National Cooperative Highway Research Program

NCHRP Synthesis 205

Performance and Operational Experience of Crash Cushions

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Performance and Operational Experience of Crash Cushions

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TRANSPORTATION RESEARCH BOARD
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Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

NATIONAL ACADEMY PRESS
Washington, D.C. 1994

Subject Areas
Highway Facility
and Design, and
Safety and Human Performance

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NCHRP SYNTHESIS 205

Project 20-5 FY 1990 (Topic 24-03)
ISSN 0547-5570
ISBN 0-309-05664-0
Library of Congress Catalog Card No. 94-61768

Price $20.00

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This Synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This Synthesis report will be of special interest to maintenance, construction, and traffic engineers and others interested in the use of impact attenuation devices or "crash cushions" for highway operations. Information is provided on the performance and operational experience of 13 crash cushion devices in current use in the United States and Canada, including physical characteristics, test results, and guidelines for use. They include both permanent and temporary devices.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The Synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Crash cushions can provide a cost-effective method for reducing or alleviating motor vehicle related injuries or fatalities, which constitute a major societal cost. This report of the Transportation Research Board presents information on the physical and impact performance characteristics of 13 crash cushions in current use in North America. Information on performance evaluation guidelines, physical characteristics, performance characteristics, selection considerations, and the operational experience of individual designs for crash cushions is provided. The Synthesis concludes with possible future trends for crash cushions and an appendix containing the crash test requirements of *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features,* a crash cushion glossary, and a bibliography.

To develop this Synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This Synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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ACKNOWLEDGMENTS

John F. Carney III, Ph.D., P.E., Associate Dean for Research and Graduate Affairs, Vanderbilt University, was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this Synthesis was provided by the Topic Panel, consisting of Daniel W. Dearasaugh, Jr., Engineer of Design, Transportation Research Board; Charles E. Dougan, Manager of Research and Materials, Connecticut Department of Transportation, Bureau of Engineering and Highway Operations; Kathleen Hancock, Director of Research Services, Vanderbilt University; Charles F. McDevitt, Project Manager/Research Structural Engineer, Federal Highway Administration, U.S. Department of Transportation; David H. Pope, State Bridge Engineer, Wyoming Department of Transportation; Richard D. Powers, Highway Engineer, Federal Highway Administration, U.S. Department of Transportation; and Roger L. Stoughton, Senior Materials and Research Engineer, California Department of Transportation, Division of New Technology, Materials, and Research.

The Principal Investigators responsible for the conduct of this Synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This Synthesis was edited by Linda S. Mason.

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, Transporation Research Board, provided valuable assistance to the consultants, the topic panel and staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

PERFORMANCE AND OPERATIONAL EXPERIENCE OF CRASH CUSHIONS

SUMMARY

Crash cushions are used to shield fixed roadside hazards such as bridge-rail ends in gore areas and the blunt ends of median barriers. These highway safety devices dissipate the kinetic energy of a vehicle in head-on crashes, arresting it in a controlled manner so that the risks of serious injuries to the occupants are minimized. Some crash cushions, when hit on their sides, will capture the errant vehicle; others will redirect it.

The first crash cushions date back to the 1960s, and many devices have been designed and crash tested since those early days. The means of dissipating kinetic energy in these crash cushions have included the following:

- Inelastic bending of ductile drums and cylinders
- Hydraulic pressure
- Friction
- Crushing and fracture of honeycomb structures
- Cyclic bending
- Axial buckling
- Stretching of ductile materials
- Inelastic bending of beams, plates, and shells
- Fracture of lightweight concrete
- Momentum transfer.

This Synthesis documents the performance characteristics of the following 13 highway safety devices:

- Guardrail Energy Absorbing Terminal (GREAT)
- Construction Zone GREAT (GREAT cz)
- Crash-Cushion Attenuating Terminal (CAT)
- Narrow Connecticut Impact Attenuation System (NCIAS)
- Low Maintenance Attenuator (LMA)
- Brakemaster
- Advanced Dynamic Impact Extension Module (ADIEM)-II
- Sand-filled plastic barrels
- Hex-Foam Sandwich System
- Hi-Dro Sandwich System
- Hi-Dro Cell Cluster
- Connecticut Impact Attenuation System (CIAS)
- Generalized Connecticut Impact Attenuation System (GCIAS).

The first seven of these systems are narrow hazard devices, 610–914 mm wide. They

are primarily used as end treatments for median and roadside barriers. The remaining six devices are designed to shield wider hazards such as walls in gore areas. All have been subjected in previous studies to a series of full-scale crash tests to evaluate their effectiveness, and the results for each crash cushion are summarized in this Synthesis.

The process of selecting an appropriate crash cushion device for a particular location requires an understanding of the common and unique characteristics of the different safety devices. While all of the crash cushions considered in this Synthesis can bring a vehicle to a controlled stop in a head-on impact, under side impact conditions some devices redirect the vehicle and some do not. Some crash cushions allow a vehicle impacting at an angle at or near the front to penetrate the system; others either redirect or capture it. Not all of the devices satisfy the crash cushion testing requirements of NCHRP Report 230 (*1*), and the initial, maintenance, and repair costs vary.

Some of the crash cushions considered in this Synthesis have been in widespread use for many years. Others are relatively new devices that have not yet been widely used. A survey document was developed as part of this Synthesis project to obtain performance and operational experience data on crash cushions. It was sent to every U.S. state department of transportation, selected highway officials from Canadian provinces, and representatives from the International Bridge, Tunnel and Turnpike Association. Fifty-one of the 72 agencies contacted returned the survey, a 71 percent response rate. The survey results show that the type of crash cushion used most often is the sand-filled plastic barrels array. This inertial device has been available since the 1970s, requires no backup structure, and has a low initial cost. It has no redirectional capability, however, and should not be used in locations where the redirection of errant vehicles is required. The five other most popular systems are the GREAT, the CAT, the Hex-Foam Sandwich System, and the Hi-Dro Cell Sandwich or Hi-Dro Cell Cluster Systems. Most of the remaining devices, developed within the last 10 years, have not established a significant track record but show great potential for effective performance.

Highway related deaths and injuries are a major, worldwide health problem. The intelligent use of crash cushions has saved many lives and reduced injuries and human suffering for more than 25 years. The continued development of effective crash cushions is a prudent investment in cost-effective injury prevention.

CHAPTER ONE

INTRODUCTION

Motor vehicle accidents are a major worldwide health problem and constitute a great economic loss to society. For example, vehicular crashes kill more Americans between the ages of 1 and 34 than any other source of injury or disease. More than 95 percent of all transportation deaths are highway related, compared with 2 percent for rail and 2 percent for air. The yearly worldwide societal costs of highway deaths and injuries runs to hundreds of billions of dollars. Indeed, the potential years of productive life that are lost before age 65 as a result of motor-vehicle related injuries or death 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 crash cushions. They shield fixed roadside hazards and dissipate the kinetic energy associated with a moving vehicle in a controlled way so that the errant vehicle is either decelerated to a safe stop or redirected away from the hazard. Crash cushions are considered for use at locations where it is not feasible to remove, relocate, modify, or otherwise shield the fixed object. Most crash cushion installations are located at the ends of median barriers and in exit ramp gores on elevated or depressed structures containing bridge-rail ends or piers.

The first crash cushion designs were developed in the 1960s. Today, there are thousands of installations of many types of crash cushions in the United States and around the world. These impact attenuation devices have different and sometimes unique characteristics. This Synthesis identifies and describes the types of crash cushions currently in use. Highway agencies can use this information to compare the relative merits of the different devices and possibly determine the best choice for a particular application.

Excluded from this Synthesis are truck-mounted attenuators and those end treatments for roadside barriers that do not meet crash cushion standards. Truck-mounted attenuators are the subject of another synthesis, and non-crash cushion roadside-barrier end treatments are not considered because of the wide variation in their impact performance and energy dissipation potential. An informative treatment of roadside-barrier end treatments is contained in the American Association of State Highway and Transportation Officials' (AASHTO) *Roadside Design Guide* (*2*).

SYNTHESIS OVERVIEW

This Synthesis presents information on the physical and impact performance characteristics of 13 crash cushion devices in current use in the United States. Chapter 2 deals first with the concepts of kinetic energy, the conservation of linear momentum, and the conservation of energy and describes how these basic laws of physics are used in designing crash cushions. It then presents a brief historical review of the evolution of full-scale crash testing procedures and associated occupant risk criteria over the last four decades and summarizes the safety performance evaluation guidelines of the 1990s. The characteristics of 13 impact attenuation devices are described in Chapter 3. They include both permanently and temporarily installed devices. Crash test results are discussed along with information regarding individual performance characteristics.

Chapter 4 deals with the various selection guidelines to be considered when choosing a particular crash cushion for a specific location. These guidelines include considerations of the site characteristics, impact performance requirements, cost, maintenance and repair requirements, and other factors. Collision and operational experiences with the individual designs are considered in Chapter 5. The results of a survey of highway agencies in the United States and Canada are summarized and synthesized. Chapter 6 deals with probable trends in crash cushion development. Appendix A contains the details of the latest crash testing requirements for crash cushions. The survey questionnaire sent to highway agencies and the summary of responses are presented in Appendices B and C. A comprehensive bibliography of early (1967–1989) crash cushion publications appears in Appendix D. Appendix E contains an updated list of publications from 1990–1994. Finally, a glossary of crash cushion and work zone terms is contained in Appendix F.

CHAPTER TWO

EVALUATIONS OF CRASH CUSHIONS

A crash cushion can be impacted by errant vehicles on the front (nose) or side. When a vehicle hits the nose of a crash cushion head-on, the vehicle is usually decelerated to a stop. In other words, the pre-impact kinetic energy stored in the vehicle is dissipated by deforming the crash cushion. Kinetic energy (KE) is defined as follows:

$$KE = 1/2\ m\ v^2 \qquad (1)$$

where
m = mass of vehicle
v = pre-impact speed of vehicle

Energy is neither created nor destroyed in this process. The work done in deforming the crash cushion (and the vehicle), W, will be equal to the initial kinetic energy of the vehicle:

$$KE = W \qquad (2)$$

Many operating crash cushions have been designed using this basic principle of the conservation of energy. This class of crash cushions requires some form of backup structure capable of resisting the impact force imparted to it through the collapsing crash cushion by the impacting vehicle.

Another class of crash cushions has been designed using another basic principle of physics, the principle of the conservation of linear momentum. The momentum of a moving vehicle is equal to the product of its mass and velocity:

$$\overrightarrow{Momentum} = m\ \vec{v} \qquad (3)$$

Some or all of this momentum can be transferred to an expendable mass of material in the path of the vehicle. A series of containers holding various amounts of sand, for example, could be hit by the errant vehicle. Since the total momentum of the system composed of the sand containers and the vehicle must be conserved, the momentum of the vehicle is reduced by the sum of the momenta of the individual sand particles. The net result is that the velocity of the vehicle is reduced in a controlled manner during the impact. Crash cushions that operate on the principle of conservation of momentum do not require a backup structure.

CRASH TESTING AND EVALUATION CRITERIA

Vehicular impacts into highway safety appurtenances such as longitudinal barriers, terminals, crash cushions, and breakaway or yielding supports are complicated, dynamic events. The impact responses of these devices usually involve large deformations, inelastic material behavior, strain-rate effects, and fracture. Modeling the intricate interactions between the deforming vehicle and barrier is a formidable task. The state of the art in computer hardware and software development has evolved to the point where powerful, versatile, user-friendly vehicle impact codes are being produced. These codes will improve the capability to accurately simulate vehicle dynamic responses and impacts with roadside features, leading to more cost-effective roadside safety devices. They will also permit a reduction in the number and expense of full-scale crash tests needed to develop new hardware. Full-scale crash testing, however, will always be required to verify the effectiveness of a safety device before it is deployed in the field.

The first recommended procedures for performing full-scale crash tests were contained in the single-page Highway Research Circular 482 published in 1962 (*3*). This document specified a 1,814-kg test vehicle, two impact angles (7 and 25 degrees), and an impact velocity of 97 km/h for testing guardrails. In 1974, an expanded set of procedures and guidelines were published as NCHRP Report 153 (*4*). This report was the first comprehensive specification to address 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. NCHRP Report 153 specified that, for head-on impacts with a test article in which lateral decelerations are low and the vehicle is brought to a stop, the maximum allowable average vehicle deceleration was 12 *g*'s. This vehicle deceleration average was calculated from the vehicle impact speed and stopping distance. In other words, the deceleration was averaged over the entire crash event. This approach permitted short-duration deceleration spikes as long as the average value for the whole event was less than or equal to 12 *g*'s. 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 reviewed NCHRP Report 153 and provided recommendations. The result of this effort was Transportation Research Circular 191 (*5*). As this circular was being published, a new project was initiated to update and revise NCHRP Report 153. The result of this project was NCHRP Report 230 (*1*), published in 1981. In many ways, NCHRP Report 153 was the first draft of NCHRP Report 230; 6 years of discussion, dissension, and clarification were required before the highway safety community reached the consensus represented by NCHRP Report 230.

RECOMMENDED PROCEDURES OF NCHRP REPORT 230

NCHRP Report 230 specifies the test procedures and the evaluation criteria to be followed in evaluating the effectiveness of roadside safety hardware. The effectiveness of a roadside appurtenance is determined through a full-scale crash testing program. The performance of a device is judged on the basis of three factors: (1) structural adequacy, (2) occupant risk, and (3) vehicle trajectory after collision. The structural adequacy of a crash cushion is evaluated by its ability to contain or redirect a selected range of vehicle sizes under specified impact conditions in a predictable and acceptable manner. The unit should remain intact during impact so that detached debris will not present a hazard to traffic. The occupant risk evaluation of a highway appurtenance is based on the calculated response of a hypothetical vehicle occupant during the vehicle-attenuator impact. The vehicle kinematics are used to estimate the impact velocity and ridedown accelerations of the occupant and limiting values are recommended. Another essential crash test requirement is that the vehicle remain upright during and after collision and that the integrity of the passenger compartment be maintained. The vehicle trajectory after collision is of concern because of the potential risk to other traffic. An acceptable vehicle trajectory after impact is characterized by minimal intrusion into adjacent traffic lanes. The specific NCHRP Report 230 safety evaluation guidelines that apply to crash cushions are listed in Table 1, and the NCHRP Report 230 crash cushion test matrix is presented in Table 2. It should be pointed out, however, that it is not necessary to conduct equivalent crash tests with both 816-kg and 1,020-kg automobiles. In fact, the 816-kg car has completely replaced the 1,020-kg automobile in U.S. crash testing with light vehicles.

The NCHRP Report 230 procedures for acquiring occupant risk data involve the numerical integration of acceleration-time data. Of primary concern are the magnitudes of the impact velocity of the hypothetical occupant with the interior of the vehicle and the maximum 10-msec average deceleration of the occupant following this impact. The value of the occupant impact velocity clearly depends on the "flail" distance available before impact occurs. NCHRP Report 230 defines these distances to be 610 mm longitudinally and 305 mm laterally. Given these conditions, NCHRP Report 230 assumes the occupant to be an unrestrained rigid body whose acceleration is zero until the impact with the vehicle interior occurs because the vehicle is decelerating. After this occupant impact occurs, NCHRP Report 230 assumes that the occupant remains in contact with the vehicle interior and thenceforth experiences the same dynamic forces as the vehicle. The recommended occupant-risk limiting values of NCHRP Report 230 are given in Table 1.

NCHRP REPORT 350

The testing and evaluation guidelines of NCHRP Report 230 have been superseded by those of NCHRP Report 350 (*6*). 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 are shown in Appendix A. Table A-1 in Appendix A contains three test levels and subdivides crash cushions into redirective and non-redirective categories. The user agency will be responsible for deciding which of the severity levels is most appropriate for a particular application. Note, however, that 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. 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 various impact conditions are illustrated in Figures A-1 and A-2, and the evaluation criteria are presented in Table A-2. It is clear that 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 crash cushions and terminals, a terminal being a device designed to shield the end of a longitudinal barrier. NCHRP Report 230 specifies 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. NCHRP Report 350, however, specifies one crash test matrix for terminals and redirective crash cushions and a second, less demanding, test matrix for non-redirective crash cushions.

TABLE 1
SAFETY EVALUATION GUIDELINES (AFTER *1*)

Evaluation Factors		Evaluation Criteria
Structural Adequacy	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.
	D.	Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.
Occupant Risk	E.	The vehicle shall remain upright during and after collision although moderate rolling, pitching, and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.
	F.	Impact velocity of hypothetical front-seat passenger against vehicle interior, calculated from vehicle accelerations and 0.61-m forward and 0.30-m lateral displacements, shall be less than: Occupant Impact Velocity (m/s) Longitudinal — Lateral $12.2/F_1$ — $9.1/F_2$ and vehicle highest 10-ms average accelerations subsequent to instant of hypothetical passenger impact should be less than: Occupant Ridedown Acceleration (*g*) Longitudinal — Lateral $20/F_3$ — $20/F_4$ Where F_1, F_2, F_3, and F_4 are appropriate acceptance factors.
	G.	(Supplementary) Anthropometric dummy responses should be less than those specified by FMVSS 208; i.e., resultant chest acceleration of 60 *g*, Head Injury Criteria of 1000, and femur force of 2250 lb (10 kN) and by FMVSS 214, i.e., resultant chest acceleration of 60 *g*, Head Injury Criteria of 1000, and occupant lateral impact velocity of 30 fps (9.1 m/s).
Vehicle Trajectory	H.	After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.
	I.	In tests where the vehicle is judged to be redirected into or stopped while in adjacent lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.
	J.	Vehicle trajectory behind the test article is acceptable.

TABLE 2
NCHRP REPORT 230 TEST MATRIX FOR CRASH CUSHIONS (AFTER *1*)

Test Number	Vehicle Mass (kg)	Impact Speed (km/h)	Impact Angle (degrees)	Impact Point	Evaluation Criteria (Defined in Table 1)
50	2,041	97	0	center nose of device	C,D,E,F,(G),H,J
51	1,020	97	0	center nose of device	C,D,E,F,(G),H,J
52	816	97	0	center nose of device	C,D,E,F,(G),H,J
53	2,041	97	20	midlength, side of device	C,D,E,H,I,J
54	2,041	97	10–15	0–0.91-m offset from center nose of device	C,D,E,F,(G),H,J

CHAPTER THREE

CHARACTERISTICS OF CRASH CUSHIONS

This chapter will address the individual characteristics of the following 13 devices:

- Guardrail Energy Absorbing Terminal (GREAT)
- Construction Zone GREAT (GREAT cz)
- Crash-Cushion Attenuating Terminal (CAT)
- Narrow Connecticut Impact Attenuation System (NCIAS)
- Low Maintenance Attenuator (LMA)
- Brakemaster
- Advanced Dynamic Impact Extension Module (ADIEM)-II
- Sand-filled plastic barrels
- Hex-Foam Sandwich System
- Hi-Dro Sandwich System
- Hi-Dro Cell Cluster
- Connecticut Impact Attenuation System (CIAS)
- Generalized Connecticut Impact Attenuation System (GCIAS).

The first seven crash cushions are narrow-hazard devices 610–914 mm wide. They shield such hazards as the blunt ends of median barriers. The remaining devices are used at wider hazard locations.

Some of these impact attenuation devices are redirective under side impact conditions and some are not. Some allow a vehicle impacting the device at an angle on the front (nose) of the device to pass or "gate" through the crash cushion and others do not. Most, but not all, crash cushions require a backup structure.

GUARDRAIL ENERGY ABSORBING TERMINAL (GREAT)

The GREAT system, manufactured and distributed by Energy Absorption Systems, Inc., is a crash cushion that shields narrow hazards such as median barrier ends, bridge pillars, and center piers (*7*). A typical installation is depicted in Figure 1. The GREAT system is manufactured in 762-, 914-, and 1,067-mm widths and various lengths, depending on the energy dissipation requirements of the specific installation. It is composed of 1 to 12 bays, with each bay containing a replaceable energy-dissipating cartridge of Hex-Foam. The cartridge is composed of a matrix of hex-shaped honeycomb filled with polyurethane foam to dissipate energy. The honeycomb is stacked in 25-mm layers in a cross-ply orientation.

When the Hex-Foam material is crushed, the walls of one honey-

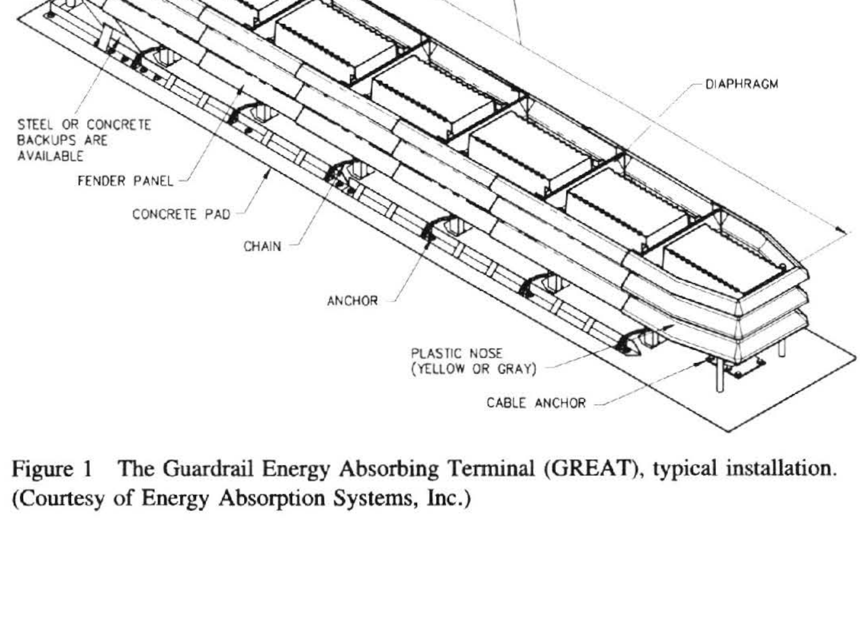


Figure 1 The Guardrail Energy Absorbing Terminal (GREAT), typical installation. (Courtesy of Energy Absorption Systems, Inc.)

Figure 2 The GREAT system after impact. (Courtesy of Energy Absorption Systems, Inc.)

comb layer shear into the walls of the adjoining layer. The polyurethane foam provides both gussetting and stabilization for all the honeycomb cells as well as additional shearing resistance when the honeycomb walls shear into the foam. Crushing of foam and honeycomb walls also occurs and adds to the overall crushing force. During crushing the compressive force level continually increases until full crush is achieved, at approximately 90 percent compression. Because of the interlocking effect of the honeycomb shear matrix, the system rebound after impact is virtually eliminated. In addition, the material provides a certain degree of strain-rate sensitivity during crushing. The early version of the Hex-Foam cartridge used a cardboard honeycomb matrix. This has been replaced in the GREAT systems with a combination of metal and honeycomb called Hex-Foam II.

The Hex-Foam cartridges are kept in place with triple-corrugated (thrie-beam) steel fender panels and separated with diaphragms. The fender panels telescope toward the rear of the crash cushion under head-on impact conditions. Side impacts are redirected by the lateral restraint provided by the fender panels, their chain anchors, and guidance cables. A GREAT system after impact is shown in Figure 2. Energy Absorption Systems, Inc. has developed standard designs of the GREAT system for a range of impact speeds. Their design table is presented in Table 3. Note that the length of a GREAT system can vary from 1,750 to 11,810 mm, depending on the design requirements. The 97-km/h GREAT unit satisfies the crash cushion test requirements of NCHRP Report 230, as summarized in Table 4.

TABLE 3
THE GREAT SYSTEM DESIGN TABLE

No. of Bays (length)	Design ▶ Velocity (km/h)	24	32	40	48	56	63	72	80	87	96	104	112
12 (11 800mm)	G's kN	—	—	—	—	—	—	—	—	—	—	—	5.0 150.3
11 (10 900mm)	G's kN	—	—	—	—	—	—	—	—	—	—	—	5.4 162.4
10 (9980mm)	G's kN	—	—	—	—	—	—	—	—	—	—	5.1 153.0	5.9 177.0
9 (9070mm)	G's kN	—	—	—	—	—	—	—	—	—	4.8 144.1	5.6 168.1	6.5 195.3
8 (8150mm)	G's kN	—	—	—	—	—	—	—	—	4.4 132.1	5.3 159.2	6.2 186.4	**7.2 216.2**
7 (7240mm)	G's kN	—	—	—	—	—	—	—	4.1 123.2	5.0 150.3	6.0 180.1	**7.0 210.4**	**8.1 243.3**
6 (6330mm)	G's kN	—	—	—	—	—	—	3.8 114.3	4.7 141.0	5.7 171.2	6.8 204.2	**8.0 240.2**	**9.3 279.3**
5 (5410mm)	G's kN	—	—	—	—	—	3.6 108.1	4.5 135.2	5.6 168.1	6.7 201.0	**8.0 240.2**	**9.4 282.4**	**10.8 324.3**
4 (4500mm)	G's kN	—	—	—	—	3.3 99.2	4.3 129.0	5.4 162.4	6.7 201.0	**8.1 243.3**	**9.6 288.2**	**11.3 339.4**	—
3 (3580mm)	G's kN	—	—	—	3.0 90.3	4.1 123.2	5.4 162.4	6.8 204.2	**8.4 243.3**	**10.1 303.3**	**12.0 360.3**	—	—
2 (2670mm)	G's kN	—	—	2.8 84.1	4.0 120.1	5.5 165.0	**7.2 216.2**	**9.1 273.1**	**11.2 336.3**	—	—	—	—
1 (1750mm)	G's kN	1.5 46.3	2.7 81.0	4.3 129.0	6.2 186.4	**8.4 252.2**	**10.9 328.3**	—	—	—	—	—	—

NOTES: 1. Above G's are average values calculated for vehicles (816 to 2041 Kg) that stop in a distance equal to 85% of the unit's length.

2. Above kN's are estimated peak forces exerted on the backup structure.

3. WARNING: SHADED AREA ▒ DENOTES EXCESSIVE DECELERATIONS BASED UPON THE OCCUPANT RISK RECOMMENDATIONS OUTLINED IN NCHRP 230 FOR 2041 Kg VEHICLES. ENERGY ABSORPTION SYSTEMS, INC. DOES NOT RECOMMEND CHOOSING UNITS FROM THIS AREA OF THE CHART.

(Courtesy of Energy Absorption Systems, Inc.)

TABLE 4
SUMMARY OF CRASH TEST RESULTS FOR THE GREAT 6-BAY SYSTEM

	NCHRP Report 230 Test Number		
	50	52	54
Vehicle mass (kg)	1,955	904	1,955
Impact speed (km/h)	98.8	104.6	98.8
Impact angle (degrees)	0	0	12
Vehicle impact location	nose	nose	nose
Vehicle stopping distance (m)	4.8	3.4	4.7
Occupant impact velocity (m/s)			
Longitudinal*	8.8	12.3	9.9
Lateral	--	--	--
Occupant ridedown acceleration (peak 10-msec average g's)			
Longitudinal	20	15.7	17.0
Lateral	--	--	--
Vehicle acceleration (peak 50-msec average g's)			
Longitudinal	--	--	--
Lateral	--	--	--

*12.3 m/s is 39.9 ft/s, which is less than the 40.0 ft/s limit of NCHRP 230.

CONSTRUCTION ZONE GREAT (GREAT cz)

This portable crash cushion is made up of the same components as the GREAT system but is built into a portable platform (*8*). The GREAT cz, shown in Figure 3, captures errant vehicles under end-on impact conditions and redirects vehicles impacting on the side of the unit. The GREAT cz is available in two standard lengths (3,660 and 6,400 mm) depending on the impact speed requirements of the construction zone. It provides temporary construction zone protection and can be moved from site to site as needed. The GREAT cz is anchored with bolts or pins, depending on the characteristics of the site.

