Connecticut Narrow Hazard Crash Cushion

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This paper describes analytical and experimental work that resulted in the development of a nonproprietary crash cushion to be used at narrow hazard sites. Examples of such locations include the ends of edge-of-road and median barriers, bridge pillars, and center piers. The first phase of the experimental program involved a series of scale-model impact tests to verify the energy dissipation predictions of the analytical model and to investigate the lateral stability characteristics of the crash cushion model. In the second phase of the experimental program, full-scale crash tests were conducted in accordance with the requirements of *NCHRP Report 230*. This new narrow hazard crash cushion satisfies the requirements of that document and is inexpensive to fabricate and repair. In addition, the system possesses a unique, self-contained backup structure, which permits its use as an end treatment for a wide variety of narrow hazards, including concrete barriers and all guardrail systems.

The favorable energy dissipation capabilities of laterally loaded metallic cylinders have led to their employment in impact attenuation devices used in highway safety applications. These crash cushions have included both portable (*1–3*) and stationary (*4,5*) devices. In both systems, energy is dissipated by deforming mild steel cylinders inelastically to deformations approaching 90 percent of their original outside diameters under high-speed impacts (60 mph) with heavy vehicles (4,500-lb).

The portable system is employed in slow-moving maintenance operations (e.g., line striping) to provide protection for both the errant motorist and maintenance personnel. The design of the stationary system is shown in Figure 1. This operational crash cushion, known as the Connecticut Impact Attenuation System (CIAS), is composed of 14 mild steel cylinders of 3- or 4-ft diameters. All of the cylinders are 4 ft high, but the individual wall thicknesses vary from cylinder to cylinder. This crash cushion is unique in that it will trap the errant vehicle when it impacts the unit on the side unless the area of impact is so close to the back of the system that significant energy dissipation and acceptable deceleration responses are unobtainable because of the proximity of the hazard. Only in this situation will the impact attenuation device redirect the vehicle into the traffic flow direction. To cope with the redirectional crash test case involving an impact near the rear of the system, steel tension straps (ineffective under compressive loading) and compression pipes (ineffective in tension) are employed. This bracing system ensures that the crash cushion will respond in a stiff manner when subjected to an oblique impact near the rear of the unit, providing the necessary lateral force to redirect the errant vehicle. On the other hand, the braced tubes retain their unstiffened responses when the attenuation system is crushed by impacts away from the back of the device. These impact attenuation devices are being employed in several states in the United States. They have been credited with saving lives and greatly reducing the injury severities (*6–9*) associated with high-speed accidents by reducing the deceleration levels of the occupants.

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ENERGY DISSIPATION CHARACTERISTICS OF STEEL CYLINDERS

Details of the analytical work that describes the initial- and post-collapse behavior of braced and unbraced metallic cylinders are reported elsewhere (*10–13*). In summary, the quasi-static collapse loads for diametrically braced cylinders (where the bracing is effective only in tension) are given by the expressions

$$P_\theta = \frac{4M_p}{R} \cdot \frac{\cos(\pi/4 + \theta/2)}{1 - \sin(\pi/4 + \theta/2)} \qquad 0 \leq \theta \leq \pi/6 \tag{1a}$$

$$P_\theta = \frac{4M_p}{R} \cdot \frac{1 - \sin\theta}{1 - \cos\theta} \qquad \pi/6 \leq \theta \leq \pi/4 \tag{1b}$$

$$P_\theta = \frac{4M_p}{R} \cdot 1 \qquad \theta \geq \pi/4 \tag{1c}$$

where

θ = bracing angle with respect to the horizontal,
R = radius of the cylinder, and
M_p = plastic moment of the cross section.

These results are illustrated in Figure 2, where the dimensionless collapse load ratio ($P_\theta R/4M_p$) is the ratio of the braced to unbraced collapse loads. The corresponding collapse modes for the three regimes have 10, 8, or 4 plastic hinges depending on the value of θ.

The post-collapse quasi-static analysis, which accounts for the effects of strain hardening by employing a modified equivalent structure technique, is presented in Reddy et al. (*11*). The effects of strain rate and the initial collapsing mode configuration on the energy dissipation characteristics of the cylinders under impact loading are reported by Veillette and Carney (*12*). A detailed impact analysis of the impact event was conducted using ABAQUS, a large, general-purpose, finite-element program with nonlinear capabilities. The effects of strain rate are incorporated in ABAQUS through the expression

$$\dot{\bar{\varepsilon}}^{pl} = D\left(\frac{\bar{\sigma}}{\sigma_0} - 1\right)^P \qquad \bar{\sigma} \geq \sigma_0 \tag{2}$$

FIGURE 1 The Connecticut Impact Attenuation System (CIAS).

