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16. ABSTRACT

This final report describes the development and full-scale crash testing of a reusable crash cushion which dissipates kinetic energy through the lateral deformation of a row of nine-high molecular weight/high density polyethylene(HMW/HDPE) cylinders. This 100 km/h impact attenuation device, called the **REACT 350**, satisfies the new crash testing requirements of *National Cooperative Highway Research Program(NCHRP) Report 350* and has been approved by the Federal Highway Administration(FHWA) for use on the National Highway System.

Most impact attenuation devices currently employed require the replacement of damaged structural components and spent energy dissipating elements following an impact event. Until these repairs and refurbishments are carried out, such safety devices are largely ineffective in that they are not able to dissipate kinetic energy in a subsequent impact such that relevant occupant risk parameters are within prescribed limits. The **REACT 350** is a reusable and self-restorative narrow hazard crash cushion. It can dissipate large amounts of kinetic energy, undergo significant deformations and strains without fracturing, and then essentially regain its original shape and energy dissipation potential following an impact with an errant vehicle.

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Final Report
for
Research Project WSDOT-GC 9938
"Maintenance Free Crash Cushion"

MAINTENANCE FREE CRASH CUSHION

by

John F. Carney III
Department of Civil and Environmental Engineering
Vanderbilt University
Box 18, Station B
Nashville, TN 37235

Technical Monitor
Richard Albin
Washington State Department of Transportation

Prepared for

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MAINTENANCE FREE CRASH CUSHION

EXECUTIVE SUMMARY

This report describes the development and full-scale crash testing of a reusable crash cushion which dissipates kinetic energy through the lateral deformation of a row of nine-high molecular weight/high density polyethylene(HMW/HDPE) cylinders. This 100 km/h impact attenuation device, called the **REACT 350.9**, satisfies the new crash testing requirements of *National Cooperative Highway Research Program(NCHRP) Report 350.* It is the first crash cushion to be approved by the Federal Highway Administration(FHWA) for use on the National Highway System under these *NCHRP Report 350* guidelines.

Most impact attenuation devices currently employed require the replacement of damaged structural components and spent energy dissipating elements following an impact event. Until these repairs and refurbishments are carried out, these safety devices are largely ineffective in that they are not able to dissipate kinetic energy in a subsequent impact in an acceptable manner such that relevant occupant risk parameters are within prescribed limits. In some cases, a significant time elapses before damaged impact attenuation devices are repaired and restored to effective operating status. This system "down-time" is a source of danger to the motoring public and presents a potentially serious tort liability exposure to the transportation agency involved. The **REACT 350.9** is a reusable and self-restorative narrow hazard crash cushion. It can dissipate large

amounts of kinetic energy, undergo significant deformations and strains without fracturing, and then essentially regain its original shape and energy dissipation potential upon removal of the load.

INTRODUCTION

Accidents involving motor vehicles are a major worldwide health problem which constitutes a great economic and social loss to society. In the United States, for instance, the potential years of productive life that are lost before age 65 as a result of motor vehicle related injuries and deaths are greater than those lost to cancer or heart disease. One cost-effective way to reduce the serious injuries and fatalities associated with vehicular impacts with fixed roadside hazards is through the use of impact attenuation devices. Crash cushions, for example, can shield fixed roadside hazards and dissipate the kinetic energy associated with an impacting vehicle in a controlled way so that the errant vehicle is either decelerated to a safe stop or redirected away from the hazard.

The vast majority of crash cushions currently employed require the replacement of damaged structural components and spent energy dissipating elements following an impact event. These impacted safety devices are largely ineffective until these repairs and refurbishments are carried out. Furthermore, a significant time often elapses before damaged crash cushions are repaired and restored to effective operating status. This system "down-time" is a source of danger to the motoring public and presents a potentially serious tort liability exposure to the transportation agency involved.

This research report deals with the development of a new crash cushion which is reusable, self-restorative, and requires very low maintenance. Kinetic energy is dissipated in this device through the collapse of laterally loaded cylinders constructed from high molecular weight/high density polyethylene(HMW/HDPE). This polymer possesses the following favorable material characteristics:

- High stiffness
- High abrasion resistance
- High chemical corrosion resistance
- High moisture resistance
- High ductility
- High toughness
- High tensile strength
- High impact resistance over a wide temperature range

As a result, a HMW/HDPE cylinder can dissipate large amounts of kinetic energy, undergo significant deformations and strains without fracturing, and then essentially regain its original shape and energy dissipation potential upon removal of the load.

REVIEW OF PREVIOUS WORK

In the 1960's the reality of traffic fatalities occurring at a rate of 1,000 per week prompted the U.S. Federal Highway Administration to initiate a research and development program to provide rapid improvement in highway safety. The development of roadside safety appurtenances was an important part of this highway safety program and a variety of devices have evolved during the last 25 years. The installation of these devices on the roadway system of the United States has substantially reduced the severity of many accidents.

The first recommended procedures for performing full-scale crash tests were contained in the single page *Highway Research Board Circular 482* published in 1962 (1). This document specified a 4000-lb test vehicle, two impact angles (7 and 25 degrees), and an impact velocity of 60 mi/h for testing guardrails. In 1974, an expanded set of procedures and guidelines were published as *NCHRP Report 153* (2). This report was the first comprehensive specification which addressed a broad range of roadside hardware including longitudinal barriers, terminals, transitions, crash cushions, and breakaway supports. Specific evaluation criteria were presented as were specific procedures for performing tests and reducing test data. In the years following the publication of *NCHRP Report 153,* a wealth of additional information regarding crash testing procedures and evaluation criteria became available, and in 1976 Transportation Research Board Committee A2A04 was given the task of reviewing *NCHRP Report 153* and providing recommendations. The result of this effort was *Transportation Research Circular No. 191* (3). As *TRC 191* was being published, a new NCHRP project was initiated to update and revise *NCHRP Report 153. The* result of this NCHRP project was *NCHRP Report 230* (4), published in 1981. In many ways *NCHRP Report 153* was the first draft of *NCHRP*

Report 230; six years of discussion, dissension, and clarification were required before the highway safety community reached the consensus represented by this document.

NCHRP Report 230 specified the test procedures and evaluation criteria to be followed in evaluating the effectiveness of roadside safety hardware. Appurtenances were grouped into three general categories: (1) longitudinal barriers and their terminals, (2) crash cushions, and (3) breakaway and yielding supports. Longitudinal barriers redirect errant vehicles away from roadside hazards and include devices such as guard rails, median barriers, and bridge railings. Crash cushions are designed to safely bring an errant vehicle to a controlled stop under head-on impact conditions and may or may not redirect when struck along the side. Breakaway and yielding supports are devices used for roadway signs and luminaries that are designed to disengage, fracture, or bend away under impact conditions.

NCHRP Report 230 was replaced in 1993 by *NCHRP Report 350*(5). This consensus document significantly increased the full scale crash testing requirements for qualifying safety hardware. In particular, the crash test matrix for crash cushions was greatly expanded, with terminals and redirective crash cushions grouped together. The evaluation criteria of NCHRP Report 350 are very similar to those of NCHRP Report 230; however, the crash testing matrix that must be addressed in the development of new crash cushions is significantly more comprehensive. The NCHRP Report 350 safety evaluation guidelines and crash test matrix for crash cushions contains three test levels and subdivides crash cushions into redirective and non-redirective categories. The user agency is responsible for deciding which of the test levels is most appropriate for a particular application. Test Level 3, with its specified impact speed of 100 km/h, is comparable to the impact speed requirements of NCHRP Report 230. The new test matrix requires a total of six or eight different crash tests for redirective crash cushions,

while non-redirective crash cushions must perform acceptably in five different crash scenarios. *NCHRP Report* 230 required four crush cushion crash tests. A redirective crash cushion is one that will redirect an errant vehicle back onto the traveled way when the impact occurs on its side. A non-redirective crash cushion obviously does not possess this characteristic. The new crash testing guidelines for redirective crash cushions are considerably more rigorous than those of non-redirective crash cushions. In fact, the capabilities of non-redirective crash cushions are significantly less than their redirective counterparts, and locations where their use is warranted are limited.

It is of interest to note that the crash testing requirements of NCHRP Report 350 do not distinguish between redirective cash cushions and terminals, a terminal being a device designed to shield the end of a longitudinal barrier. NCHRP Report 230 specified different crash testing requirements for crash cushions and terminals. In the future, there will probably be only one crash test matrix and evaluation criteria for all crash cushions and terminals.

ENERGY DISSIPATION MECHANISMS IN SAFETY APPURTENANCES

Currently available highway safety hardware dissipate energy in a variety of ways (6,7). Examples include:

- Crushing of cartridges filled with polyurethane foam enclosed in a hex-shaped cardboard honeycomb matrix.
- An extension process in which a W-beam guardrail is permanently deformed and deflected.

- A cable/brake assembly which does work by developing fraction forces between brakes and a wire rope cable.
- Shearing off a multitude of steel band sections between slots in a W-beam guardrail.
- Transferring the momentum of an errant vehicle into sand particles contained in frangible plastic barrels.
- Crushing lightweight perlite concrete modules.
- Plastically deforming clusters of steel cylinders.

The laterally loaded steel cylinder crash cushion devices (8-12)possess some attractive energy dissipation characteristics. These include the ability to achieve deformations approaching 95 percent of their original diameters, a stable load-deformation behavior, an insensitivity to the direction of loading, and a high energy dissipation capability per unit mass. However, these systems are sacrificial. There is great potential for improving their collective effectiveness by replacing the mild steel cylindrical energy dissipaters with HMW HDPE cylinders.

PROCEDURES

An extensive series of quasi-static and impact experiments were carried out in an earlier project(13) to establish the energy dissipation, self-restoration, and hysteresis characteristics of HMW/HDPE cylinders as functions of temperature and loading rate. The quasi-static and impact testing program involved individual cylinders laterally loaded between two rigid plates to partial or complete collapse. Cylinder diameters, wall thicknesses, deformation levels, loading cycles, rates of loading, and test temperatures

were varied over a wide range of values. The important findings of this experimental program were as follows:

1. Material fracture does not occur, even at test temperatures of zero degrees Fahrenheit.
2. HMW/HDPE cylinders do not respond elastically when loaded and subsequently unloaded. Instead, they possess the large energy dissipating hysteretic behavior. The unloading phase of a loading cycle is characterized by a sharp drop in the load, followed by the restoration of the oval configuration of the cylinder.
3. When cylinders are loaded to complete collapse for the first time, they restore themselves to approximately 90% of their original diameters upon removal of the load. Further loading cycles to complete collapse result in a 96-99% restoration of the previous shape.
4. When cylinders are loaded to 50% collapse, restoration approaches 96% after the first loading and 94% after five cycles of loading.
5. The load-deformation and energy dissipation responses are only slightly affected by repeated loading to complete collapse.
6. The strain rate sensitivity(SRS) of a HMW/HDPE cylinder, defined as the ratio of its impact to quasi static energy dissipation capacity, is a function of temperature. The energy dissipation capacity is largely unaffected by the rate of loading at low temperatures. At high temperatures, however, this rate of loading has a significant effect on the energy dissipated. This increased strain rate sensitivity with temperature rise increases the energy dissipation potential of the cylinder and counteracts to a great

extent the decrease in energy dissipation capacity which occurs with an increase in temperature under quasi static test conditions. In other words, the increased strain rate sensitivity with temperature of HMW/HDPE significantly diminishes the effect of temperature change on the energy dissipation characteristics of HMW/HDPE cylinders under impact, as opposed to quasi-static, loading conditions.

In this project, the HMW/HDPE 100 km/h narrow hazard crash cushion(**REACT 350.9**) was designed using the experimental information summarized above. The device is shown in Figure 1. It is composed of nine HMW/HDPE cylinders with wall thicknesses varying from 20.23 mm in the nose cylinder to 35.18 mm in the rear cylinder. All cylinder diameters are 0.92 m, and all cylinder heights are 1.22 m. Two 25.40 mm diameter cables are located on each side of the device to assist in redirecting vehicles impacting the crash cushion on the side. Steel chain links, attached to the bottom connection at the interfaces of cylinders 6-7, 7-8, and 8-9 and sliding on a 38.10 mm diameter rod (part of the support structure) also contributes to the development of the lateral resisting force required to redirect errant vehicles impacting on the side. The other key parts of the **REACT 350.9** are the stand-alone backup structure and front cable support assemblies.

