National Cooperative Highway Research Program

NCHRP Synthesis 182

Performance and Operational Experience of Truck-Mounted Attenuators

A Synthesis of Highway Practice

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National Cooperative Highway Research Program

Synthesis of Highway Practice 182

Performance and Operational Experience of Truck-Mounted Attenuators

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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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 will be of interest to maintenance, construction, and traffic engineers, and others interested in the use of safety apparatus for highway operations. Information is provided on the performance and operational experience of truck-mounted attenuators, including physical characteristics, test results, and guidelines for use.

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.

There is growing use of truck-mounted attenuators (TMAs) for highway traffic, maintenance, and construction operations. This report of the Transportation Research Board describes the current state of the practice with respect to the use of TMAs. Experience with TMA design is summarized, and field experience and guidelines for use are discussed based on a review of the literature and a survey of the states.

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.

CONTENTS

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This synthesis was completed by the Transportation Research Board under the supervision of Robert E. Skinner, Jr., Director for Studies and Information Services. The Principal Investigators responsible for conduct of the synthesis were Sally D. Liff, Senior Program Officer and Scott A. Sabol, Program Officer. This synthesis was edited by Linda Mason.

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Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Charles E. Dougan, Director of Research and Materials, Connecticut Department of Transportation; Virginia M. Lorenz, Traffic Safety Engineer, New Mexico State Highway Department; Morton Oskard, Highway Research Engineer, Federal Highway Administration, Office of Safety and Traffic Research and Development; Hayes E. Ross, Jr., Professor and Research Engineer, Texas Transportation Institute, Texas A & M University System; Roger L. Stoughton, Senior Materials and Research Engineer, California Department of Transportation; Harry W. Taylor, Highway Engineer, Federal Highway Administration, Office of Highway Safety; and Maurice Witteveen, Engineer of Maintenance, Michigan Department of Transportation.

Frank R. McCullagh, Engineer of Design, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

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

PERFORMANCE AND OPERATIONAL EXPERIENCE OF TRUCK-MOUNTED ATTENUATORS

SUMMARY

Highway work zones are the site of nearly 700 deaths annually. Protective trucks are sometimes used to shield construction and maintenance activities from errant vehicles, especially for mobile operations. Truck-mounted attenuators (TMAs) are cushioning systems attached to the rear of these protective trucks to lessen the effects of collisions on errant vehicle and protective truck occupants.

This synthesis presents information on performance and use of TMAs that has been collected from state highway agencies by means of a survey and from a review of the literature. The synthesis covers physical characteristics; results of crash, vibration, and moisture tests; field experience relating to maintenance and accidents; and costs. Operational requirements and practices of users are discussed; specifically, characteristics of carrying vehicles, delineation, driver protection requirements, shadow distance, traffic volumes, and guidelines for use in various types of operations and roadways.

TMA technology has been derived from experience gained with application of roadside crash cushions. A prototype "mobile" crash cushion was built in 1972 by placing an array of 55-gallon steel drums on a low trailer. Promising results from crash tests encouraged the Texas Department of Transportation (TxDOT) to try the new device in service. Due to its size, the crash cushion trailer proved difficult to handle in many operational situations. From this experience and a desire to improve the practicality of the device, TxDOT eliminated the trailer by attaching the drum array directly to and cantilevered off the rear of a dump truck. Although not crash tested, this assembly was probably the first TMA.

In the mid 1970s, three groups, Connecticut DOT/University of Connecticut, California DOT (Caltrans), and Energy Absorption Systems, Inc. (EASI), worked somewhat independently on improving the TMA concept. The Connecticut system employed 2-ft (0.6-m) diameter steel cylinders enclosed within a telescoping box-beam frame. Caltrans, working with EASI, experimented with a vermiculite concrete system before developing a TMA composed of aluminum honeycomb cartridges in cooperation with Hexcel Corporation. After some early concept evaluation, EASI developed two TMA systems, one using foam-filled paper honeycomb cells (Hex-Foam) introduced in 1981, and a second using formed aluminum sheet metal cartridges and honeycomb cells combined in a TMA denoted as Alpha 1000, introduced in 1986. The ability to vertically pivot the TMA 90 degrees, improving the maneuverability of the TMA-equipped truck, is a feature that has been added to more recent TMA models.