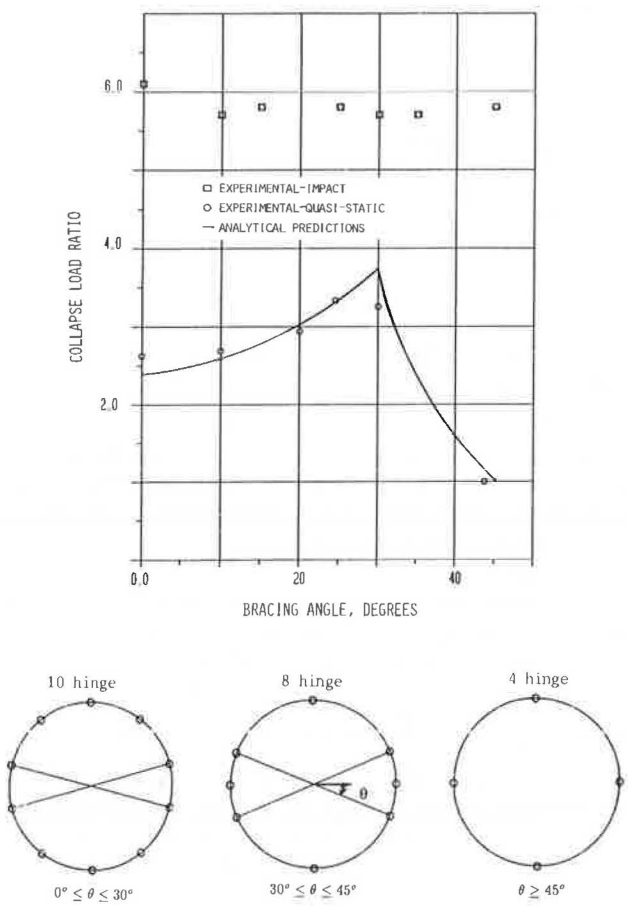

FIGURE 2 Dimensionless initial collapse loads vs. bracing angle for quasi-static and impact loading.

where

$\dot{\bar{\varepsilon}}^{pl}$ = equivalent plastic strain rate,
$\bar{\sigma}$ = equivalent stress,
σ_0 = quasi-static yield stress, and
D and p = material parameters equal to 40.4 and 5.0, respectively for mild steel.

Some typical ABAQUS results for an unbraced tube are presented in Figure 3 and illustrate the importance of accounting for strain rate effects in the numerical modeling of impact problems.

SCALE MODEL EXPERIMENTS

The scale model experiments were conducted on a specially constructed impact apparatus, described in Figure 4. The rig includes a sledge that is fired from a gas gun whose velocity is controlled by setting the gas tank's priming pressure. The launching of the sledge is software controlled through a data acquisition's digital input/output card. Two light beams, set up 5 in. apart and perpendicular to the striker's trajectory, are employed to determine its impact velocity. The exit door is constructed in such a way as to prevent the striker from reentering the guiderail area after rebounding off the impacted tube and possibly damaging the electronic instrumentation. A high-speed camera, operating at 6,000 frames per second, records the displacement-time history of the events. Force-time histories are obtained by the use of quartz load cells located on the impacting mass and the backup plate. The charges from these load cells are converted in the amplifier to voltages and recorded in digital form on a personal computer at 31.4 kHz through a data acquisition system. Dis-

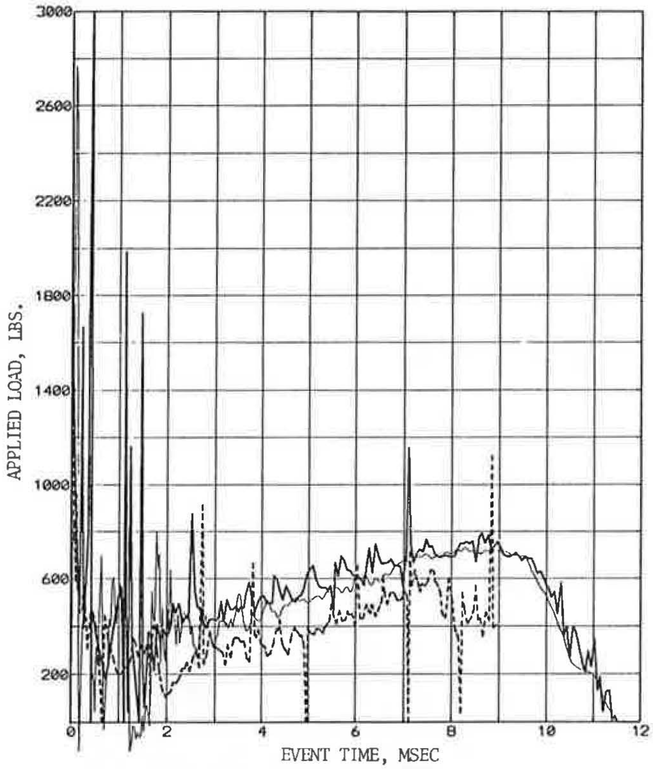

FIGURE 3 Sledge/tube force history with strain rate (heavy line), without strain rate (dashed line), and experimental (light line).

placement-time information is obtained from a frame-by-frame analysis of the high-speed film using an NAC film motion analyzer interfaced with a SUN 3/50 workstation. The force-deformation record of the event is then obtained from combining the force-time and displacement-time histories.