Following the design of the HMW/HDPE crash cushion, a full scale crash testing program was conducted at TTI in accordance with the guidelines of *NCHRP Report 350*. The results of this crash testing program are summarized in the next section of this report.

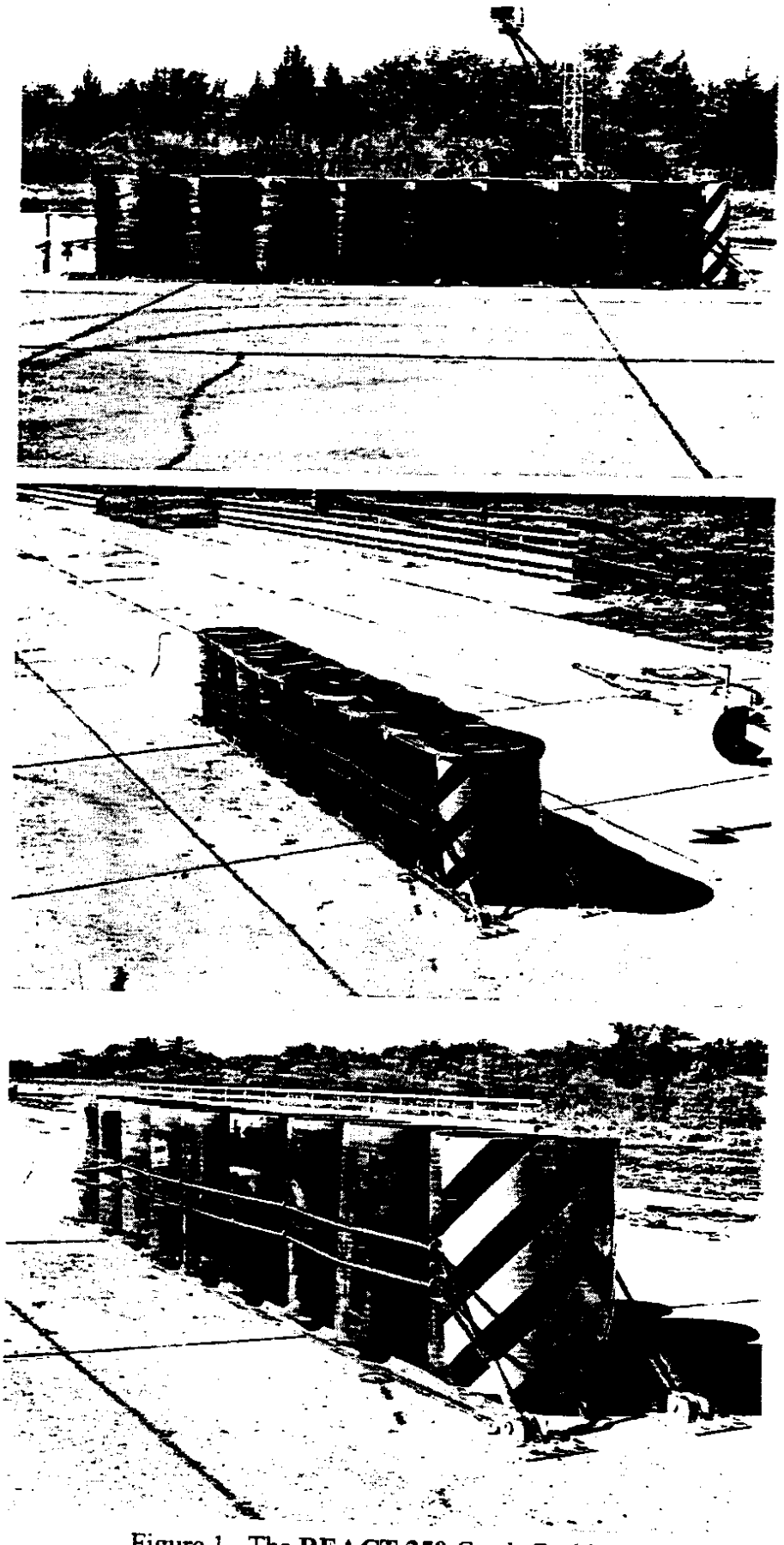


Figure 1. The **REACT 350** Crash Cushion

DISCUSSION

The target impact speed for all of the **REACT 350.9** tests was 100 km/h. The results of this crash test series are summarized in Tables 1 and 2 and discussed below.

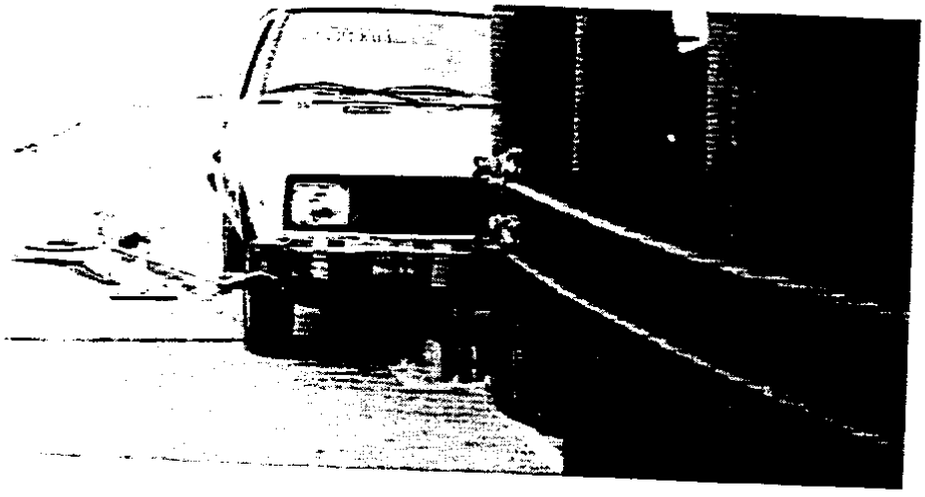
The first test conducted, test 3-30, involved a nose impact with a width/4 offset using an 820 kg car. The 7.32 m long crash cushion partially collapsed (4.79 m) under this moderate kinetic energy loading and then restored itself to 89 % of its original length almost immediately following the impact. All evaluation criteria were met, and the occupant impact velocity(8.73 m/s) and subsequent ridedown deceleration(13.49 g's) values were below the preferred values of 9 m/s and 15 g's, respectively. The vehicle was brought to a controlled stop, and the impact sequence for this crash test is shown in Figures 2-4. There were braking devices attached to the nose cylinder in this test. The intended purpose of these devices was to prevent or delay the restoration of the system following impact. These braking devices did not function, and the test results demonstrated that they were not needed. A modified brake system was installed for the next test. Since the next test was to involve a pickup truck with 2.44 times the kinetic energy loading of this first test, a ninth cylinder was added to the array. The first eight cylinders were not changed, and the partial collapse of the system in the first test is proof that this ninth cylinder at the rear of the system would have no effect on the first test result. Finally, the I-beams in the nose cylinder were moved up slightly to provide some additional vehicular vertical stability in the pickup tests. The crash cushion was then restored to its full original length by a combination of heating of selected cylinders and

Table 1. Crash Tests Conducted Satisfying All *NCHRP Report 350* Requirements

NCHRP Report 350 Test Designation	Vehicle	Impact Speed (km/h)	Impact Angle (deg)	Impact Point	Date Conducted
3-30	820C	100	0	Nose of device, width/4 offset	3/8/94
3-31	2000P	100	0	Center nose of device	4/26/94
3-32	820C	100	15	Center nose of device	4/27/94
3-33	2000P	100	15	Center nose of device	5/31/94
3-38	2000P	100	20	Critical impact point	1/4/95
3-37	2000P	100	20	Length of need	3/14/95

Table 2. Summary of Crash Test Results

NCHRP Report 350 Test Designation	3-30	3-31	3-32	3-33	3-38	3-37
Vehicle mass (kg)	820	2,000	820	2,000	2,000	2,000
Impact speed (km/h)	98.94	97.01	99.00	97.20	101.92	102.50
Impact angle (degrees)	0	0	15.73	15.05	20.70	20.33
Vehicle impact location	nose, with width/4 offset	nose	nose	nose	critical impact point	length of need
Vehicle stopping distance (m)	4.79	6.97	4.59	7.07	NA	NA
Occupant impact velocity (m/s) longitudinal (12 max. allowable)	8.73	6.23	10.06	6.26	8.95	8.62
lateral (12 max. allowable)	4.44	0.32	1.97	4.01	6.90	4.01
Occupant ridedown acceleration (peak 10 msec avg g's) longitudinal (20 max. allowable)	13.49	19.43	7.80	11.75	9.59	15.18
lateral (20 max.allowable)	4.84	6.73	5.90	4.51	19.88	18.10
Assessment	Passed all requirements	Passed all requirements	Passed all requirements	Passed all requirements	Passed all requirements	Passed all requirements