The size and design of a TMA are very sensitive to collision performance requirements. If design conditions involving large errant vehicles at high impact speeds are specified, then the TMA may become too large and be operationally impractical. The first generation

of TMAs has been designed for moderate impact speeds of up to 45 mph (72 km/h). Development of TMAs able to withstand higher impact speeds is expected in the near future.

Only since 1985 has there been a sufficient number of TMAs to observe in-service capabilities and to develop application and operational procedures. Fewer than 700 TMAs were in use in 1985, with this number growing to more than 2,400 in 1991. For many highway agencies, those six years were a trial phase. The rapid growth of TMA numbers suggests their general acceptance, although there are highway agencies that have not identified a major need for TMAs.

Application of TMAs is primarily concentrated in mobile operations such as pavement striping and crack repair on high-volume roads. Use of TMAs in stationary operations is reported by several states.

In-service collision information is limited at this time and does not permit a statistical analysis; further research in this area is suggested. Some state agencies have reported a number of minor injury or property damage only accidents that might otherwise have ended in a severe injury or fatality without a TMA. Even with so few data, it is clear that TMAs are performing as intended.

CHAPTER ONE

INTRODUCTION

A truck-mounted attenuator, or TMA, is an energy absorbing safety device attached to the rear of a heavy vehicle, typically a dump truck, for the purpose of protecting motorists and workers from the consequences of rear-end collisions. Examples of a TMA mounted to a dump truck are shown in Figures 1, 2, 3, and 4.

TMAs have existed for more than 15 years, but they have become prevalent since 1985. Most TMAs are proprietary devices that are purchased from commercial companies. Without guidelines, highway agencies and other users have difficulty comparing the relative merits of different TMAs. Design, performance, and operational experience have been needed to guide potential users in the procurement and application of TMAs.

FIGURE 1 HEXFOAM TMA.

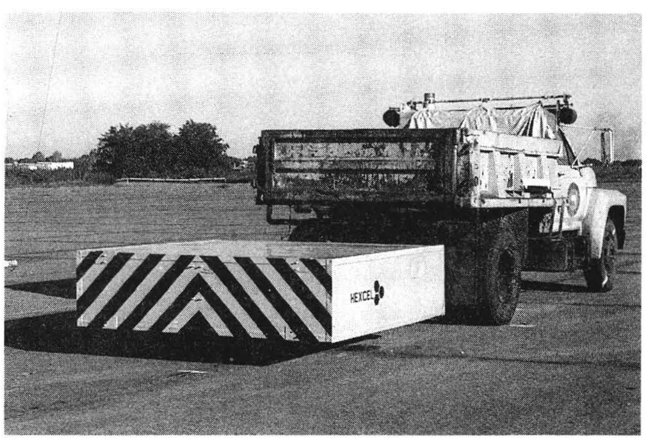


FIGURE 2 HEXCEL TMA.

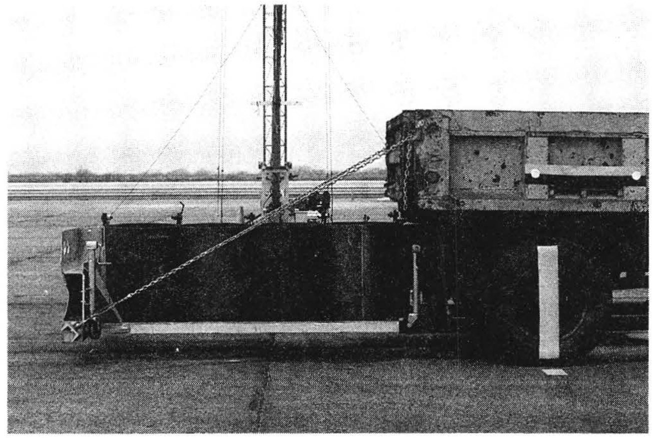


FIGURE 3 Connecticut Crash Cushion System (CCC).