The complete scale-model impact testing program was reported previously (*14*). However, two typical examples are presented below in which 2-in.-diameter mild steel tubes were employed. System configuration 1 is illustrated in Figure 5. It is composed of a single row of eight annealed and unannealed, 18- and 20-gauge tubes. The back tube in the chain contains 0° bracing. The deformed configuration is shown in Figure 6, and the force-deflection record of the event is presented in Figure 7. In this example, the load cell data were obtained from the force transducer affixed to the rear of the system.

The second example system differs from the first one in that the back tube is made from a different gauge stock and is stiffened with 15° double bracing. This system is shown in Figure 8, and the post-impact configuration is presented in Figure 9. The force-deflection results for system 2 are given in Figure 10 in which two curves are presented. The solid curve is the response of a load cell that was attached to the impacting mass, while the dashed curve is the output from the load cell located at the rear of the system. It is interesting to note that the responses of the front and rear load cells are quite different, even though their total areas are essentially equal both to each other and to the kinetic energy of the impacting mass. This difference in response is caused by the inertia of the crash cushion model. In the early stages of the

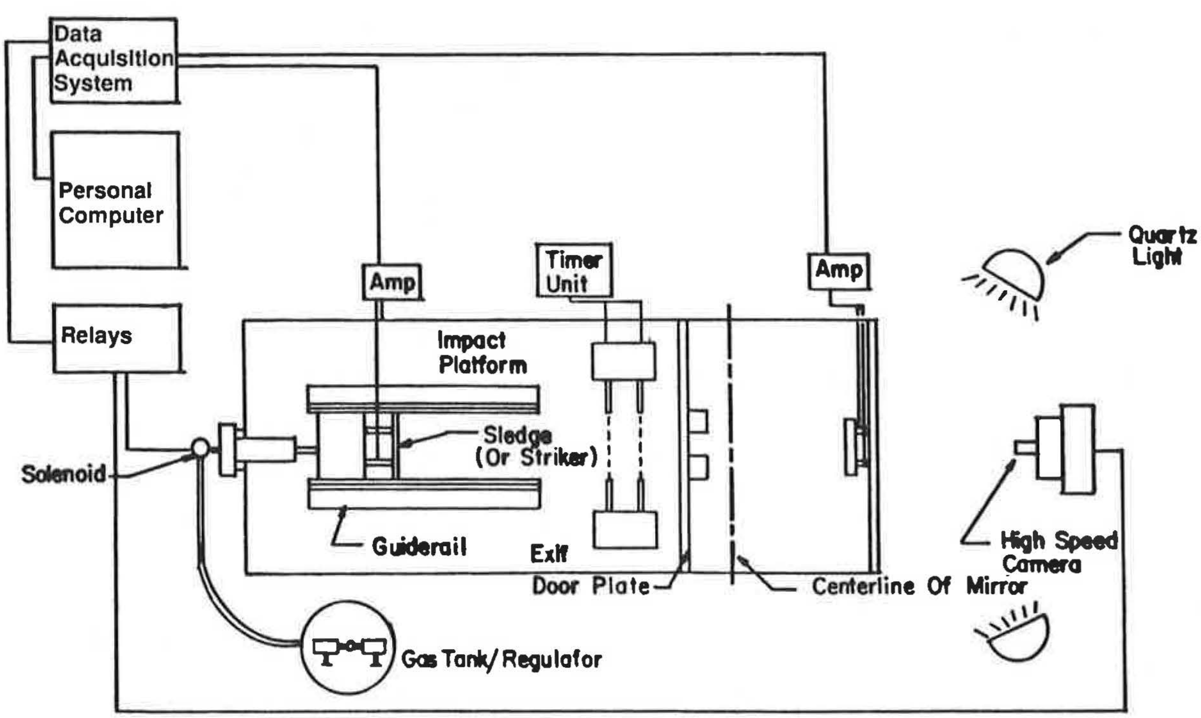

FIGURE 4 Impact apparatus.