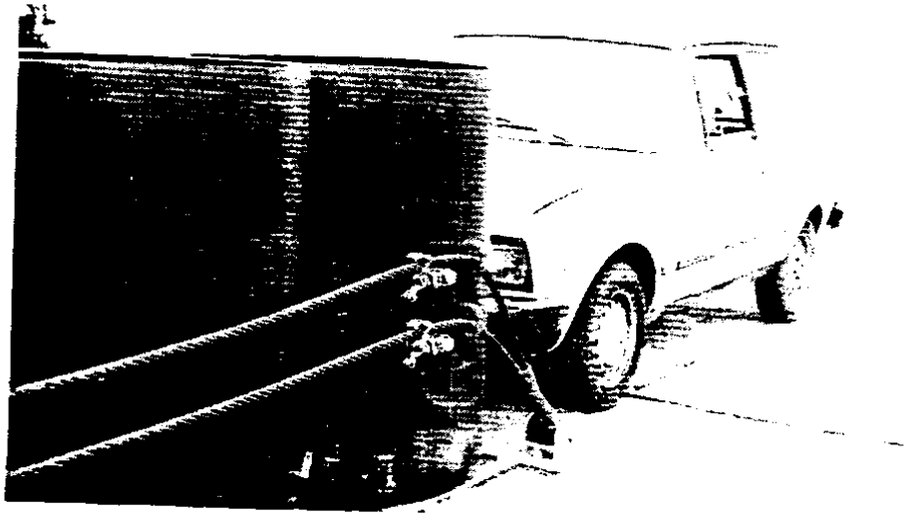


Figure 2. Vehicle/crash cushion geometrics for NCHRP Report 350 Test 3-30

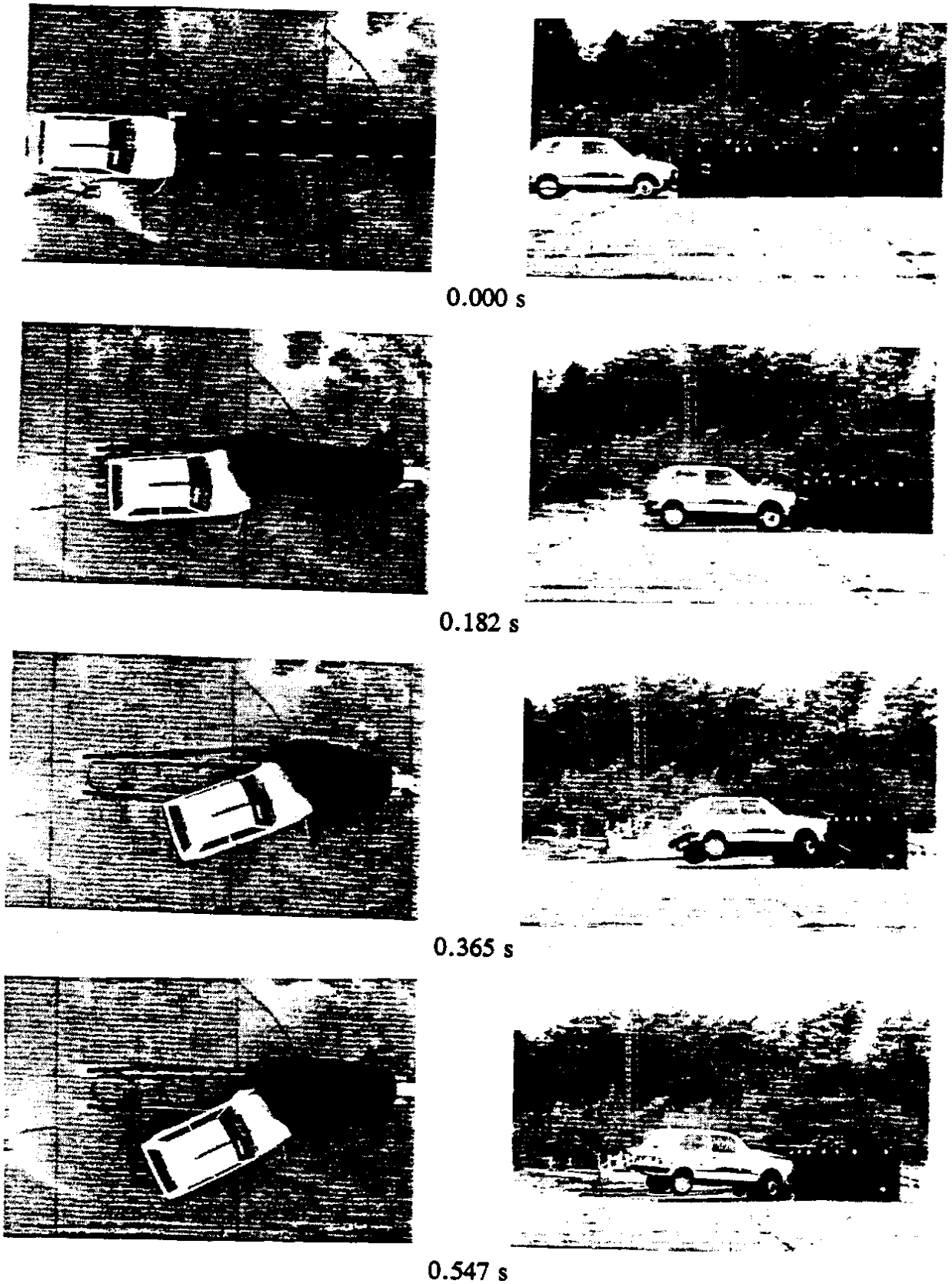
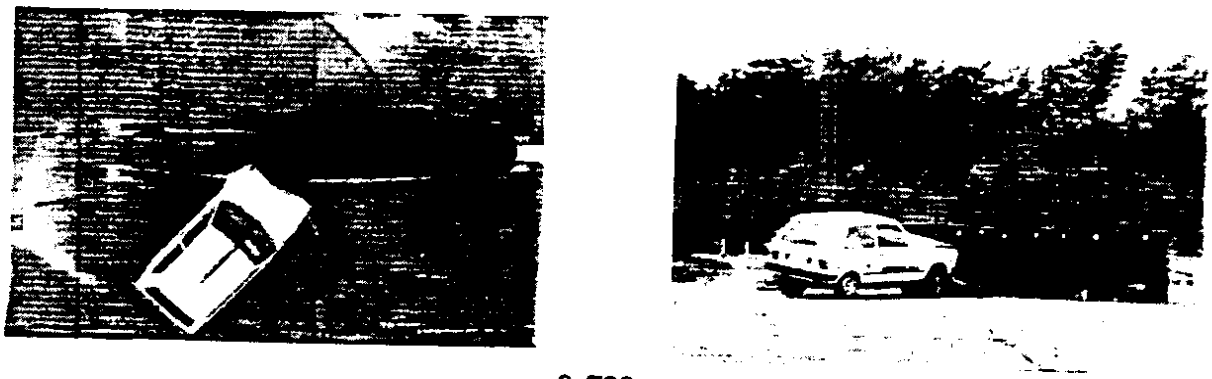


Figure 3. Sequential photographs for NCHRP Report 350 Test 3-30. (overhead and perpendicular views)



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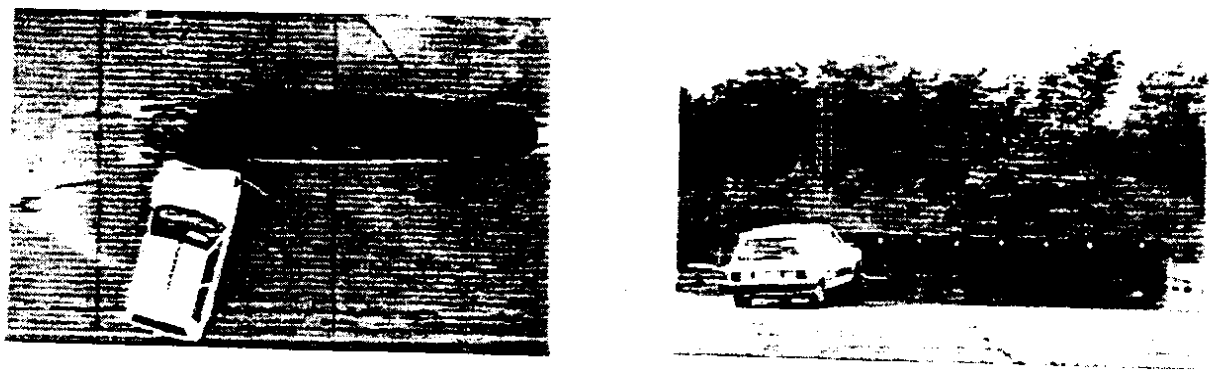

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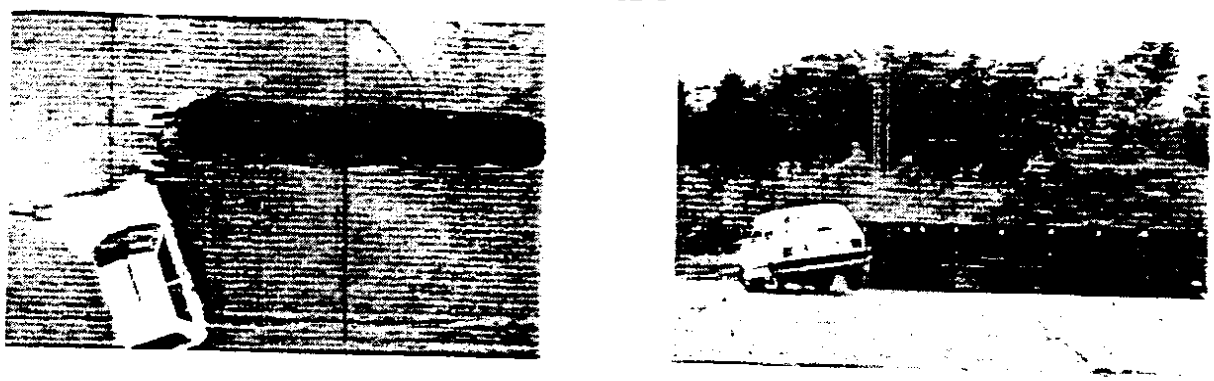

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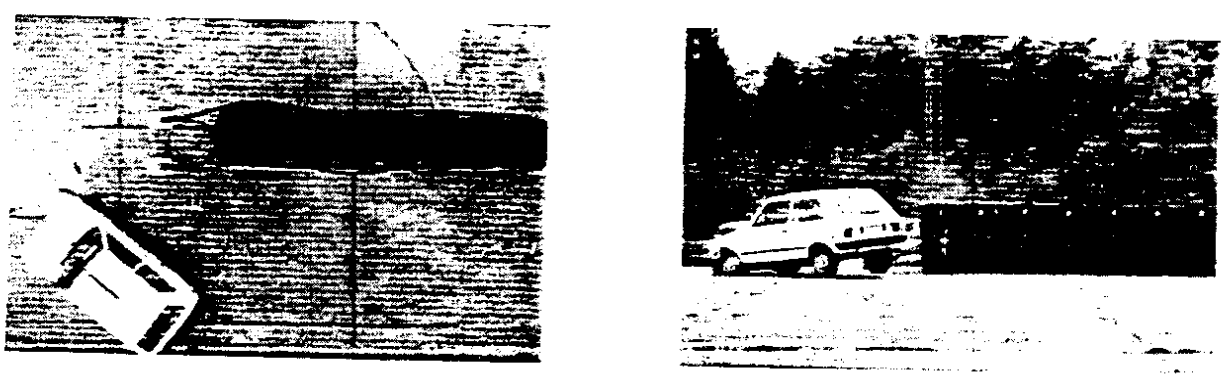

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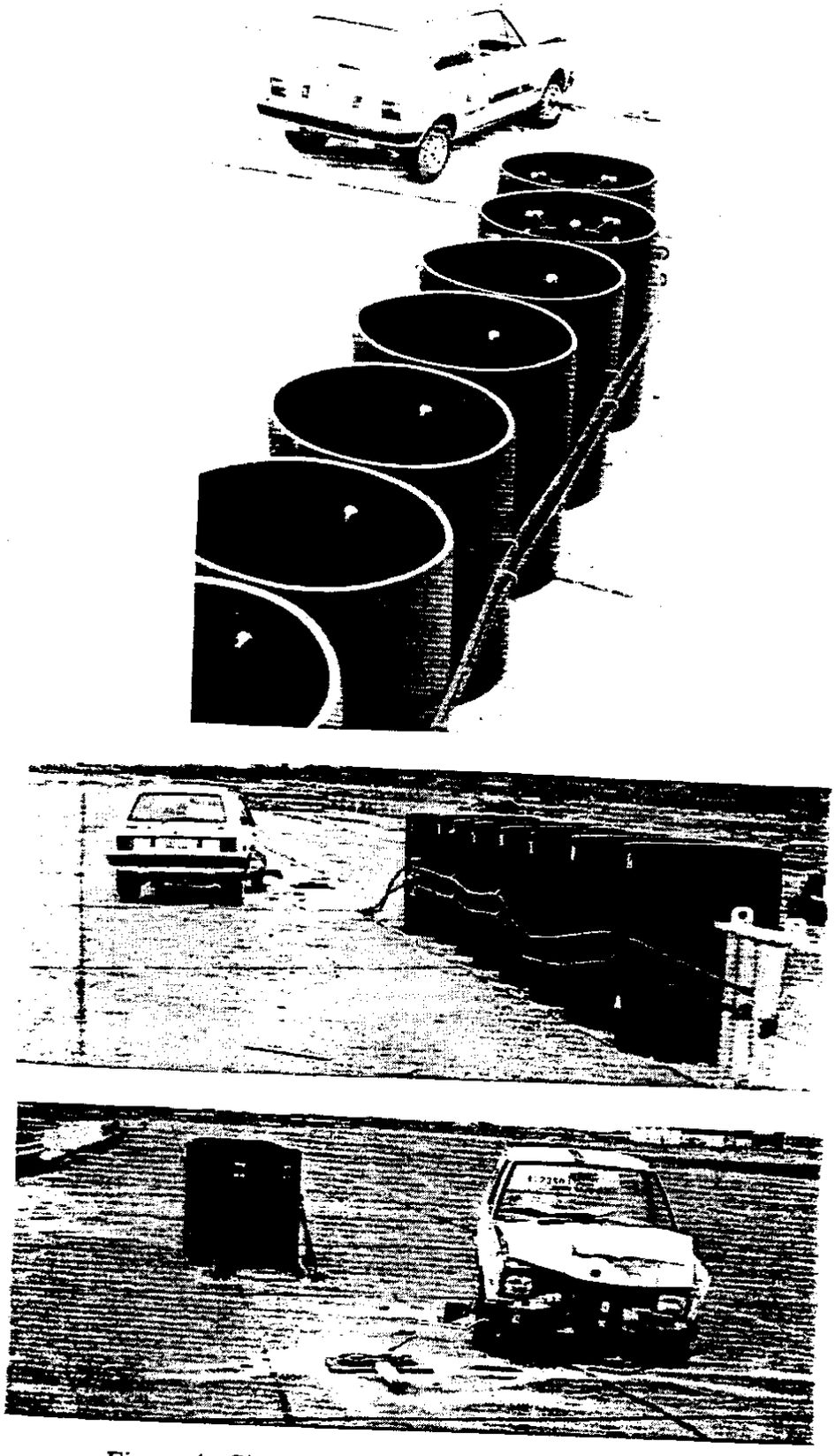


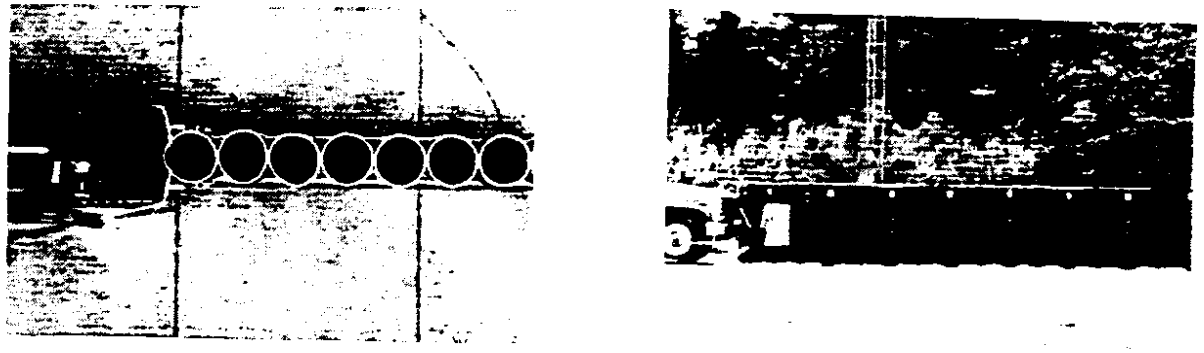
Figure 4. Site after NCHRP Report 350 Test 3-30.

providing a tension loading to the front of the system with a cable attached to a service vehicle.