CRASH-CUSHION ATTENUATING TERMINAL (CAT)

A narrow-hazard crash cushion, the CAT is shown in Figure 4 (*9*). Its major components include steel rails, wood posts that fit inside steel foundation tubes, a channel strut, a cable assembly, and a bearing plate. Note that the steel rails are slotted. In fact, although only two rows of slots are visible in Figure 4, there are four such rows in each rail. The slots are 88.9 mm long and 22.2 mm high and are separated by 7.9-mm-long steel land sections. The rails nearest the impact end of the CAT are made of 12-gauge steel and are 3.8 m long. They partially overlap the succeeding 10-gauge rails of the same length. During an end-on impact, some energy is dissipated during the fracturing of the wooden posts that occurs as the system telescopes back upon itself. A significant percentage of the energy is dissipated, however, by the shearing off of the multitude of steel land sections between the slots in the rails along the length of the system. The CAT can be transitioned to median and shoulder guardrails, concrete safety shape median barriers, and vertical walls or piers. It satisfies the crash cushion test requirements of NCHRP Report 230 and is manufactured and distributed by Syro Inc., a subsidiary of Trinity Industries, Inc. Table 5 summarizes the crash test results.

NARROW CONNECTICUT IMPACT ATTENUATION SYSTEM (NCIAS)

The NCIAS dissipates energy by plastically deforming mild steel cylinders (*10,11*). It is suitable for use in front of narrow roadside hazards such as bridge piers, parapets, and exposed ends of longitudinal barriers. Since the NCIAS has a stand-alone backup structure, it does not rely on the narrow hazard for anchorage. The NCIAS, shown in Figure 5, consists of a single row of eight 914-mm diameter mild steel cylinders of different thicknesses, which are formed from flat plate stock. All cylinders are 1,219 mm high, and a total of four 25.4-mm-diameter cables (two on each side of the system) provide lateral stability and assist in redirecting errant vehicles under side impact conditions. The NCIAS is 7.3 m long and 914 mm wide.

Other features of the NCIAS include the following:

- A stand-alone, concrete-filled, steel tubular backup structure, which also provides support for the ends of the four cables, permitting them to develop the tension required to redirect vehicles that hit the system on its side;
- A steel plate cable support at the front of the crash cushion;
- Lateral deflection limiters, 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;
- 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 hit, it will wrap itself vertically around the front end of the vehicle, effectively capturing it; and
- 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 NCIAS meets all of the crash cushion test requirements of NCHRP Report 230. Crash test results are presented in Table 6. Figure 6a shows the NCIAS intact and Figure 6b shows the results of a 100-km/h head-on impact with a 2,041-kg automobile.

LOW MAINTENANCE ATTENUATOR (LMA)

The LMA is a narrow-hazard crash cushion 10.1 m long and approximately 1 m wide. It is manufactured and distributed by Energy Absorption Systems, Inc. and recommended for use at narrow-hazard locations in high-frequency impact areas. The LMA system is shown in Figure 7 (*12*). The energy-dissipating elements are reusable elastomeric cylinders. Although all cylinders have outside diameters of 711.2 mm, the lengths and wall thicknesses

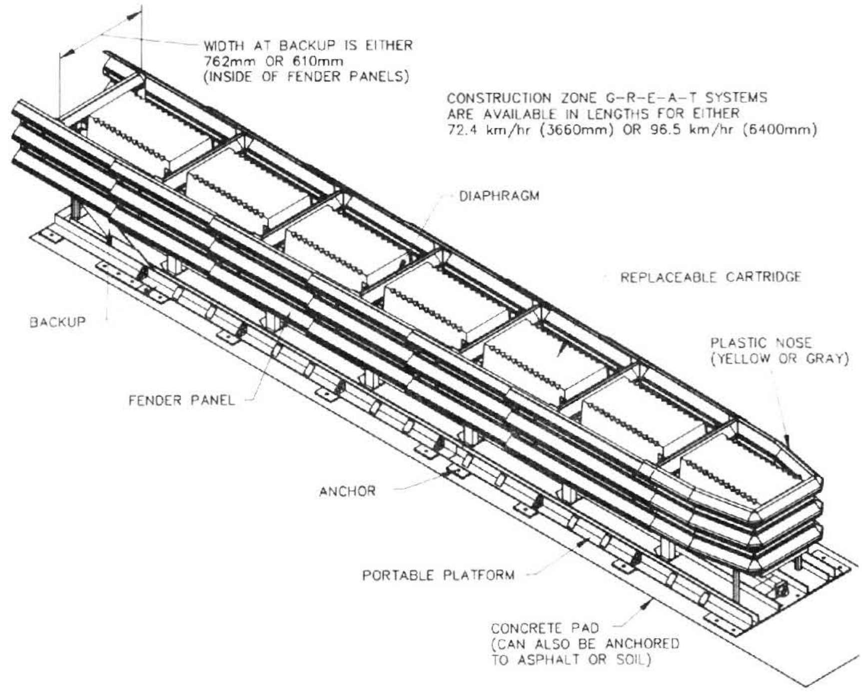


Figure 3 The Construction Zone GREAT (GREAT cz). (Courtesy of Energy Absorption Systems, Inc.)

vary as shown in the figure. The elastomeric cylinders are surrounded by a framework of triple-corrugated steel diaphragms and guardrails (thrie-beam). The LMA thrie-beam diaphragm serves as an attachment point for the rubber cylinders and a framework supporting the fender panels. When hit from the side, the thrie-beam diaphragms are restrained from lateral movement by restraining chains. A restraining cable is also incorporated into the first two thrie-beam diaphragms of the system to control sideways movement during angled impacts on the nose. The LMA thrie-beam fender panels add side fendering (redirecting) capability and structural stability to the system. The fender panels overlap and telescope rearward as the system collapses. Under nose impacts the system collapses, dissipating the kinetic energy of the vehicle and bringing it to a controlled stop. Under side impact conditions, the vehicle is redirected.

The LMA system satisfies the crash cushion test requirements of NCHRP Report 230 (see Table 7). The initial cost of this device is high; however, it has a low maintenance cost because of its reusable energy-absorbing materials, and can be placed back in service quickly. An LMA system after impact is shown in Figure 8.

BRAKEMASTER

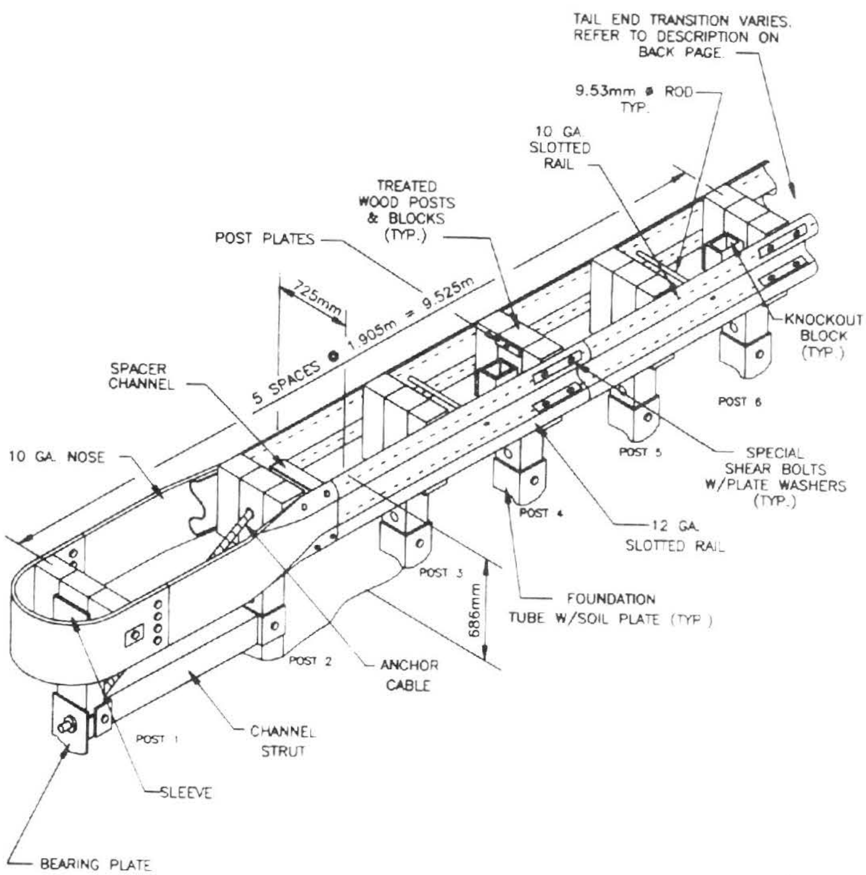
The Brakemaster crash cushion is manufactured and distributed by Energy Absorption Systems, Inc. It is used to shield narrow hazards such as double-sided guardrail ends, bridge pillars, and lighting and sign supports. The Brakemaster system, illustrated in Figure 9 (*13*), consists of a framework of W-beam steel guardrail panels that move rearward during head-on impacts. Vehicles that hit the system from the side are redirected. Other system components include the following:

- An embedded anchor assembly in the front of the device,
- A galvanized sheet metal breakaway assembly to accept frontal impacts,
- Two spring-loaded brakes mounted to wire rope cable (attached to the embedded anchor in front and the downstream guardrail posts in the rear) that dissipate energy through friction as they slide over the cables,
- A brake/tension support that positions and guides the cable/brake assembly,
- A panel/strap assembly that includes tension straps that transfer the loads developed in side impacts to the brake tension support,
- Three diaphragm assemblies that support and position the panel/straps and slide on the cable/brake during collapse of the system, and
- A transition strap assembly that transfers the tension developed in side impacts to the upstream panels and the downstream guardrail.

The Brakemaster is 9,600 mm long and 610 mm wide. The crash test results, presented in Table 8, satisfy the crash cushion testing requirements of NCHRP Report 230.

ADVANCED DYNAMIC IMPACT EXTENSION MODULE (ADIEM)-II

The ADIEM-II dissipates kinetic energy during an impact by crushing lightweight perlite concrete modules (*14*). Perlite is a lightweight aggregate used in highly porous concrete. This material is molded into modules and coated to prevent water penetration. Ten of these modules are inserted into an anchored concrete base



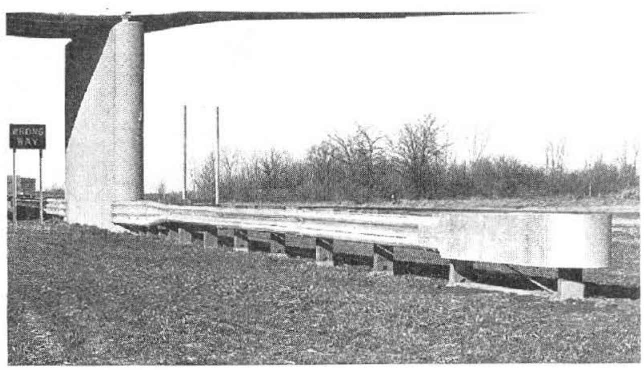


Figure 4 The Crash-Cushion Attenuating Terminal (CAT). (Courtesy of Syro, Inc., a subsidiary of Trinity Industries, Inc.)

that slopes upward from front to back. The perlite modules contain wire mesh reinforcements. The system, shown in Figure 10, is manufactured and distributed by Syro, Inc., a subsidiary of Trinity Industries, Inc.

The ADIEM-II is a modified version of the ADIEM, an energy dissipating end treatment for concrete barriers. The orginal ADIEM satisfied the NCHRP Report 230 crash testing requirements for terminals. However, it did not meet all of the crash cushion test requirements of that document. The ADIEM-II, however, does satisfy these crash cushion requirements. The relevant crash test summary for this device is presented in Table 9. It is of interest to note that NCHRP Report 230 terminal test 45 is used in place of crash cushion test 52 in this table. Both tests involve light automobile impacts into the nose of the device. However, terminal test 45 calls for an impact point that is offset from the center of the nose while crash cushion test 52 specifies a center-of-nose impact. Terminal test 45 was substituted for crash cushion test 52 in the crash test matrix for this device.

SAND-FILLED PLASTIC BARRELS

Crash cushions made up of arrays of sand-filled frangible plastic barrels dissipate kinetic energy in an impacting vehicle by transferring its linear momentum to the sand particles in the barrels (*15*). Energy Absorption Systems, Inc. and Roadway Safety Service, Inc. manufacture and distribute versions of these inertial crash cushions, known respectively as the Energite and Fitch sand barrel

TABLE 5
SUMMARY OF CRASH TEST RESULTS FOR THE CAT

	NCHRP Report 230 Test Number			
	50	52	53	54
Vehicle mass (kg)	1,995	834	2,014	2,027
Impact speed (km/h)	95.5	96.1	98.1	104.0
Impact angle (degrees)	0.5	1.0	14.6	12.7
Vehicle impact location	nose	nose	midlength	nose
Vehicle stopping distance (m)	8.2	2.5	--	65.5
Occupant impact velocity (m/s)				
Longitudinal	6.9	10.9	3.3	6.1
Lateral	1.5	1.4	4.9	0.1
Occupant ridedown acceleration (peak 10-msec average g's)				
Longitudinal	16.3	20.6	1.1	4.0
Lateral	5.4	0.6	5.9	--
Vehicle acceleration (peak 50-msec average g's)				
Longitudinal	8.8	15.9	2.9	7.3
Lateral	1.8	1.3	4.9	3.5

TABLE 6
SUMMARY OF CRASH TEST RESULTS FOR THE NCIAS

	NCHRP Report 230 Test Number			
	50	52	53	54
Vehicle mass (kg)	2,045	817	2,037	2,041
Impact speed (km/h)	97.9	97.8	98.5	96.7
Impact angle (degrees)	0	0	20	15.5
Vehicle impact location	nose	nose	midlength	0.5 m offset on nose
Vehicle stopping distance (m)	6.2	4.4	--	5.9
Occupant impact velocity (m/s)				
Longitudinal	8.9	9.0	10.3	9.3
Lateral	--	--	5.3	2.4
Occupant ridedown acceleration (peak 10-msec average g's)				
Longitudinal	15.6	13.5	13.0	10.3
Lateral	--	--	12.8	4.7
Vehicle acceleration (peak 50-msec average g's)				
Longitudinal	--	--	--	--
Lateral	--	--	--	--

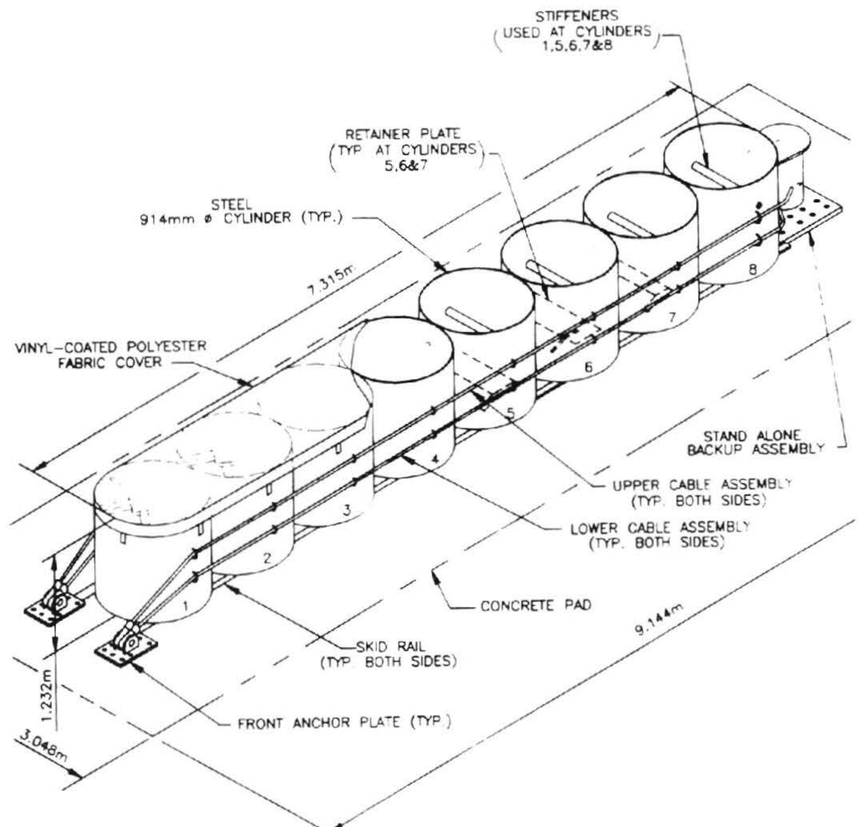


Figure 5 The Narrow Connecticut Impact Attenuation System (NCIAS). (Courtesy of Syro, Inc., a subsidiary of Trinity Industries, Inc.)

Figure 6a The NCIAS intact.

Figure 6b Impact result of a 100 km/h head-on collision by 2,041 kg automobile.

systems. The Energite version of the inertial barrier module is shown in Figure 11, and the Fitch module schematic is illustrated in Figure 12. Both have diameters and heights of 914.4 mm. Individual modules from the two distributors have been intermixed in specific applications.

Some typical sand-filled plastic barrel crash cushions are shown in Figure 13. Note that each module is free standing and no backup structure is used. The modules contain varying amounts of sand, ranging from 91 kg to as much as 1,905 kg. Obviously, a large number of system configurations could be assembled. The variable choices include the number of barrels, the cluster configuration, the sand weight in each row of the array, and the barrel size. It is very important that the sand-filled plastic barrel array be properly designed for site-specific conditions. Both manufacturers have developed standard arrays, given system requirements with respect to vehicle weight, impact velocity, maximum vehicle decelerations, and hazard shape and size. Some typical barrier applications are shown in Figure 14, and a post-impact view of a sand-filled plastic barrel crash cushion is shown in Figure 15.

It should be emphasized that sand-filled plastic barrel crash cushions are non-redirective devices. Angled impacts near the rear of these devices can result in impalement on the corner of the rigid hazard if the system is not properly designed. The Federal Highway Administration (FHWA) recommends that the outside modules in the rear row of an inertial barrier overlap (in width) the shielded fixed object by at least 762 mm to reduce the severity of these "coffin corner" impacts. The recommendations of the FHWA and one manufacturer regarding site conditions at sand-filled plastic barrel installations are presented in Figure 16.

It is important that the sand used in this type of crash cushion be clean and have a moisture content of 3 percent or less. A higher moisture content can result in frozen sand in cold weather conditions, producing large blocks of sand that can adversely affect crash cushion performance and create a hazard to surrounding traffic (*16*). It has been found that mixing rock salt with the sand helps to prevent wet sand from freezing under most conditions. The use of sacked sand in these systems is not an acceptable practice.

The design procedure used in sand barrel installations involves applying the principle of the conservation of linear momentum. The details of this design approach are contained in AASHTO's *Roadside Design Guide* (*2*).

Clearly, it is possible to construct an infinite variety of sand barrel cluster configurations and module weights. A collection of crash test data for a sampling of these designs is presented in Table 10.

HEX-FOAM SANDWICH SYSTEM

Like the GREAT, the Hex-Foam Sandwich System dissipates kinetic energy by crushing Hex-Foam cartridges (*17*). The GREAT system is used at narrow hazards; the Hex-Foam Sandwich System is designed to shield a variety of hazard widths. A Hex-Foam Sandwich System, shown in Figure 17, consists of crushable Hex-Foam cartridges, tubular steel diaphragms, and telescoping fender panels. In head-on impacts, vehicles are brought to a controlled stop through the crushing of the Hex-Foam cartridges; side impacts are redirected by the fendering system. The three standard Hex-Foam Sandwich System units are shown in Figure 18. Bidirectional units are also available, and custom units are obtainable through Energy Absorption Systems, Inc., the manufacturer and distributor of the Hex-Foam Sandwich System. The required length of a given Hex-Foam Sandwich System is a function of the impact speed. The design data presented in Table 11 were developed to aid in the selection of the appropriate, site-specific length of this crash cushion. Crash test results for the Hex-Foam Sandwich System are summarized in Table 12.

HI-DRO SANDWICH SYSTEM

This impact attenuation device, manufactured and distributed by Energy Absorption Systems, Inc., dissipates kinetic energy in a head-on collision by forcing water stored in nylon fabric, vinyl-coated tubes up through orifices located at the tops of the tubes while moving the system mass rearward (*18*). The device is illustrated in Figure 19, and a system after impact is shown in Figure 20. Its construction is similar to that of the Hex-Foam Sandwich System, except that the Hex-Foam cartridges are replaced by arrays of water-filled tubes. As with the Hex-Foam Sandwich System, a variety of system widths and lengths are available (see Table 13). Where freezing temperatures are expected, calcium chloride or

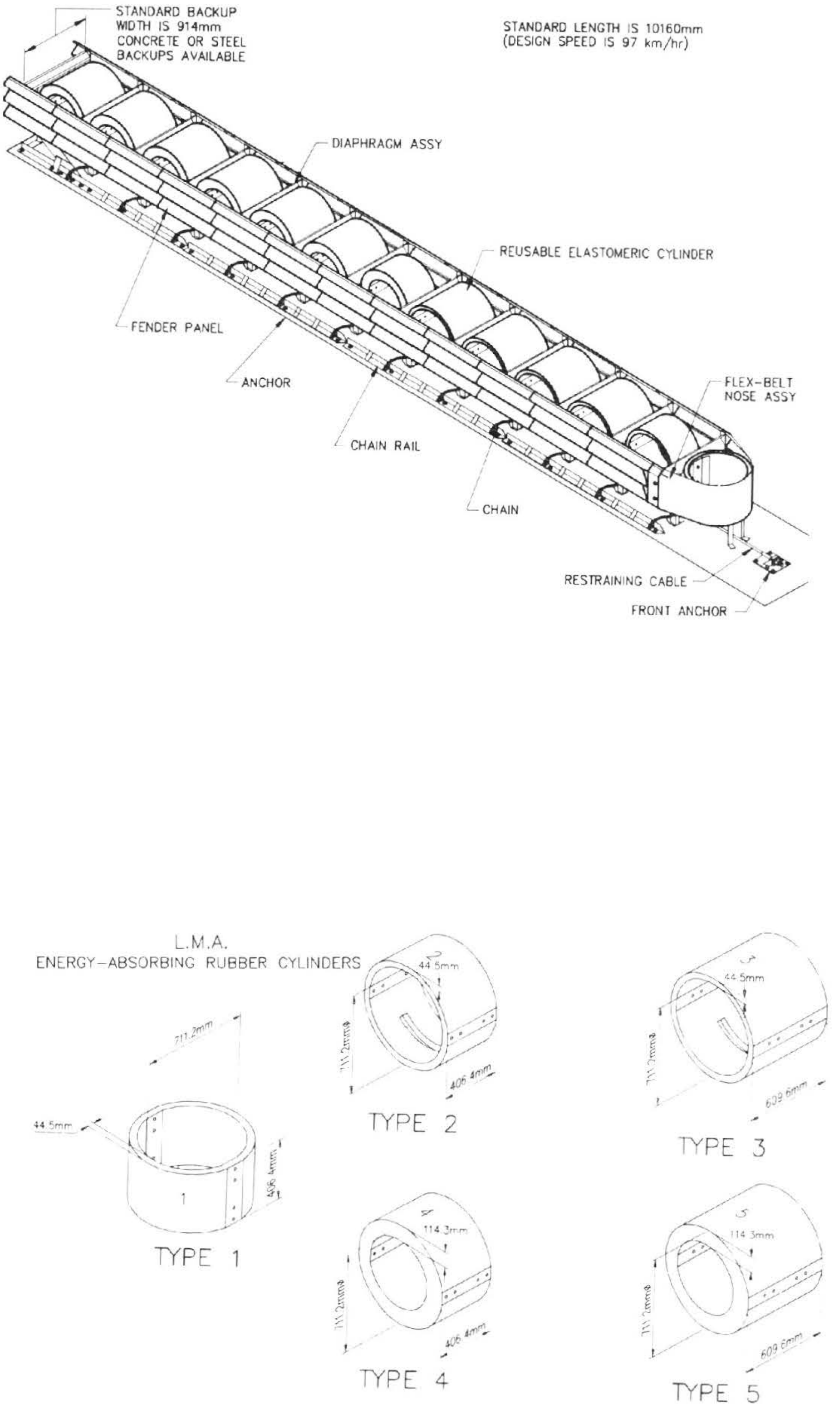


Figure 7 The Low Maintenance Attenuator (LMA). (Courtesy of Energy Absorption Systems, Inc.)

antifreeze should be added to the water stored in the tubes. The Hi-Dro Sandwich System was developed 10 years before the publication of NCHRP Report 230 and has not been tested according to its guidelines. It should be noted that Hi-Dro Sandwich units can be converted to Hex-Foam Sandwich systems relatively easily. The Hex-Foam Sandwich System requires less maintenance than the Hi-Dro Sandwich System and is less susceptible to vandalism.

HI-DRO CELL CLUSTER

The Hi-Dro Cell Cluster uses the same tubes as the Hi-Dro Cell Sandwich System. The tubes are bolted together in a cluster and wrapped with a flexible belt. A backup structure is required. The Hi-Dro Cell Cluster is designed to be used in applications where the normal traffic speeds are 72 km/h or less and a redirective capability is not required. Energy Absorption Systems, Inc. has developed a deceleration chart, shown in Figure 21, which can be used as a design aid in sizing the system for a particular installation. An example of a Hi-Dro Cell Cluster is shown in Figure 22.

CONNECTICUT IMPACT ATTENUATION SYSTEM (CIAS)

The CIAS, shown in Figure 23, is composed of 14 mild steel cylinders of 0.91- or 1.22-m diameters, formed from straight mild steel plate sections (*20*). These cylinders are bolted together, rest on a concrete pad, and are attached to an appropriate backup structure. The CIAS dissipates kinetic energy by plastically deforming the steel cylinders and is unique in that it will trap an errant vehicle under most side impact conditions. The vehicle will be redirected back onto the roadway only when the impact location is so close to the rear of the system that it is impossible to obtain an acceptable vehicle deceleration response because of the proximity of the hazard.

Steel tension straps (ineffective under compressive loading) and compression pipes (ineffective in tension) are used to cope with this redirectional crash case involving an impact near the rear of the system. 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 lateral force necessary to redirect the errant vehicle. The braced cylinders retain their unstiffened response when the attenuation system is crushed by impacts away from the back of the device. In a head-on impact, for example, the tension bracing is loaded in compression and buckles. The compression bracing, being welded to the cylinder at one end only, carries no load during the collapse process because its free end separates from the cylinder wall when collapse occurs. The internal bracing system is activated only under side impact conditions. A plan view of a CIAS installation in pre-impact and collapsed configurations is shown in Figure 24.

The CIAS has satisfied the crash test matrix for crash cushions of NCHRP Report 230 as summarized in Table 14.

TABLE 7
SUMMARY OF CRASH TEST RESULTS FOR THE LMA

NCHRP Report 230 Test Number	50	52	53	54
Vehicle mass (kg)	2,120	838	1,962	1,950
Impact speed (km/h)	96.9	92.2	97.7	100.1
Impact angle (degrees)	0	0	21	12
Vehicle impact location	nose	nose	midlength	nose
Vehicle stopping distance (m)	7.3	4.6	--	6.9
Occupant impact velocity (m/s)				
Longitudinal	8.8	10.7	6.0	8.7
Lateral	0.0	2.2	7.0	3.1
Occupant ridedown acceleration (peak 10-msec average *g*'s)				
Longitudinal	13.3	15.2	3.1	14.1
Lateral	0.0	1.3	10.6	3.0
Vehicle acceleration (peak 50-msec average *g*'s)				
Longitudinal	--	--	--	--
Lateral	--	--	--	--

GENERALIZED CONNECTICUT IMPACT ATTENUATION SYSTEM (GCIAS)

As its name implies, this family of crash cushions is the generalized version of the CIAS. These designs have the same performance characteristics as the CIAS in that they will capture errant vehicles under most side impact conditions and redirect vehicles only when impacts are close to the rear of the devices. As in the CIAS, this trapping/redirection response is accomplished through the use of a diametrical bracing system that is activated under side impact conditions (*20*).

Three representative versions of the GCIAS are shown in Figure 25. The system in Figure 25a is a 100-km/h device suitable for wide hazard location and a narrower 100-km/h crash cushion is illustrated in Figure 25b. A lower design speed GCIAS is shown in Figure 25c. This crash cushion was designed for impacts of up to 70 km/h. A sample GCIAS is shown after impact in Figure 26.

The GCIAS satisfies all of the requirements of NCHRP Report 230, and a summary of the crash test results is shown in Table 15.