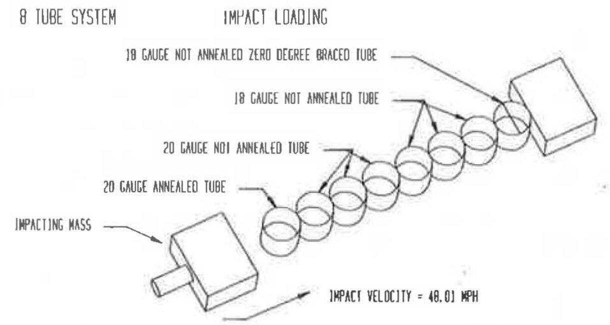

FIGURE 5 **Mixed eight-tube system configuration 1.**

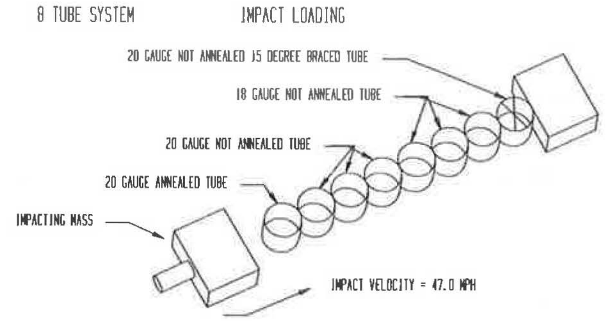

FIGURE 8 **Mixed eight-tube system configuration 2.**

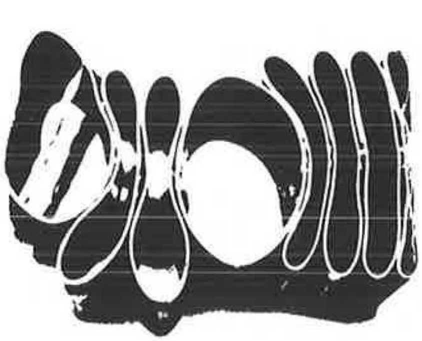

FIGURE 6 **Deformed configuration 1.**

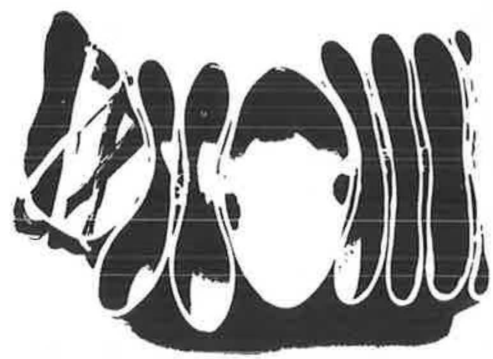

FIGURE 9 **Deformed configuration 2.**

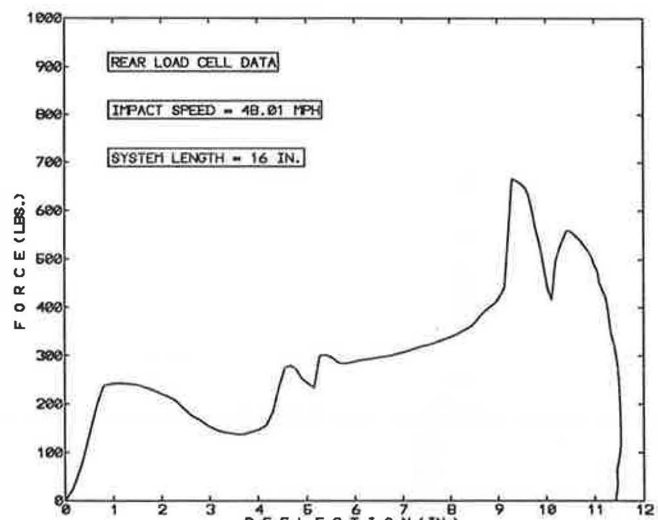

FIGURE 7 **Force-deflection response for system configuration 1.**

impact event, the acceleration of the crash cushion is in the same direction as the velocity of the impacting mass. It follows, therefore, that the force magnitude felt by the transducer attached to the impacting mass will be greater than that registered by the load cell affixed to the rear of the system. This phenomenon reverses itself later in the impact event when the system begins to decelerate.

CRASH CUSHION DESIGN

The final crash cushion design is shown in Figures 11 through 14. The system is composed of a single row of eight 3-ft-diameter mild steel cylinders of different thicknesses (see Figure 11), which are formed from flat plate stock. All cylinders are 4 ft high, and a total of four 1-in.-diameter cables (two on each side of the system) provide lateral stability and assist in redirecting errant vehicles under side impact conditions. The 24-ft length was chosen as the probable minimum acceptable length for the crash cushion if *NCHRP Report 230* (*15*) crash test requirements were to be met. The 3-ft width was selected because most narrow highway hazards are approximately 2 ft wide and the crash cushion should be slightly wider than this dimension.