The second test was 3-31 and involved a head-on impact with a 2000 kg pickup truck. All of the test criteria were again met, and Figures 5-6 present the collapse process for this test. The occupant impact velocity was 6.23 m/s, and the subsequent ridedown deceleration was 19.43 g's. The brake system again did not activate, and again it was not needed. Minor changes were made to this brake device for the next test. The I-beams in the first two cylinders were permanently deformed in this test. Since the goal was to develop a reusable crash cushion which will not require replacement parts after an impact, these I-beams were replaced with stiffer box beams for the next test.

The third test was 3-32, a nose impact with a 820 kg automobile at an impact angle of 15 degrees. This impact event is shown in Figures 7-8, which show that the test vehicle was brought to a controlled stop. As in the previous two tests, all test criteria were met(occupant impact velocity was 10.06 m/s and ridedown deceleration was 7.80 g's), and the brake system did not activate. It was now clear that a brake system was not needed, and it was removed from the device. There are three benefits associated with discarding the brake system:

1. The design is simplified.
2. A possible snagging component is eliminated.
3. No one needs to release the device after an impact. The crash cushion is automatically ready to accept another collision.



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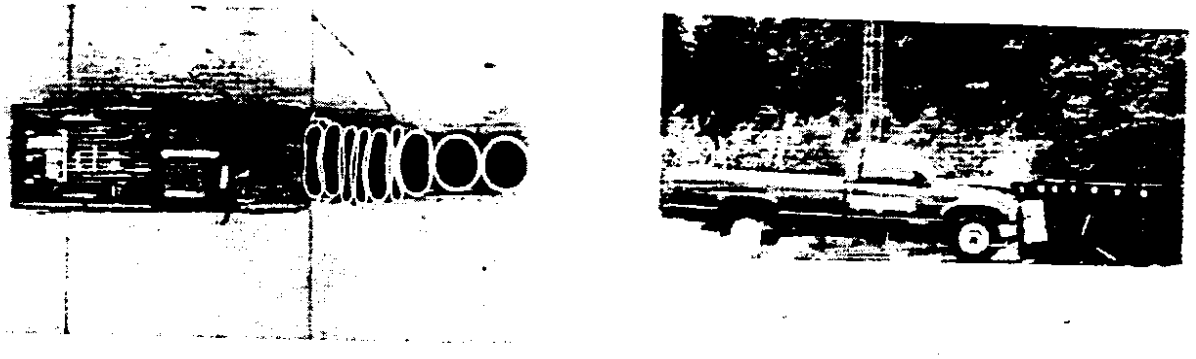

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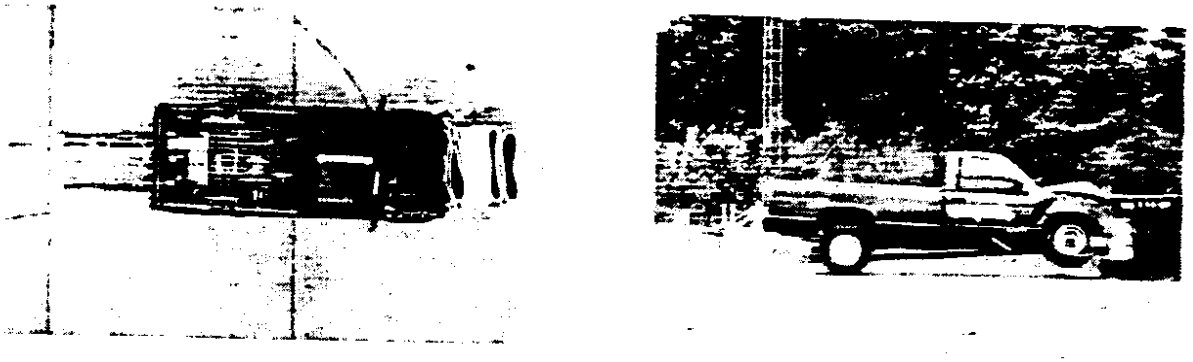

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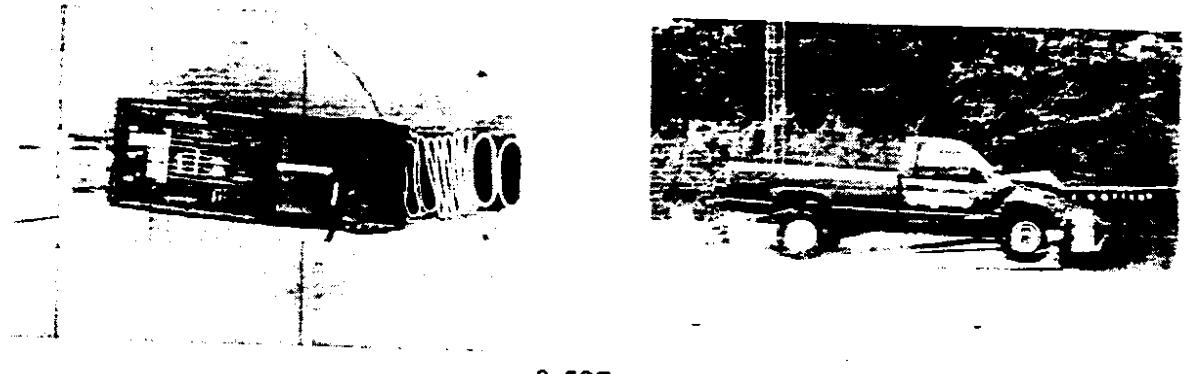

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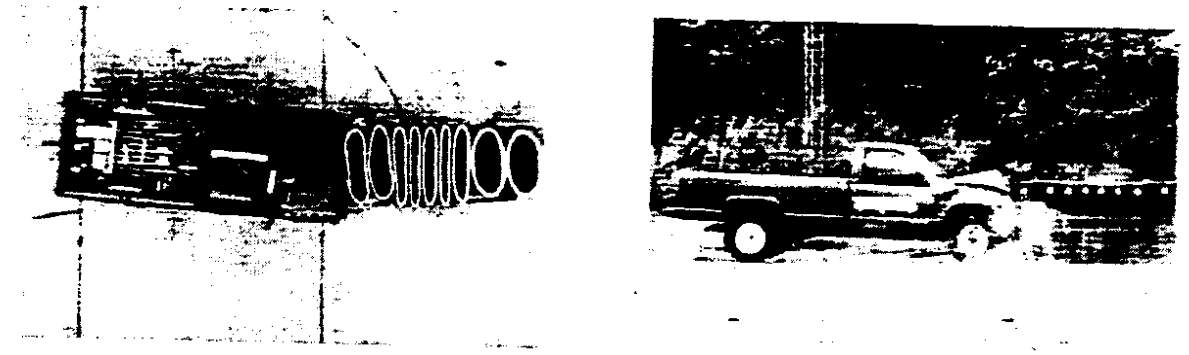
Figure 5. Sequential photographs for NCHRP Report 350 Test 3-31. (overhead and perpendicular views)



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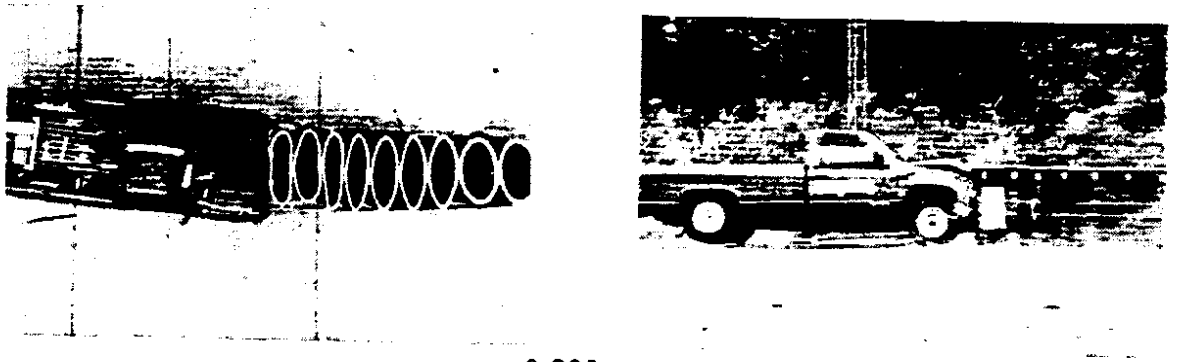

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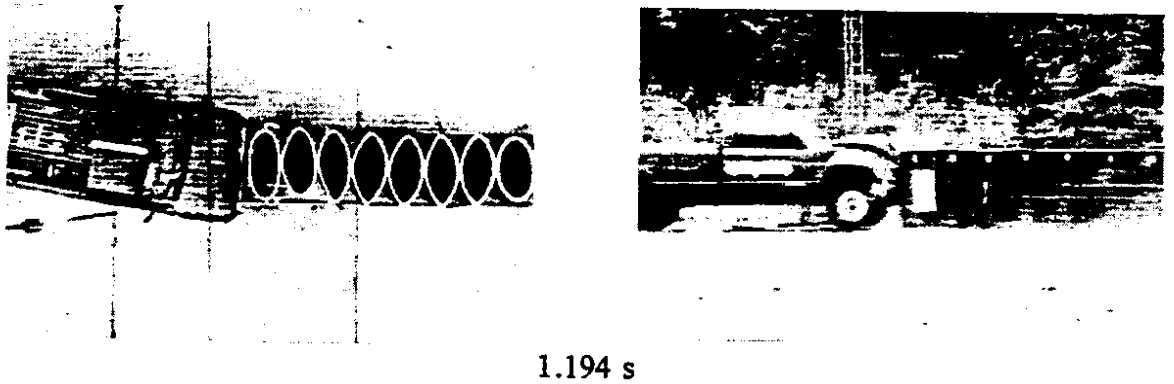

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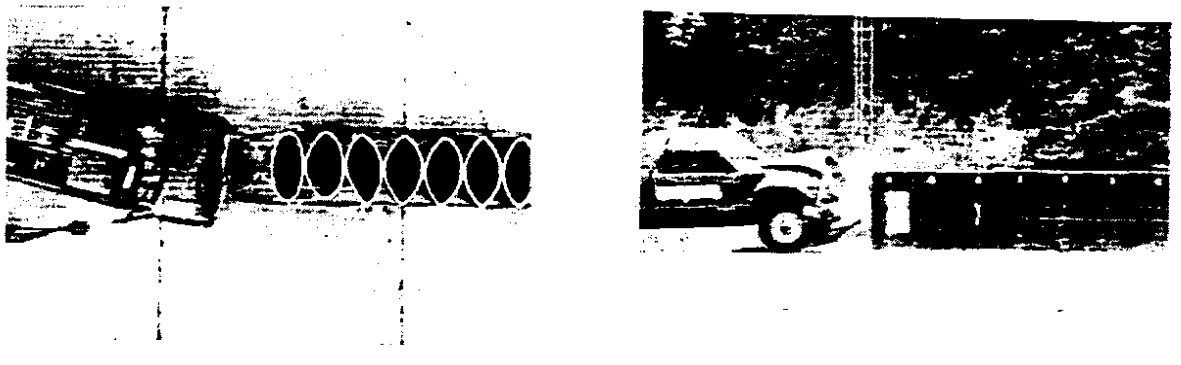

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Figure 5. Sequential photographs for NCHRP Report 350 Test 3-31 continued. (overhead and perpendicular views)

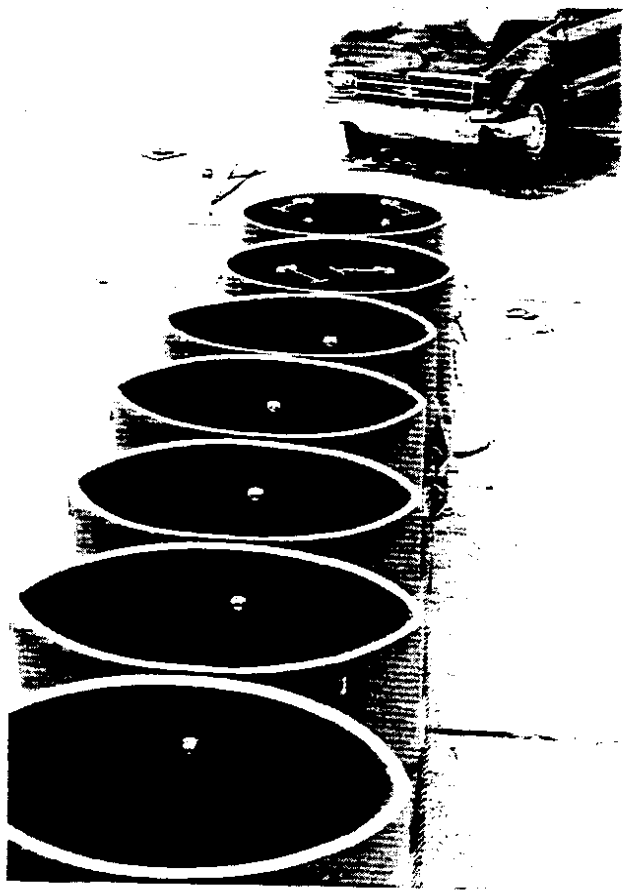


Figure 6. Site after NCHRP Report 350 Test 3-31.

