in the Hi-Dri system at 60 mph. The reason for this dramatic reduction is made quite clear by momentum analysis. The energy-absorbing materials in the Hi-Dri cushion weigh slightly more than one-tenth of those in the Hi-Dro cushion—about 500 lbm versus about 5,000 lbm (152 kg versus 1520 kg). This weight reduction has produced the excellent light-car response demonstrated here while allowing increase in the secondary erecting cable shear-pin strength and corresponding improvement in fendering impact modes. But even peak forces on the light car with this attenuator will not exceed the average force on the same car when it impacts a constant-force attenuator designed for the heavy car.

The attenuator does not approach constant-stroke behavior as nearly for different velocities as for different vehicle weights, but it does offer significant force reductions for lower speed impacts, as compared to fixed-force systems.

MAINTENANCE CONSIDERATIONS

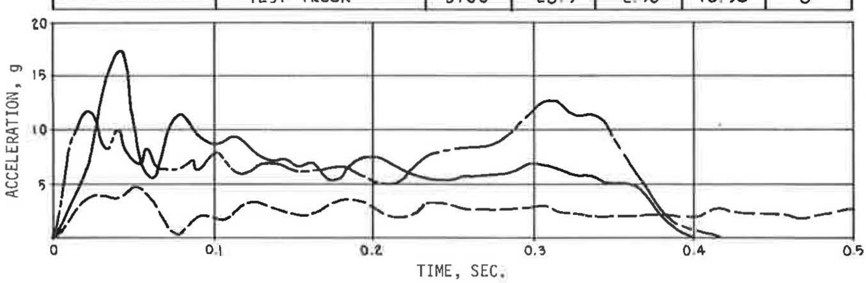
The problem of placing an attenuator back into service as quickly as possible following a high-speed head-on impact is significant. It deserves, and has received, intensive design attention. The costs of materials, manpower, and equipment expended in maintenance efforts constitute a very significant part of the overall attenuator cost.

Several attempts have been made to gather appropriate crash information for evaluation of actual attenuator performance. The California Division of Highways has a study

Figure 7. Three views of attenuator during and following 29-mph head-on impact immediately after 60-mph angle impact.

Figure 8. Constant-stroke characteristics of attenuator.

SYMBOL	VEHICLE	WEIGHT (lb.)	IMPACT SPEED (mph)	AVERAGE DECELERATION (g)	ATTENUATOR STROKE (ft)	CAR CRUSH (ft)
———————	VOLKSWAGEN	1800	58	8.62	12.25	.79
—·—·——	RAMBLER	3700	56	7.22	13.67	.83
— — — —	TEST TRUCK	3700	28.5	2.50	10.50	0



in progress (5) in which three different attenuator designs at nine freeway sites are monitored. Extensive records have been maintained on systems at a total of nine installations, giving a complete economic history. Also, at three of the sites, a closed-circuit television record is made of each impact, from which vehicle speed, mass, and trajectory can be estimated. Reported accidental property losses and injuries are also being tabulated.

Table 1 gives a summary of the data recorded through July 1973. (Each row gives data for one impact.) It illustrates one important feature of attenuator economics that must be addressed in the near future. Maintenance costs can far outstrip initial costs in relatively short periods of use. This has been a significant problem in many areas already. Money earmarked to assist states in the purchase and installation of attenuator hardware has not always found counterpart funds for maintenance. Hence many good attenuator installations have gone wanting for repairs; other sites are not protected at all because maintenance budgets are inadequate to sustain installations.

In the California study of impacts on steel drum attenuator systems in actual service during a 2-year period, repair costs averaged about $1,000 per impact in reported accidents and more than $200 per unreported accident. But a more important consideration than repair cost is the risk of bodily injury to maintenance personnel, due to accidents during the repair process, measured in terms of man-hours of exposure to traffic. For the steel drum barriers, in reported accidents, this averaged over 40 man-hours per accident, whereas for the water tube attenuator and the Fibco sand barrier exposure averaged about 20 man-hours per reported accident (5).

The Hi-Dri attenuator system is known to have still further maintenance man-hour advantages over the water cell attenuator. Although the same basic hardware is employed, the concrete cartridges are designed to allow quick replacement. Individual cartridges are light enough to be handled easily by two men. They are set into the eight to 10 bays between the major plates or diaphragms. Each cartridge consists of eight to 12 individual cells glued into a structural unit between thin plates and covered by waterproof material to form a cartridge. The total weight of the nine cartridges needed for the average attenuator is less than 500 lbm (227 kg), easily carried in a half-ton pickup truck.

The cartridges are inserted in the top of the unit. They rest on small metal brackets bolted to the main diaphragms. This makes it possible to place the cartridge into the attenuator without field adjustment. A complete set of recharge cartridges has been placed into the unit by two men in as little as 75 s, under ideal conditions. Under actual field conditions, with a trained two-man crew the time should be significantly less than the average values reported in the California study.