Other unique features of the Connecticut narrow hazard crash cushion include

- A stand-alone concrete-filled steel tubular backup structure (see Figure 12), which also provides support for the ends of the four cables, permitting them to develop the tension required to redirect vehicles when impacting the system on its side.
- A steel plate cable support at the front of the crash cushion.
- Lateral deflection limiters, shown in Figure 13, which limit the amount of lateral deflection in the system and assist in the redirective process. These deflection limiters are connected to the pavement inside cylinders 5, 6, and 7 and are activated only under side impact conditions. The allow-

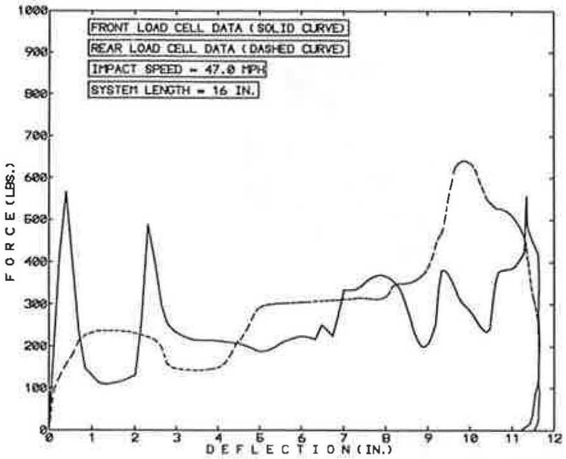

FIGURE 10 Force-deflection response for system configuration 2.

FIGURE 11 Connecticut narrow hazard crash cushion. Cylinder 1 (nose): 1/8 in.; cylinder 2: 3/16 in.; cylinder 3: 1/4 in.; cylinder 4: 1/4 in.; cylinder 5: 1/4 in.; cylinder 6: 5/16 in.; cylinder 7: 3/8 in.; cylinder 8: 1/4 in.

FIGURE 12 Stand-alone concrete-filled steel tubular backup structure.

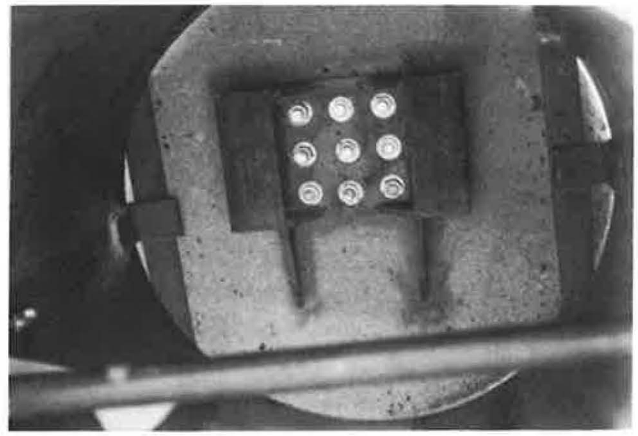

FIGURE 13 Lateral deflection limiters.

FIGURE 14 Box beam stops and tension rods.

able lateral deflections in these cylinders are 9, 6, and 3 in., respectively.

- Box beam stops (in cylinders 1 and 2) and tension rods (in cylinder 1), which prevent the errant vehicle from vaulting over the crash cushion or submarining under the unit. If the cylinder at the nose of the system is impacted, it will wrap itself vertically around the front end of the impacting vehicle, effectively capturing it. These devices are shown in Figure 14.
- Diametrically placed compression pipes (welded at one end and effective only in compression) in cylinders 5, 6, and 7 and a compression-tension pipe in cylinder 8 to further aid in the redirective process under side impact conditions.

THE FULL-SCALE CRASH TESTING PROGRAM

A total of 11 crash tests were conducted at ENSCO's Georgetown, Delaware, facility during the development of this crash cushion. Five of these 11 tests involved side impacts with the system at 20° or 25°. It was during this series of tests that the backup structure and displacement limiter designs were developed. The resulting increase in lateral stiffness eliminated the pocketing problems that plagued the earlier redirective tests.

The matrix of the crash-cushion tests required by *NCHRP Report 230* includes tests 50, 52, 53, and 54. A photographic summary of these tests is presented in Figures 15 through 19, and the detailed test data, including occupant risk values, are given in Table 1. *NCHRP Report 230* test 52 was conducted twice to demonstrate that the design changes instituted after the first test 52 (documented in the "Comments" column of Table 1) had no adverse effect on system performance during a head-on impact. A comparison of the two sets of occupant risk data confirms this fact. All of the safety performance requirements of *NCHRP Report 230* associated with structural adequacy, occupant risk, and vehicle trajectory have been satisfied in this crash testing program.