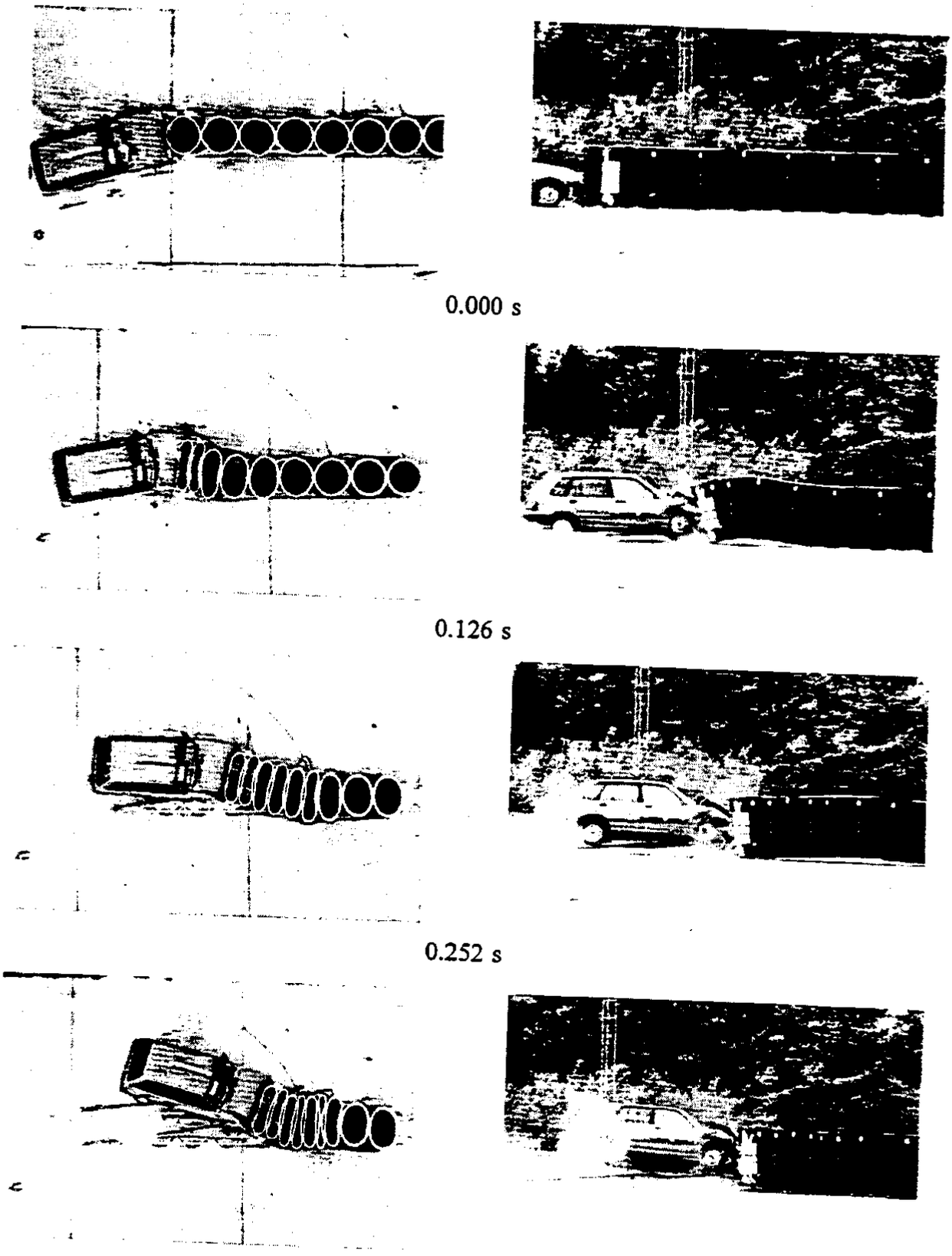
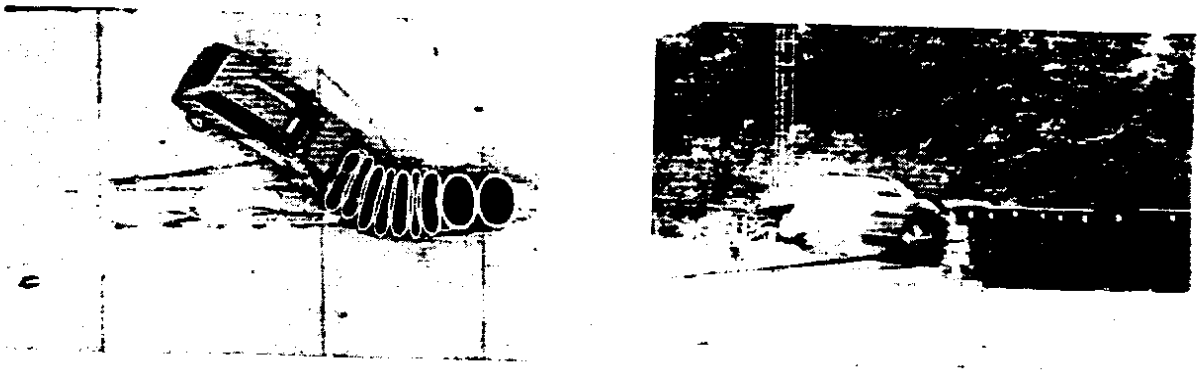
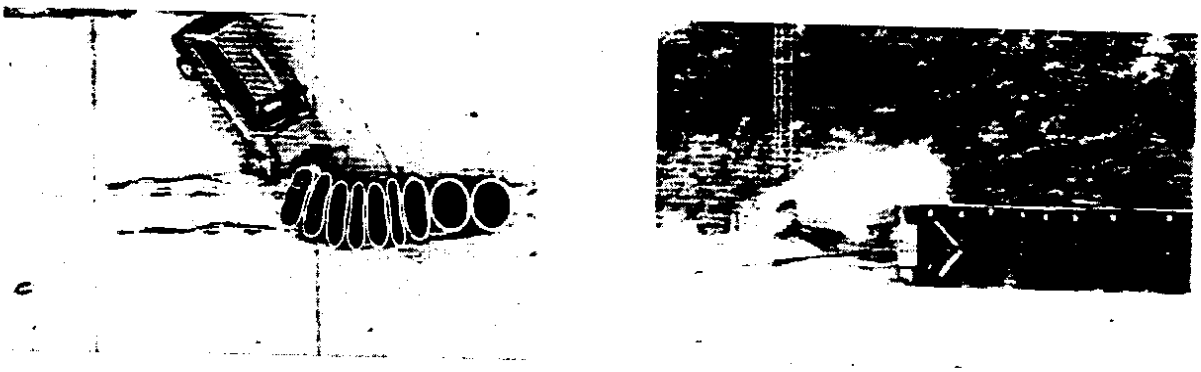


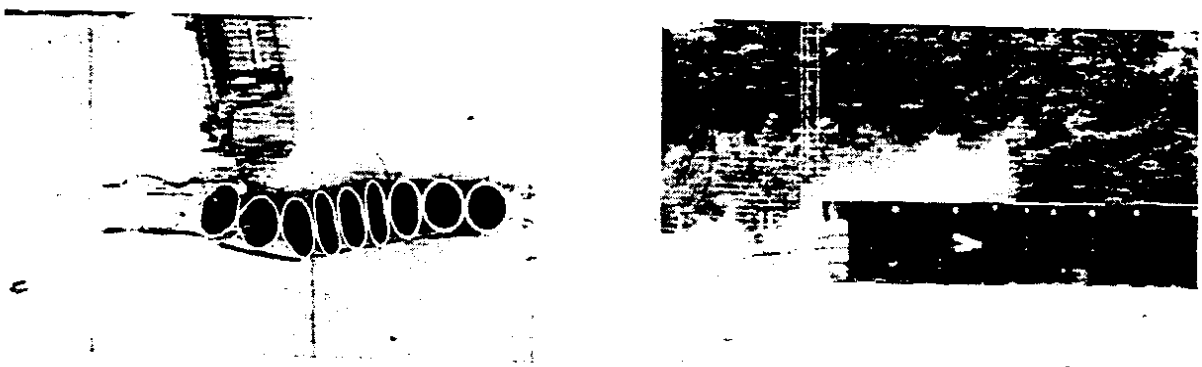
Figure 7. Sequential photographs for NCHRP Report 350 Test 3-32. (overhead and perpendicular views)



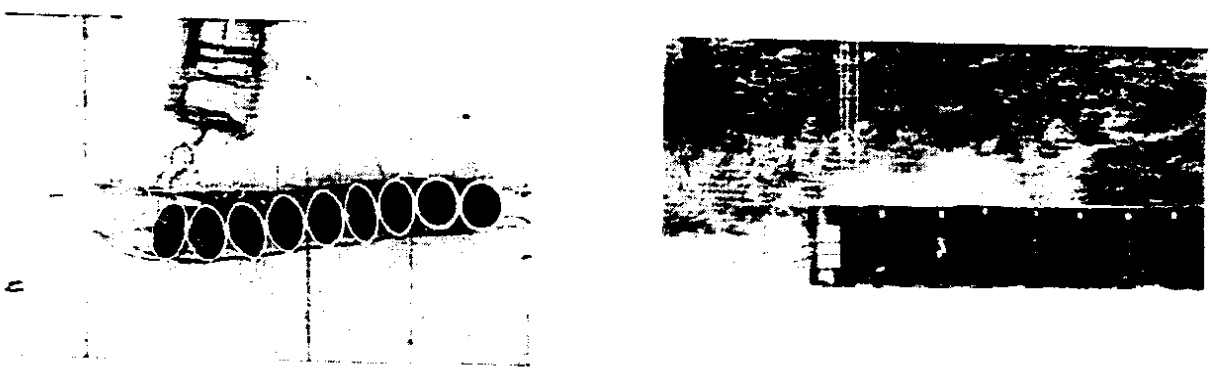
0.505 s



0.631 s



0.757 s



0.884 s

Figure 7. Sequential photographs for NCHRP Report 350 Test 3-32 continued. (overhead and perpendicular views)