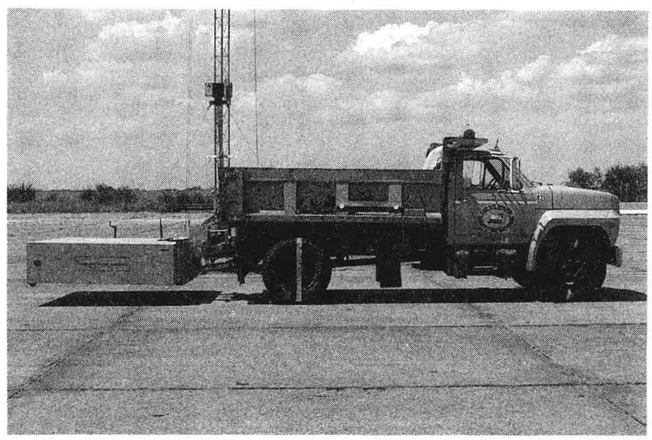


FIGURE 4 ALPHA 1000 TMA.

This synthesis presents information on physical characteristics, results of crash, vibration, and moisture tests, field experience, and costs. Operational requirements and practices of users including types of operations, characteristics of carrying vehicles, delineation, driver protection requirements, shadow distance, guidelines for use, and overall experience are also included. A glossary of TMA and work zone terms follows the reference section.

TMA PURPOSE

The primary application of TMAs is in roadway sections undergoing maintenance or rehabilitation. Approximately 140 workers and 640 motorists are killed annually, and many more are injured, due to traffic collisions in highway work zones (*1*). One major type of accident is the result of motorists running into slow-moving or stationary construction equipment even though advance warning is provided. The slow-moving or stationary equipment, such as striping or pavement repair trucks, can represent a formidable hazard even to traffic moving at reduced work zone speeds. A truck with a crash cushion mounted at the rear and positioned between traffic approaching from the rear and the work activity can reduce the consequences of such collisions for both motorists and truck drivers.

Although both drivers benefit from the cushioning effect (reduced *g* level) of the TMA, the errant motorist benefits more. Even without a TMA, the truck driver usually has a lower risk of injury due to two factors. First, the seat back and headrest combination provides good rear collision protection for the truck driver and is superior even to the full restraint protection afforded occupants of errant vehicles in frontal collisions. Second, the barrier or shadow truck typically is more massive than errant vehicles and sustains less injury-producing velocity change.

HISTORY OF TMA

In the late 1960s, with a strong national direction provided by the U.S. Safety Act of 1966 and the Blatnik Congressional Hearings in 1968, highway agencies began incorporating the "forgiving highway" principle into the highway network. Through research, roadside safety features such as longitudinal barriers and breakaway sign and luminaire supports were developed and improved. Importantly, a new safety feature called crash cushions was developed for placement at permanent and semipermanent fixed hazard sites.

With the early and dramatic success of crash cushions as reported by Viner and Boyer (*2*), the Texas Department of Transportation (TxDOT) took another step and began developing a crash cushion for temporary application. The Texas Crash Cushion Trailer, developed, tested, and reported in 1972 by Marquis and Hirsch (*3*), was perhaps the first of these devices. This early design consisted of 55-gallon steel drums welded together and mounted on a low, flat trailer which was towed behind a truck. Although functional for a head-on impact by a 4,000-lb (1800-kg) car at 60 mph (97 km/h), this early prototype proved to be awkward and difficult to handle at many job sites. However, the concept of a portable crash cushion was clearly demonstrated.

To overcome operational problems of trailering a 22-ft (6.7-m) long crash cushion, TxDOT personnel constructed a crash cushion suspended off the rear of a protective vehicle. This first-generation TMA consisted of 16 steel 55-gallon drums arranged in four longitudinal rows with four drums in each row. This device was used in the field although no vehicle crash tests were performed (*4*).

In 1975, Connecticut DOT began funding the development of a portable crash cushion that could be suspended off the rear of a dump truck. The system, developed by Carney (*5,6,7*), consisted of four 2-ft (0.6-m) diameter steel cylinders attached within a telescoping box-beam frame.