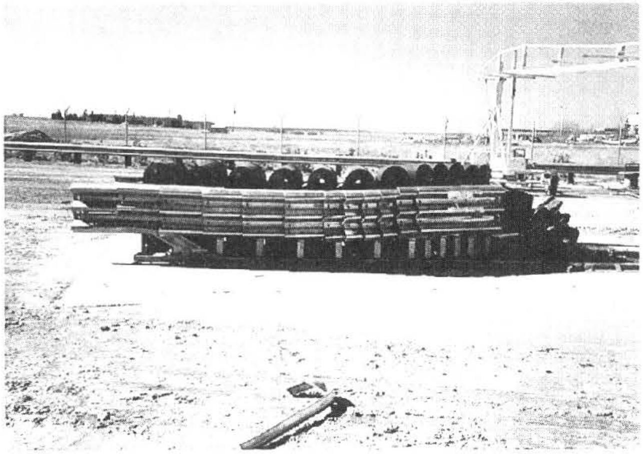


Figure 8 The LMA after impact. (Courtesy of Energy Absorption Systems, Inc.)

TABLE 8
SUMMARY OF CRASH TEST RESULTS FOR THE BRAKEMASTER

NCHRP Report 230 Test Number	50	52	53	54
Vehicle mass (kg)	2,001	821	1,963	2,016
Impact speed (km/h)	100.8	97.7	93.9	105.0
Impact angle (degrees)	0	0	20	15
Vehicle impact location	nose	nose	midlength	nose
Vehicle stopping distance (m)	7.1	4.2	--	7.0
Occupant impact velocity (m/s)				
Longitudinal	7.7	10.5	7.3	8.0
Lateral	0.7	--	4.4	2.2
Occupant ridedown acceleration (peak 10-msec average g's)				
Longitudinal	14.1	17.0	12.4	11.4
Lateral	2.6	--	10.5	1.7
Vehicle acceleration (peak 50-msec average g's)				
Longitudinal	12.7	20.2	7.0	9.3
Lateral	1.5	2.4	6.9	2.1

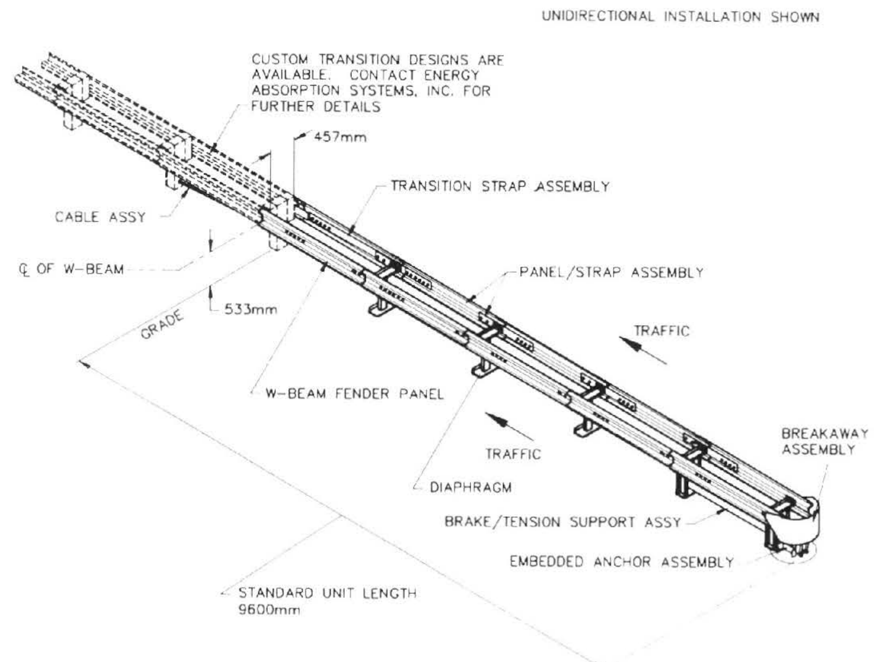


Figure 9 The Brakemaster. (Courtesy of Energy Absorption Systems, Inc.)

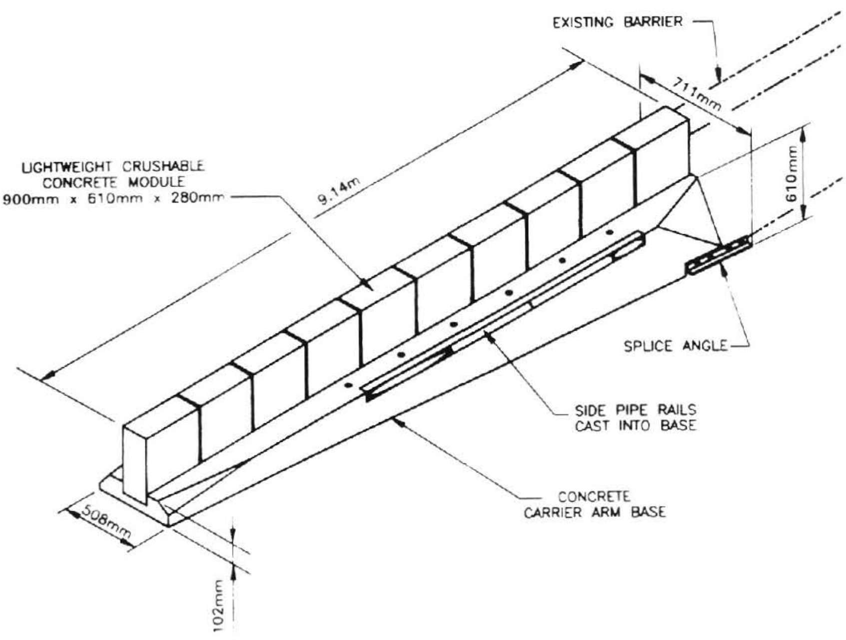


Figure 10 The Advanced Dynamic Impact Extension Module (ADIEM)-II. (Courtesy of Syro, Inc., a subsidiary of Trinity Industries, Inc.)

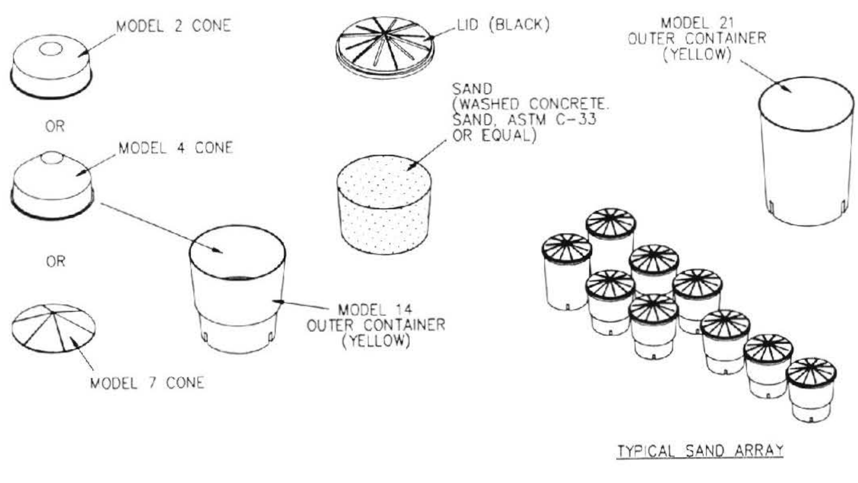


Figure 11 The Energite III System. (Courtesy of Energy Absorption Systems, Inc.)

TABLE 9
SUMMARY OF CRASH TEST RESULTS FOR THE ADIEM-II

NCHRP Report 230 Test Number	45	50	53	54
Vehicle mass (kg)	816	2,039	2,041	2,041
Impact speed (km/h)	94.3	97.0	96.8	91.7
Impact angle (degrees)	0	0	21.2	13.0
Vehicle impact location	15" offset	head on	midlength	nose
Vehicle stopping distance (m)	3.0	7.8	--	6.2
Occupant impact velocity (m/s)				
Longitudinal	11.4	9.1	5.5	8.9
Lateral	2.7	NA	7.9	1.4
Occupant ridedown acceleration (peak 10-msec average g's)				
Longitudinal	10.6	6.3	7.5	7.0
Lateral	1.6	--	12.8	1.9
Vehicle acceleration (peak 50-msec average g's)				
Longitudinal	--	--	8.1	9.2
Lateral	--	--	15.9	1.4

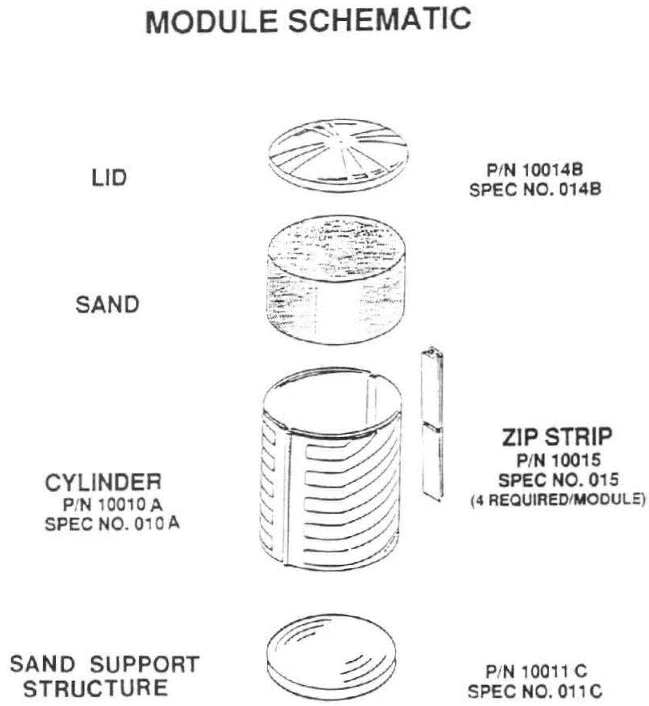


Figure 12 The Fitch Inertial Barrier System. (Courtesy of Roadway Safety Service, Inc.)

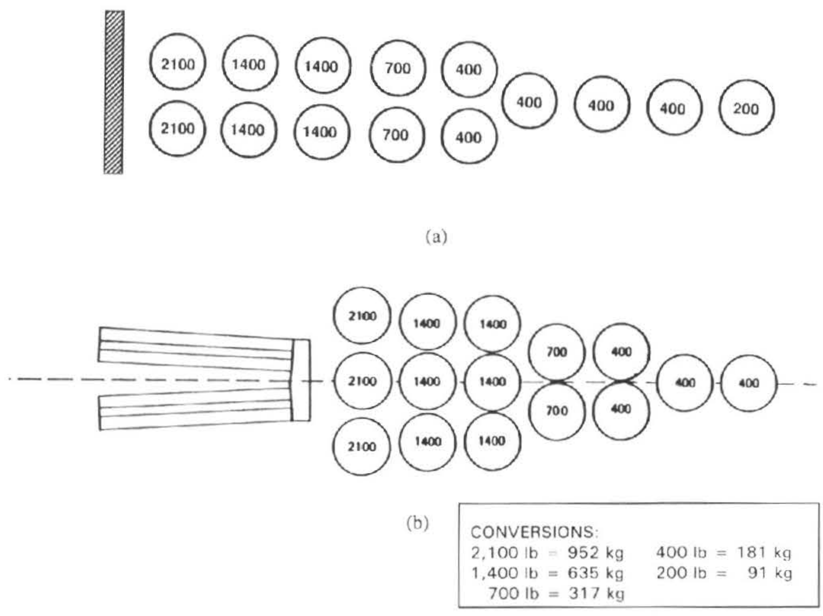


Figure 13 Some typical sand-filled plastic barrel crash cushions.

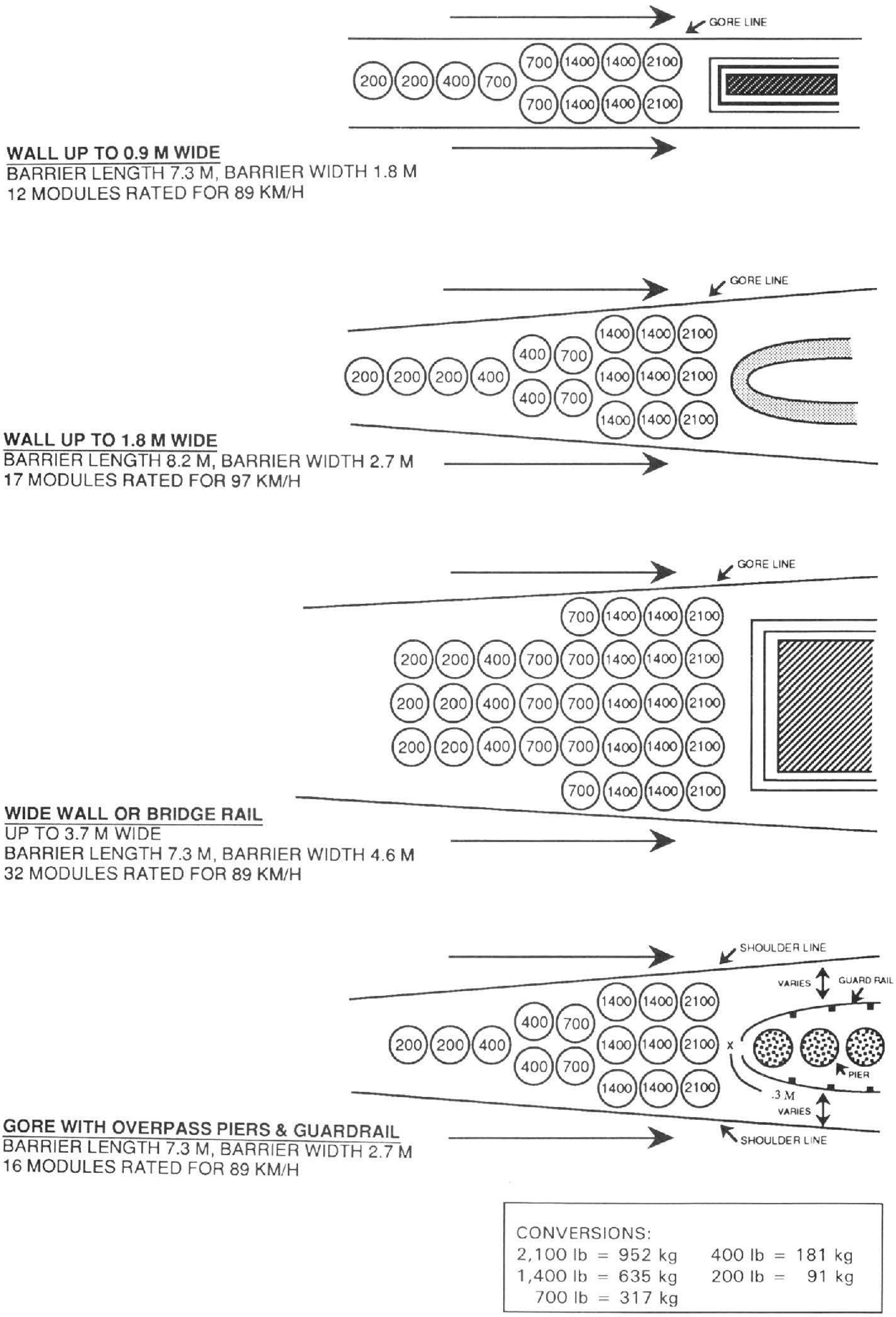


Figure 14 Typical barrier applications for sand-filled plastic barrel crash cushions. (Courtesy of Roadway Safety Service, Inc. (exclusive of metric conversions))

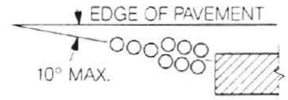
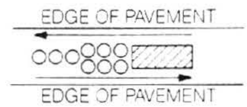
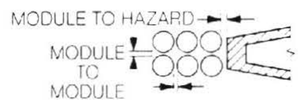
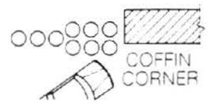
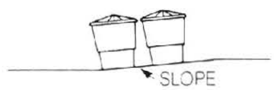
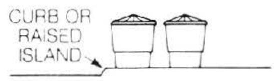
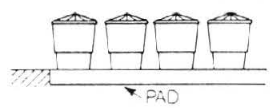
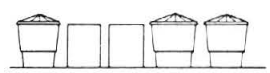
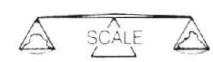
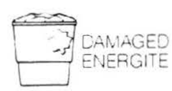
Condition	FHWA Recommendations	Energy Absorption Recommendations	
1. Angle of array in relation to center line of obstacle	Not recommended for more than 10°	Same as FHWA	
2. Bidirectional traffic	Offset array to avoid impact to the rear module from wrong-way vehicles	Same as FHWA	
3. Module spacing: module to module module to hazard	 None given 1' to 2'	 6" 1' minimum	
4. "Coffin" corner	Shield 30" outside of hazard	Stop vehicle prior to impact with hazard	
5. Sloping sites (lateral and longitudinal)	5% grade maximum	Same as FHWA	
6. Curbs and raised islands	No more than 4" high	Remove all curbs and raised islands	
7. Foundation pads	Flat surface; concrete or asphalt	Same as FHWA	
8. Intermixing of brands of modules	Approved	Approved	
9. Maintenance	Keep site clear of debris and snow	Same as FHWA	
10. Sand densities	100 lbs/cf	Determine in the field	
11. Single rows of modules	Not recommended	Same as FHWA	
12. Vandalism	Check periodically for damages	Same as FHWA	

Figure 16 Recommendations regarding site conditions at sand-filled plastic barrel crash cushion installations. (Courtesy of Energy Absorption Systems, Inc.)

Figure 15 Sand-filled plastic barrel crash cushion after impact. (Courtesy of Energy Absorption Systems, Inc.)

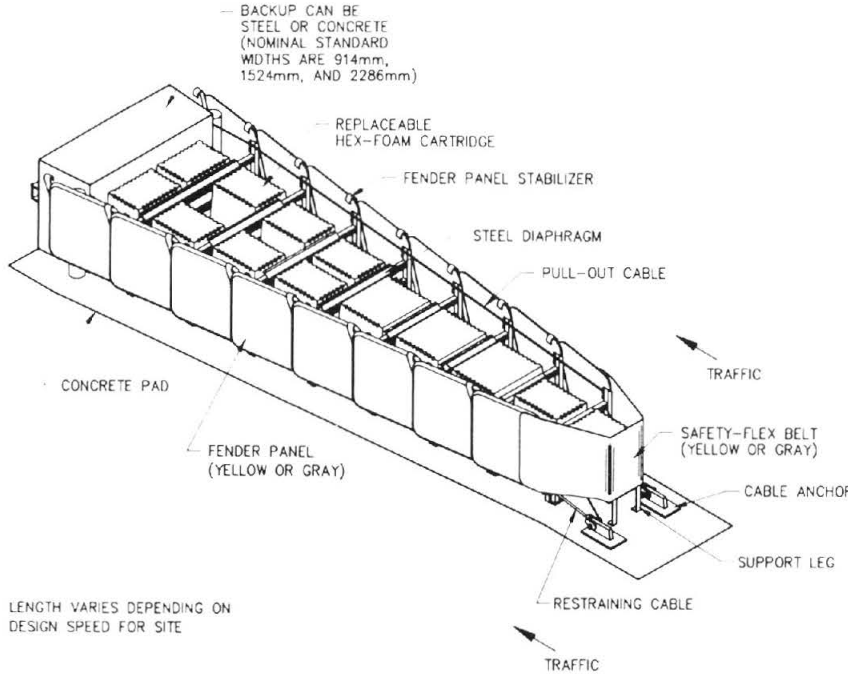


Figure 17 The Hex-Foam Sandwich System. (Courtesy of Energy Absorption Systems, Inc.)

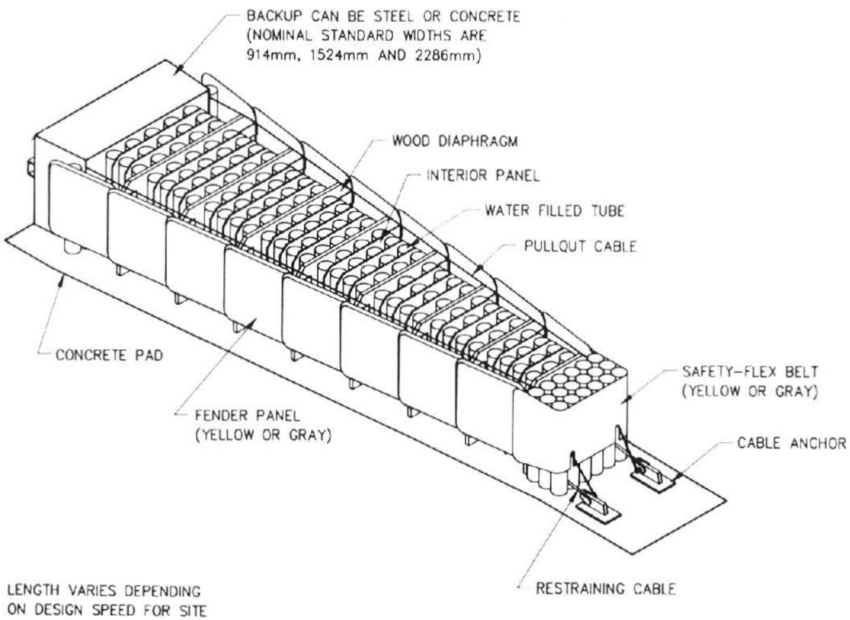


Figure 19 The Hi-Dro Sandwich System. (Courtesy of Energy Absorption Systems, Inc.)

Figure 18 appears on page 23.

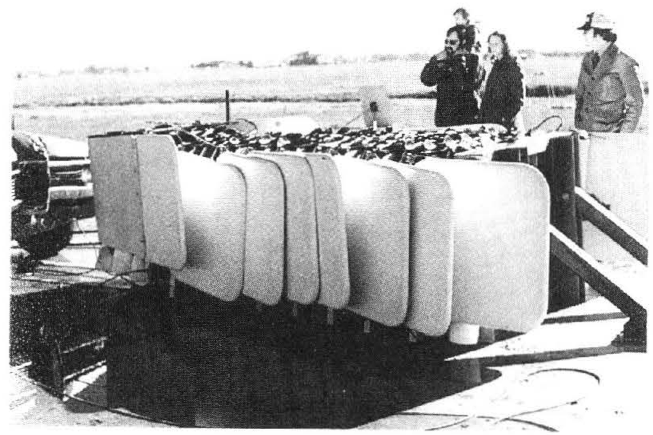


Figure 20 The Hi-Dro Sandwich System after impact. (Courtesy of Energy Absorption Systems, Inc.)

TABLE 10
SUMMARY OF CRASH TEST RESULTS FOR SAND-FILLED PLASTIC BARREL CRASH CUSHIONS

	NCHRP Report 230 Test Number							
	50 (Fig. 13a)	50 (Fig. 13b)	50 (Fig. 13b)	50 (Fig. 13b)	52 (Fig. 13b)	52 (Fig. 13b)	53 (Fig. 13b)	53 (Fig. 13b)
Vehicle mass (kg)	1,996	1,951	1,954	1,956	818	819	818	826
Impact speed (km/h)	92.5	94.3	94.6	97.5	96.7	93.3	95.6	96.5
Impact angle (degrees)	0	0	0	0	0	0	14.9	15
Vehicle impact location	nose	nose	nose	nose	nose	nose	corner of gore	corner of gore
Vehicle stopping distance (m)	9.4	7.5	7.2	7.3	5.9	6.7	3.5	3.5
Occupant impact velocity (m/s)								
Longitudinal	6.2	8.0	7.5	8.1	8.9	8.2	11.6	11.4
Lateral	--	--	--	--	--	--	2.4	1.0
Occupant ridedown acceleration (peak 10-msec average g's)								
Longitudinal	13.8	13.7	15.4	10.7	10.2	18.4	19.2	18.5
Lateral	--	--	--	--	--	--	0.9	3.2
Occupant ridedown acceleration (peak 50-msec average g's)								
Longitudinal	7.9	11.2	11.2	5.1	--	10.1	--	--
Lateral	--	--	--	--	--	--	--	--

TABLE 11
THE HEX-FOAM SANDWICH SYSTEM DESING TABLE

No. of Bays	Nominal length *	Design Velocity kph	63	72	80	87	96	104	112
4	(3187mm)	Average G's kN (peak)	6.0 200.2	7.6 244.6	9.3 311.4	11.4 378.1	——	——	——
5	(3873mm)	G's kN	5.0 155.7	6.3 200.2	7.7 244.6	9.4 289.1	11.1 355.8	——	——
6	(4559mm)	G's kN	4.2 133.4	5.3 177.9	6.6 200.2	8.0 244.6	9.5 289.1	11.1 355.8	——
7	(5245mm)	G's kN	——	4.6 155.7	5.7 177.9	6.9 222.4	8.2 266.9	9.7 311.4	11.2 355.8
8	(5931mm)	G's kN	——	——	5.1 155.7	6.1 200.2	7.3 222.4	8.5 266.9	9.9 311.4
9	(6617mm)	G's kN	——	——	4.5 133.4	5.5 177.9	6.5 200.2	7.7 244.6	8.9 289.1
10	(7303mm)	G's kN	——	——	——	5.0 155.7	5.9 177.9	6.9 222.4	8.0 244.6
11	(7988mm)	G's kN	——	——	——	——	5.4 177.9	6.3 200.2	7.3 222.4
12	(8674mm)	G's kN	——	——	——	——	5.0 155.7	5.8 177.9	6.8 200.2

WARNING: SHADED AREA [ ] DENOTES EXCESSIVE DECELERATIONS BASED UPON THE OCCUPANT RISK RECOMMENDATIONS OUTLINED IN NCHRP 230 FOR 2041 kg VEHICLES.

*Total length of unit as measured from front face of backup to forward edge of front cartridge. Values shown in table above are based on 85% efficiency.

(Courtesy of Energy Absorption Systems, Inc.)

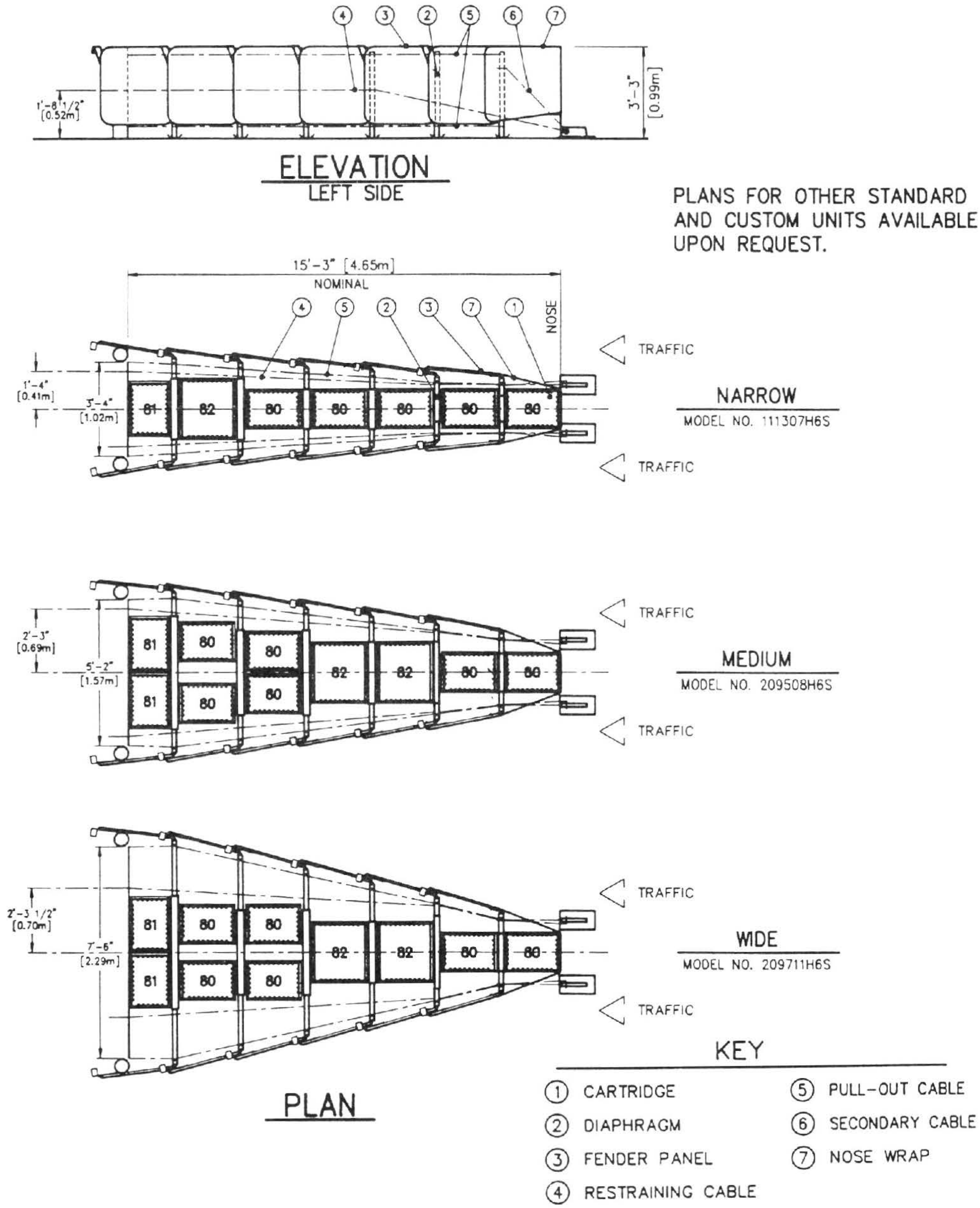


Figure 18 Three standard Hex-Foam Sandwich System units. (Courtesy of Energy Absorption Systems, Inc.)