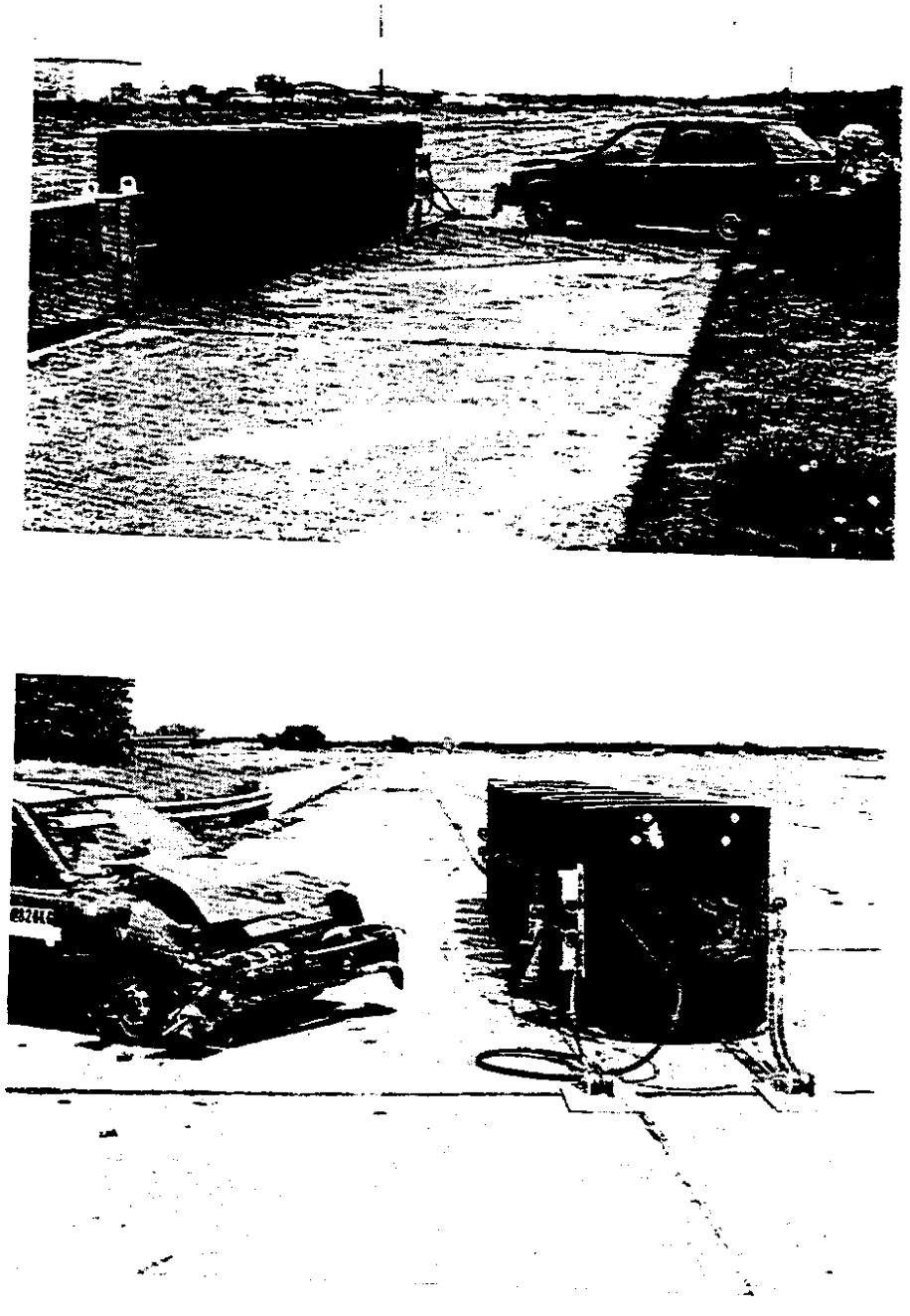


Figure 8. Site after NCHRP Report 350 Test 3-32.

Heaters which were used to aid in the restoration process in the early tests were also discarded following this test It was determined that full restoration could be obtained by simply attaching a cable to the nose cylinder and over-restoring the cushion for a few minutes following the impact event.

Test number four, 3-33, was a demanding test involving a 2000 kg pickup truck impacting the nose of the device at an impact angle of 15 degrees. All test criteria were again met. In fact, the occupant impact velocity(6.26 m/s) and ridedown acceleration(11.75 g's) were both well below the preferred values. Figures 9-10 show the capture of the pickup truck during this severe impact event. The successful performance in tests 3-30, 3-31, 3-32, and 3-33 meant that all nose impact tests required by *NCHRP Report 350* had been passed.

The first redirective crash test conducted was 3-38, in which a 2000 kg pickup truck impacts the side on the device at the critical impact point at an angle of 20 degrees to the longitudinal axis of the system. The critical impact point is defined as that location on the side of the device that first contacts the vehicle when the line of action of the vehicle centerline is aligned on the center of the rigid backup structure. The impact sequence is shown in Figure 11. Note that the critical impact location is on the fifth cylinder, only about 3.96 m from the rear of the crash cushion. The pickup was smoothly redirected, and all *NCHRP Report 350* evaluation criteria were again met. In fact, the occupant impact velocity(8.95 m/s) and ridedown acceleration(9.59 g's) were both below the preferred values.

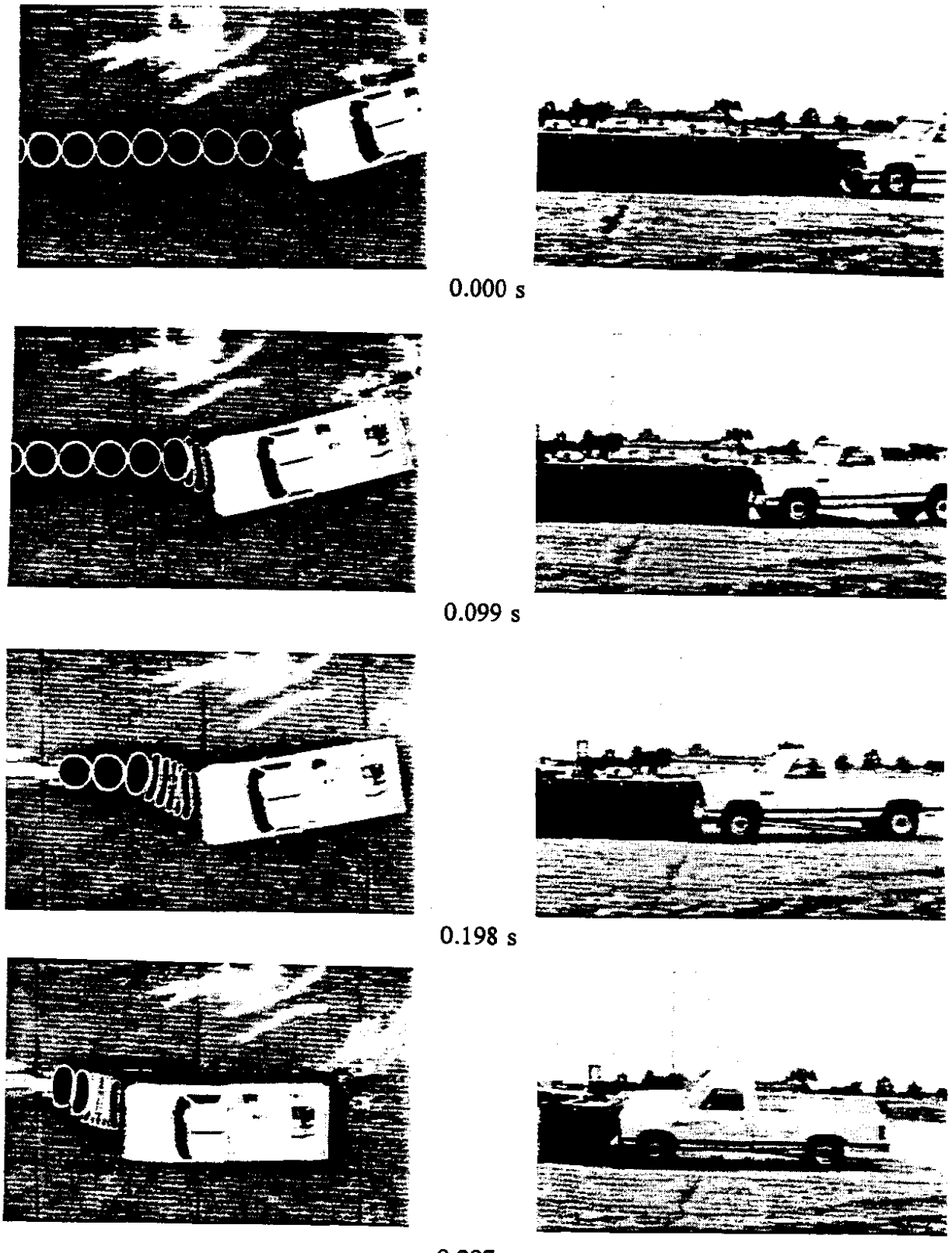


Figure 9. Sequential photographs for NCHRP Report 350 Test 3-33. (overhead and perpendicular views)

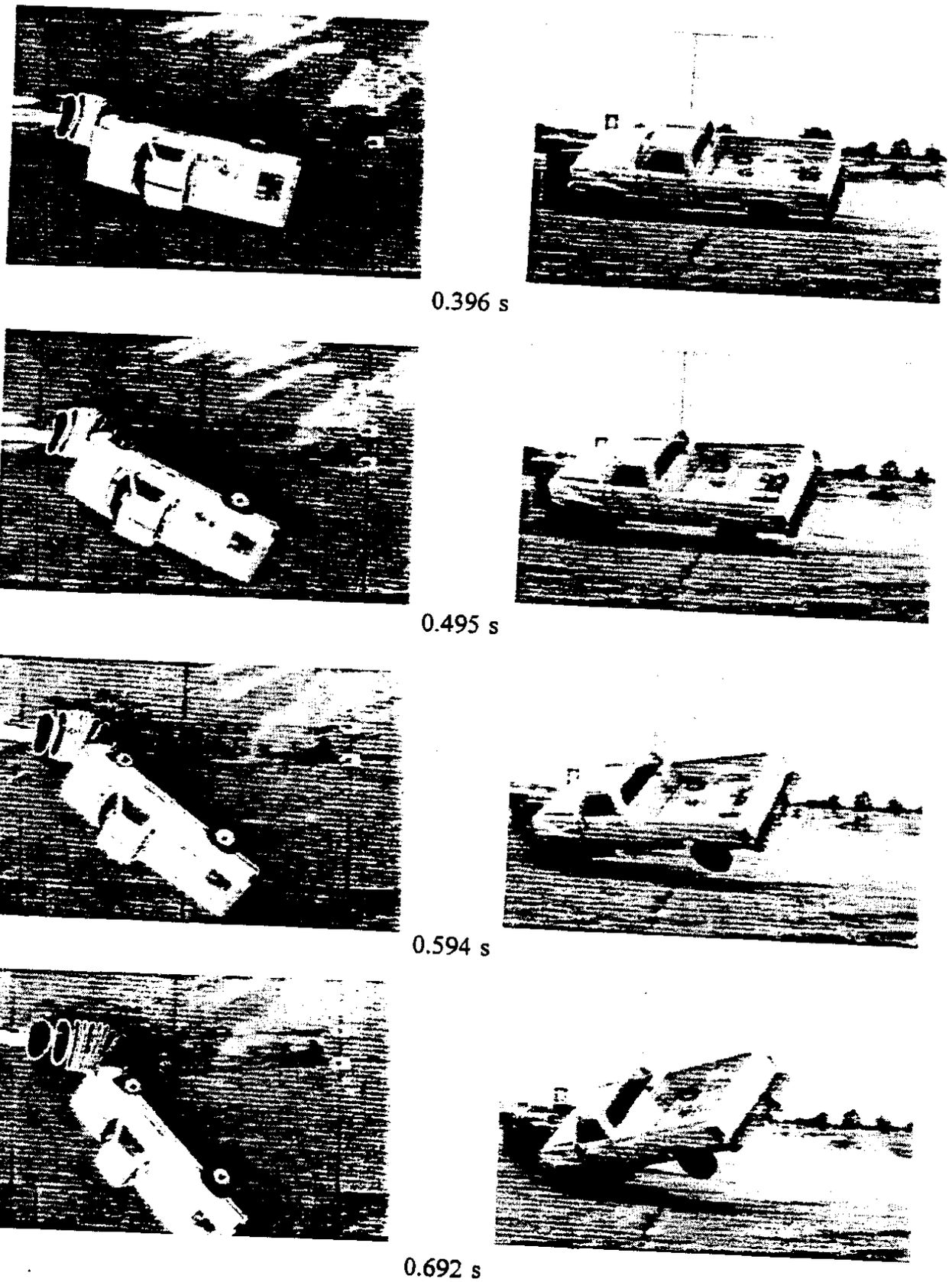


Figure 9. Sequential photographs for NCHRP Report 350 Test 3-33 continued. (overhead and perpendicular views)

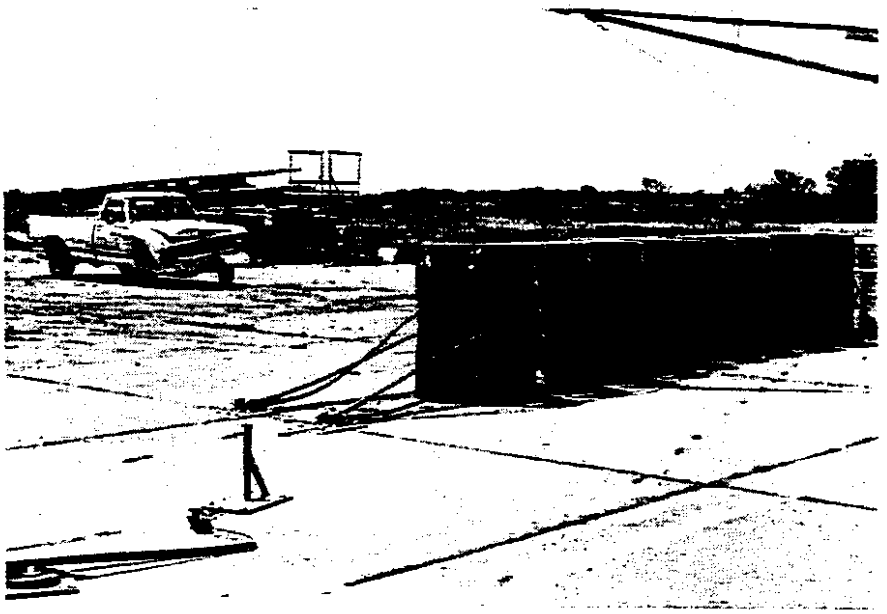


Figure 10. Site after NCHRP Report 350 Test 3-33.