In 1975, Stoughton and Stoker (*8*) reported on crash tests at the California Department of Transportation (Caltrans) of TMAs developed by Energy Absorption Systems, Inc. (EASI). These early units were composed of vermiculite cells encased in an 8ft x 6ft x 2ft (2.4m x 1.8m x 0.6m) plywood box and suspended off the rear-end of a 10,000-lb (4536-kg) dump truck. Based on trial tests, EASI refined its design. Caltrans did a series of five successful crash tests on the revised TMA and purchased 80 of the revised units. The tests are reported in "Vehicular Impact Tests of a Truck Mounted Attenuator Containing Vermiculite Concrete Cells" (*9*).

Due to the relatively heavy weight of the revised vermiculite cell TMA and some problems with durability due to normal vehicle vibrations while traveling on the highway, the Caltrans Division of Equipment initiated a research project to develop a TMA using lighter materials. Schiefferly and Marlow of Caltrans reported in 1983 results of eight crash tests of a TMA made of aluminum honeycomb cartridges contained within a box measuring 7 ft x 7.7 ft x 2 ft (2.1 m x 2.3 m x 0.6 m) (*10*).

After earlier (1974–75) exploratory evaluation (*8*), Energy Absorption Systems, Inc. developed two TMA systems in the mid 1980s: Hex-Foam, introduced in 1981, used a matrix of hex-shaped cardboard honeycomb filled with polyurethane foam (*11,12,13*), and the Alpha 1000, introduced in 1985, which used formed aluminum sheet metal cells (*14*).

TMA technology has developed from "scratch" in about 15 years. In many ways, the design requirements for TMAs have continually changed as highway agencies have experimented with different uses and methods to integrate the devices into their routine maintenance and construction activities. Collision test evaluation procedures for TMAs were not specifically defined until publication of *NCHRP Report 230* in 1981 (*15*) and even then the procedures were only briefly discussed. Prior to 1981, TMA developers had to rely on testing guidelines applicable to crash cushions contained in *NCHRP Report 153* (*16*) and *Transportation Research Circular No. 191* (*17*). As testing and user agencies gained crash test and operational experience, the crash test procedures were modified. Reported accidents, while too few to allow statistical conclusions, generally have indicated excellent performance of TMAs developed under these early test requirements. More comprehensive vehicle crash test procedures are being developed. In addition, highway agencies have become more aware of the need for TMAs to operate for several years under adverse environmental conditions and have developed screening tests to identify the more rugged units.

State highway agency use of TMAs has increased from fewer than 100 units in 1980 to about 700 in 1985 and more than 2,400 in 1991. Operational application of TMAs varies among states from limited, flexible guidelines to comprehensive treatment in traffic control plans. It is noted that there is no mention of TMAs in the current *Manual on Uniform Traffic Control Devices* (MUTCD) (*18*). The 1983 MUTCD *Handbook* (*19*) has a sole reference to TMAs. In 1989, the AASHTO *Roadside Design Guide* briefly discussed TMAs and their general capabilities (*20*). Thus, the most authoritative documents on traffic control have only recently begun to adequately address TMAs or present guidance for their use.

TMA SYSTEMS

Designs to date, as shown in Table 1, include both industry (manufacturer) and government (developer) devices. Based on the survey conducted for this synthesis, it is estimated that two commercial companies, Energy Absorption Systems and Hexcel, together have produced about 97 percent of all TMAs. Some of the earlier Energy Absorption Systems models are not represented in Table 1; the two models shown represent part of their current TMA product line. The Hexcel crash cushion was developed by Caltrans in conjunction with Hexcel in the early 1980s in a project directed at a lower weight TMA (*10*). The Renco TMA is a recent develop-