TABLE 12
SUMMARY OF CRASH TEST RESULTS FOR THE HEX-FOAM SANDWICH SYSTEM

	NCHRP Report 230 Test Number			
	50	52	54	54
Vehicle mass (kg)	2,026	898	2,130	1,960
Impact speed (km/h)	95.4	104.8	100.1	97.0
Impact angle (degrees)	0	0	12	14
Vehicle impact location	nose	nose	nose	nose
Vehicle stopping distance (m)	5.0	3.9	4.7	4.6
Occupant impact velocity (m/s)				
Longitudinal	8.1	11.1	8.8	9.0
Lateral	2.0	2.7	2.7	--
Occupant ridedown acceleration (peak 10-msec average *g*'s)				
Longitudinal	16.0	15.2	19.1	13.6
Lateral	5.3	2.6	9.8	--
Vehicle acceleration (peak 50-msec average *g*'s)				
Longitudinal	--	--	--	--
Lateral	--	--	--	--

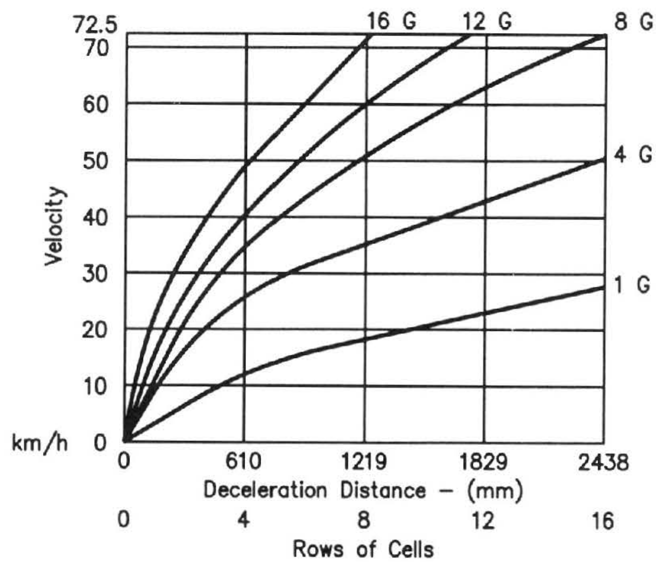


Figure 21 The Hi-Dro Cell Cluster deceleration chart. (Courtesy of Energy Absorption Systems, Inc.)

TABLE 13
THE HI-DRO SANDWICH SYSTEM DESIGN TABLE

No. of Bays (Length)	Design Velocity (Km/hr)	63	72	80	87	96	104	112
12 (8.52m)	G's kN					5.7 175	6.7 205	7.8 235
11 (7.84m)	G's kN				5.2 160	6.2 190	7.3 220	8.5 255
10 (7.15m)	G's kN			4.7 145	5.7 175	6.8 205	8.0 240	9.3 280
9 (6.46m)	G's kN		4.3 130	5.3 160	6.4 195	7.6 230	8.9 270	10.3 310
8 (5.78m)	G's kN	3.8 115	4.8 145	5.9 180	7.1 215	8.5 255	9.9 300	11.5 345
7 (5.09m)	G's kN	4.3 130	5.4 165	6.7 205	8.1 245	9.6 290	11.3 340	
6 (4.41m)	G's kN	4.9 150	6.2 190	7.7 235	9.3 280	11.1 335		
5 (3.72m)	G's kN	5.8 175	7.4 225	9.1 275	11.0 330			
4 (3.04m)	G's kN	7.2 220	9.1 275	11.2 340				

Notes:
1. Total length of unit as measured from front face of backup to forward edge of front cells. Values shown in table above are based on 75% efficiency. Actual efficiency in in excess of 83%.
2. Formula for calculating the force on the backup structure: (20)(Average G's from Design Data Table)(1.5)=Force measured in kN. (Numbers in above table have been rounded up to the nearest 5)
3. WARNING: SHADED AREA [shaded box] DENOTES EXCESSIVE DECELERATIONS BASED UPON THE OCCUPANT RISK RECOMMENDATIONS OUTLINED IN NCHRP 230 FOR 4500 LB [2000 kg] VEHICLES.

(Courtesy of Energy Absorption Systems, Inc.)

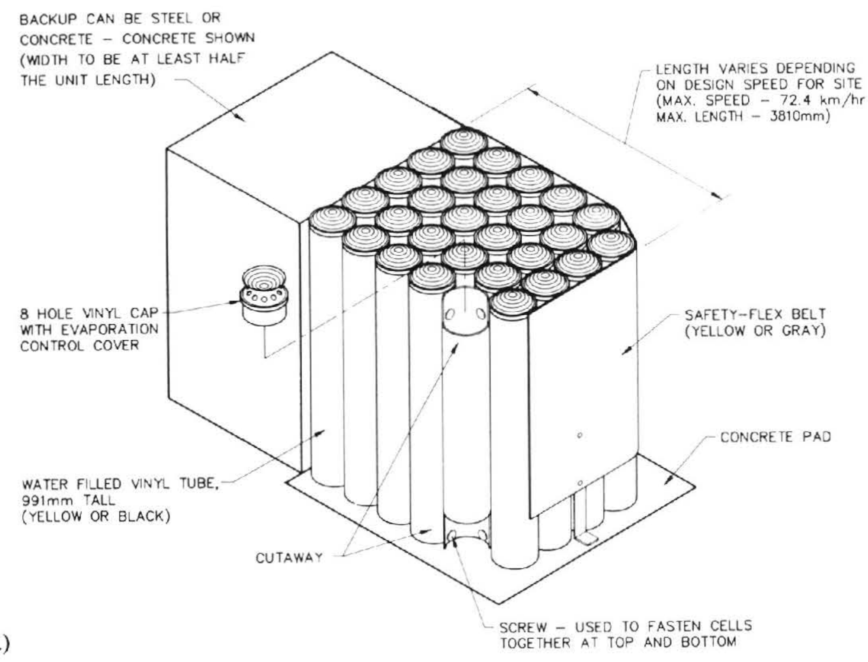


Figure 22 The Hi-Dro Cell Cluster.
(Courtesy of Energy Absorption Systems, Inc.)

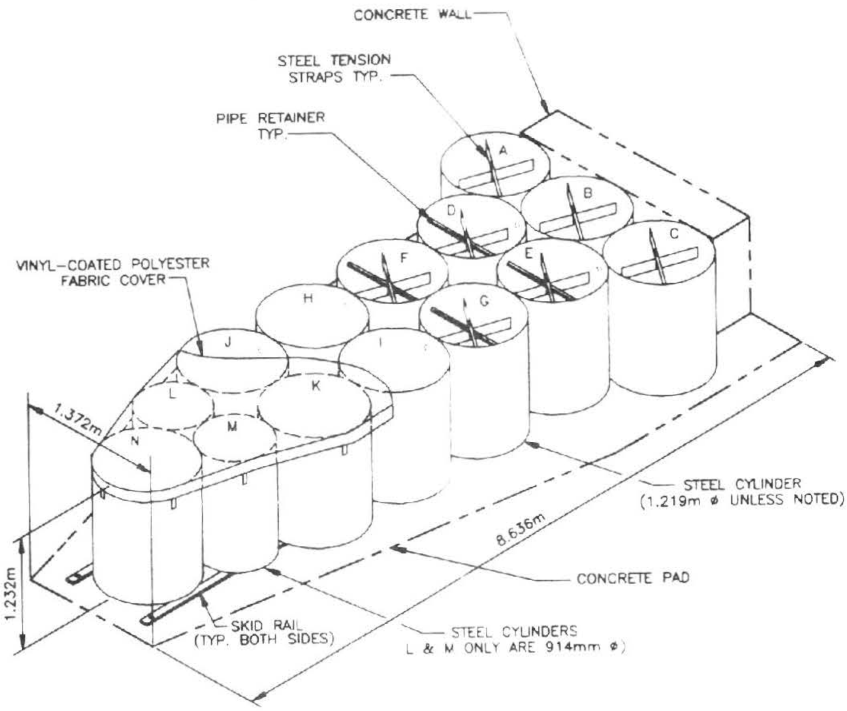


Figure 23 The Connecticut Impact Attenuation System (CIAS). (Courtesy of Syro, Inc., a subsidiary of Trinity Industries, Inc.)

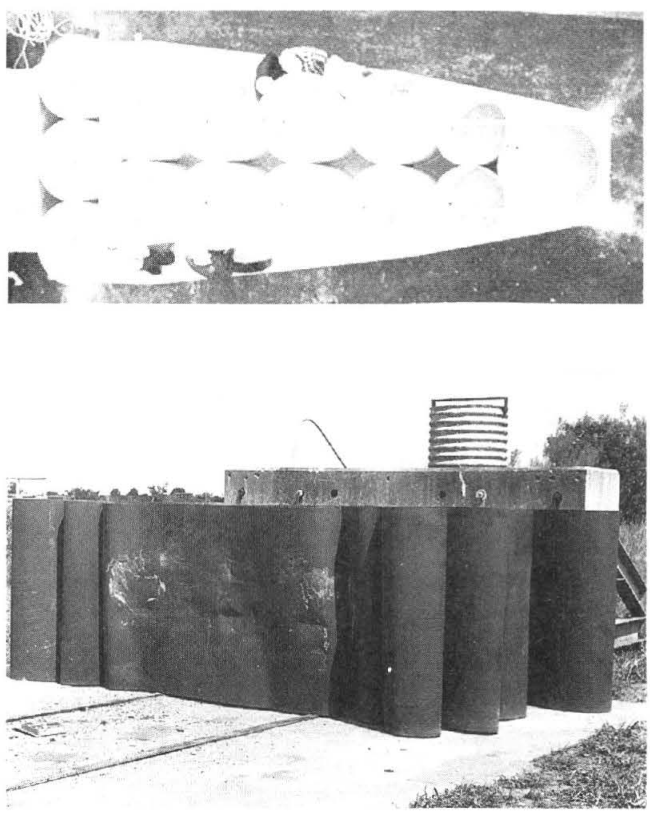


Figure 24 The CIAS pre-impact and after impact.

TABLE 14
SUMMARY OF CRASH TEST RESULTS FOR THE CIAS

	NCHRP Report 230 Test Number				
	50	50	52	53	54
Vehicle mass (kg)	2,039	2,039	816	2,039	2,039
Impact speed (km/h)	98.8	99.1	97.9	93.3	97.2
Impact angle (degrees)	0	0	0	15	20
Vehicle impact location	nose	nose	nose	corner of test hazard	along side
Vehicle stopping distance (m)	7.0	6.7	4.9	--	5.5
Occupant impact velocity (m/s)					
Longitudinal	7.8	8.1	10.6	9.8	8.4
Lateral	1.4	--	--	4.4	3.5
Occupant ridedown acceleration (peak 10-msec average g's)					
Longitudinal	12.6	12.8	12.8	9.6	20.6
Lateral	0.9	--	--	11.6	1.5
Vehicle acceleration (peak 50-msec average g's)					
Longitudinal	10.4	9.4	11.6	9.5	13.3
Lateral	--	--	--	--	--

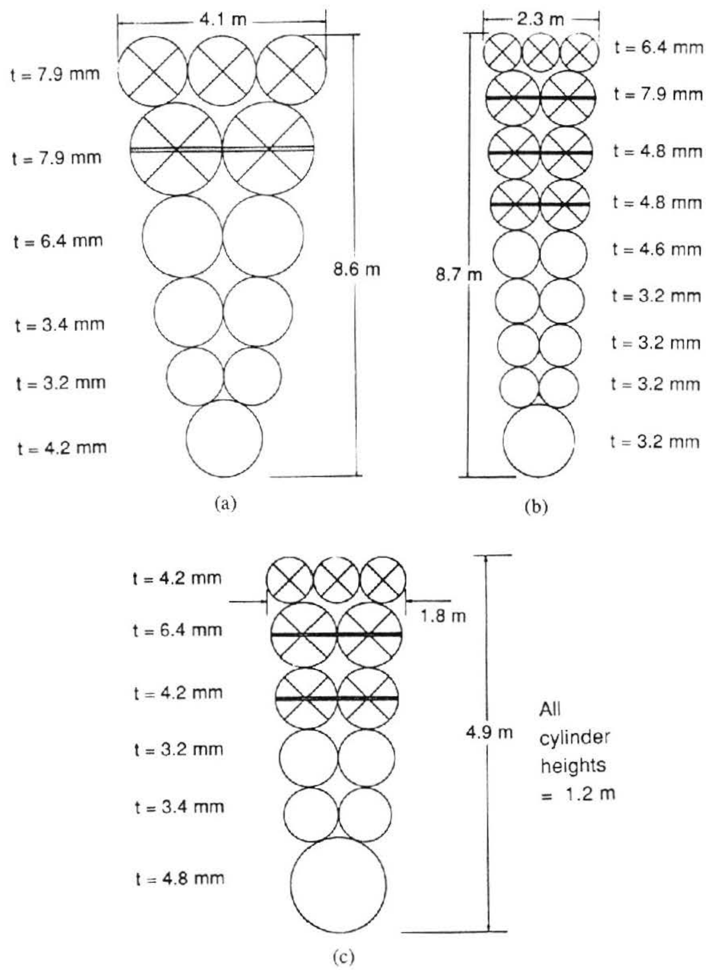


Figure 25 Three representative versions of the Generalized Connecticut Impact Attenuation System (GCIAS).

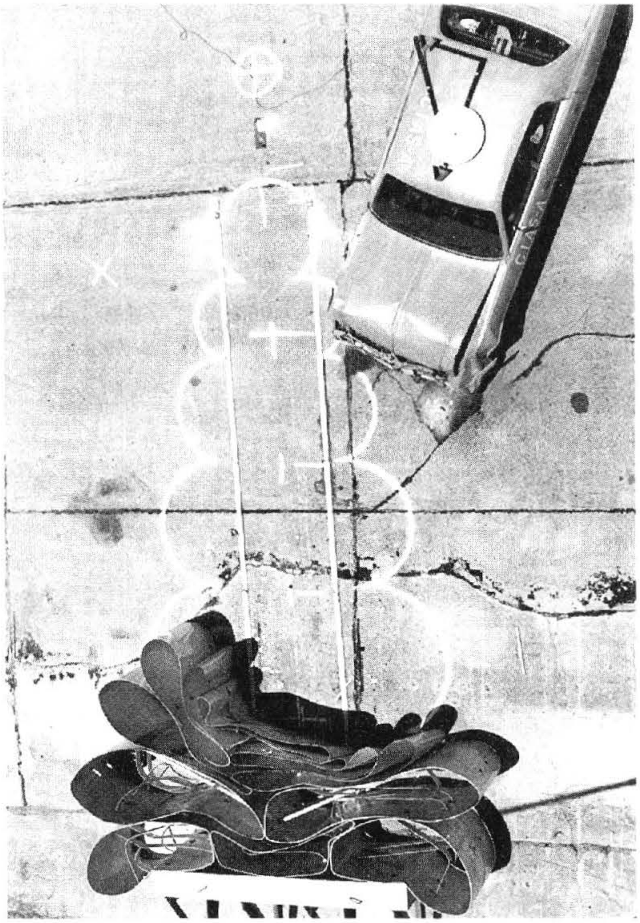


Figure 26 The GCIAS after impact.

TABLE 15
SUMMARY OF CRASH TEST RESULTS FOR THE GCIAS

Device	GCIAS (Fig. 25a*)	GCIAS (Fig. 25a)	GCIAS (Fig. 25b)	GCIAS (Fig. 25b)	GCIAS (Fig. 25c)	GCIAS (Fig. 25c)
NCHRP Report 230 Test Number	50	52	53	54	50	52
Vehicle mass (kg)	2,132	828	2,039	2,039	2,048	812
Impact speed (km/h)	96.9	103.0	103.9	98.9	76.7	72.6
Impact angle (degrees)	0	0	15	15	0	0
Vehicle impact location	nose	nose	corner of test hazard	nose	nose	nose
Vehicle stopping distance (m)	7.2	5.6	--	10.4	4.1	3.2
Occupant impact velocity (m/s)						
Longitudinal	6.2	10.5	--	7.0	7.4	8.1
Lateral	0.4	--	--	3.4	1.2	--
Occupant ridedown acceleration (peak 10-msec average *g*'s)						
Longitudinal	8.6	16.1	--	7.6	16.9	11.2
Lateral	1.7	--	--	6.3	0.3	--
Vehicle acceleration (peak 50-msec average *g*'s)						
Longitudinal	6.9	11.3	--	5.6	15.5	10.3
Lateral	1.9	1.2	--	3.3	1.4	1.0

*This GCIAS configuration differed slightly from the system shown in Figure 25a (See *20*).

CHAPTER FOUR

SELECTION CONSIDERATIONS

Thirteen impact attenuation devices are described in Chapter 3. They all have the capability to dissipate kinetic energy when hit head-on, bringing an errant vehicle to a controlled stop so that the occupant risk requirements of NCHRP Report 230 are satisfied. Under side impact conditions, some of the devices will redirect the vehicle and some will not. Some will allow the vehicle that hits at an angle at or near the front of the device to penetrate or gate through the system. Others will redirect or capture the vehicle under this impact scenario. The initial, maintenance, and repair costs of the various systems vary. Some devices satisfy all of the crash cushion testing requirements of NCHRP Report 230 and some do not. Some have generalized designs available depending on the system length, width, and energy dissipation requirements of the particular site. Some are narrow-hazard devices, while others shield wide hazards. Most systems require backup structures, and kinetic energy is dissipated in a wide variety of ways.

Some characteristics of the 13 impact attenuation devices are summarized in Table 16 and are discussed in more detail below.

Redirection Versus Trapping

Most of the crash cushions will redirect an errant vehicle under side impact conditions. Some have essentially no redirective capabilities. There are both philosophical and safety issues involved. Of course, this issue does not arise with respect to narrow-hazard crash cushions that shield such things as the ends of median and roadside longitudinal barriers. Such devices are typically no more than 6 m long and 610–914 mm wide. As such, they have almost no innate lateral stability or energy dissipation potential. Means must be devised, therefore, to redirect errant vehicles under side impact situations with these narrow devices. These means include cables, thrie beam, chain links, and other sorts of deflection-limiting devices. There are seven crash cushions in this narrow-hazard category.

- Guardrail Energy Absorbing Terminal (GREAT)
- Construction Zone GREAT (GREAT cz)
- Crash-Cushion Attenuating Terminal (CAT)
- Narrow Connecticut Impact Attenuation System (NCIAS)
- Low Maintenance Attenuator (LMA)
- Brakemaster
- Advanced Dynamic Impact Extension Module (ADIEM)-II.

The wide-hazard devices are the following:

- Sand-filled plastic barrels
- Hex-Foam Sandwich System
- Hi-Dro Sandwich System
- Hi-Dro Cell Cluster
- Connecticut Impact Attenuation System (CIAS)
- Generalized Connecticut Impact Attenuation System (GCIAS).

The Hex-Foam Sandwich System and the Hi-Dro Sandwich System both have essentially the same redirective capabilities. In fact, Hi-Dro Sandwich Systems are often converted to the less maintenance-intensive Hex-Foam Sandwich Systems with relative ease. The process involves the installation of steel diaphragms in the first two bays and other modifications needed to accept the hex-foam cartridges. Side impacts are deflected by means of a fender panel system. However, it should be noted that neither the Hex-Foam Sandwich System nor the Hi-Dro Sandwich System have passed NCHRP Report 230 Test 53. This test calls for a 97-km/h impact with a 2,041-kg automobile at the mid-length point of the crash cushion at an impact angle of 20 degrees with respect to the line of symmetry of the device.

The Hi-Dro Cell Cluster and sand-filled plastic barrel systems have essentially no redirective capabilities. This fact makes these devices more energy absorbent under side impact conditions than the narrow-hazard systems and the Hex-Foam Sandwich and Hi-Dro Sandwich Systems. However, care should be taken in the design and placement of these devices. An angled side impact near the rear of the sand-filled plastic barrel crash cushion, for example, could result in vehicle impalement on the corner of the rigid hazard. This is less of a problem with the Hi-Dro Cell Cluster, which is recommended for use only at locations with probable impact speeds of 72 km/h or less. Sand-filled plastic barrel crash cushions are the single most used impact attenuation device on the U.S. highway system. Their initial cost is low and no backup structure is required. There are many installations, however, in which the use of sand-filled plastic barrels is not appropriate. They should not be used at locations where a redirective capability is required under side impact conditions.

The CIAS and the GCIAS will trap an errant vehicle under most side impact conditions. If the impact region is so close to the back of the device that significant energy dissipation and acceptable deceleration response are unobtainable because of the proximity of the hazard, the CIAS will redirect the vehicle back into the traffic flow direction. This trapping/redirection capability is achieved through the diametrical bracing system contained in the cylinders near the rear of the device.

Gating Versus Non-Gating Devices

A non-gating crash cushion is one that can redirect vehicles along its entire length under side impact conditions. A gating crash cushion is designed to allow controlled penetration of a vehicle when hit upstream of what is called its length of need. The length of need of a crash cushion is that part of the device that is designed to contain or redirect an errant vehicle. As long as the appropriate location of the length of need has been established at a given

TABLE 16
CHARACTERISTICS OF IMPACT ATTENUATION DEVICES

Device	Redirective Under Side Impact	Gating Device	Satisfies Crash Cushion Testing Requirements of NCHRP Report 230	Narrow Hazard Device	Multiple System Configurations Available
Guardrail Energy Absorbing Terminal (GREAT)	yes	no	yes	yes	yes
Construction Zone GREAT (GREAT cz)	yes	no	yes	yes	yes
Crash-Cushion Attenuating Terminal (CAT)	yes	yes	yes	yes	no
Narrow Connecticut Impact Attenuation System (NCIAS)	yes	no	yes	yes	no
Low Maintenance Attenuator (LMA)	yes	no	yes	yes	no
Brakemaster	yes	no	yes	yes	no
ADIEM	yes	yes	yes	yes	no
Sand-Filled Plastic Barrels	no	yes	yes	no	yes
Hex-Foam Sandwich System	yes*	no	no**	no	yes
Hi-Dro Sandwich System	yes*	no	no**	no	yes
Hi-Dro Cell Cluster	no	yes	no	yes	yes
Connecticut Impact Attenuation System (CIAS)	***	no	yes	no	no
Generalized Connecticut Impact Attenuation System (GCIAS)	***	no	yes	no	yes

* Has not passed NCHRP Report 230 Test 53.
** Has not passed NCHRP Report 230 Test 53. This system was developed prior to the existence of NCHRP Report 230 and is considered by the Federal Highway Administration to be acceptable for use on federal-aid highway projects when requested by a state highway agency.
*** Will trap under most side impact conditions and redirect when impacted near rear of device.

location, a gating response is an acceptable one. However, care should be taken to ensure that a gating vehicle will not be subjected to a secondary impact or pose a danger to other traffic.

NCHRP Report 230 Test Requirements

The crash cushion test matrix for NCHRP Report 230 is given in Table 2. Four tests are required and most of the operational crash cushions discussed in this synthesis have passed all four tests. However, the Hex-Foam Sandwich System and the Hi-Dro Sandwich Systems have not passed Test 53, which calls for a side impact with a 2,041-kg vehicle at 20 degrees to the line of symmetry of the device. The Hi-Dro Cell Cluster is a low-speed impact attenuation device that is not intended for use in redirective applications. This system is not designed for 97-km/h impacts and has not been so tested. An overall crash cushion crash test results summary is contained in Table 17.

Multiple System Configurations

Seven of the 13 crash cushions have several different system configurations. A choice of system length, width, and energy dissipation capacity is available with the GREAT system, the GREAT cz, sand-filled plastic barrels, the Hex-Foam Sandwich System, the Hi-Dro Sandwich System, the Hi-Dro Cell Cluster, and the GCIAS.