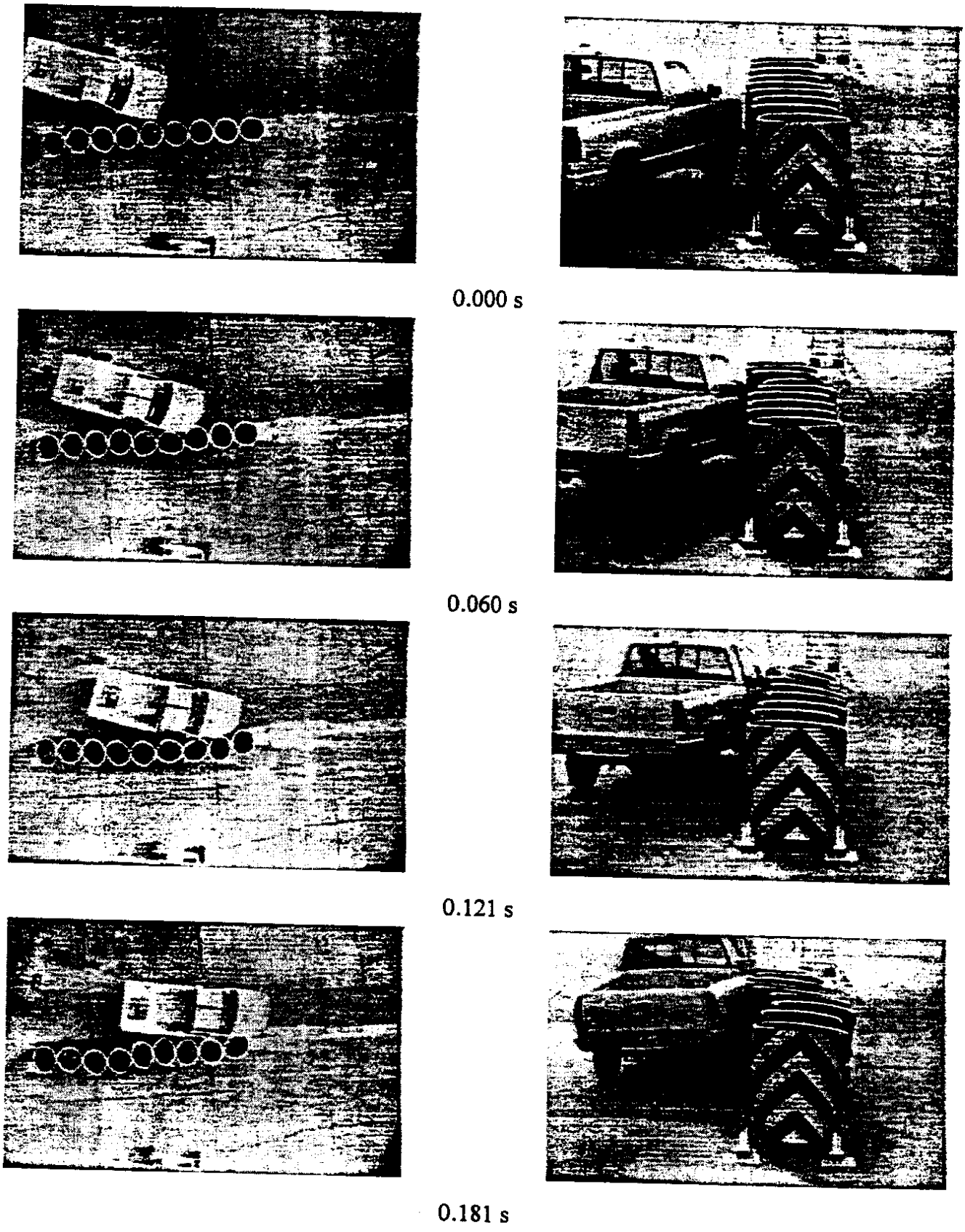


Figure 11. Sequential photographs for NCHRP Report 350 Test 3-38. (overhead and gut downstream views)

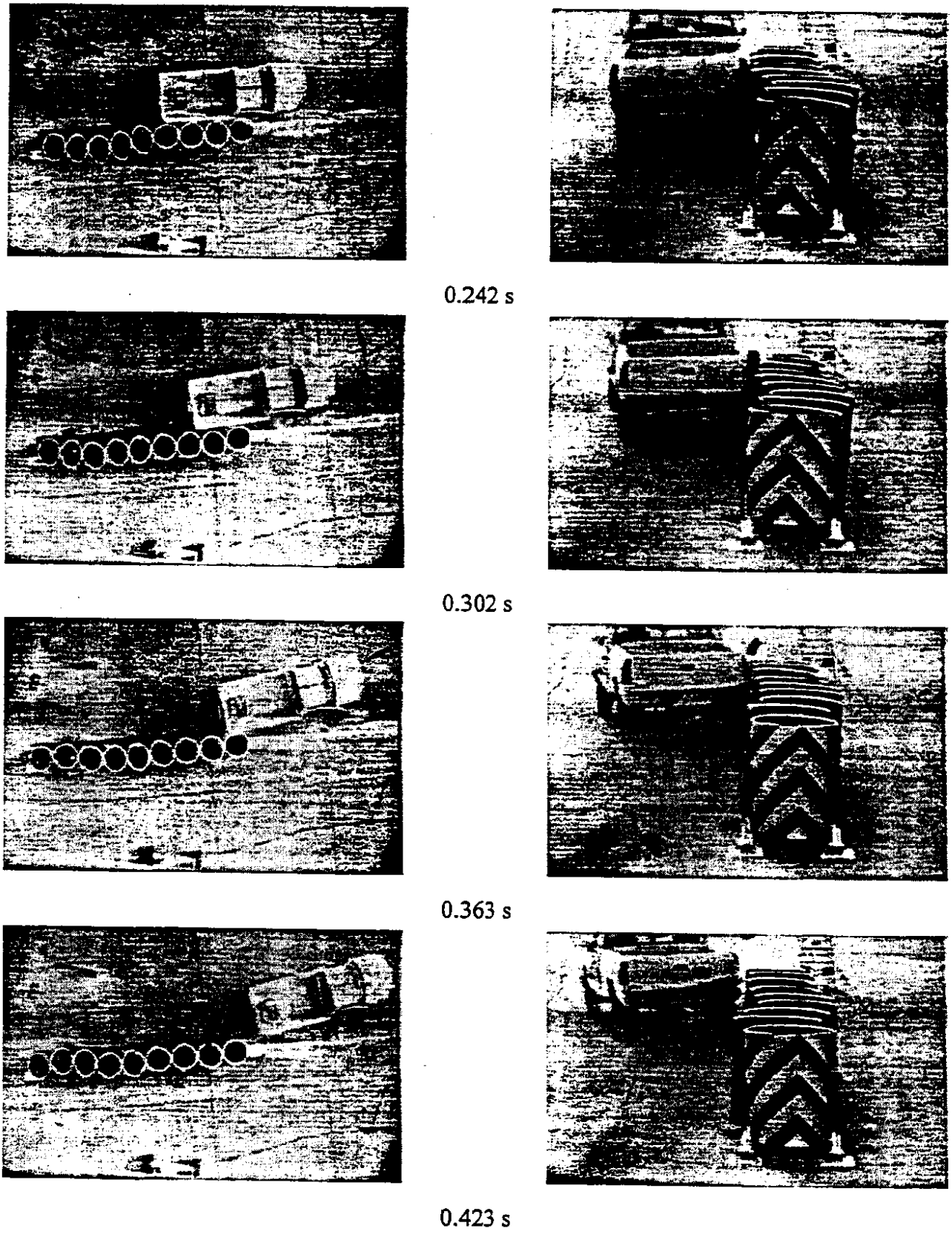


Figure 11. Sequential photographs for NCHRP Report 350 Test 3-38 continued. (overhead and gut downstream views)

The final redirective test conducted was 3-37. This test also calls for a 2000 kg pickup truck to impact the side of the device at 20 degrees, but the impact location must be at the length-of-need. The length-of-need is defined as that part of a longitudinal barrier or terminal designed to contain and redirect an errant vehicle. For the **REACT 350.9**, this point is at the interface of the front and second cylinders in the device. The crash test sequence for this test is shown in Figure 12. The pickup truck was again smoothly redirected, and all required evaluation criteria, summarized in Table 2, were comfortably met.

Two additional nongating, redirective crash cushion tests are described in *NCHRP Report 350*: tests 3-36 and 3-39. Test 3-36 specifies a 15 degree impact at the length-of-need with an 820 kg automobile, while test 3-39 is a reverse direction, mid-length, 20 degree impact with a 2000 kg pickup truck. Neither of these crash tests were conducted. Test 3-36 was considered to be unnecessary to conduct in view of the excellent performance obtained in test 3-37 with the pickup truck under identical crash test conditions. The reverse hit test(3-39) was not required because of the symmetrical design on the **REACT 350.9**.