TABLE 1
CHARACTERISTICS OF TMAs

Manufacturer \Developer	Energy Absorbing Material	TMA Cushion[a] Length ft	Width ft	Height ft	System Weight (lb)[b]	Design Capacity 1,000 ft-lb[c]
Energy Absorption Systems, Inc.						
Hex-Foam	Cardboard Honeycomb/ Polyurethane Foam	7.0	7.9	2.1	1,400	365
Alpha 1000	Aluminum Cells	6.8	7.75	1.9	700-1,100	305
Hexcel						
TMCC	Aluminum Honeycomb	7.0	7.7	2.0	1,000	305
Transpo-Safety						
Cushion Safe	Water-filled Tubular vinyl cells	2.3	7.7	2.7	3,000	not available
Renco, Inc.[d]						
Ren-Gard	Fibrous Honeycomb	7.0	7.7	2.0	1,120	305
Texas Dept of Hwy & Public Trans	Steel barrels[e]	23.0	5-10	3.0	2,010	481
Connecticut	Steel Cylinder	9.3	6.0	2.8	1,500	305

[a] To convert to m, multiply ft by 0.305.
[b] Includes various types of support assemblies. To convert to kg, multiply by 0.454.
[c] To convert to joules, multiply ft-lb by 1.356.
[d] Not currently being specified.
[e] from (*31*)

ment that may be worthy of future consideration by prospective users (*21*).

The Hex-Foam energy-absorbing cartridges are made of hexagonal paper honeycombed cells filled with polyurethane foam. Acceptable performance in several crash tests has been achieved on the Hex-Foam TMA with vehicles weighing between 1,600 and 5,400 lb (725 and 2450 kg). Impact speeds up to 48 mph (78 km/h) have been used for the 4,500-lb (2040 kg) vehicle tests.

The TMA Alpha 1000, shown in Figure 4, is an energy-absorbing cartridge mounted in a frame and encased in an aluminum shell with a cartridge weight of 350 lb (160 kg) and a system weight of 700 to 1,000 lb (320 to 450 kg). The Alpha 1000 system has been tested with 1,800- and 4,500-lb (810- and 2040-kg) vehicles at 45 mph.

The California Department of Transportation (Caltrans) assisted in the development of a lightweight TMA consisting of Hexcel aluminum honeycombed sections for absorbing energy. The unit, shown in Figure 2, is cantilevered from the rear of a maintenance truck. This is the lightest available TMA cushion with a cartridge weight of 350 lb (160 kg) exclusive of truck mounting and lift hardware. It has performed adequately in Caltrans tests at impact speeds of 45 mph (72 km/h) using vehicles weighing approximately 2,250 lb (1020 kg) and 4,500 lb (2040 kg).

The University of Connecticut, in a study for the Connecticut Department of Transportation, developed a TMA using a row of vertical steel cylinder sections mounted on a sliding support frame. The assembly of cylinder sections and support frame, shown in Figure 3 cantilevered from the rear of a maintenance truck, weighs about 1,500 lb (680 kg). When struck by a vehicle, the frame slides forward. The maximum stroke of the TMA is approximately 8 ft (2.4 m). This design has performed well during crash testing with vehicles weighing up to 4,500 lb (2040 kg) and impact speeds up to 47 mph (76 km/h).

OVERVIEW

The design principles and collision mechanics of TMAs are discussed in Chapter Two, including discussion of the roll-ahead distance of the protective vehicle. Also presented are methods to investigate the effects of fatigue and moisture on the length of service life and performance of a TMA. Operational experience of TMAs, as acquired from a survey questionnaire submitted to state highway agencies, is presented in Chapter Three. Guidelines based on information collected for this synthesis to assist highway agencies in selecting a TMA are contained in Chapter Four. Crash test evaluation procedures and typical crash test results of TMA systems are presented in Appendix A and environmental test protocols developed by California and the Texas Transportation Institute are shown in Appendix B. Appendix C contains the survey questionnaire sent to the state highway agencies together with responses received from 14 frequent users of TMAs. Recommended guidelines for operating TMA-equipped trucks, as developed by the Texas Department of Transportation, are presented in Appendix D, and Appendix E lists typical general specifications. A glossary of TMA and work zone terms follows the reference section.