Cost Considerations

All of the impact attenuation devices considered in this synthesis are cost-effective systems. There is a range, however, in the initial maintenance and refurbishment costs of these products. Some systems are sacrificial and must usually be replaced after a major impact; however, the initial costs of some of these devices are low. The CAT and the sand-filled plastic barrels are examples of

TABLE 17
SUMMARY OF CRASH TEST RESULTS

Device		NCHRP Report 230 Test Number	Vehicle Mass (kg)	Impact Speed (km/h)	Impact Angle (degrees)	Vehicle Impact Location	Vehicle Stopping Distance (m)	Occupant impact Velocity (m/s)		Occupant Ridedown Acceleration (peak 10 msec avg g's)		Occupant Ridedown Acceleration (peak 50 msec avg g's)	
								Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
GREAT (6-Bay)		50	1,955	98.8	0	nose	4.8	8.8	--	20	--	--	--
		52	904	104.6	0	nose	3.4	12.3	--	15.7	--	--	--
		54	1,955	98.8	12	nose	4.7	9.9	--	17.0	--	--	--
CAT		41	1,994	95.4	0.5	nose	--	6.9	--	16.3	5.4	8.8	1.8
		52	834	96.1	1	nose	--	10.9	1.4	20.6	0.6	15.9	1.3
		53	2,012	98.2	14.6	midlength	--	3.3	4.9	1.1	5.9	2.9	4.9
		54	2,025	103.9	12.8	nose	--	6.1	0.1	4.0	--	7.3	3.5
NCIAS		50	2,045	97.9	0	nose	6.2	8.9	--	15.6	--	--	--
		52	817	97.8	0	nose	4.4	9.0	--	13.5	--	--	--
		53	2,037	98.5	20	midlength	--	10.3	5.3	13.0	12.8	--	--
		54	2,041	96.7	15.5	0.5 m offset on nose	5.9	9.3	2.4	10.3	4.7	--	--
LMA		50	2,120	96.9	0	nose	--	8.8	0	13.3	0	--	--
		52	838	92.2	0	nose	--	10.7	2.2	15.2	1.3	--	--
		53	1,962	97.7	21	midlength	--	6.0	7.0	3.1	10.6	--	--
		54	1,950	100.1	12	nose	--	8.7	3.1	14.1	3.0	--	--
Brakemaster		50	2,000	100.7	0	nose	--	7.7	0.7	14.1	2.6	12.7	1.5
		52	820	97.7	0	nose	--	10.5	--	17.0	--	20.2	2.4
		53	1,962	93.6	20	midlength	--	7.3	4.4	12.4	10.5	7.0	6.9
		54	2,013	104.9	15	nose	--	8.0	2.2	11.4	1.7	9.3	2.1
ADIEM-II		45	816	94.3	0	15"" offset	3.0	11.4	2.7	10.6	1.6	--	--
		50	2,039	97.0	0	head on	--	9.1	NA	6.3	--	--	--
		53	2,041	96.8	21.2	midlength	--	5.5	7.9	7.5	12.8	8.1	15.9
		54	2,041	91.7	13	nose	6.2	8.9	1.4	7.0	1.9	9.2	1.4
Sand-	Fig. 13a	50	1,996	92.5	0	nose	9.4	6.2	--	13.8	--	7.9	--
Filled	Fig. 13b	50	1,951	94.3	0	nose	7.5	8.0	--	13.7	--	11.2	--
Plastic	Fig. 13b	50	1,954	94.6	0	nose	7.2	7.5	--	15.4	--	11.2	--
Barrels	Fig. 13b	50	1,956	97.5	0	nose	7.3	8.1	--	10.7	--	5.1	--
	Fig. 13b	52	818	96.7	0	nose	5.9	8.9	--	10.2	--	--	--
	Fig. 13b	52	819	93.3	0	nose	6.7	8.2	--	18.4	--	10.1	--
	Fig. 13b	--	818	95.6	14.9	corner of gore	3.5	11.6	2.4	19.2	0.9	--	--
	Fig. 13b	--	826	96.5	15	corner of gore	3.5	11.4	1.0	18.5	3.2	--	--

TABLE 17
SUMMARY OF CRASH TEST RESULTS (*Continued*)

Device		NCHRP Report 230 Test Number	Vehicle Mass (kg)	Impact Speed (km/h)	Impact Angle (degrees)	Vehicle Impact Location	Vehicle Stopping Distance (m)	Occupant impact Velocity (m/s)		Occupant Ridedown Acceleration (peak 10 msec avg g's)		Occupant Ridedown Acceleration (peak 50 msec avg g's)	
								Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
Hex-Foam		50	2,026	95.4	0	nose	5.0	8.1	2.0	16.0	5.3	--	--
		52	898	104.8	0	nose	3.9	11.1	2.7	15.2	2.6	--	--
		54	2,130	100.1	12	nose	4.7	8.8	2.7	19.1	9.8	--	--
		54	1,960	97.0	14	nose	4.6	9.0	--	13.6	--	--	--
CIAS		50	2,039	98.8	0	nose	7.0	7.8	1.4	12.6	0.9	10.4	--
		50	2,039	99.1	0	nose	6.7	8.1	--	12.8	--	9.4	--
		52	816	97.9	0	nose	4.9	10.6	--	12.8	--	11.6	--
		53*	2,039	93.3	15	corner of test hazard	--	9.8	4.4	9.6	11.6	9.5	--
		54	2,039	97.2	20	along side	5.5	8.4	3.5	20.6	1.5	13.3	--
GCIAS	Fig. 25a*	50	2,132	96.9	0	nose	7.2	6.2	0.4	8.6	1.7	6.9	1.9
	Fig. 25a	52	828	103.0	0	nose	5.6	10.5	--	16.1	--	11.3	1.2
	Fig. 25b	53	2,039	103.9	15	corner of test hazard	--	--	--	--	--	--	--
	Fig. 25b	54	2,039	98.9	15	nose	10.4	7.0	3.4	7.6	6.3	5.6	3.3
	Fig. 25c	50	2,048	76.7	0	nose	4.1	7.4	1.2	16.9	0.3	15.5	1.4
	Fig. 25c	52	812	72.6	0	nose	3.2	8.1	--	11.2	--	10.3	1.0

* This GCIAS configuration differed slightly from the system shown in Figure 25a (See *20*).

devices in this category. Other impact attenuation devices have high initial costs but can be rapidly refurbished on site after an impact. The LMA, for example, has a high purchase price but can be used over and over again without replacing its energy-dissipating components. This crash cushion might be a good choice at an installation that is expected to be hit frequently. Systems with low initial costs might not lend themselves to rapid, on-site refurbishment and would be better suited for use at locations where the anticipated frequency of impacts is low.

All of the crash cushions considered in this synthesis have been crash tested on level terrain. Therefore, it is important that field installations be designed to closely approximate flat terrain.

CHAPTER FIVE

OPERATIONAL EXPERIENCE OF DESIGNS

Some of the 13 impact attenuation devices considered in this Synthesis have been in widespread use for many years (*21*). Examples of systems that have developed an extensive operational record include sand-filled plastic barrels, the GREAT system, and the Hi-Dro Cell Sandwich System. Many of the devices are relatively new and have not been widely installed.

To systematically obtain data on the performance and operational experience of permanent and temporary impact attenuation devices, a survey document was developed and sent to every U.S. state department of transportation, selected highway officials from Canadian provinces, and designated representatives from the International Bridge, Tunnel and Turnpike Association.

The six-page survey document is presented in Appendix B, and a detailed summary of the individual responses to the questions is presented in Appendix C. A synthesis of the survey results follows.

Survey Synthesis

The first survey item identified the responding agency. A total of 72 survey questionnaires were sent out and 51 responses were obtained—a 71 percent response rate.

Question number two asked for the number of permanent and temporary crash cushions/terminals in use under the agency jurisdiction in 1980, 1985, 1992, and 1995 (projected). The raw data totals for these 4-year periods are 4,644, 7,912, 15,776, and 17,587. Some responses did not provide this information, so these numbers are certainly lower bounds on the actual numbers of impact attenuation systems in use. It is of interest to note, however, that the figures suggest a doubling of the number of these safety devices between 1985 and 1992.

Agencies were asked to identify the different crash cushion/terminal devices in use under their jurisdiction, along with the approximate number of each type and their recent average purchase price. The crash cushions most used were the sand-filled plastic barrels. Approximately 4,000 of these installations were reported. Other very popular devices included the GREAT system (1,877 installations), the CAT (850 units), the Hex-Foam Sandwich System (412 units), and the Hi-Dro Sandwich System/Hi-Dro Cell Cluster devices (826 units).

Non-collision maintenance experience for each crash cushion used revealed some problems that were common to virtually all devices:

- Snow accumulation/drifting
- Vandalism
- Trash accumulation
- Debris, weeds, and mower damage
- Training
- Stocking parts
- Exposure of repair crews
- Obtaining replacement parts.

Device-specific, non-collision maintenance problems are summarized below.

The GREAT system usually required less than one person-hour per month for non-collision maintenance. Maintenance problems for this system included the following:

- Complicated and time-consuming to repair;
- Modules deteriorate and replacement parts are expensive;
- Nose needs to be replaced frequently; and
- Non-galvanized hardware rusts up and is hard to replace.

The CAT generally required less than one person-hour per month for non-collision maintenance. Typical maintenance work included the following:

- Replacing end delineation (sheeting),
- Cleaning and inspecting bolts and connections, and
- Checking anchorage.

The sand-filled plastic barrels, like the GREAT system and the CAT, also usually required less than one person-hour per month. Typical maintenance problems with the system included the following:

- Replacing sand because of containers made of deteriorating foam and brittle plastic, sand solidifying or freezing due to moisture (use 3:1 sand/salt filler), and lids not staying closed on units;
- Colors fading out of barrels resulting in poor appearance;
- The need for a large amount of space for setup because of the size of the array;
- Difficulty in installing correct amounts of sand and maintaining integrity of complete array;
- Vibrations causing individual units within a set to move out of place;
- Seams splitting and barrels cracking because of use and aging;
- Nuisance hits requiring clean-up and replacement parts; and
- Accumulation of debris and damage to barrels from mowing.

The Hi-Dro Sandwich System/Hi-Dro Cell Cluster devices apparently required more non-collision maintenance than most other systems, with many agencies reporting the need to spend more than one person-hour per month. Maintenance problems included the following:

- Replenishing antifreeze;
- Straightening devices when pushed out of alignment in toll lanes;
- Checking water level in tubes;

- Maintaining fluid at an acceptable level and replacing tubes that separate from caps;
- Replacing delineation and cables;
- Keeping area clean between cells and repairing side plates;
- Repairing units that are periodically scraped or damaged by the wind;
- Removing deicing debris from around the units;
- Replacing cartridge in icing condition;
- Keeping track of unit deforming and water cell deteriorating with age;
- Checking of wooden parts that deteriorate and weaken the system;
- Repairing old water-filled systems that leak;
- Conducting maintenance too often; and
- Replacing units about every 15 years because of poor aging.

Information on the non-collision life spans for the remaining impact attenuation devices was sparse and is included in the miscellaneous category of the question number four summary in Appendix C.

Some information was reported on the types of training agency personnel received related to the construction, maintenance, purpose, and performance of impact attenuation devices. Some training was provided in almost all cases, often by the manufacturer of the device. Training sometimes included training manuals and videos; however, a number of agencies reported only word of mouth training.

Most agencies reported that actual collision experience with impact attenuation devices was not available. Those few that did respond to this important question reported generally good collision performance and very few fatalities in impacts with these safety devices.

Operational problems with the various highway safety devices centered on the following six systems:

- GREAT
- CAT
- Sand-filled plastic barrels
- Hex-Foam Sandwich System
- Hi-Dro Sandwich System
- Hi-Dro Cell Cluster.

Operational problems encountered with the GREAT system included the following:

- Insufficient space available for the device sometimes, causing more frequent hits due to exposure;
- Exposure of repair crews to traffic as systems are located in the typically narrower gore and median areas;
- Possibility of side impacts causing extensive damage;
- Difficult to repair for low-damage hits;
- Installation in fast-paced work zone taking too long; and
- Long time needed to repair after low-speed, minor hits.

With regard to problems on operations of the CAT device, the following was reported. The CAT as a median pier (MP) terminal, with a transition section, is an option in wide-median locations. It is more expensive and difficult to install and repair. Its minor advantage—redirection during an approach to the left side of a median pier corner—does not override its unpredictability in many other accident scenarios. Among the maintenance or construction crews interviewed, no one prefered this unit to the barrel array.

Chronically wet conditions in the MP locations create problems, and more wet wood post problems are expected in the future—beyond that of removing frozen-in-place post stubs in the winter. One double fatality involving an MP CAT and a small car was reported.

The CAT as a shoulder terminal has well-drained shoulders to avoid the wet post problems cited for the MP CAT. However, reshaping the tops of the steel foundation tubes to enable removal of broken post stubs requires extensive labor. Tube damage is often caused by underbodies or wheels of cars—especially those that slide sideways into outside shoulder CATs. One double fatality involving an outside shoulder CAT and a large car was reported.

Major, repeated, and numerous installation errors on Sentre and CAT terminals inspired one state to require training and certification of all prospective installers. Other operational problems reported included the following:

- Minor impacts can cause extensive work for maintenance to make repairs,
- The device is difficult to repair in-place, and
- Minor impacts can be costly in replacement parts and staff hours.

The sand-filled plastic barrels elicited the following comments relating to operational problems:

- There was debris scatter (i.e., sand, plastic parts, and pieces of various sizes);
- When hit, barrels of any manufacture required special equipment to remove sand from the roadway (also a safety problem); and
- Some agencies found they could not expect to have these arrays properly placed and filled in repair.

Some respondents also mentioned the laborious process of shoveling spilled fill material following accidents and indicated a preference for repairing the simpler GREAT units in their suitable locations. Problems with regard to this included the following:

- Having to fill barrels by hand;
- Experiencing difficulty under field conditions filling barrels with exactly the correct weight of sand, which appears to be critical; and
- Having difficulty providing a safe work area while replacing damaged sand drum attenuators.

The Hex-Foam Sandwich System had only a few operational problems reported, such as the following:

- Side impacts can cause extensive damage;
- Bolts, when struck, can get stuck in cartridges, making them difficult to remove;
- The system is complicated and time consuming to repair; and
- Extensive replacement parts are required.

Operational difficulties associated with the Hi-Dro Sandwich/Hi-Dro Cell Cluster systems included the following:

- Antifreeze is used, which may be considered a hazardous material when released.
- The systems are complicated and time consuming to repair and require expensive replacement parts.
- Restoring devices expose maintenance workers to high-speed traffic for 4 to 8 hours.
- Wet pavement requires sanding.
- Secondary accidents due to wet pavement occur after impacts.
- Minor hits require major repair effort if diaphragms break.
- After a hit, the device does not pull back to its original shape when being repaired.

The responding agencies were invited to state their reasons for preferring one type of safety device over another. A summary of agency comments on the various safety devices follows.

Those agencies that reported a preference for the GREAT system provided a variety of reasons: it requires little maintenance and is easy to repair with readily available parts that are reusable, costs less overall, and functions well in a variety of different situations. With regard to design, the GREAT system was preferred because it affords enhanced safety for motoring public, relatively short installed length, redirective ability, longevity of components, aesthetic appearance, and relatively simple construction. Also, the system's relatively narrow width allows use at locations where roadway width is a problem.

Advantages of the Hex-Foam Sandwich System as reported by several agencies include that it seems to collapse better than the GREAT system when hit indirectly. Also, the Hex-Foam units require less maintenance than Hi-Dro units and are compact and quick to reposition and refurbish. More importantly, there is no spillage of toxic material. One agency reported that by using primarily Hex-Foam units, its maintenance personnel could become proficient in maintaining units and the department could limit the number of spare parts required to maintain the units.

With regard to the Hi-Dro Sandwich System, one agency reported that the Hi-Dro Cell Clusters are ideal for toll lanes because they can be put back in service immediately after an impact, and no loose materials are scattered to cause a hazard to employees or the public. It was also reported that the system is easier, cheaper, and quicker to repair after a collision compared to the CAT.

Repair crews prefer the sand-filled plastic barrels because they require less maintenance, are easier to repair and/or replace, and have fewer parts compared to the GREAT, Hex-Foam Sandwich, and CAT systems, all of which have numerous parts. If devices are impacted head-on, they can be repaired more quickly and function better. However, most impacts are not head-on and require several replacement parts. Parts for the sand barrels are also more readily available and simplified assembly requires smaller crews and less equipment; therefore, the modules are easier and less costly to maintain. Sand barrels are also interchangeable and movable. It was reported that one type of sand barrel, the Energite Module Inertial made by Energy Absorption Systems, (see Chapter 3) can be relocated successfully and is good for temporary use. However, because the sand barrels do not meet the latest performance guidelines, the Hex-Foam and water-filled sandwich systems, GREAT, CIAS and NCIAS, and CAT Guiderail Terminals are preferred from a safety standpoint, with CIAS and NCIAS being the most cost-effective crash cushions, and CAT being the most cost-effective guardrail terminal.

Other general comments on the various crash cushions reported by agencies include the following. One agency reported that existing water tube crash cushions require a lot of time and effort to repair following a collision. Therefore, other types of crash cushions are preferred and water tube crash cushions are no longer purchased. Beyond that, choice depends mainly on site conditions and geometry.

Another agency noted that cartridge units (i.e., GREAT and Hex-Foam Sandwich System) provide potential for a broader range of vehicle weights from 1,600 to 5,400 lb (726 to 2,449 kg). They also are restored quickly, resulting in reduced exposure for maintenance personnel.

Of the terminals mentioned by agencies, the CAT, Sentre, and TREND have unique parts and are more complex to repair. One system mentioned, the ET-2000, was reported to be very simple and uses mostly standard guardrail components. This system was put into service in 1992, but little information is available to evaluate its performance and repair aspects.

Devices using sand or cartridges are preferred by one agency over devices such as the Hi-Dro Cell Cluster because devices of these types require less maintenance. In addition, sand eliminates the possibility of an unwanted or hazardous reaction during accidents involving chemicals.

Although location dictates type of cushion, some agencies are trying to maintain uniformity so that maintenance personnel do not have to learn numerous cushion types. Most agencies require contractors to use temporary safety devices. Most of these contractors purchase or lease their own devices.

Agencies were asked if temporary crash cushions were typically included in traffic control plans. Most agencies answered in the affirmative, but a significant number include such devices only occasionally.

In summary, the most used type of crash cushion is the sand-filled plastic barrels array. This inertial device has been available since the 1970s, requires no backup structure, and has a low initial cost. It has no redirectional capability, however, and should not be used in locations where the redirection of errant vehicles is required. The five other most popular systems are the GREAT, the CAT, the Hex-Foam Sandwich System, and the Hi-Dro Cell Sandwich or Hi-Dro Cell Cluster Systems. Most of the remaining devices were developed within the last 10 years and have not established a significant track record.

Finally, although there are operational problems associated with the six most used systems (and indeed all 13 devices), these impact attenuation devices are cost-effective systems. When an appropriate device for a specific application is properly installed and maintained, lives are saved and injuries reduced. Regularly scheduled training sessions are necessary for all personnel engaged in constructing, maintaining, and repairing crash cushions and other highway safety devices. One example of how crash cushions save lives in a cost-effective manner is provided in the 20 years of records on crash cushion accidents kept by the Wisconsin Division of FHWA. These records show that there were 1,083 accidents involving crash cushions between 1972 and 1991. In these 1,083 events, there were few injuries and no fatalities. The report concludes that "more than 244 people would have been seriously injured or killed if impact attenuators had not been installed (*22*)."

CHAPTER SIX

FUTURE TRENDS

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 crash testing guidelines. In fact, the guidelines of NCHRP Report 350 with respect to crash cushions are significantly more demanding than those of NCHRP Report 230.

One important aid to the development of more efficient, cost-effective impact attenuation devices of the near future will be the availability of powerful vehicle impact/crash simulation computer codes. The state of the art in computer hardware and software development has evolved to the point where powerful, versatile, user-friendly vehicle impact/handling simulation codes are being produced. The availability of such computer simulation tools will enable design engineers and researchers to develop safer roadways and more effective roadside safety features. Current full-scale crash testing of safety appurtenances such as longitudinal barriers, crash cushions, terminals, and luminaire supports are almost entirely limited to a few impact scenarios involving tracking vehicles. Most actual accidents bear little resemblance to these idealized crash test conditions. However, the significant expense associated with full-scale testing (some of which will always be necessary), coupled with the practical limitations of crash testing technology, combine to limit the number and variety of impact scenarios to be tested. An improved capability to accurately simulate vehicular dynamic responses and impacts with roadside features will result in more cost-effective roadway designs and roadside safety features. It will also permit a reduction in the number and expense of full-scale crash tests needed to develop new hardware. Most importantly, lives will be saved, as a better understanding of hardware performance will improve hardware designs.

Future crash cushion development efforts will lead to impact attenuation devices that are more cost effective. With few exceptions, current highway safety appurtenances have significant maintenance costs. Following a vehicular impact, the energy-dissipating material and other system components often must be discarded and replaced. Furthermore, because of this cost and the fact that the staff of transportation agencies are usually spread rather thin, impacted safety devices sometimes remain unrefurbished for long periods. This unsafe situation represents a danger to the motoring public and an increased liability exposure to the managing transportation entity involved.

The root of the problem lies in the sacrificial nature of the energy-dissipating media used in current impact attenuation devices. It might be feasible to develop inexpensive systems to dissipate large amounts of kinetic energy, undergo large deformations and strains without fracturing, and, 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 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 the motoring public and the maintenance personnel involved in maintaining and repairing damaged hardware would be greatly enhanced.

The intelligent use of energy dissipation systems has saved many lives and reduced injuries and human suffering for more than 25 years. Highway related deaths and injuries are a major, worldwide health problem. In both absolute terms and in relation to the occurrence of other injuries and diseases, the opportunities for highway injury reductions are numerous. Given the size of the problem, it is clear that attention should be directed towards its alleviation. Investment in the development of improved impact attenuation devices is an investment in cost-effective injury prevention. These systems will protect all elements of the driving population—the high risk groups (intoxicated, elderly, teenage drivers) as well as everyone else.

To be effective, however, crash cushions 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 test videos are helpful in these sessions. Crash cushions are sophisticated devices. If maintenance crews understand not only how but also why system components are constructed in a particular way, dangerous mistakes like filling sand barrels with concrete will be avoided.

Finally, there is an urgent need for increased in-service evaluations of crash cushions and all other 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. Useful goals and procedures for the in-service evaluation of new or extensively modified highway safety features are contained in AASHTO's *Roadside Design Guide* (*2*).

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APPENDIX A

CRASH TEST REQUIREMENTS OF NCHRP REPORT 350

TABLE A-1
NCHRP REPORT 350 TEST MATRIX FOR TERMINALS AND CRASH CUSHIONS (*6*)

Test Level	Feature	Feature Type[d]	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[g] (See Table 5.1)
				Vehicle	Nominal Speed (km/h)	Nominal Angle, θ (deg)		
1	Terminals and Redirective Crash Cushions	G/NG	1-30	820C	50	0	(b,e)	C,D,G,H,I,(J),K,N
		G/NG	S1-30[a]	700C	50	0	(b,e)	C,D,G,H,I,(J),K,N
		G/NG	1-31	2000P	50	0	(b)	C,D,G,H,I,(J),K,N
		GO/NG	1-32	820C	50	15	(b)	C,D,G,H,I,(J),K,N
		GO/NG	S1-32[a]	700C	50	15	(b)	C,D,G,H,I,(J),K,N
		GO/NG	1-33	2000P	50	15	(b)	C,D,G,H,I,(J),K,N
		G	1-34	820C	50	15	(b,e)	C,D,G,H,I,(J),K,N
		G	S1-34[a]	700C	50	15	(b,e)	C,D,G,H,I,(J),K,N
		G	1-35	2000P	50	20	(b)	A,D,G,L,M
		NG	1-36	820C	50	15	(b)	A,D,G,H,I,(J),M
		NG	S1-36[a]	700C	50	15	(b)	A,D,G,H,I,(J),M
		NG	1-37	2000P	50	20	(b)	A,D,G,L,M
		NG	1-38	2000P	50	20	(b)	A,D,G,L,M
		G/NG	1-39	2000P	50	20	(b)	C,D,G,K,L,M,N
	Nonredirective Crash Cushions[f]	G	1-40	820C	50	0	(e,h)	C,D,G,H,I,(J),K
		G	S1-40[a]	700C	50	0	(e,h)	C,D,G,H,I,(J),K
		G	1-41	2000P	50	0	(h)	C,D,G,H,I,(J),K
		G	1-42	820C	50	15	(h)	C,D,G,H,I,(J),K,N
		G	S1-42[a]	700C	50	15	(h)	C,D,G,H,I,(J),K,N
		G	1-43	2000P	50	15	(h)	C,D,G,H,I,(J),K,N
		G	1-44	2000P	50	20	(h)	C,D,G,K,L

[a] Test is optional. See Section 3.1.
[b] See Figure 3.2 for impact point.
[c] See Section 3.3.3 for tolerances on impact conditions.
[d] G/NG - Test applicable to gating and nongating devices.
GO/NG - Test optional for gating device (see discussion in Section 3.2.2.2) but applicable to nongating device.
G - Test applicable to gating device only.
NG - Test applicable to nongating device only.
[e] See discussion in Section 3.2.2.2.
[f] See discussion in Section 3.2.2.1 relative to nonredirective crash cushions.
[g] Criteria in parenthesis are optional.
[h] See Figure 3.3 for impact point.

TABLE A-1 (*Continued*)

Test Level	Feature	Feature Type[d]	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[g] (See Table 5.1)
				Vehicle	Nominal Speed (km/h)	Nominal Angle, θ (deg)		
2	Terminals and Redirective Crash Cushions	G/NG	2-30	820C	70	0	(b,e)	C,D,F,H,I,(J),K,N
		G/NG	S2-30[a]	700C	70	0	(b,e)	C,D,F,H,I,(J),K,N
		G/NG	2-31	2000P	70	0	(b)	C,D,F,H,I,(J),K,N
		GO/NG	2-32	820C	70	15	(b)	C,D,F,H,I,(J),K,N
		GO/NG	S2-32[a]	700C	70	15	(b)	C,D,F,H,I,(J),K,N
		GO/NG	2-33	2000P	70	15	(b)	C,D,F,H,I,(J),K,N
		G	2-34	820C	70	15	(b,e)	C,D,F,H,I,(J),K,N
		G	S2-34[a]	700C	70	15	(b,e)	C,D,F,H,I,(J),K,N
		G	2-35	2000P	70	20	(b)	A,D,F,L,M
		NG	2-36	820C	70	15	(b)	A,D,F,H,I,(J),M
		NG	S2-36[a]	700C	70	15	(b)	A,D,F,H,I,(J),M
		NG	2-37	2000P	70	20	(b)	A,D,F,L,M
		NG	2-38	2000P	70	20	(b)	A,D,F,L,M
		G/NG	2-39	2000P	70	20	(b)	C,D,F,K,L,M,N
	Nonredirective Crash Cushions[f]	G	2-40	820C	70	0	(e,h)	C,D,F,H,I,(J),K
		G	S2-40[a]	700C	70	0	(e,h)	C,D,F,H,I,(J),K
		G	2-41	2000P	70	0	(h)	C,D,F,H,I,(J),K
		G	2-42	820C	70	15	(h)	C,D,F,H,I,(J),K,N
		G	S2-42[a]	700C	70	15	(h)	C,D,F,H,I,(J),K,N
		G	2-43	2000P	70	15	(h)	C,D,F,H,I,(J),K,N
		G	2-44	2000P	70	20	(h)	C,D,F,K,L

[a] Test is optional. See Section 3.1.
[b] See Figure 3.2 for impact point.
[c] See Section 3.3.3 for tolerances on impact conditions.
[d] G/NG - Test applicable to gating and nongating devices.
GO/NG - Test optional for gating device (see discussion in Section 3.2.2.2) but applicable to nongating device.
G - Test applicable to gating device only.
NG - Test applicable to nongating device only.
[e] See discussion in Section 3.2.2.2.
[f] See discussion in Section 3.2.2.1 relative to nonredirective crash cushions.
[g] Criteria in parenthesis are optional.
[h] See Figure 3.3 for impact point.

TABLE A-1 (*Continued*)

Test Level	Feature	Feature Type[d]	Test Designation	Impact Conditions[c]			Impact Point	Evaluation Criteria[g] (See Table 5.1)
				Vehicle	Nominal Speed (km/h)	Nominal Angle, θ (deg)		
3	Terminals and Redirective Crash Cushions	G/NG	3-30	820C	100	0	(b,e)	C,D,F,H,I,(J),K,N
		G/NG	S3-30[a]	700C	100	0	(b,e)	C,D,F,H,I,(J),K,N
		G/NG	3-31	2000P	100	0	(b)	C,D,F,H,I,(J),K,N
		GO/NG	3-32	820C	100	15	(b)	C,D,F,H,I,(J),K,N
		GO/NG	S3-32[a]	700C	100	15	(b)	C,D,F,H,I,(J),K,N
		GO/NG	3-33	2000P	100	15	(b)	C,D,F,H,I,(J),K,N
		G	3-34	820C	100	15	(b,e)	C,D,F,H,I,(J),K,N
		G	S3-34[a]	700C	100	15	(b,e)	C,D,F,H,I,(J),K,N
		G	3-35	2000P	100	20	(b)	A,D,F,L,M
		NG	3-36	820C	100	15	(b)	A,D,F,H,I,(J),M
		NG	S3-36[a]	700C	100	15	(b)	A,D,F,H,I,(J),M
		NG	3-37	2000P	100	20	(b)	A,D,F,L,M
		NG	3-38	2000P	100	20	(b)	A,D,F,L,M
		G/NG	3-39	2000P	100	20	(b)	C,D,F,K,L,M,N
	Nonredirective Crash Cushions[f]	G	3-40	820C	100	0	(e,h)	C,D,F,H,I,(J),K
		G	S3-40[a]	700C	100	0	(e,h)	C,D,F,H,I,(J),K
		G	3-41	2000P	100	0	(h)	C,D,F,H,I,(J),K
		G	3-42	820C	100	15	(h)	C,D,F,H,I,(J),K,N
		G	S3-42[a]	700C	100	15	(h)	C,D,F,H,I,(J),K,N
		G	3-43	2000P	100	15	(h)	C,D,F,H,I,(J),K,N
		G	3-44	2000P	100	20	(h)	C,D,F,K,L

[a] Test is optional. See Section 3.1.
[b] See Figure 3.2 for impact point.
[c] See Section 3.3.3 for tolerances on impact conditions.
[d] G/NG - Test applicable to gating and nongating devices.
GO/NG - Test optional for gating device (see discussion in Section 3.2.2.2) but applicable to nongating device.
G - Test applicable to gating device only.
NG - Test applicable to nongating device only.
[e] See discussion in Section 3.2.2.2.
[f] See discussion in Section 3.2.2.1 relative to nonredirective crash cushions.
[g] Criteria in paranthesis are optional.
[h] See Figure 3.3 for impact point.