This was demonstrated recently in the test environment. Following several head-on impacts reported in this test series, the attenuator was pulled to its original position by a half-ton pickup truck. After the shear pins were replaced in the erection cable clevises, the spent cartridges were removed and replaced. A two-man crew completely refurbished the attenuator in less than 12 min. Under most conditions, the total time of reservicing should be no more than 20 to 25 min, or less than 1 man-hour per accident, with no more equipment than can be carried to the site in a half-ton pickup.

The relatively sophisticated design of the support hardware for this system makes it capable of sustaining repeated fendering impacts without much loss of head-on capability. This feature can offer a significant extra margin of protection between visits of the maintenance crew.

WEATHERABILITY

Users of attenuator systems are understandably concerned with weather resistance capability. This was recognized at the early stages of development of the Hi-Dri system. The vermiculite concrete is kept moisture-free and protected from the erosive effects of the elements by casing the light in a pleated aluminum foil wrap and sealing with a roofing tar-and-chip coating. Further protection is provided by a sealed, weather-resistant fiber cartridge package, which also provides for quick and easy reburbishment. In the unlikely event that moisture should penetrate these three barriers, it is improb-

Figure 9. Fixed-stroke comparisons.

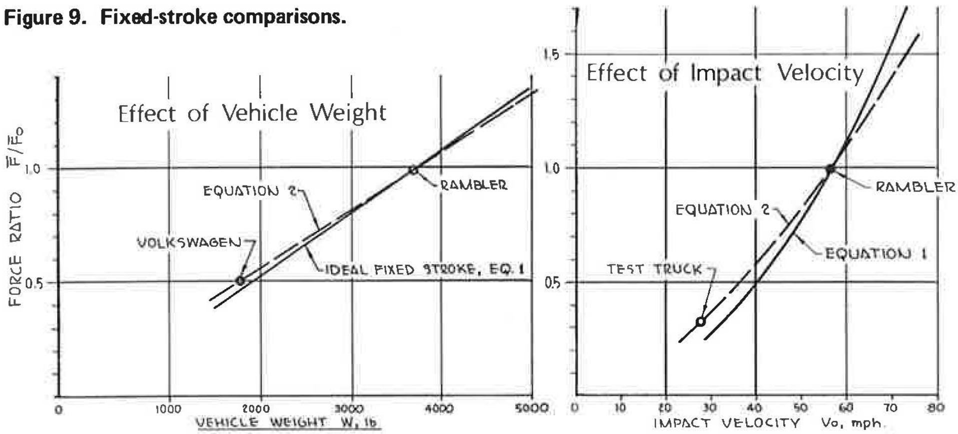


Table 1. Attenuator comparison.

Barrier	Year	Total Cost of Repair (dollars)	Injury	Disabled Vehicle	Estimated Speed (mph)	Man-Hours of Exposure to Traffic
Sand inertial (Fibco)	1971	1,334	yes	yes	65	36
	1972	646	no	no	60	10
Total		1,980				46
Average		940			62.5	23
Steel (Texas)	1971	2,806	yes	yes	55	38
		2,200	yes	yes	65	50
	1972	529	yes	yes	65	53
		686	no	yes	65	46
		675	yes	yes	50	58
		1,180	no	yes	60	42
		196	no	yes	55	8
	1973	558	yes	yes	65	35
		654	yes	yes	55	52
Total		9,484			470	382
Average		1,053.77			59	42.4
Water tube	1971	99	yes	yes	65	11
		88	no	yes	65	10
	1972	329	yes	yes	55	23
		117	no	yes	40	14
		152	yes	yes	55	18
		358	yes	yes	65	24
		246	yes	yes	65	18
	1973	2,058	yes	yes	60	—[a]
		283	no	yes	60	25
		96	yes	yes		13
Total		3,826			530	156
Average		382.60			59	19.5

Note: 1 mph = 1.6 km/h.
[a]Not stated.

able that attenuator performance will be substantially deterioriated. The asphaltic cement used in the preparation of the concrete cells is, in itself, moisture resistant. Cells used in an early test program were removed from the site, left in the open, and exposed to the rain, sun, frost, and wind for more than a year without measurable decrement of strength characteristics.

CONCLUSIONS

The following conclusions are warranted by the results of tests covered in this and previous reports (1, 2, 3, 4).

1. The performance of the Hi-Dri attenuator is significantly better than that of the Hi-Dro cushion attenuator, especially for lightweight vehicle impacts;
2. Multiple-hit capability without service following a severe side angle hit has been demonstrated;
3. The velocity-sensitive characteristics of the Hi-Dri cartridges make it possible to design the shortest possible unit for a range of car weights and impact velocities, while providing a margin of safety for high-velocity impacts that exceed design specifications;
4. The Hi-Dri attenuator may be refurbished after 60-mph (97-km/h) frontal impact by two men in a light pickup truck in less than 30 min or less than 1 man-hour of exposure to traffic per accident;
5. Traffic interference from flying debris during impact with the attenuator is eliminated (there is no debris discharge from a Hi-Dri unit when struck within design conditions); and
6. Design provision for three levels of moistureproofing has eliminated concerns regarding weatherability.

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