CHAPTER TWO

COLLISION AND ENVIRONMENTAL DESIGN FACTORS OVERVIEW

The purpose of a TMA is to lessen the severity of collision dynamics to a level that can be tolerated by occupants of errant vehicles and protective trucks without major injury. Accordingly, human tolerance to injury-producing collision forces serves as the basis for TMA designs. The front passenger-seat occupant is generally at greater risk to injury than the errant vehicle driver, who in turn, is at greater risk than the protective truck driver. Thus, by providing TMAs that safely accommodate the unrestrained front-seat errant vehicle passenger, the collision dynamics will normally be less critical for the two drivers. Additionally, TMA systems reduce damage to the shadow vehicle, helping to keep it in service.

Occupant risk is based on the flail space model in which the unrestrained occupant moves forward during the initial stage of a frontal collision and strikes the instrument panel or windshield and remains in contact with these surfaces throughout the collision (*15,22*). Severity of the resulting injury is directly related to the velocity with which the occupant strikes the instrument panel or windshield, and to vehicle deceleration intensity during the last or "ridedown" phase. Preferred and maximum limits for occupant impact velocity are 30 and 40 ft/sec (9 and 12 m/sec), respectively. Preferred and maximum limits for ridedown decelerations are 15 and 20 *g*'s, respectively.

Most operational TMAs are proprietary and have been designed and extensively tested by their manufacturers. Commonly used TMAs generally employ the concepts of absorption of kinetic energy; a second concept, transfer of momentum, used in the design of one class of permanent crash cushions, e.g., sand drums, is used less often. The kinetic energy concept is illustrated in Figure 5 (*20*). Kinetic energy of the errant vehicle is absorbed by the "crushable" or "plastically deformable" materials of the TMA cushion. Some energy is also dissipated by the crushing of the front of the impacting vehicle and sliding/drag of the protective vehicle, but this is neglected when comparing capabilities of different TMA systems. The mechanics illustrated in Figure 5 have been simplified to show a uniform crushing force as contrasted to current TMA designs that have optimally staged crush resistance to handle a range of vehicle masses.

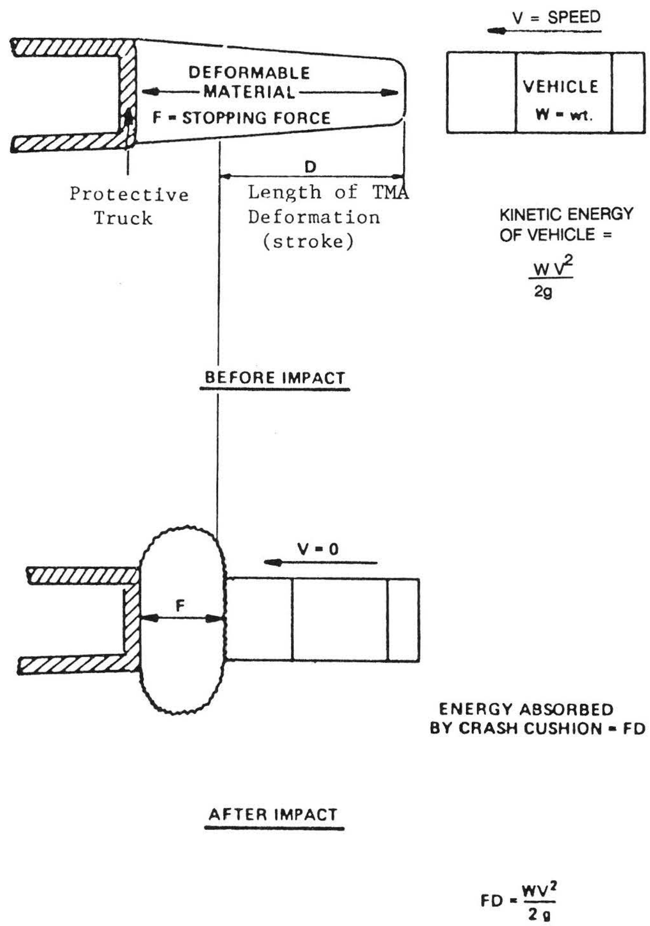


FIGURE 5 Kinetic energy principle (*17*).