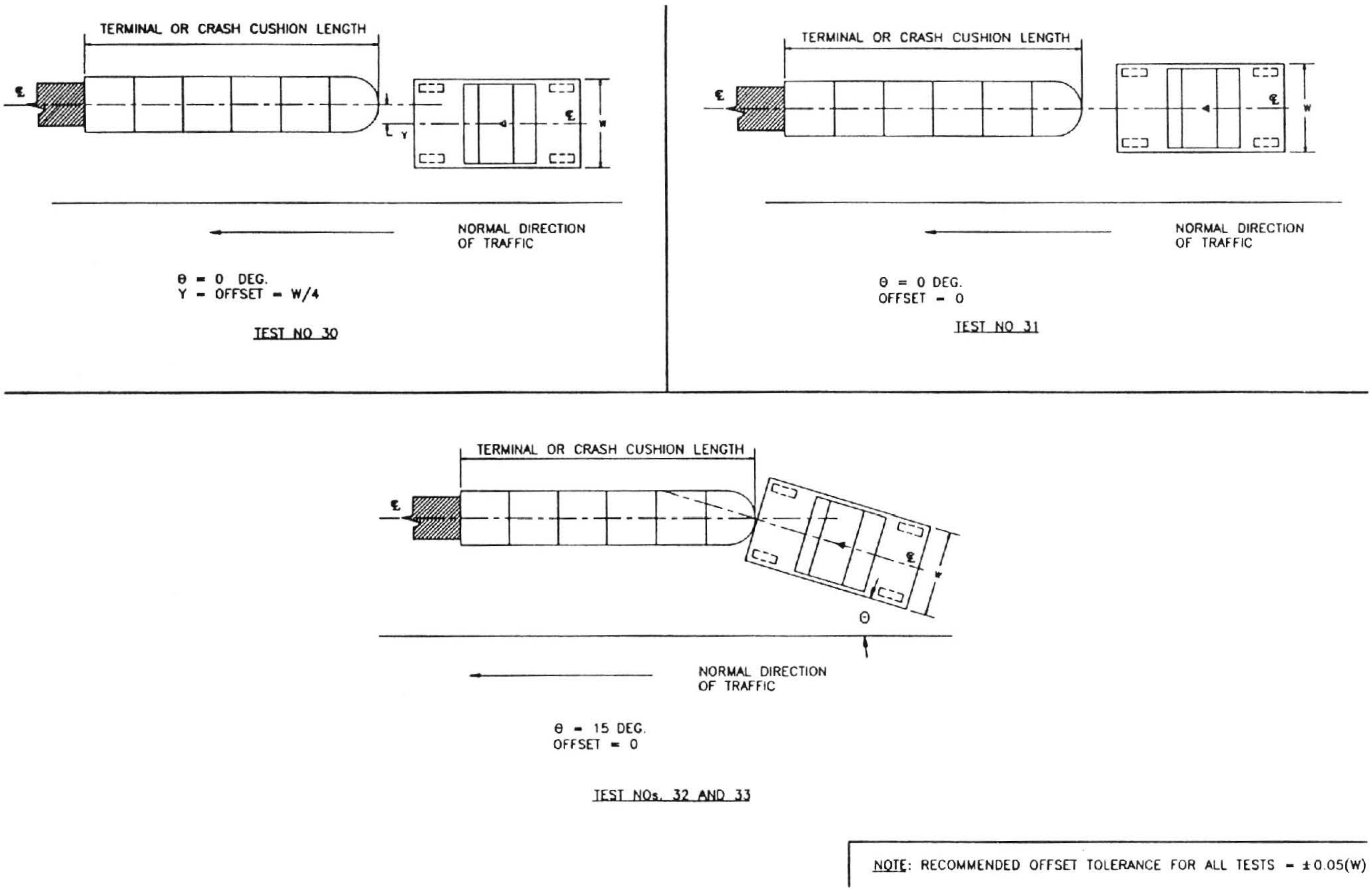

Figure A-1 Impact conditions for terminal and redirective crash cushion tests (*6*).

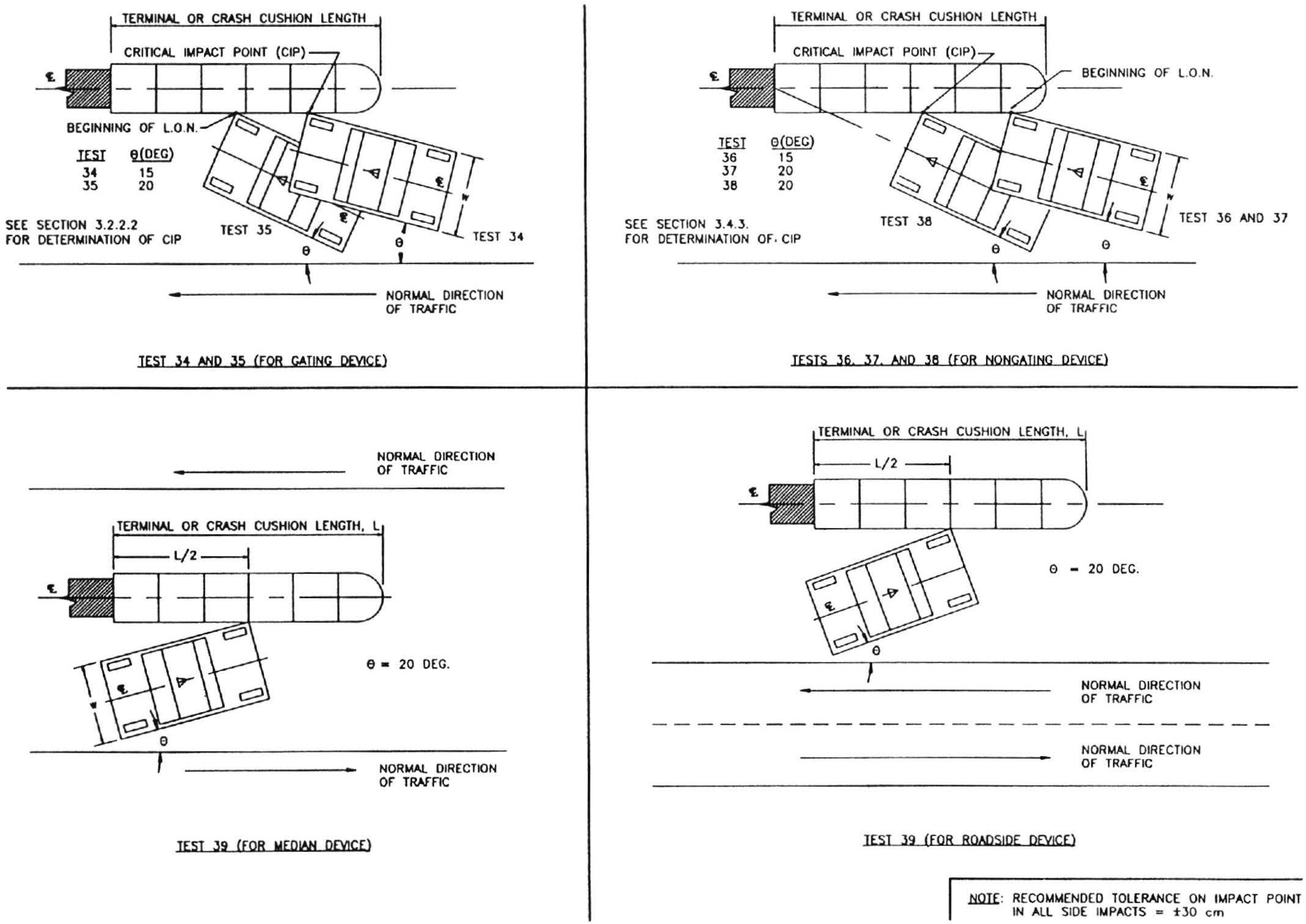

Figure A-1 Impact conditions for terminal and redirective crash cushion tests (*6*).

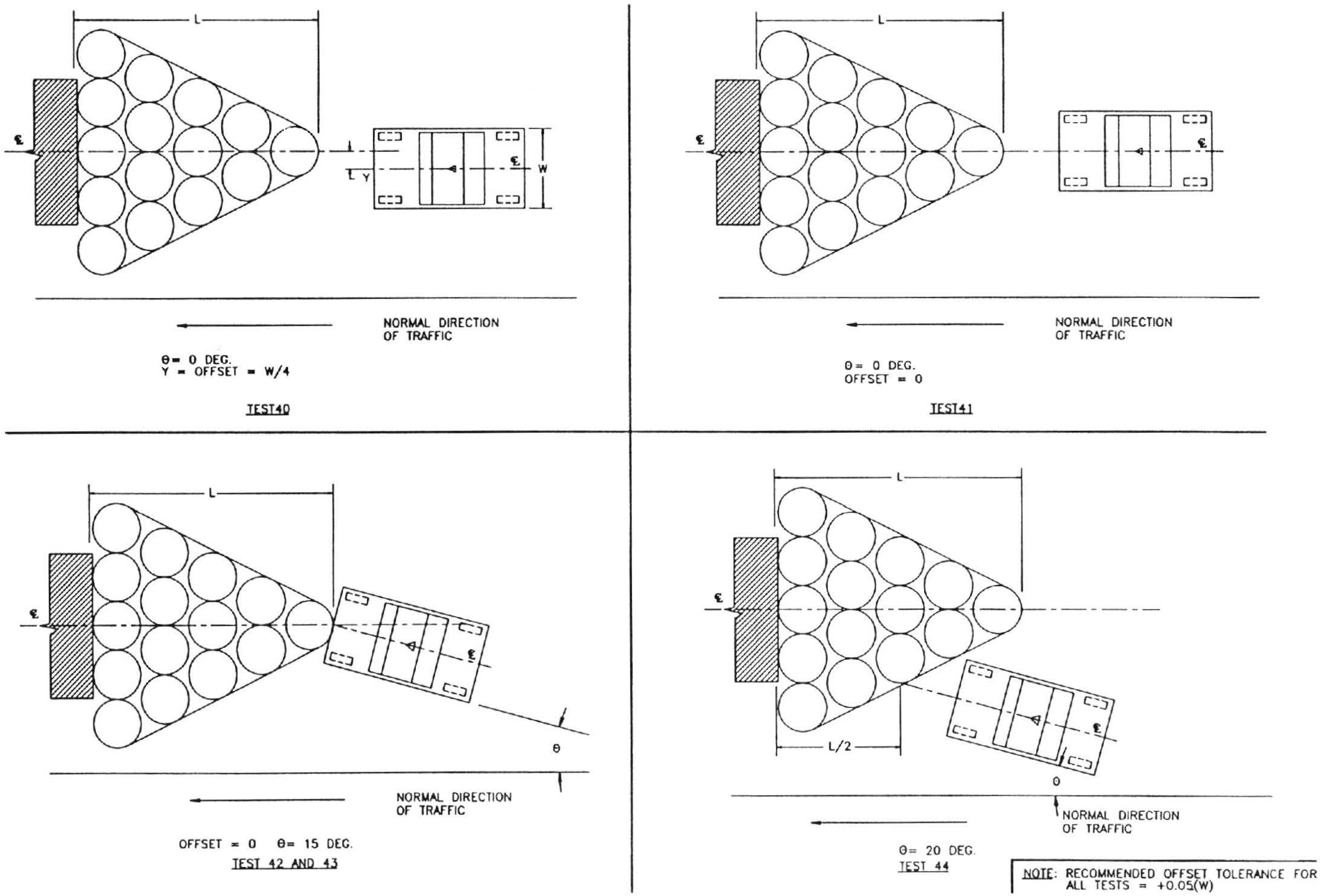

Figure A-2 NCHRP Report 350 impact conditions for nonredirective crash cushion tests (*6*).

TABLE A-2
SAFETY EVALUATION GUIDELINES (after *6*)

Evaluation Factors		Evaluation Criteria	Applicable Tests[a]
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral defection of the test article is acceptable.	10, 11, 12, 20, 21, 22, 35, 36, 37, 38
	B.	The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.	60, 61, 70, 71, 80, 81
	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	30, 31, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53
Occupant Risk	D.	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted. See discussion in Section 5.3 and Appendix E.	All
	E.	Detached elements, fragments, or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	70, 71
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	All except those listed in Criterion G.
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	12, 22, 30[b], 31[b], 32[b], 33[b], 34[b], 35[b], 36[b], 37[b], 38[b], 39[b], 40[b], 41[b], 42[b], 43[b], 44[b]
	H.	Occupant impact velocities (see Appendix A, Section A5.3 for calculation procedure) should satisfy the following:	

Occupant Impact Velocity Limits (m/s)

Component	Preferred	Maximum	Applicable Tests[a]
Longitudinal and Lateral	9	12	10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81
Longitudinal	3	5	60, 61, 70, 71

Evaluation Factors		Evaluation Criteria	Applicable Tests[a]
	I.	Occupant ridedown accelerations (see Appendix A, Section A5.3 for calculation procedure) should satisfy the following:	

Occupant Ridedown Acceleration Limits (G's)

Component	Preferred	Maximum	Applicable Tests[a]
Longitudinal and Lateral	15	20	10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81

Evaluation Factors		Evaluation Criteria	Applicable Tests[a]
	J.	(Optional) Hybrid III dummy. Response should conform to evaluation criteria of Part 571.208, Title 49 of Code of Federal Regulation, Chapter V (10-1-88 Edition). See Section 5.3 for limitations of Hybrid III dummy.	10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	All
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction (see Appendix A, Section A5.3 for calculation procedure) should not exceed 20 G's.	11, 21, 35, 37, 38, 39
	M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39
	N.	Vehicle trajectory behind the test article is acceptable	30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81

[a]Test numbers refer to last two digits in Test Designation for each Test Level unless otherwise noted.
[b]For Test Level 1 only.

APPENDIX B

SURVEY QUESTIONNAIRE

Performance and Operational Experience of
Permanent and Temporary Crash Cushions

SURVEY OF CRASH CUSHION / TERMINAL
TECHNOLOGY FOR NCHRP SYNTHESIS

1. General Information:

   (a) Agency ______________________

   (b) Responder ______________________

   Title ______________________

   (c) Phone No. ______________________

   Address ______________________

   ____

   ____

   ____

2. Number of Crash Cushions/Terminals (both permanent and temporary) in Use:

   (a) 1980 __________

   (b) 1985 __________

   (c) Current (1992) __________

   (d) 1995 (projected) __________

3. Crash Cushion (permanent or temporary) or Terminal: Approx. No. in Use:

Type A

   (a) Manufacturer ______________________

   (b) Model No. ______________________

   (c) Average unit purchase cost (latest) __________ __________

Type B

   (a) Manufacturer ______________________

   (b) Model No. ______________________

   (c) Average unit purchase cost (latest) __________ __________

Type C

   (a) Manufacturer ______________________

   (b) Model No. ______________________

   (c) Average unit purchase cost (latest) __________ __________

Type D

   (a) Manufacturer ______________________

   (b) Model No. ______________________

   (c) Average unit purchase cost (latest) __________ __________

Type E

   (a) Manufacturer ______________________

   (b) Model No. ______________________

   (c) Average unit purchase cost (latest) __________ __________

4. Crash Cushion/Terminal Maintenance Experience (non-collision):

Person hours required per unit (check one)	Type A (a)	Type B (b)	Type C (c)	Type D (d)	Type E (e)
More than 1 person-hr/week					
Less than 1 person-hr/week, but more than 1 person-hr/month					
Less than 1 person-hr/month					

Typical maintenance problems:

Type A

Type B

Type C

Type D

Type E

Estimate of non-collision life of device in years	Type A (a)	Type B (b)	Type C (c)	Type D (d)	Type E (e)

5. Delineation — describe standards for painting, targeting, and lighting devices:

6. Training for Agency Personnel: (check one or more)

(a) Instructional ☐

(b) Training Manual ☐

(c) Video ☐

(d) Word of mouth ☐

(e) Training provided in house ☐

(f) Training provided by manufacturer ☐

7. Collision Experience

Reported incidents, number	Type A (a)	Type B (b)	Type C (c)	Type D (d)	Type E (e)
Vehicle less than 4500 lb					
Vehicle more than 4500 lb					
Total					
Injuries					
Fatalities					

(Please provide accident reports if available.)

8. Please provide your procurement specifications for crash cushions and terminals.

9. Please provide your warranting criteria for the installation of crash cushions/terminals.

10. Operational problems encountered with devices:

Type A

____

____

Type B

____

____

Type C

____

____

Type D

____

____

Type E

____

____

11. State reasons you prefer one type of device over another type:

____

____

____

____

____

12. Do you require contractors to use temporary devices? (a) Yes ☐ No ☐

If yes, when? (b) ________________________________

If yes, does the contractor

(c) use your agency's devices? Yes ☐ No ☐

(d) purchase/lease own? Yes ☐ No ☐

If contractor's specifications differ from your agency's, please provide.

13. Are temporary crash cushions typically included in Traffic Control Plans?

Yes ☐ No ☐ Occasionally ☐

14. Source from which readers of the synthesis report can obtain copies of videos, training manuals, warrants, specifications, plans:

Name ________________________________

Address ________________________________

____

____

____

Telephone ______________________

Please return to:

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

Phone: (615) 322-0055
Fax: (615) 322-3365

APPENDIX C

SUMMARY OF SURVEY RESPONSES

LIST OF AGENCY CODES USED IN SURVEY

ALHD	Alabama Highway Department
AKDOT/PF	Alaska Department of Transportation
ARDOT	Arkansas Department of Transportation
CADOT	California Department of Transportation
CAGGB	Golden Gate Bridge, Highway & Transportation District
CANATU	Alberta Transportation & Utilities, Canada
CANMHT	Province of Manitoba, Dept. of Highways and Transportation, Canada
CANNBDOT	New Brunswick Department of Transportation, Canada
CANSHT	Saskatchewan Highways & Transportation, Canada
CODOT	Colorado Department of Transportation
CTDOT	Connecticut Department of Transportation
DEPOT	Delaware Department of Transportation
DCDPW	District of Columbia Department of Public Works
GADOT	Georgia Department of Transportation
IDDOT	Idaho Department of Transportation
ILDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
KSDOT	Kansas Department of Transportation
KYDOT	Kentucky Department of Transportation
LADOTD	Louisiana Department of Transportation and Development
MEDOT	Maine Department of Transportation
MDDOT	Maryland Department of Transportation
MATA	Massachusetts Turnpike Authority
MIDOT	Michigan Department of Transportation
MNDOT	Minnesota Department of Transportation
MSDOT	Mississippi Department of Transportation
MOHTD	Missouri Highway & Transportation Department
NEDOR	Nebraska Department of Roads
NVDOT	Nevada Department of Transportation
NJDOT	New Jersey Department of Transportation
NJEA	New Jersey Expressway Authority
NYSDOT	New York State Department of Transportation
NCDOT	North Carolina Department of Transportation
NDDOT	North Dakota Department of Transportation
OHTC	Ohio Turnpike Commission
OKDOT	Oklahoma Department of Transportation
OKTA	Oklahoma Turnpike Authority
ORDOT	Oregon Department of Transportation
PADOT	Pennsylvania Department of Transportation
RIDOT	Rhode Island Department of Transportation
SCDH	South Carolina Department of Highways
TNDOT	Tennessee Department of Transportation
TXDOT	Texas Department of Transportation
TXTA	Texas Turnpike Authority
VTAOT	Vermont Agency of Transportation
VADOT	Virginia Department of Transportation
N.VADOT	Virginia (North District) Department of Transportation
WADOT	Washington Department of Transportation
WVDOT	West Virginia Department of Transportation
WIDOT	Wisconsin Department of Transportation

2. NUMBER OF CRASH CUSHIONS/TERMINALS (BOTH PERMANENT AND TEMPORARY) IN USE:

Control No.	1980	1985	Current (1992)	1995 (projected)
ALHD	26	43	73	69
AKDOT/PF	0	0	0	0
ARDOT	—	—	318	318
CADOT	840	1021	1000	1000
CAGGB	16	16	16	16
CANATU	4	7	13	15
CANMHT	1	1	2	3
CANNBDOT	0	0	2	2
CODOT	—	—	181	181
CTDOT	—	—	213	250
DCDPW	57	127	167	200
GADOT	25	60	160	200
IDDOT	11	14	21	21
ILDOT	—	—	390	390
INDOT	168	341	1102	1102
KSDOT	42	56	284	317
KYDOT	129	317	699	850
LADOTD	—	136	215	280
MEDOT	—	3	25	35
MDDOT	6	18	198	230
MATA	—	—	840	820
MIDOT	250	335	415	575
MNDOT	349	538	622	900
MSDOT	8	10	41	66
MOHTD	47	59	91	97
NEDOR	4	4	126	139
NJDOT	—	76	293	293
NJEA	—	—	816	816
NYSDOT	1900	2000	2226	2400
NCDOT	56	127	173	222
NDDOT	—	—	3	0
OHTC	—	—	16	100
OKDOT	300	900	1500	1700
OKTA	—	748	1741	2000
ORDOT	15	45	100	120
PADOT	102	193	454	462
RIDOT	41	47	78	90
SCDH	50	75	100	120
TNDOT	—	72	176	200
TXTA	—	1	2	50
VTAOT	2	2	2	2
VADOT	81	141	265	265
N.VADOT	—	—	146	175
WADOT	—	250	250	250
WVDOT	60	75	100	125
WIDOT	54	54	121	121
Totals	4,644	7,912	15,776	17,587

Note: Missing entries indicated by —, but if the 1995 projected data was not indicated, the 1992 data was entered with the assumption it would remain approximately the same (also, WIDOT's 1980 and 1985 data are from 1973).

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

Guardrail Energy Absorbing Terminal (GREAT®)

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO.*
ALHD	Energy Absorption Systems, Inc.	GREAT®	2
ARDOT	Energy Absorption Systems, Inc.	GREAT® 200200SF6	7
CADOT	Energy Absorption Systems, Inc.	GREAT®	—
CANATU	Energy Absorption Systems, Inc.	GREAT® System	3
CANMHT	Energy Absorption Systems, Inc.	GREAT®	1
CANNBDOT	Energy Absorption Systems, Inc.	GREAT®	1
CTDOT	Energy Absorption Systems, Inc.	[GREAT® Systems] All 60 mph systems	16
DEDOT	Energy Absorption Systems, Inc.	GREAT®	—
DCDPW	Energy Absorption Systems, Inc.	GREAT® System (foam cartridges)	47
GADOT	Energy Absorption Systems, Inc.	GREAT®	135
IDDOT	Energy Absorption Systems, Inc.	GREAT®	38
ILDOT	Energy Absorption Systems, Inc.	GREAT® System	30
INDOT	Energy Absorption Systems, Inc.	GREAT®	174
KSDOT	Energy Absorption Systems, Inc.	GREAT®	29
KYDOT	—	GREAT®	153
KYDOT	—	GREAT® (temp.)	322
LADOTD	Energy Absorption Systems, Inc.	GREAT® (Guard Rail Energy Absorption Terminal)	159
MEDOT	Energy Absorption Systems, Inc.	(Varies Narrow — Medium & Wide) The GREAT® System	3
MDDOT	Energy Absorption Systems, Inc.	GREAT® System	58
MSDOT	Energy Absorption Systems, Inc.	(perm.) Hex-Foam® GREAT® (5 bay-9 bay)	31
MIDOT	Energy Absorption Systems, Inc.	[GREAT® (Guardrail Energy Absorbing Terminal)] 4-bay to 9-bay, mostly 3' width, some 2'6" width	50
MNDOT	Energy Absorption Systems, Inc.	GREAT®	9
MOHTD	Energy Absorption Systems, Inc.	GREAT®	10
NEDOR	Energy Absorption Systems, Inc.	Hex-Foam® GREAT® System	15
NVDOT	Energy Absorption Systems, Inc.	Guardrail Energy Absorbing Terminal "Construction Zone" (aka GREAT®cz)	—
NVDOT	Energy Absorption Systems, Inc.	Guardrail Energy Absorbing Terminal (aka GREAT®)	—
NJDOT	Energy Absorption Systems, Inc.	GREAT® (perm. or temp.)	28
NYSDOT	Energy Absorption Systems, Inc.	GREAT® crash cushion	12
NCDOT	Energy Absorption Systems, Inc.	(majority used in workzones) GREAT® (Hex-Foam®); 6 bay and 10 bay	140
NDDOT	Energy Absorption Systems, Inc.	GREAT®	2
OKDOT	Energy Absorption Systems, Inc.	Hex-Foam® GREAT®cz	15
OKDOT	Energy Absorption Systems, Inc.	Hex-Foam® GREAT®	30
OKTA	Gulf Industries, Inc.	GREAT® Systems, 206206 SF5	38
ORDOT	Energy Absorption Systems, Inc.	GREAT®	16
PADOT	Energy Absorption Systems, Inc.	GREAT®	2
RIDOT	Transpo Ind. Co.	GREAT®	—
SCDH	Energy Absorption Systems, Inc.	GREAT® Systems, 206-206SF9 and other various	45
TNDOT	—	Guardrail Energy Attenuator Terminal (GREAT®), (65) 200 200 FG (33) 300 300 (SF4-SF7)	98

TXDOT	—	GREAT®	—
VADOT	Energy Absorption Systems, Inc.	(# of bays vary 5-7 bays; width varies 2'0"-3'0"; length varies 5'9"-37'9")(perm. 5-7 bays; temp. 3 & 6 bays, 45 & 60 MPH) GREAT®	—
N.VADOT	Energy Absorption Systems, Inc.	GREAT® System	114
WADOT	Energy Absorption Systems, Inc.	GREAT®/GREAT®cz 200-200, 206-206, 300-300	—
WVDOT	Energy Absorption Systems, Inc.	GREAT®	45
TOTAL			1,877

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

Crash-Cushion Attenuating Terminal (CAT®)

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO. IN USE*
CADOT	Syro Steel Co.	CAT®	4
CANATU	Syro Steel Co.	CAT®	2
CTDOT	Syro Steel Co.	[CAT® Guiderail Terminal; all cost figures are complete & installed] 60 mph CAT®	58
DEDOT	Syro Steel Co.	CAT®	—
ILDOT	Syro Steel Co.	CAT® System	25
INDOT	Syro Steel Co.	CAT® or median pier crash cushion	95
INDOT	Syro Steel Co.	CAT® as shoulder terminal	227
KYDOT	—	CAT®	163
MEDOT	Syro Steel Co.	CAT® System	1
MDDOT	Syro Steel Co.	CAT® System	20
MATA	Syro Steel Co.	(crash cushion attenuating terminal) CAT®	2
MIDOT	Syro Steel Co.	CAT® (Combination Attenuation Terminal)	10
MOHTD	Syro Steel Co.	CAT®.	2
NEDOR	Syro Steel Co.	CAT®	20
NCDOT	—	CAT®	4
PADOT	Syro Steel Co.	CAT®	216
TXTA	Syro Steel Co.	A01 CAT®	1
VADOT	Syro Steel Co.	CAT® crash cushion (sacrificial slotted guardrail)	—
WADOT	Syro Steel Co.	—	—
TOTAL			850