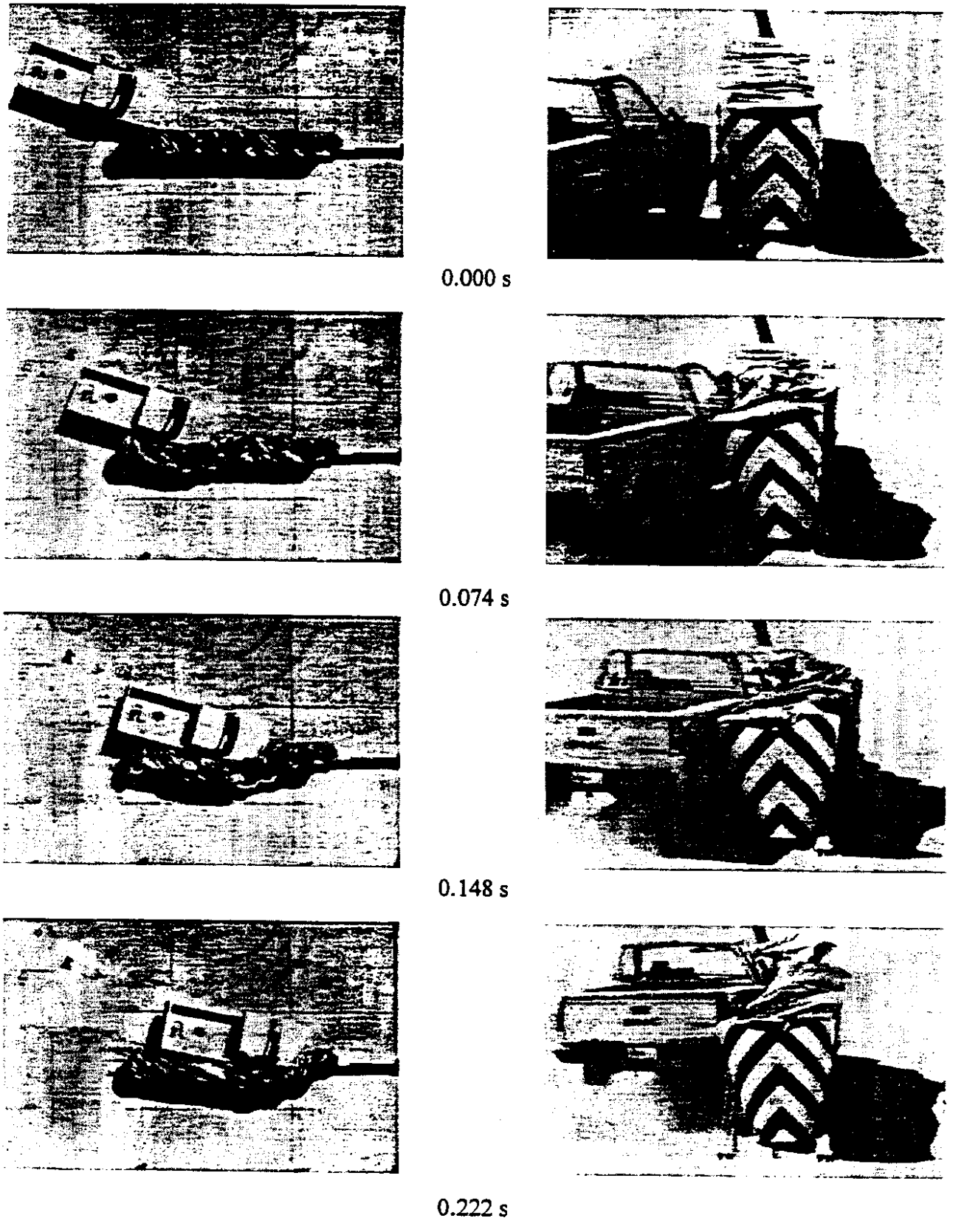


Figure 12. Sequential photographs for NCHRP Report 350 Test 3-37. (overhead and gut views)

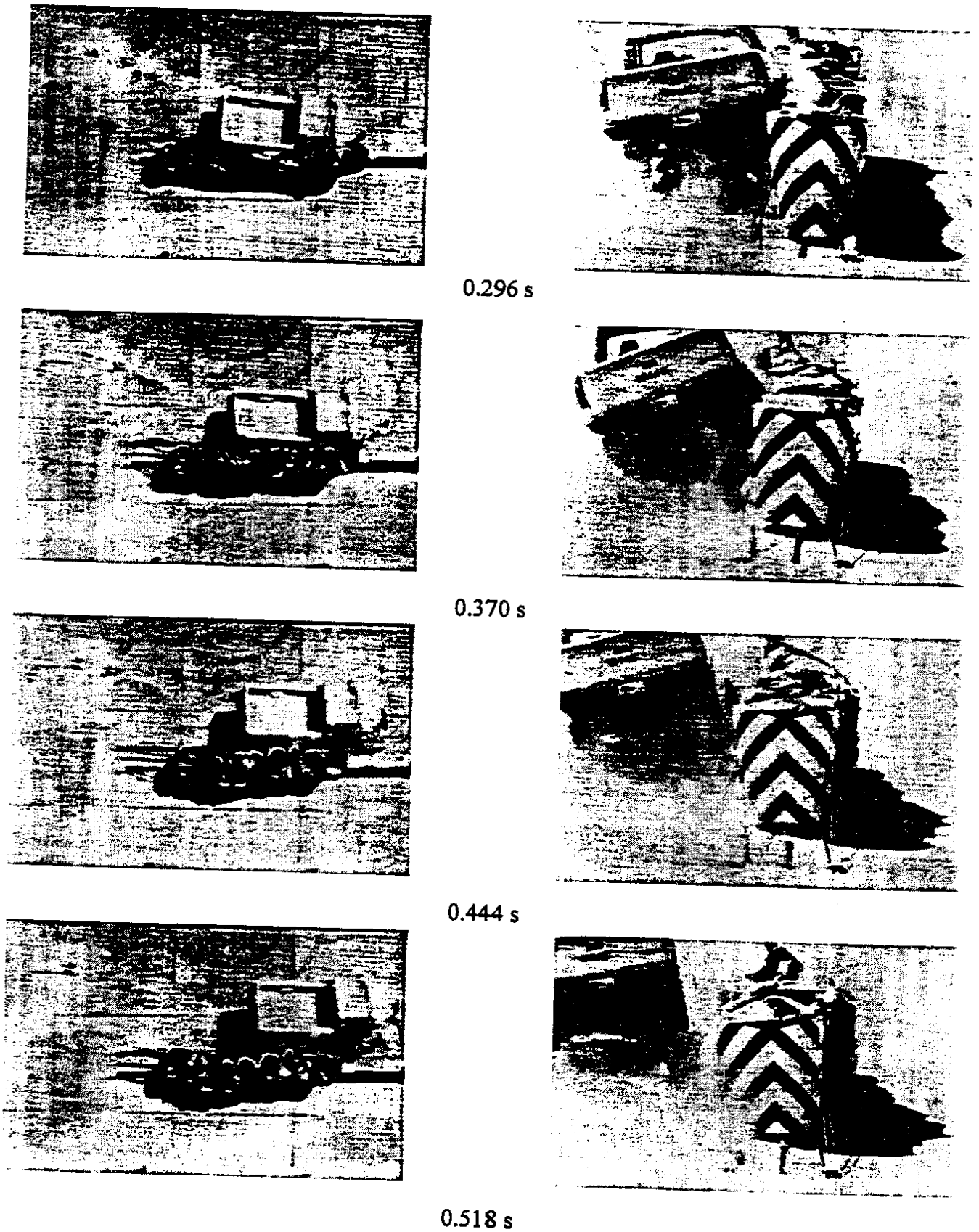


Figure 12. Sequential photographs for NCHRP Report 350 Test 3-37 continued. (overhead and gut views)

CONCLUSIONS

This report summarizes the development and full-scale crash test results of a reusable, low maintenance crash cushion called the **REACT 350.9**. It dissipates kinetic energy by deforming a single row of nine HMW/HDPE cylinders. Following an impact, these cylinders essentially restore themselves to their original shapes. The result is that the **REACT 350.9** is immediately capable of handling another impact because there is no necessity of first replacing damaged or expended energy dissipating elements.

This crash cushion has been fully approved for use on the National Highway System by the Federal Highway Administration. It was the first crash cushion to satisfy the new crash testing requirements of *NCHRP Report 350*. The **REACT 350.9** is qualified as a test Level 3 device and is suitable for use in 100 km/h operating speed applications. It can dissipate the kinetic energy of a high speed impact event, undergo significant deformations and strains without fracturing, and then essentially regain its original configuration and energy dissipation capacity following the collision. The potential safety benefits to both DOT maintenance personnel and the motoring public are therefore substantial.

APPLICATION AND IMPLEMENTATION

The Federal Highway Administration reviewed the crash test results reported herein and, on April 12,1995, it declared the **REACT 350.9** to be fully acceptable for use on projects in the National Highway System if proposed by a State highway agency. The **REACT 350.9** is the first crash cushion to be certified under the *NCHRP Report 350* guidelines. A schematic of the **REACT 350.9** is shown in Figure 13.

The following related documents are important extensions to this Report and can be obtained or reviewed at the WSDOT Olympia Service Center, Design Office, in Olympia, Washington:

- The crash testing report from TTI entitled "Crash Testing a Reusable Polyethylene Narrow Impact Attenuation System(14).
- The design drawings for the **REACT 350.9**.
- The video of the full scale crash tests.
- The NCHRP synthesis on the "Performance and Operational Experience of Crash Cushions"(7).

For the first part of the 21st century, a continuing need will exist for effective roadside safety hardware. Crash cushions, truck-mounted attenuators, terminals, longitudinal barriers, and other appurtenances designed to enhance the safety of roadways have proven their cost effectiveness. The crashworthiness of these devices continues to be improved as new systems are developed under more sophisticated cash testing guidelines.

This project has demonstrated that it is feasible to develop systems to dissipate large amounts of kinetic energy, undergo large deformations and strains without fracturing, and,

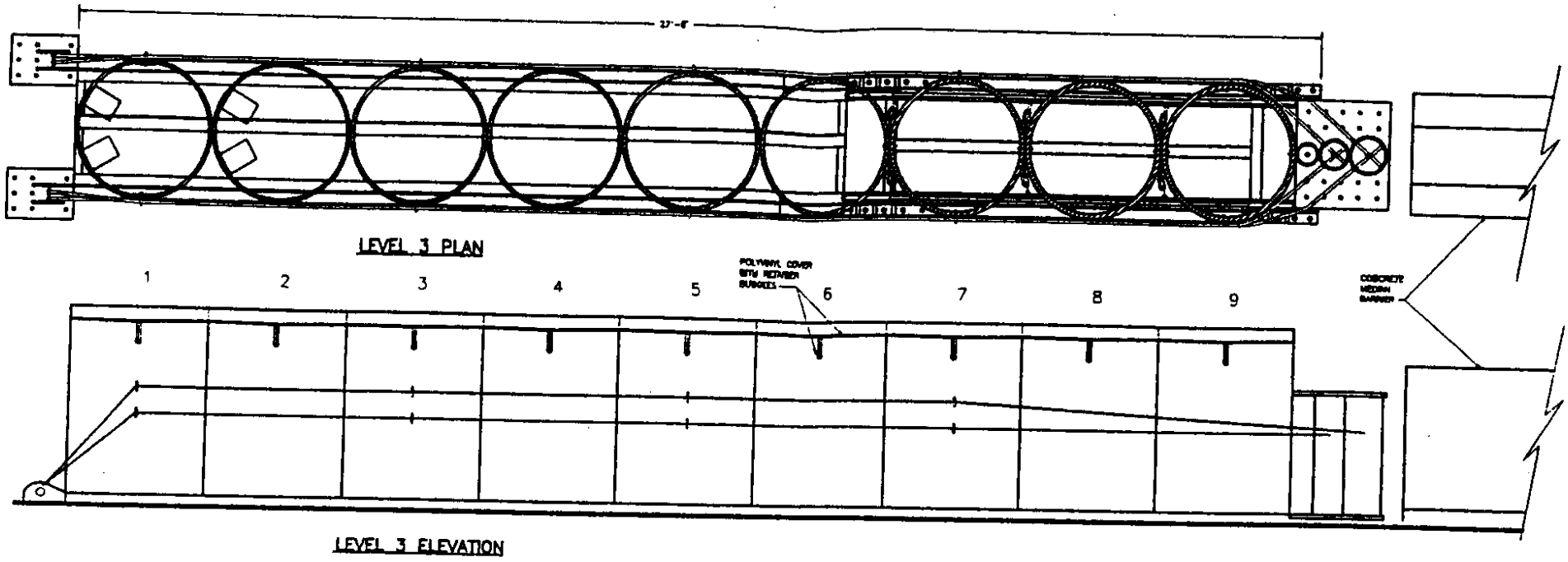


Figure 13. Schematic View of the **REACT 350.9** Crash Cushion

most importantly, restore themselves to their original size, shape, and energy dissipation potential when the forcing function is removed.

The potential financial, legal, and safety payoffs for highway operations associated with developing additional highway safety devices that are essentially maintenance free are enormous. Maintenance costs associated with the repair of impact safety devices would be greatly reduced or eliminated. Tort liability exposure related to damaged or collapsed hardware would be significantly decreased. Finally, the safety of motoring public and the maintenance personnel involved in maintaining and repairing damaged hardware would be greatly enhanced.

To be effective, roadside safety hardware must be installed and maintained properly. There is a continuing need for agencies using these highway safety devices to organize periodic training sessions for their maintenance personnel. These training sessions are necessary to deal with how the device in question performs under impact and also to present the construction and installation details for a particular crash cushion device. Crash videos are helpful in these sessions. Most safety hardware are sophisticated devices. If maintenance crews understand not only how but also why system components are constructed in a particular way, dangerous mistakes will be avoided.

Finally, there is an urgent need for increased in-service evaluations of all highway safety devices. They are usually crash tested under tire tracking impact conditions on level terrain; however, most accidents involve irregular terrain and many are associated with non-tracking vehicles. It is only through scrupulous documentation of the field experience of these safety devices that unforeseen performance deficiencies can be identified and corrected.

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