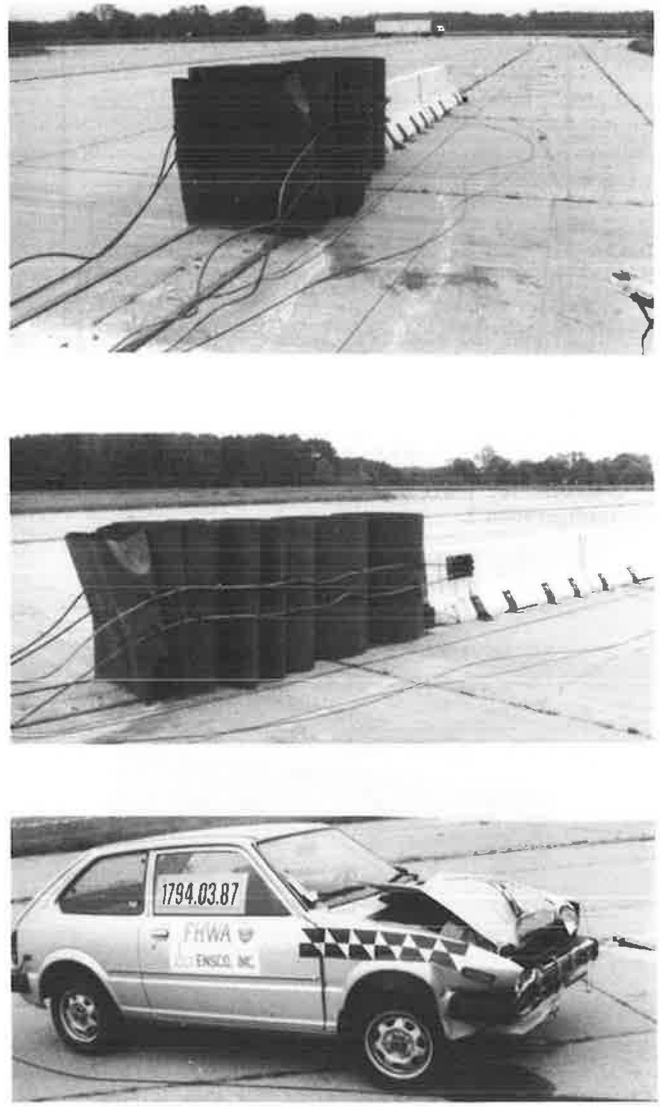

FIGURE 16 ***NCHRP Report 230*** **test 52.**

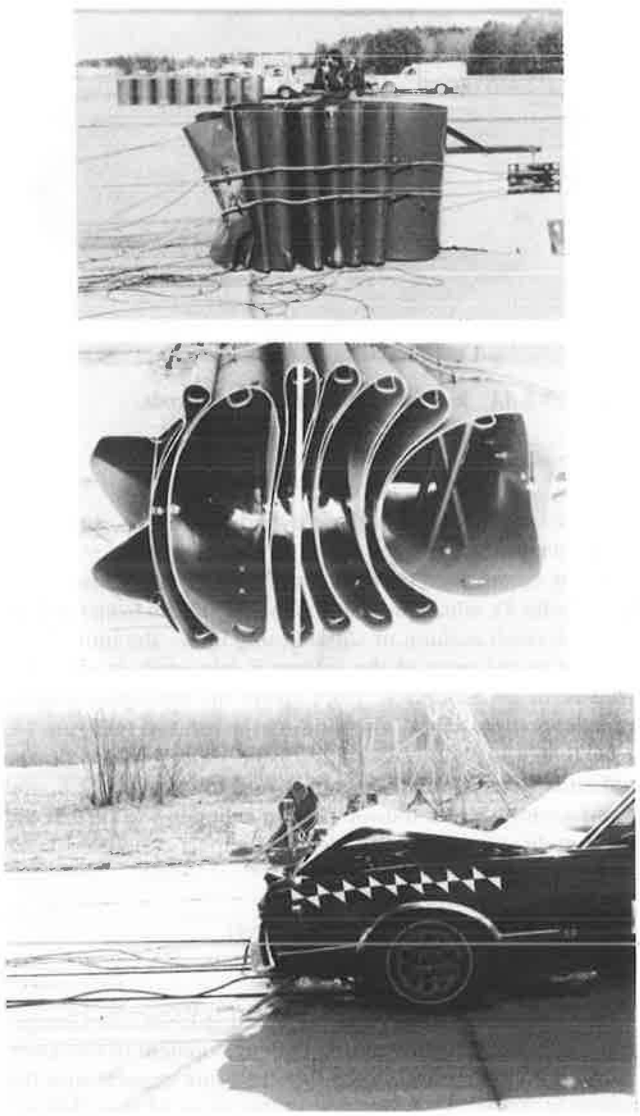

FIGURE 15 ***NCHRP Report 230*** **test 50.**

CONCLUSIONS

The development of a new, nonproprietary, narrow hazard crash cushion was described in this paper. This crash cushion satisfies the performance requirements of *NCHRP Report 230*. The development of the device involved the following three phases:

- Analytical modeling of the crash cushion,
- Scale model impact tests, and
- Full-scale crash tests.