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

Sand-Filled Plastic Barrels

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO. IN USE*
ARDOT	Fibco, Inc.	Fitch Model 03 (Std.)	216
ARDOT	Fibco, Inc.	Fitch Model (Non-Std.)	15
ARDOT	Energy Absorption Systems, Inc.	Energite® Model 03 (Std.)	77
ARDOT	Energy Absorption Systems, Inc.	Energite® Model 03 (Non-Std.)	3
CADOT	Energy Absorption Systems, Inc.	Energite® sand barrels	—
CADOT	Roadway Safety Services, Inc.	Fitch sand barrels	—
CANATU	Roadway Safety Services, Inc.	Fitch Inertial Barrier System (free standing sand filled plastic containers)	2
CANMHT	Energy Absorption Systems, Inc.	Energite® III (14 barrels/system)	1
CODOT	Roadway Safety Services, Inc.	Fitch	—
CTDOT	Roadway Safety Services, Inc./Transpo Industries, Inc.	[Sand-filled plastic barrels; Fibco & Energite®: Types 400, 700, 1400, 2100	71
DEDOT	Roadway Safety Services, Inc.	Fitch Inertial System	—
DCDPW	Energy Absorption Systems, Inc. Roadway Safety Services, Inc.	Sand barrels	44
GADOT	Energy Absorption Systems, Inc.	Sand barrels	25
IDDOT	Energy Absorption Systems, Inc.	Energite® III	6
ILDOT	Roadway Safety Services, Inc. Energy Absorption Systems, Inc.	Fitch & other sand barrels	290
INDOT	Roadway Safety Services, Inc. Energy Absorption Systems, Inc.	Fitch & other sand (or gravel) barrel arrays	406
KSDOT	Energy Absorption Systems, Inc.	Energite® III	184
KSDOT	Energy Absorption Systems, Inc.	Module (drum) inertial	17
KSDOT	Roadway Safety Services, Inc.	Fitch Inertial Barrel	7
KYDOT	Roadway Safety Services, Inc.	Fitch	10
MEDOT	Energy Absorption Systems, Inc.	Energite®	20
MDDOT	Fibco, Inc.	Fitch System	74
MATA	Roadside Safety Services, Inc.	(sand drum attenuators) Fitch Initial Barrier System	2
MATA	Energy Absorption Systems, Inc.	(sand drum attenuators) (Temp. construction installations which are designed for lower speeds (50 MPH).) Energite® III System	17
MIDOT	Energy Absorption Systems, Inc.	Inertial Barrier (sand-filled barrels) Energite® II and III modules 200# to 1400#	30
MNDOT	Energy Absorption Systems, Inc.	Energite® System	264
MSDOT	Energy Absorption Systems, Inc. Fibco, Inc.	(perm.) Energite® Inertia Barrier System Fitch Inertia Barrier System	7
MOHTD	Energy Absorption Systems, Inc.	Sand barrels; also Fitch system	56
NEDOR	Energy Absorption Systems, Inc.	Crash barrel (sand filled) Energite®	554
NEDOR	Energy Absorption Systems, Inc. Fibco, Inc.	Energite® III Fitch crash barrel (sand filled)	104
NEDOR	Roadway Safety Services, Inc.	Fitch Inertial Barrier	15
NVDOT	Roadway Safety Services Inc./ Energy Absorption Inc.	Fitch Inertia System/ Energite® System	—
NJDOT	Energy Absorption Systems, Inc.	Energite® III (perm. or temp.)	—
NJDOT	Fibco, Inc.	Fitch Inertial Barrier (perm. or temp.)	—
NYSDOT	Energy Absorption Systems, Inc. Roadway Safety Services, Inc.	Inertial barrier module	2200
NDDOT	Energy Absorption Systems, Inc.	The Energite® III System (temp.)	7
OKDOT	—	(15 modules/installation typical) Fitch (sand filled modules)	400
OKDOT	Energy Absorption Systems, Inc.	(15 modules/installation typical) Sand filled modules	1,000
OKTA	Gulf Industries, Inc.	Attenuator crash barrel units	650

ORDOT	Roadway Safety Services, Inc.	Fitch inertial barriers (no new installs., no cost history found) Fitch Barrels	7
PADOT	Roadway Safety Services, Inc.	Fitch	3
PADOT	Energy Absorption Systems, Inc.	Energite® System	2
RIDOT	Transpo Ind. Co./Fibco, Inc.	Fitch barrels	—
RIDOT	Transpo Ind. Co./Energy Absorption systems, Inc.	Energite® crash cushion	—
SCDH	Energy Absorption Systems, Inc.	Inertial barrels	—
TNDOT	—	Inertial sand module, 22 Module Array	—
TXDOT	—	sand-filled plastic barrels	—
VADOT	Fibco, Inc.	(# of modules required vary 3-15 for 6'0" width) (perm. 8-15 modules; temp. 3-11 modules) Fitch sand modules	—
VADOT	Energy Absorption Systems, Inc.	(# of modules required vary 3-15 for 6'0" width) (perm. 8-15 modules; temp. 3-11 modules) Energite® (sand module)	—
N.VADOT	Fibco, Inc.	Fitch sand barrels	17
VTAOT	Fibco, Inc. - Boston, MA	Fitch Inertial Barrier	2
WADOT	—	Energite® & Fitch Inertial Barriers	—
WVDOT	Energy Absorption Systems, Inc.	Sand barrel	30
TOTAL			3,992

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

Hex-Foam® Sandwich System

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO. IN USE*
ALHD	Energy Absorption Systems, Inc.	Hex Foam Sandwich 8 Bay 209508HBS	—
CADOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich	—
CANNBDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich System	1
DEDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich System	—
DCDPW	Energy Absorption Systems, Inc.	Hex-Foam®	40
INDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich System	36
KSDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich System	28
LADOTD	Energy Absorption Systems, Inc.	Hex-Foam®	9
MIDOT	Energy Absorption Systems, Inc.	(8-bay and 10-bay; narrow, median, and wide) Hex-Foam® Sandwich Systems	20
MSDOT	Energy Absorption Systems, Inc.	(6 bay-10 bay) Hex-Foam® Sandwich (perm.)	14
MOHTD	Energy Absorption Systems, Inc.	Hex-Foam®	20
NEDOR	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich System	6
NJDOT	Energy Absorption Systems, Inc.	Hex-Foam® (perm.)	3
NYSDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich	2
NCDOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich	15
OKDOT	Energy Absorption Systems, Inc.	Hex-Foam®	25
ORDOT	Energy Absorption Systems, Inc.	Hex-Foam®	12
PADOT	Energy Absorption Systems, Inc.	Hex-Foam®	147
RIDOT	Transpo Ind. Co.	Hex-Foam®	—

SCDH	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich Systems, 209 509 H45 & other Various	10
TNDOT	—	Hex-Foam® Sandwich, 209800 H 8syc, 204 1010 H 10sy, WX10-60-03, 204 507 H 105, 209 509 H 55	22
TXDOT	—	Hex-Foam® Sandwich System	—
N.VADOT	Energy Absorption Systems, Inc.	Hex-Foam® Sandwich Systems	3
WADOT	Energy Absorption Systems, Inc.	varies: 27 standard + custom	—
TOTAL			412

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

Hi-Dro® Sandwich System/Hi-Dro® Cell Cluster

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO. IN USE*
ALHD	Energy Absorption Systems, Inc.	Hi-Dro® Cell 2 Bay	—
ALHD	Energy Absorption Systems, Inc.	Hi-Dro® Cell 10 Bay 2041300N10S	—
ALHD	Energy Absorption Systems, Inc.	Hi-Dro® Cell Cluster	1
CAGGB	Energy Absorption Systems, Inc.	Hi-Dro® W 40-54-83 (126)	16
CTDOT	Energy Absorption Systems, Inc.	Hex-Foam® and water-filled sandwich system [All 60 mph systems, various widths]	34
DCDPW	Energy Absorption Systems, Inc.	Hi-Dro® cell	15
GADOT	Energy Absorption Systems, Inc.	Hi-Dro® Cells	4
ILDOT	Energy Absorption Systems, Inc.	Hi-Dry/Hi-Dro® Cell	16
KYDOT	—	Hi-Dro®	30
LADOTD	Energy Absorption Systems, Inc.	Hi-Dro® Cell	47
MEDOT	Energy Absorption Systems, Inc.	Hi-Dro® Sandwich 209509S5S	1
MDDOT	—	Hydrocell	6
MSDOT	Energy Absorption Systems, Inc.	Hi-Dro® Cell Cluster and Sandwich (perm.)	3
MIDOT	Energy Absorption Systems, Inc.	(6-bay to 10-bay; narrow, median, and wide) Hi-Dro® Sandwich System	275
NJDOT	Energy Absorption Systems, Inc.	Hi-Dro® (perm.)	86
NYSDOT	Energy Absorption Systems, Inc.	Hi-Dro® Sandwich	12
NCDOT	Energy Absorption Systems, Inc.	Hi-Dro®	10
NDDOT	Energy Absorption Systems, Inc.	Hi-Dro® Crash Cushion	1
OKTA	Gulf Industries, Inc.	Hi-Dro® and Foam Cushion Unit	76

ORDOT	Energy Absorption Systems, Inc.	Hydrocell	50
ORDOT	Energy Absorption Systems, Inc.	Hydrocell Cluster	15
PADOT	Energy Absorption Systems, Inc.	Hi-Dro®	40
RIDOT	Transpo Ind. Co.	Hi-Dro®	—
SCDH	Energy Absorption Systems, Inc.	Hi-Dro® Sandwich Systems	15
TNDOT	—	Hi-Dro® Cell Cluster, 48, 58, 70, 85, 95, 270 cell cluster y	18
TNDOT	—	Hi-Dro® Cell Sandwich, 111 307 s6sy, 11 311 s8sy, 111 410 n8sy, 209 800 s8sy 204 1000 n 10sy, 204 1400 n 12sy, 209 711 s6sy, 209 509 n s6sy, 209 1000 n 6sy	22
TXDOT	—	Hydraulic crash cushion	—
TXTA	Energy Absorption Systems, Inc.	Hi-Dro® Sandwich System 204711S10S	1
VADOT	Energy Absorption Systems, Inc.	Hi-Dro® and Hex Foam Sandwich Crash Cushions (no. of bays vary 5-7 bays)(width at back-up varies 3'0"-8'9");length varies 9' 11 1/2"-27' 11 1/2")(perm. installations)	—
N.VADOT	Energy Absorption Systems, Inc.	Hi-Dro® Sandwich Systems	12
WADOT	Energy Absorption Systems, Inc.	no recent purchases; approaching 0 in use, being replaced	—
WVDOT	Energy Absorption Systems, Inc.	Hi-Dro® Cell	20
TOTAL			826

3. CRASH CUSHION (PERMANENT OR TEMPORARY) OR TERMINAL

MISCELLANEOUS

CODE	*MANUFACTURER*	*MODEL NO.*	*APPROX NO. IN USE*
CANATU	—	Steel drum — "Texas Barrel"	2
CTDOT	Currently purchased thru competitive bids	(Connecticut Impact-Attenuation System (CIAS); Narrow Connecticut Impact-Attenuation System (NCIAS)) CIAS & NCIAS	12
KSDOT	—	Hi-Dry	2
KYDOT	—	Brakemaster®	20
KYDOT	—	Steel Barrels	1
NCDOT	NCDOT	55 gallon drum composites with sandwich fender panels	2
PADOT	Energy Absorption Systems, Inc.	Water Wall	15
TNDOT	Connecticut	(2) CIAS, (2) NCIAS	4
TXDOT	—	Low Maintenance End Treatment	—
TXDOT	—	Texas Crash Cushion, Steel Drum	—
WVDOT	Energy Absorption Systems, Inc.	Hi-Dry Sandwich	5
TOTAL			63

4. CRASH CUSHION/TERMINAL MAINTENANCE EXPERIENCE (NON-COLLISION)

Guardrail Energy Absorbing Terminal (GREAT®)

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
ALHD		X	X
CADOT			X
CANATU			X
CANMHT			X
CTDOT			X
GADOT	X		
IDDOT			X
ILDOT			X
INDOT			X
KSDOT			X
MEDOT			X
MDDOT		X	
MIDOT			X
MNDOT			X
MSDOT			X
MOHTD			X
NEDOR		X	
NYSDOT			X
NCDOT			X
OKDOT (cz)		 X	X
OKTA			X
ORDOT			X
PADOT			X
SCDH			X
N.VADOT	X		
WADOT			X
WVDOT			X

CODE	TYPICAL MAINTENANCE PROBLEMS
CANATU	Check anchorage periodically (cable is tight and chains are in placed); creates snow drift.
CANMHT	Snow accumulation/drifting.
IDDOT	Modules deteriorated and have to be replaced.
ILDOT	Periodic inspections.
INDOT	Debris, broken staples, vandalism, stocking small parts, training.
KSDOT	Trash accumulation.
MSDOT	Removing debris that accumulates under the cartridges.
NEDOR	Sand and debris collect under system and in system slide rails.
NVDOT	Vandalizing of Hex-Foam® cartridges and deteriorating of cartridge covering (8 years estimation); also, with the GREAT®cz (construction zone) system anchoring devices sometimes require damage to pavement.
NCDOT	Replacement of nose and cartridges, upgrade to current EA specs; takes too long to install in fast paced workzone.
OKDOT	No special maintenance required; (cz) — Routine inspection required during construction period.
OKTA	Very limited maintenance work is required other than cleaning around the system.
PADOT	Nose needs to be replaced frequently, difficulty in getting parts.
SCDH	Improper cartridge alignment, use of damaged cartridges after a hit has occurred.
N.VADOT	Non-galvanized hardware rusts up, becomes un-moveable and hard to replace.
WVDOT	Clean debris, check hexfoam.

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)
ALHD	12
CADOT	100
CANATU	20
CANMHT	20
CTDOT	10
GADOT	1/2
IDDOT	>20
INDOT	10-15
KSDOT	>10
MEDOT	30
MDDOT	15
MIDOT	15
MOHTD	15
NEDOR	10-15
?NVDOT	10
?NVDOT	20
NYSDOT	20
NCDOT	15-20 (Foam cartridges 8-10 yrs)
OKDOT (cz)	20 10
OKTA	12
PADOT	20
SCDH	12-15
N.VADOT	30
WADOT	20
WVDOT	20

4. CRASH CUSHION/TERMINAL MAINTENANCE EXPERIENCE (NON-COLLISION)

Crash-Cushion Attenuating Terminal (CAT®)

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
CANATU			X
CTDOT			X
ILDOT			X
INDOT			X
MEDOT			X
MDDOT			X
MATA			X
MIDOT			X
MOHTD			X
NEDOR			X
NCDOT			X
PADOT			X
TXTA		X	
WADOT			X

CODE	TYPICAL MAINTENANCE PROBLEMS
CANATU	Check anchorage, remove debris
ILDOT	Periodic inspections
INDOT	CAT® as median pier crash cushion — Debris, weeds, mower damage, stocking small parts, training; CAT® as shoulder terminal — Debris, weeds, stocking small parts, training
MATA	None/Oxidation zinc coating
NCDOT	Replacement of end delineation (sheeting)
TXTA	Clean and inspect bolts and connections

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)
CANATU	20
CTDOT	10
INDOT	>10
MEDOT	>10
MDDOT	10
MATA	25
MIDOT	20
MOHTD	10
NCDOT	30
TXTA	20
WADOT	20

4. CRASH CUSHION/TERMINAL MAINTENANCE EXPERIENCE (NON-COLLISION)

Sand-Filled Plastic Barrels

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
ARDOT			X
CADOT			X
CANATU			X
CANMHT			X
CODOT			X
CTDOT			X
GADOT		X	
IDDOT			X
ILDOT			X
INDOT			X
KSDOT			X
MEDOT			X
MDDOT			X
MATA			X
MIDOT			X
MNDOT			X
MSDOT			X
MOHTD			X
NEDOR			X
NYSDOT		X	
OKDOT			X
OKTA			X
ORDOT			X

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
PADOT			X
SCDH			X
VTAOT			X
N.VADOT			X
WADOT			X
WVDOT		X	

CODE	TYPICAL MAINTENANCE PROBLEMS
ARDOT	Early Fitch models had problem with separation of the rivets, maintenance only performed as need after collisions.
CADOT	Missing or stolen lids. Seams on old original design Fitch barrels (polyethylene) split and leaked.
CANATU	Very little maintenance is required unless a crack has occurred.
CANMHT	Snow accumulation/drifting, grader damage clearing snow, kids jumping on lids.
CODOT	Cracking barrels, frozen sand, inverted lids.
GADOT	Repairing or replacing outside barrels; colors fade out of barrels and they look bad; also, due to size of the array a lot of space is needed for setup.
IDDOT	Barrels getting old and breaking apart, sand freezing.
ILDOT	Periodic inspections.
INDOT	Debris, loose lids, mower damage to barrels, vandalism.
KSDOT	Low maintenance — slow to fill with sand; Other unspecified module (drum) inertial [not Energite® III] has problem of trash accumulation and cracks easily in cold weather.
MEDOT	Installing right amounts of sand, very hard to maintain integrity of complete array.
MDDOT	Deterioration of foam and brittle plastic; sand freezes in winter; lids pop off on occasion requiring sand replacement.
MATA	Occasional surface cleaning.
MIDOT	If located on or near a structure, vibration will cause 220# barrels to move out-of-place. This type unit is only used for wide hazards and temporary (construction zones) installations.
MSDOT	Keeping lids closed on sand units, maintaining location of individual units within a set.
MOHTD	Vandalism to lids; lids can be stolen.
NEDOR	Make sure sand is mixed with calcium chloride pellets or flakes to keep sand from freezing during winter months.
NVDOT	Vandalizing of covers, solidification of sand due to moisture (use 3:1 sand/salt filler), deterioriation of container.
NYSDOT	Covers are stolen or blow off in high winds, clean-up can be difficult, snow removal can be difficult.
OKDOT	Energy Absorption Systems, Inc. — no special maintenance required; Fibco, Inc. — Fitch old style barrel split along seams.
OKTA	Lids periodically have to be replaced, sand has to be replenished, flying objects from vehicles knock holes that must be repaired or replaced.
ORDOT	They are being phased out. Some vandalism occurs. No other type of sand barrel available. Require little maintenance unless hit.
PADOT	Lids become loose. Lids cannot be replaced because barrels change shape. Barrels crack letting sand escape.
RIDOT	Fibco — too flexible; Energite® — not versatile, sand spill.
SCDH	Cracking of plastic barrels due to aging which results in sand loss; improper positioning.
VTAOT	Keeping snow removed from front of barriers.
WADOT	Becomes brittle with age, mess to clean up after impact.
WVDOT	Clean sand and salt, clean debris.

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)
INDOT	10
KSDOT	10
MEDOT	>2
MDDOT	15
MATA	40
MIDOT	10
MOHTD	10
NEDOR	15-20
NYSDOT	10
OKDOT	10
Energy Absorption Systems, Inc.	
Fibco, Inc.	6
OKTA	7
Energite®	15
Fitch	—
SCDH	10
VTAOT	25
N.VADOT	8
WADOT	10
WVDOT	15

Hex-Foam® Sandwich System

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
ALHD			X
CADOT			X
CTDOT			X
INDOT			X
KSDOT			X
MIDOT			X
MSDOT			X
MOHTD			X
NEDOR		X	
NYSDOT		X	
NCDOT		X	
OKDOT			X
ORDOT			X
PADOT			X
SCDH			X
N.VADOT		X	
WADOT			X

CODE	TYPICAL MAINTENANCE PROBLEMS
ALHD	Clean debris.
CTDOT	Complicated and time-consuming to repair, extensive replacement parts.
INDOT	Debris, broken staples, vandalism, stocking small parts.
KSDOT	Trash accumulation; problems with cable tension; snow covers help eliminate some debris problems.

NEDOR Sand and debris collect under system and in system slide rails.

NYSDOT Electric motor wires corrode.

NCDOT Replace Hex-Foam® cartridges, nose and occasionally a few fender panels.

OKDOT No special maintenance required.

SCDH Improper tensioning of guide cables, use of damaged cartridges after a hit has occurred.

TNDOT (All work done by contract.)

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)
ALHD	15
CADOT	100
CTDOT	10
INDOT	10-15
KSDOT	>10
MIDOT	mfr's est. 12-15
MOHTD	10
NEDOR	10-15
NYSDOT	10
NCDOT	15-20 (foam cartridges 8-10 yrs)
OKDOT	15
SCDH	12-15
TNDOT	25
N.VADOT	30
WADOT	20

4. CRASH CUSHION/TERMINAL MAINTENANCE EXPERIENCE (NON-COLLISION)

Hi-Dro® Sandwich System/Hi-Dro® Cell Cluster

CODE	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
ALHD Sandwich Cluster		X	X
CAGGB	X		
CTDOT			X
DCDPW		X	
GADOT		X	
ILDOT			X
MEDOT			X
MDDOT			X
MIDOT		X	
MSDOT			X
NYSDOT			X
NCDOT			X
OKTA		X	
ORDOT			X
PADOT			X
SCDH		X	
TXTA		X	
N.VADOT	X		
WADOT			X
WVDOT		X	

CODE	TYPICAL MAINTENANCE PROBLEMS
ALHD	Replenish antifreeze and clean accumulated debris; Hi-Dro® Cell Cluster — debris collecting under and around the unit.
CAGGB	Impact attenuators in toll lanes need to be straightened when pushed out of alignment. Water level in tubes needs to be checked.
DCDPW	Low water — antifreeze solution level.
GADOT	Replacing delineation and cables.
ILDOT	Periodic inspections.
MDDOT	Keeping area clean between cells, repair of side plates.
MSDOT	Maintaining the fluid at an acceptable level, replacing tubes that separate from caps.
NYSDOT	Parts inventory required.
NCDOT	Check fluid levels 4 times a year.
OKTA	Periodically the units are scraped or damaged by wind. Also de-icing debris has to be removed from around the units.
ORDOT	Wooden posts and anti-freeze get rotten over time.
RIDOT	Hi-Dro® (icing condition) replacement of cartridge, too much maintenance.
SCDH	Unit deformation due to aging, deterioration of water cells due to aging.
TNDOT	Cluster: Tends to age poorly and has to be replaced in about 15 years. Some problems with the cells decaying; Sandwich: None.
TXTA	Clean and inspect for proper levels of liquid, check all attachments.
N.VADOT	Wood parts deteriorate and weaken system; non-galvanized hardware rusts up, becomes unmoveable, and hard to replace.
WADOT	Water freezes and antifreeze is an environmental concern.
WVDOT	Check water and antifreeze, clean debris.

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)
ALHD	
Sandwich	15
Cluster	20
CAGGB	>20
CTDOT	10
GADOT	1
MEDOT	20
MIDOT	10-12
NYSDOT	10
NCDOT	20
OKTA	15
PADOT	20
SCDH	12-15
TXTA	30
N.VADOT	12
WADOT	20
WVDOT	10

4. CRASH CUSHION/TERMINAL MAINTENANCE EXPERIENCE (NON-COLLISION)

MISCELLANEOUS

CODE	Device	> 1 Person-hr/wk	< 1 Person-hr/wk, > 1 Person-hr/mo	< 1 Person-hr/mo
CANATU	Steel drum — "Texas Barrel"			X
CTDOT	CIAS and NCIAS			X
KSDOT	Hi-Dry			X
NCDOT	55 Gallon Drum Composites with Sandwich Fender Panels			X
PADOT	Water Wall			X
WVDOT	Hi-Dry Sandwich			X

CODE	TYPICAL MAINTENANCE PROBLEMS
CANATU	Steel drum — "Texas Barrel": Drums and back-up structures require periodic painting. Rusting of drums is a problem.
KSDOT	Hi-Dry: Removal of sand dust dirt and debris
NCDOT	55 Gallon Drum Composites with Sandwich Fender Panels: Replacement of sheeting on nose
WVDOT	Hi-Dry Sandwich: Clean debris, check foam

CODE	ESTIMATE OF NON-COLLISION LIFE OF DEVICE (in Years)	
CANATU	Steel Drum — "Texas Barrel"	10
CTDOT	CIAS and NCIAS:	10
KSDOT	Hi-Dry:	8-10
NCDOT	55 Gallon Drum Composites with Sandwich Fender Panels:	30
TNDOT	NCIAS and CIAS:	25
WVDOT	Hi-Dry Sandwich:	20

5. DELINEATION — DESCRIBE STANDARDS FOR PAINTING, TARGETING, AND LIGHTING DEVICES

CODE	*COMMENTS*
ALHD	Some units are delineated with reflective painting, also type 1 object markers attached to each unit.
ARDOT	None.
CADOT	Standard installations require that a Type "P" or Type "R" panel be attached to the nose of the crash cushion. See attached Standard Plans. [No standards for painting, no standards for lighting devices.]
CAGGB	Reflectors on front of attenuators in toll lanes.
CANATU	The GREAT® system and SENTRE system require painting of nose piece. Delineation is accomplished with keep right or left hazard board as well as with standard 3 posts (delineators) placement in front of unit.
CANMHT	GREAT® — RB-25 (keep right sign), 0.4 x 0.4 m hazard marker, flashing amber light; Energite III — RB-25; flashing amber light.
CODOT	[sent spec. sheet] all supplemental delineation panels shall be single sheet aluminum, 0.080" minimum thickness; specs on metals for bolts, etc; Yellow with black stripes (perm) or orange and white reflectorized stripes (temp).
CTDOT	Installation of a Type I Object Marker mounted on the nose of the device. (Federal designation DE-9, 9-reflector diamond panel.)
DCDPW	Traffic signs/covered by street lights.
GADOT	Standard delineation Chevron hashmarks on nose guard. Additional delineation in areas of high frequency hits involves: Pavement X-hatching, raised pavement markers, jiggle bar markers and surface

	mounted delineator post with reflective tape on top of posts.
IDTD	Use manufacturers' specifications.
ILDOT	No standard — Do use reflective material on nose of some systems.
INDOT	We do not have a drawing for applying reflectors to the GREAT®'s nose; and we advise the use of button reflectors on posts along the Sentre's redirecting cable, to warn mowers to not ride over the cable. But we do not specify delineation for these terminals, generally.
KSDOT	Object markers at end of barriers, 10" x 2" type II high performance reflective sheeting on all modules adjacent to traffic.
KYDOT	Object Marker Type 1 on nose.
LADOTD	No standards; installed and maintained in accordance with manufacturers' recommended procedures.
MEDOT	Standard interstate + MUTCD.
MDDOT	Reflective tape/paint, delineators, chevrons.
MATA	Permanent sand drum attenuators receive chevron sign panels when located in gore areas. The runaway truck ramp is lit during nighttime hours.
MIDOT	Obstacle markers (yellow and black stripes) are placed on 1st barrel of sand-filled barrel array and on nose covers of other attenuators. Pavement edge lines are emphasized and occasionally flashing yellow caution lights are used.
MNDOT	Snow Plow Markers used when ET-2000 or ELT crash cushion is used.
MSDOT	An 18" x 18" diamond shape sign covered with 3M's high intensity yellow sheeting mounted on the nose of GREAT® system or first barrel of a set of sand filled barrels.
MOHTD	In accordance with MUTCD — varies with location and site geometry; Roadside Design Guide; Missouri Highway "Policy, Procedure & Design Manual."
NEDOR	Permanent — Standard 9-button signs with 3-inch delineators on nose of each system or 3M reflective tape (yellow or white). No lighting used on devices; Temporary — An object marker is placed either above or on the attenuator.
NVDOT	Type I Object marker or array of 3-1/4" diameter Prismatic Reflectors riveted to nose.
NJDOT	Non-sand, permanent Hi-Dro Cushion, Hex-Foam, and GREAT® systems have 30" x 30" diagonal or chevron type reflective sheeting mounted on the nose as shown in attached detail.
NJEA	Roadway is painted once a year using water base paint and reflective beads. Reflectors are used on all types of permanent terminal ends.
NYSDOT	Hazard markers for target; reflectorized tape (would be helpful if tape was provided by manufactuerer); gore area delineation as per MUTCD; occasional flashing lights; no lights necessary where overhead lighting exists.
NDDOT	Hi-Mast Lighting; Reflective sheeting on nose.
OKDOT	Sand Filled Module is delineated using a 9-button, 24" x 24", diamond shaped object marker. Same marker used on GREAT®cz. The vast majority of the balance are in areas which are lighted.
OKTA	Most units are marked with Type 1 Object Markers. On the devices that are painted, the standard safety paint is used as needed for touch-up work, if the units are lighted it is just due to the fact that they are near roadway lighting.
ORDOT	Reflectorized object marker, configured to reflect existing traffic pattern.

PADOT Type B Warning Lights; Clearance Markers.

SDCH Most units are equipped with a yellow nose cone or a small chevron flat sheet sign on the approach. Some units are simply marked with a reflective sheeting in a chevron pattern.

TNDOT All attenuators have hazard markers.

TXDOT See attached sheet "Delineators and Object Markers for Vehicle Impact Attenuators."

TXTA Gore markings and roadway delineators; reflective Chevron mounted on Hi-Dro Sandwich System crash cushion.

VTAOT None provided.

VADOT Chevron sign-orange with black stripes used in construction (temp.) zones. Chevron-yellow with black stripes used in permanent locations.

WADOT MUTCD (3C-3) Type 3 object marker (30 x 30) on the nose [see attachment C]. Standard (pavement) lane markings. Gores usually illuminated.

WVDOT Use high intensity hazard markers.