The new impact attenuation device is composed of eight mild steel cylinders, formed from flat plate stock, and possesses the unique features of

- Displacement limiting devices, which allow the crash cushion to be compliant under side impact conditions while still possessing the lateral stiffness required to redirect the errant vehicle;
- A trapping mechanism in the nose cylinder, which prevents vaulting or submarining; and
- A stand-alone backup structure, which permits the crash cushion to be used as an end treatment for a wide variety of narrow hazards.

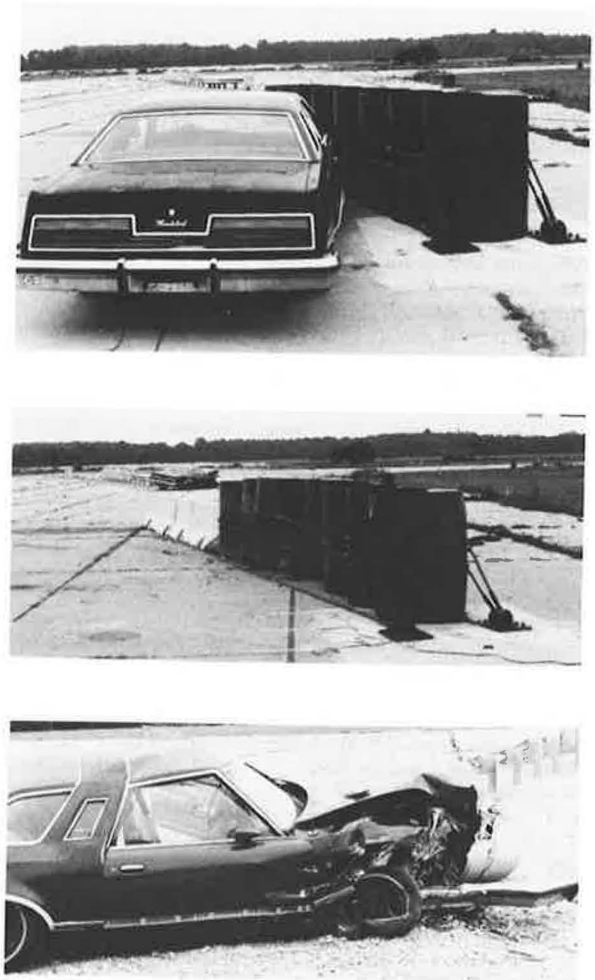

FIGURE 17 *NCHRP Report 230* test 53.

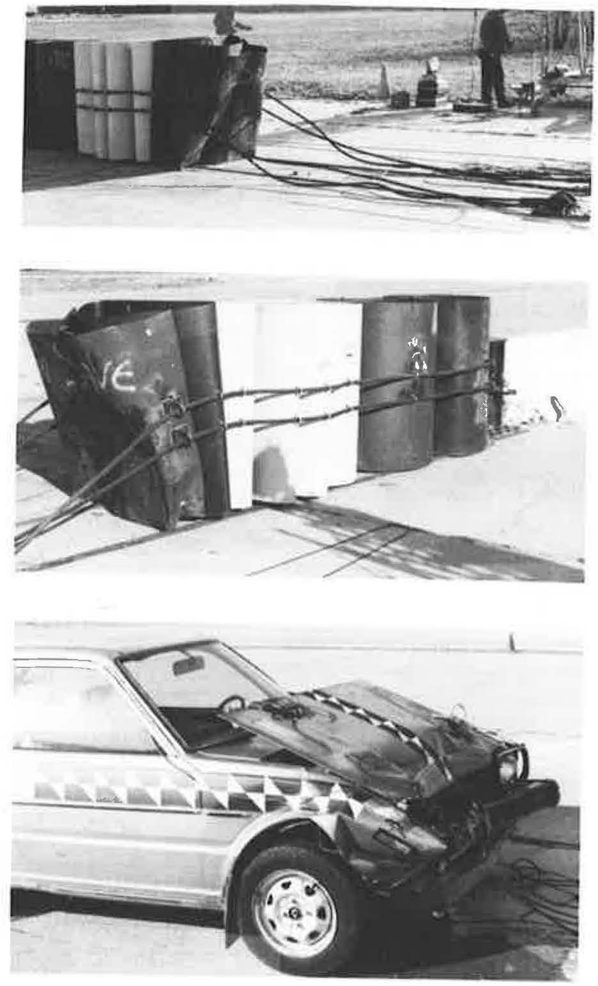

FIGURE 19 *NCHRP Report 230* test 52.