6. TRAINING FOR AGENCY PERSONNEL

CODE No.	*Instructional*	*Training Manual*	*Video*	*Word of Mouth*	*Training In House*	*Training By Manufacturer*
ALHD	X	X		X	X	X
AKDOT/PF				X		X
ARDOT					X	
CADOT				X	X	X
CAGGB				X		
CANATU	X			X		X
CANNBDOT					X	X
CODOT				X		X
CTDOT		X			X	
DCDPW		X			X	
GADOT	X			X	X	X
IDTD	X			X		
ILDOT			X	X	X	X
INDOT				X	X	X
KSDOT		X		X		X
LADOTD						X
MEDOT	X		X			X
MDDOT	X			X	X	
MATA					X	X
MIDOT	X	X	X	X	X	X
MNDOT				X		

CODE No.	Instruc-tional	Training Manual	Video	Word of Mouth	Training In House	Training By Manufacturer
MSDOT	X	X		X	X	X
MOHTD		X	X	X	X	
NEDOR			X		X	X
NJDOT				X		
NJEA	X				X	
NVDOT					X	
NYSDOT	X			X	X	
NCDOT		X	X	X	X	X
NDDOT		X				X
OKDOT			X		X	X
OKTA	X			X	X	X
ORDOT					X	X
PADOT				X	X	
RIDOT		X			X	X
SCDH	X			X		X
TXTA				X		
VTAOT	X			X		
WADOT	X		X	X	X	X
WVDOT	X					

Reported Incidents, Number

CODE No.	Vehicle < 4500 lb	Vehicle > 4500 lb	Total	Injuries	Fatalities	Comments:
HEX-FOAM SANDWICH SYSTEM:						
MSDOT	3*	—	3	—	0	*veh. size usu. unavailable
NCDOT	32	0	32	0	0	
HI-DRO SANDWICH SYSTEM / HI-DRO CELL CLUSTER:						
NCDOT	17	0	17	0	0	
OKTA	10	4	14	3	0	
MISCELLANEOUS:						
KSDOT	2	0	2	1	0	Hi-Dry
TOTALS OF UNSPECIFIED DEVICES:						
CTDOT	—	—	60	25	0	
CTDOT	—	—	88	24	1	
ORDOT	—	—	12	6	1	1990
ORDOT	—	—	11	6	—	1991
ORDOT	—	—	7	1	—	1992

7. COLLISION EXPERIENCE

	Reported Incidents, Number					
CODE No.	*Vehicle* < 4500 lb	*Vehicle* > 4500 lb	*Total*	*Injuries*	*Fatalities*	*Comments:*
GUARDRAIL ENERGY ABSORBING TERMINAL (GREAT®):						
GADOT	54	5	59	—	1	FY 91
MSDOT	14*	—	14	2	0	*veh. size usu. unavailable
NCDOT	20	2	22	3	0	
KSDOT	7	0	7	2	0	
OKTA	0	1	1	0	0	
SAND-FILLED PLASTIC BARRELS:						
CADOT	—	—	981	401	16	[PDO 564] Energite sand barrels
CADOT	—	—	578	562	16	Fitch sand barrels
KSDOT	3	0	3	1	0	Energite sand barrels
KSDOT	25	0	25	5	0	unspecified sand barrels
MSDOT	2*	0	2	—	0	*veh. size usu. unavailable
OKTA	54	10	64	16	1	

10. OPERATIONAL PROBLEMS ENCOUNTERED WITH DEVICES

Guardrail Energy Absorbing Terminal (GREAT®)

CODE	*COMMENTS*
CTDOT	Complicated and time-consuming to repair; expensive replacement parts.
GADOT	Sometimes there is not sufficient available space for the device and hits are more frequent than they should be due to exposure.
MDDOT	Tracks are repaired or replaced when struck.
MSDOT	No debris skirts are available for this type device.
NEDOR	Side impacts can cause extensive damage.
NJDOT	Difficult to repair for low damage hits; maintenance personnel are subject to extra exposure in field due to time to repair low speed and minor hits.
NYSDOT	High average repair cost.
ORDOT	Entire system collapses making it more expensive to replace.
PADOT	Attenuator gets snagged by vehicles moving in "opposite" direction. Hit by turning vehicles.

Crash-Cushion Attenuating Terminal (CAT®)

CODE	*COMMENTS*
CTDOT	Difficult to repair due to in-place state and anchorage of the original installation.
INDOT	*CAT® as Median Pier Terminal:* The MP CAT®, with a transition section, is an option in wide median locations. No one interviewed among our Maintenance or Construction crews prefers this unit to the barrel array. It is more expensive and difficult to install and repair. We believe that its minor advantage — redirection during an approach to the left side of a median pier corner — does not override its unpredictability in many other accident scenarios. We have chronically wet conditions in the MP locations, and expect more wet wood post problems in the future — beyond that of removing frozen-in-place post stubs in the winter. We have had one double fatality involving an MP CAT® and a small car, reported in the VAT and CAT® Attenuating Terminals Final Report. *CAT® as Shoulder Terminal:* Our well-drained shoulders do not cause the wet post problems cited for the MP CAT®. However, repair crews have had to labor long and hard to reshape the steel foundation tubes at their tops, to enable removal of broken post stubs. Tube damage is often caused by underbodies or wheels of impacting cars — especially of those that slide sidways into shoulder CAT®s. We have had one double fatality involving an OS CAT® and a large car, after the CAT® report was published. [Our repair crews like the Sentre better than the buried end (our Guard Rail End Treatment type I) and CAT®, because more repairs involve only above-ground parts. We have accumulated little accident data about these terminals, but they have not been involved in any fatalities that this reporter is aware of, in Indiana.] Major, repeated, and numerous installation errors to [Sentre and] CAT® terminals inspired INDOT to require training and certification of all prospective installers.
NEDOR	Minor impacts can cause extensive work for maintenance to make repairs, costly replacement and staff hours.

Sand-Filled Plastic Barrels

CODE	*COMMENTS*
CANMHT	Debris scatter, i.e., sand, plastic parts/pieces of various sizes.
CODOT	Barrels of any manufacture, when impacted, require special equipment to remove sand from roadway which is also a safety problem; after a crash sand is scattered all over if barrels were impacted.
CTDOT	Clean-up of scattered debris, nuisance hits require clean-up and replacement parts.
INDOT	For about three years, we have been using gravel in what we used to call "sand barrel arrays." Nearly every respondent commented that they like gravel barrel arrays for their simplicity, because you can send nearly anyone out to repair one and expect to have it done right. Some knowledgeable people said you might assume, but cannot expect, to have these arrays properly placed and filled in repair. Some respondents also mentioned the laborious process of shoveling up spilled fill material, following accidents, and indicated a preference to repair the simpler GREAT® units in their suitable locations.
KSDOT	Filling barrels by hand.
MEDOT	Under field conditions it is very difficult to fill the barrel with exactly the correct weight of sand, which appears to be critical.
MATA	Provide safe work area to replace damaged sand drum attenuators.
MIDOT	Debris from impact may be widely scattered. Messy to clean-up.
NEDOR	None — Cleanup can take a little while.
NJDOT	Fitch inertial barrier is complicated to repair; Energite® III is easier to assemble, replace, and repair.
NDDOT	The single row sandfilled barrel attenuation device has not been accepted by FHWA. We will have to delete it from our standard drawings.

10. OPERATIONAL PROBLEMS ENCOUNTERED WITH DEVICES

Hex-Foam® Sandwich System

CODE	*COMMENTS*
CTDOT	Complicated and time-consuming to repair, extensive replacement parts.
GADOT	Entire system collapses making it more expensive to replace.
INDOT	Favorable comments by experienced repair personnel, although the earlier comment about repairs in tight work zones applies here, also.
NEDOR	Side impacts can cause extensive damage.
ORDOT	When struck bolts can get stuck in cartridges making it difficult to remove them.

10. OPERATIONAL PROBLEMS ENCOUNTERED WITH DEVICES

Hi-Dro® Sandwich System/Hi-Dro® Cell Cluster

CODE	*COMMENTS*
CAGGB	Flex-belts become loose when cell clusters are pushed together; loose belts are then caught on passing vehicles.
CTDOT	Old water-filled systems eventually leak, rendering them less effective under impact; complicated and time-consuming to repair; expensive replacement parts.
GADOT	Availability of repair parts.
LADOTD	Hi-Dro® Cell: must use anti-freeze in cold climate which is considered a hazardous material when released.
MDDOT	Obtaining replacement parts.
MIDOT	Secondary accidents due to wet pavement after impacts; restoring device results in exposing maintenance workers to high speed traffic for 4-8 hrs. Wet pavement requires sanding.
MSDOT	Maintaining the fluid at an acceptable level, replacing tubes that separate from caps.
NYSDOT	Minor hits require major repair effort if diaphragms break.
NCDOT	Once hit, it does not pull back to original shape when being repaired.
ORDOT	Maintenance crews fabricate wood product items. Hardware purchased from local distributor.

10. OPERATIONAL PROBLEMS ENCOUNTERED WITH DEVICES

MISCELLANEOUS

CODE	*DEVICE*	*COMMENTS*
CTDOT	CIAS and NCIAS	Lifting equipment required on site during repair.
NCDOT	NCDOT's 55 Gallon Drum Composites with sandwich fender panels	Are to be upgraded to Hex-Foam® Sandwich in near future.

11. STATE REASONS YOU PREFER ONE TYPE OF DEVICE OVER ANOTHER TYPE

CODE	*COMMENTS*
ALHD	We prefer the Hex-Foam® Sandwich [over the GREAT® System] because it seems to collapse better than the GREAT® System when impacted by a non-direct hit.
ARDOT	No preference.
CADOT	Existing water tube crash cushions require a lot of time and effort to repair following a collision. Other types are preferred. The water tube crash cushions are no longer purchased. Beyond that, choice depends mainly on site conditions and geometry.
CAGGB	The Hi-Dro® Cell Clusters are ideal for toll lanes since they can immediately be put back in service after an impact, and no loose materials are scattered to cause a hazard to employees or the public.
CANATU	We are still evaluating these crash cushion products. No preference on any products at this time.
CANMHT	Indifferent as our Department has only the two aforementioned devices.
CANNBDOT	Hex-Foam® System allows for greater flexibility for adjustment of width in gore area and angling in gore area.
CODOT	Sand barrel attenuator is preferred because of lower cost, if it is appropriate for the site.
CTDOT	Repair crews prefer sand-filled plastic barrels due to simplicity and availability of parts. Since the Sand Barrels do not meet latest performance guidelines, the Hex-Foam® and water-filled sandwich systems, the GREAT® systems, the CIAS and NCIAS, and the CAT®

Guiderail Terminal are preferred from a safety standpoint, with the CIAS and NCIAS being the most cost-effective "crash cushions," and the CAT® being the most cost-effective guiderail terminal.

DCDPW — Sand barrels: easy to repair.

GADOT — The GREAT® is preferred due to the availability of repair parts, the repairs are easy to make and they function well in all the different situations we have placed them.

IDDOT — Do not really have preference — usually specify what attenuator fits the situation — although we are looking for other options due to the cost of the GREAT® systems in District 1.

ILDOT — We prefer to use the most economical installation suitable for the particular location.

INDOT — Some people would prefer that all terminals be installed on concrete slabs. Barrel arrays are preferred in the median because of their effectiveness, simplicity, and ease of replacement. The GREAT® is appreciated because of its relative ease of repair, even compared to the barrel array. But the GREAT® and barrel array are usually used in different situations. The barrel array is used in wide medians where redirection is not a priority and where the sprayed gravel would not hamper traffic. The GREAT® is used mostly in more compact locations, and those where a shorter terminal is needed.

Some prefer the Sentre to the CAT®, for its ease of repair. The Sentre's ability to follow a curve was favorably mentioned, for placement on loops.

In general, our people would like to have a limited array of simple and effective terminals for each application. Maintaining stock of repair parts and staying informed about design features and changes are two frustrating requirements for our people during this time when we have not yet developed a comprehensive roadside safety management system.

KSDOT — Energite® Module Inertial — can be successfully relocated, good for temporary use; barrel systems are low maintenance and movable.

LADOTD — Prefer GREAT®: 1. versatile, 2. easier maintenance, 3. overall less cost.

MEDOT — We use whatever might look easier to maintain on permanent; low initial cost for temporary.

MDDOT — Less maintenance on Fibco, Inc's. Fitch System of sand barrels.

MATA — Breakaway Cable Terminal easier to repair or replace; Energite® III System, sand drum attenuators, ease of storage, parts replacement.

MIDOT — Crash cushions — cartridge units (i.e., GREAT® and Hex-Foam® Sandwich System) provide potential for a broader range of vehicle weights 1600# to 5400#. They also are restored quickly, resulting in reduced exposure for maintenance personnel. Terminals — each terminal has its merits. The CAT®, Sentre, and TREND have more unique parts and are more complex to repair. The ET-2000 is a very simple system that uses mostly standard guardrail components. This system was put in service in 1992, not enough information is available to evaluate performance and repair aspects.

MNDOT — The Eccentric Loader Breakaway Cable Terminal (ELT) is non-proprietary, is least expensive and is used extensively if 10:1 slopes for 9 ft. behind the barrel are present. The ET-2000 is used in lieu of the ELT when there is a limited amount of level ground behind the end terminal. Other types are used at special need locations.

MSDOT — We prefer the Hex-Foam units which require less maintenance than Hi-Dro® units. By utilizing primarily Hex-Foam® units, our Maintenance personnel can become proficient in maintaining units and the Department limits the number of spare parts required to maintain the units.

MOHTD — Sand barrels are interchangeable with a low parts count. Easy to replace.

NEDOR — The sand barrel attenuators require less maintenance, have less parts and are easier to repair/replace; The Hex-Foam® GREAT®, Hex-Foam® Sandwich System, and CAT® have numerous parts. If devices are impacted head-on, they can be repaired more quickly and function better. However, most impacts are not head-on and require several replacement parts.

NVDOT	Design: GREAT® preferred due to enhanced safety for motoring public, relatively short installed length, redirective ability, ease of repair, longevity of components, aesthetics, relative simplistic construction.
NJDOT	Maintenance prefers the easy storage and repair of the sand barrel type that is available in half barrel parts. Standardization industry wide would be preferred for inventory cost reduction.
NJEA	No preference.
NYSDOT	Inertial Barrier Modules preferred — simplified assembly requires small crew and less equipment; easier and less costly maintenance. GREAT® System preferred — parts reusable; little maintenance required.
NCDOT	GREAT® is preferred due to ease of maintenance and repair. As one Division Maintenance Engineer states, every time he goes out to a cushion, it's a different animal. Although location dictates type of cushion, we are trying to maintain uniformity so that maintenance personnel to not have to know numerous cushion types.
NDDOT	We have tried and they seem to be the best for our situation.
OKDOT	Prefer Energite® single piece barrel and insert to Fitch multi-piece system. Reduces maintenance time substantially after impact. All component parts can be carried in a pickup.
OKTA	Each device serves the needs in the areas used. They are all unique.
ORDOT	The GREAT® and Hex-Foam® systems have fewer parts, are easier to maintain but are more expensive.
PADOT	Prefer GREAT® because it is easy to repair. Its relatively narrow width lets us use it at locations where roadway width is a problem.
RIDOT	Prefer Hex-Foam® because it is compact and quick to reposition and refurbish; also, no spillage of toxic material.
SCDH	Devices using sand or cartridges are preferred over devices such as the Hi-Dro® Cell Cluster. Devices of these types require less maintenance. In addition, sand eliminates possibility of an unwanted or hazardous reaction during accidents involving chemicals.
TNDOT	No preference.
TXDOT	We have no preferences, some devices fit the space limitations better than others.
TXTA	The Hi-Dro® Sandwich system is easier, cheaper, and quicker to repair after a collision [than the CAT®].
WADOT	Prefer barrels for low initial cost. Prefer impact attenuators with "black box" replacement parts to save time and for crew safety (maintenance).
WVDOT	Depends on site characteristics.

12. DO YOU REQUIRE CONTRACTORS TO USE TEMPORARY DEVICES?

Code	Yes	No	If Yes				
			When	Does the Contractor Use your agency's devices?		Does the Contractor Purchase/ lease own?	
				Yes	No	Yes	No
AKDOT/PF Central Region	X		anytime Jersey Barrier terminates within clear zone		X	X	
AKDOT/PF Northern Region			when temporary concrete median barrier cannot be terminated properly without using crash cushion			X	
ARDOT	X		as specified in plans		X	X	
CADOT	X		when the engineer decides it is necessary [Blunt end protection (of temporary concrete barriers, etc.) is required within 12.0 ft of edge of traveled way]		X	X	
CAGGB		X	the need has not occurred				
CANATU	X		when condition dictate a need			X	
CANMHT		X					
CANNBDOT		X					
CODOT	X		when and where specified on the plans		X	X	
CTDOT	X		to terminate temporary longitudinal barrier (Jersey Barrier)		X	X	
DEDOT	X		at concrete barrier ends, at guardrail ends, at fixed objects		X	X	
DCDPW	X		when temporary PCC barriers are used to close the lane on channelize traffic		X	X	
GADOT	X		in traffic control or detours where fixed objects are in the clear zone (They become property of GDOT when work is completed.)		X	X	
IDDOT	X		we have specified temps on projects using our systems and also requiring contractor to use their own; mainly at cross-over locations near structure parapets	X		X	
ILDOT	X		GREAT®cz used in some locations	X		X	
INDOT	X		we require contractors to provide temporary devices when taking down existing protection during construction; when barrier walls are used to delineate traffic; if there is no proper transition, or if it is close to the travel lane. We require truck mounted attenuators for painting operations.		X	X	
KSDOT	X		traffic through construction zones, barrier ends, bridge columns, fixed objects		X	X	
KYDOT	X						
LADOTD	X		construction zones to protect barrier ends in detours	X		X	
MEDOT	X		to protect D.F.O.		X	X	
MDDOT	X		if more than a one day operation		X	X	
MATA	X		at the approach ends of temporary concrete barrier		X	X	
MIDOT	X		Temporary and permanent barrier endings which cannot be located outside the appropriate clear zone and/or when a less costly crashworthy terminal is not acceptable.	X		X	
MNDOT	X		when a vehicle hazard is present	X			
MSDOT	X		where geometrics or other limitations warrant use		X	X	
MOHTD	X		when shown on plans		X	X	
NEDOR	X		when Jersey barriers are used to divide or separate traffic	X		X	
NVDOT			hazard is within clear zone				
NJDOT	X		N/A		X	X	
NJEA	X		lane closings		X		X
NYSDOT	X		when the designer determines they are necessary for the safety of the public traveling through the work zone.		X	X	
NCDOT	X		obstruction within clear zone (i.e., approach end of Temporary Concrete Barrier)	X		X	
NDDOT	X		where hazards exist during construction		X	X	
OKDOT	X		in construction work zones to protect known hazards		X	X	
OKTA	X		bridge construction, toll plaza construction, temporary crossovers		X	X	
ORDOT	X		when situation warrants		X	X	
PADOT	X		when using temporary barrier		X	X	

Code	Yes	No	If Yes: When	Does the Contractor: Use your agency's devices? Yes	No	Purchase/ lease own? Yes	No
RIDOT	X		during construction			X	
SCDH	X		widening projects in high volume areas such as interstates		X	X	
TNDOT	X		when in the contract plans		X	X	
TXDOT			when specified in the plans, approved devices such as the GREAT®cz are used	sometimes	unknown		
TXTA		X					
VTAOT	X		protect worker barrier (concrete) cannot be offset properly		X	X	
VADOT	X		to protect motorist from hitting a fixed object (also see attachment 3)		X	X	
WADOT	X		as shown in traffic control plans in the contract		X	X	
WVDOT	X		on expressways		X	X?	

13. ARE TEMPORARY CRASH CUSHIONS TYPICALLY INCLUDED IN TRAFFIC CONTROL PLANS?

CODE	*Yes*	*No*	*Occasionally*
AKDOT/PF Central Region	X		
AKDOT/PF Northern Region		X	
ARDOT			
CADOT			X
CAGGB		X	
CANATU			X
CANMHT		X	
CANNBDOT		X	
CODOT	X		
CTDOT	X		
DEDOT			X
DCDPW			X
GADOT	X		
IDDOT			X
ILDOT			X
INDOT			X
KSDOT	X		
KYDOT			X
LADOTD	X		
MEDOT	X		
MDDOT			X
MATA	X		
MIDOT	X		
MNDOT	X		
MSDOT			X

CODE	*Yes*	*No*	*Occasionally*
MOHTD	X		
NEDOR	X		
NVDOT			
NJDOT	X		
NJEA	X		
NYSDOT			X
NCDOT	X		
NDDOT	X		
OKDOT	X		
OKTA	X		
ORDOT	X		
PADOT	X		
RIDOT	X		
SCDH	X		
TNDOT			X
TXDOT	X		
TXTA		X	
VTAOT			X
VADOT	X		
WADOT			X
WVDOT	X		

APPENDIX D

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APPENDIX F

GLOSSARY OF CRASH CUSHION AND WORK ZONE TERMS (*6*)

ACI—American Concrete Institute.

AISC—American Institute of Steel Construction.

AISI—American Iron and Steel Institute.

ASTM—American Society for Testing and Materials.

Ballast—Mass added to vehicle, other than simulated occupant(s) and instrumentation, to simulate cargo and/or to achieve desired test inertial mass.

Bogie—A device used as a surrogate for a production model test vehicle. Existing bogies are four-wheeled devices that are towed into the test article. They are typically designed to replicate the dynamic response of a vehicle for specific tests, e.g., tests of breakaway features. Bogies typically can be used for both low and high speed tests.

Center of mass (c.m.)—Point within test vehicle at which its total mass can be assumed to be concentrated.

Clear zone—The total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles. This area may consist of a shoulder, a recoverable slope, a nonrecoverable slope, and/or a clear run-out area. The desired width is dependent upon the traffic volumes and speeds and on the roadside geometry.

Crash cushion—A device designed primarily to stop a vehicle safely within a relatively short distance. A redirective crash cushion is designed to contain and redirect a vehicle impacting downstream from the nose of the cushion. A non-redirective crash cushion is designed to contain and capture a vehicle that hits downstream from the nose of the cushion.

Crash test—A test in which a production model test vehicle or a surrogate test vehicle impacts or traverses a highway feature.

Critical impact angle (CIA)—For a given test and the attendant range of vehicular impact angles, the CIA is the angle within this range judged to have the greatest potential for causing a failure when the test is assessed by the recommended evaluation criteria. For most tests, impact angles can range from 0 up to 25 degrees.

Critical impact point (CIP)—For a given test the CIP is the point(s) along the longitudinal dimension of a feature judged to have the greatest potential for causing a failure when the test is assessed by the recommended evaluation criteria.

Curb mass—Mass of test vehicle with standard equipment, maximum capacity of engine fuel, oil, and coolant and, if so equipped, air conditioning and additional optional mass engine. It does not include occupants or cargo.

Device—Refers to a design or a specific part thereof, such as a breakaway device. Note that the terms "device" and "feature" are often synonymous.

Evaluation criteria—Criteria used to assess the results of a crash test or to assess the in-service performance of a feature.

Feature—Refers to a specific element of a highway. It may be a hardware item and its associated foundation, such as a sign or barrier installation, or it may be a geometric element, such as a side slope or a ditch cross section.

Flail space—Hypothetical space in which a hypothetical occupant is permitted to move during impact.

Gating device (feature)—A device designed to allow controlled penetration of a vehicle when impacted upstream of the beginning of the LON. Note that there is some distance between the end of a gating device and the beginning of the LON of the device.

Geometric feature—A roadside cross-section element such as a ditch section, an embankment, a driveway or a median crossover, or a curb. It also includes drainage structures such as inlets and culvert ends and devices such as grates used to enhance the safety of these features.

Gross static mass—Sum of test inertial mass and mass of surrogate occupant(s).

HVOSM—Highway-Vehicle-Object-Simulat ion-Model computer program.

Hybrid III dummy—An anthropomorphic dummy, representing the 50th percentile male, the specifications of which are contained in part 572, Subpart E, Title 49 of the Code of Federal Regulations, Chapter V (10-1-88 Edition).

Impact angle (θ)—Angle between normal direction of traffic and approach path of test vehicle into the test article. The test article should be oriented as it would typically be in service with respect to the normal direction of traffic.

Impact point—The initial point on a test article contacted by the impacting test vehicle.

Impact severity (IS)—A measure of the impact severity of a vehicle of mass M, impacting at a speed V, at an impact angle θ. It is defined as follows: $IS=1/2M(V\sin\theta)^2$

Length of need (LON)—That part of a longitudinal barrier or terminal designed to contain and redirect an errant vehicle.

Longitudinal barrier—A device whose primary functions are to prevent vehicular penetration and to safely redirect an errant vehicle away from a roadside or median hazard. The three types of longitudinal barriers are roadside barriers, median barriers, and bridge rails.

Non-gating device—A device with redirectional capabilities along its entire length. Note that the end of a non-gating device is the beginning of the LON for the device.

Pendulum—A device used as a surrogate for a production model test vehicle. A mass is attached to cables which are in turn suspended from a fixed point. The mass is raised to a selected height and released, allowing gravity to accelerate the mass as it swings into the test article. The structure of the mass can be designed to replicate the dynamic crush properties of a production model test vehicle. It is basically a low-speed test device.

Permanent feature (device)—A feature with an anticipated long duration of service, as opposed to those used in a work or construction zone, which have a relatively short duration of service.

Pocketing—If, upon impact, a redirective device undergoes relatively large lateral displacements within a relatively short longitudinal distance, pocketing is said to have occurred. Depending on the degree, pocketing can cause large and unacceptable vehicular decelerations.

Production model test vehicle—A commercially available vehicle with properties matching those required in a given test.

SAE—Society of Automotive Engineers.

Sprung mass—A mass which is supported by a vehicle's suspension system, including portions of the mass of the suspension members.

Snagging—When a portion of a test vehicle, such as a wheel, engages a vertical element in a redirective device, such as a post, snagging is said to have occurred. The degree of snagging depends on the degree of engagement. Snagging may cause large and unacceptable vehicular decelerations.

Support structure—A system used to support a sign panel, chevron panel, luminaire, utility lines, mailbox, or emergency call box. The system includes the post(s), pole(s), structural elements, foundation, breakaway mechanism if used, and accompanying hardware used to support the given feature.

Surrogate occupant—A dummy, set of sand bags, or other artifact used to simulate the effects and/or to study the dynamic response of an occupant in a vehicle.

Surrogate test vehicle—A bogie, pendulum device, or other substitute device designed to replicate the dynamic response of a production model vehicle when in collision with a roadside feature.

Temporary feature (device)—A feature used in a work, construction, or maintenance zone. Its duration of use is normally relatively short, usually one year or less.

Terminal—A device designed to treat the end of a longitudinal barrier. A terminal may function by (a) decelerating a vehicle to a safe stop within a relatively short distance, (b) permitting controlled penetration of the vehicle behind the device, (c) containing and redirecting the vehicle, or (d) a combination of a, b, and c.

Test article (test feature)—All components of a system, including the foundation as relevant, being evaluated in a crash test. Note that the system may be a geometric feature such as a ditch or driveway slope.

Test inertial mass—Mass of test vehicle and all items rigidly attached to a vehicle's structure, including ballast and instrumentation. Mass of surrogate occupant(s), if used, is not included in test inertial mass.

Test level (TL)—A set of conditions, defined in terms of vehicular type and mass, vehicular impact speed, and vehicular impact angle, that quantifies the impact severity of a matrix of tests.

Test vehicle—A commercially available production model vehicle or an approved surrogate vehicle used in a crash test to evaluate the impact performance of a test article.

Track width—Center-of-tire-to-center-of-tire distance for a given axle of a vehicle.

Transition—That part of a longitudinal barrier system between and connecting sections of differing lateral stiffness and/or sections of differing design or geometry.

Truck-mounted attenuator (TMA)—An energy-absorbing device attached to the rear of a truck or utility vehicle. A TMA is designed to provide a controlled stop of a vehicle impacting the rear of the truck.

Unsprung mass—All mass which is not carried by the suspension system but is supported directly by the tire or wheel and considered to move with it.

Utility pole—A support structure used to support power transmission lines or communication lines.

Work zone traffic control device—A device used in a work zone to regulate, warn, and guide road users and advise them to traverse a section of highway or street in the proper manner. Work zone traffic control devices of interest herein include signs, plastic drums, and lights that may be used thereon; cones, barricades, chevron panels, and their support systems; and any other such device(s) commonly exposed to traffic that may pose a hazard to occupants of a vehicle and/or to work zone personnel.

DATE DUE

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