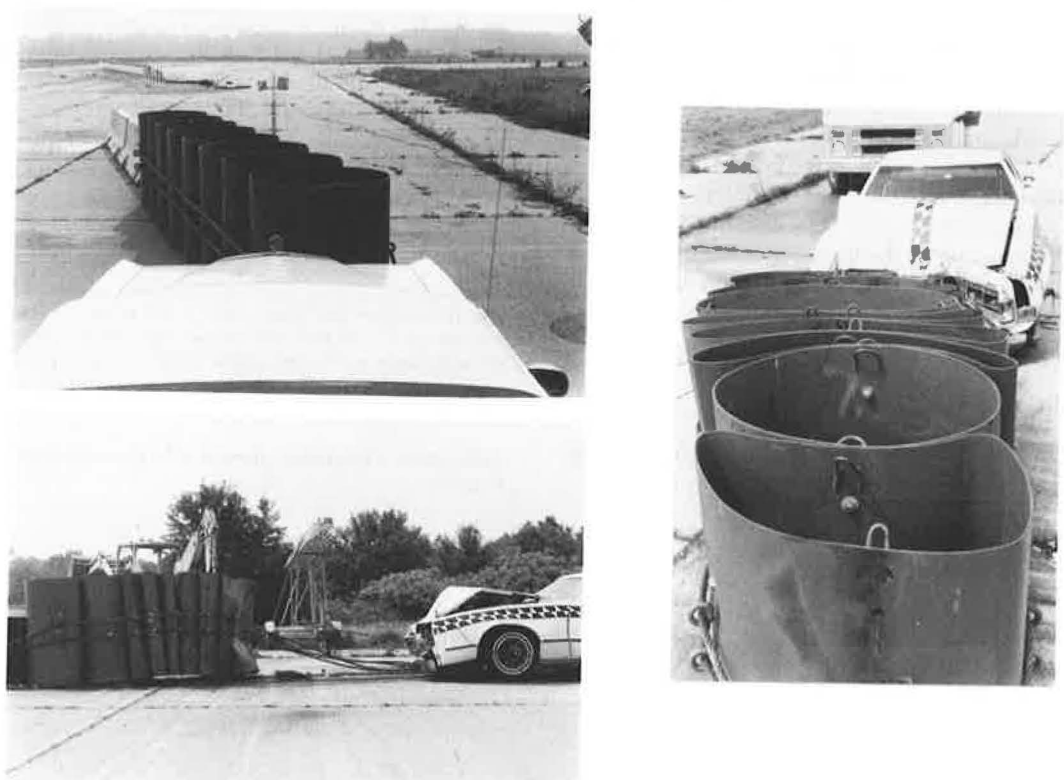

FIGURE 18 *NCHRP Report 230* test 54.

TABLE 1 SUMMARY OF CRASH TEST RESULTS

NCHRP 230 Test Number	Vehicle Weight (lb)	Impact Speed (mph)	Angle of Impact (degrees)	Vehicle Impact Location	Vehicle Stopping Distance (ft)
50	4513	60.9	0	Nose	20.4
52	1797	60.5	0	Nose	14.0
53	4495	61.2	20	Midlength	—
54	4505	60.1	15.5	1.5 ft offset From Nose	19.3
52	1802	60.8	0	Nose	14.4

NCHRP 230 Test Number	Occupant Impact Velocity (fps)		Occupant Ridedown Acceleration (10 msec avg. g's)		Comments
	Longitudinal	Lateral	Longitudinal	Lateral	
50	29.3	—	15.6	—	Cylinder #8 had 15 degree bracing and was 3/8 in. thick.
52	37.6	—	14.5	—	Cylinder #8 thickness reduced to 1/4 in.
53	33.8	17.5	13.0	12.8	Cable diameters changed from 3/4 to 1 in. Bracing in Cylinder #8 changed to 0 degrees and stand alone backup used. Compression pipes added to cylinders 5,6, and 7.
54	30.4	7.8	10.3	4.7	No changes.
52	29.5	—	13.5	—	No changes.

In addition to the ease of fabrication and installation of this system, the Connecticut narrow hazard crash cushion promises to be a low maintenance device. It employs the same types of mild steel cylinders that have been successfully used for 4 years in the CIAS. During this time period, the Connecticut Department of Transportation has fully restored numerous impacted installations in 1 to 2 hr, removing deformed cylinders and replacing them with new ones (*9*). Under most impact conditions, only the crushed steel cylinders will require replacement. Detailed information regarding the design, fabrication, and construction of the Connecticut narrow hazard crash cushion can be obtained from the Division of Research of the Connecticut Department of Transportation.

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