COLLISION DESIGN FACTORS

Design Impact Conditions

In the design of a TMA (as well as permanent crash cushions), three principal factors of the colliding vehicle are used: mass, closing speed, and location or direction of force. Recognizing that the colliding vehicle may be a motorcycle or a fully loaded tractor-trailer, the mass can range from less than 1,000 lbs (454 kg) to more than 80,000 lbs (36 300 kg). Closing speeds can range from less than 10 mph (16 km/h) to more than the maximum legal speed of up to 65 mph (105 km/h). Force application can range from head-on to off-center, angled hits into the sides of a device. The number of possible combinations of factors is unlimited and it is not practical or economically feasible to develop devices that will accommodate every possible collision. The goal for TMA developers has been to devise systems that will perform adequately for most collisions.

TMAs that are short, for truck maneuverability, and lightweight, for ease of handling, are generally preferred. As with crash cushions, the dimensional and mass properties are affected by the range of design impact conditions. For instance, a minimum stroke distance (and TMA length) is necessary to safely decelerate an impacting vehicle; the stroke distance requirement increases with the square of the impact speed. The minimum stroke distance must be increased for heavier vehicles so as not to subject lighter vehicles to harsh deceleration forces. While it is technically possible to design TMAs for the widest range of impact conditions, the resulting size and mass properties can quickly render the TMA device as operationally impractical as the 1972 Texas Highway Department barrel trailer. It is most important that the design impact conditions are carefully selected to represent the most frequent accidents.

The first design impact conditions for TMAs were presented in 1981 in the Commentary of *NCHRP Report 230* (*15*) (updated by *NCHRP Report 350*, currently in press.) The four vehicle crash tests recommended in *Report 230* to evaluate prototype hardware are shown in Table 2. Tests 50 and 54 employ a 4,500-lb (2040-kg) sedan impacting the TMA at 0 and 10-15 degree angles, respectively, and both at 45 mph (72 km/h). Tests 51 and 52 are 0-degree impacts at 60 mph (97 km/h) for 2,250-lb (1020-kg) and 1,800-lb (816-kg) sedans, respectively. It is noted that most TMA tests have been conducted at 45 mph (72 km/h) rather than 60 mph (97 km/h); this modification is recommended in the Commentary section of *Report 230*. Special instructions for these tests include that the truck should be in second gear, and the brakes on the truck should be locked; in addition to occupant risk requirements for the impacting vehicle, the truck skid/roll-ahead distance should be reported. It is noted that truck skid/roll-ahead distance can affect crash test results, primarily the collision energy dissipated by the TMA and the occupant risk measurements. Whereas the truck in second gear with emergency brakes applied represents typical in-service conditions, one testing agency (*4*) has conducted the 1,800-lb (820-kg) car test with the truck against a rigid wall in order to standardize the test conditions; results indicated high occupant risk values for two TMA designs.

A proposed TMA crash test matrix is presented in Table 3; this table reflects test data reported in *NCHRP Report 350* (*23*). The matrix is presented for information only to alert the reader of possible pending changes. It is expected that present TMA designs can meet these test criteria for Test Level 2. However, it may be several years after the new crash test matrix is formalized before new hardware can be designed and successfully crash tested to meet the new requirements. An important difference in the revised test matrix is the addition of severity level concept to TMA. Test numbers preceded by a 2 refer to a Test Level 2 and generally correspond to the 1981 test matrix. Test numbers preceded by a 3 refer to a Test Level 3 and represent a new TMA test requirement at 60 mph (97 km/h).

Crash test evaluation procedures and a summary of results from TMA crash tests are contained in Appendix A.

Roll-Ahead Distance

Roll-ahead distance is the distance relative to the work vehicle that the protective vehicle moves during and after the collision. This is an important factor in establishing proper space between the protective vehicle and the workers. Principal factors in estimating roll-ahead distance are speed and mass of errant vehicle and mass and drag resistance of the protective vehicle; design and performance of a TMA have a secondary effect on roll-ahead distance.

The equation for roll-ahead distance for a stationary operation is the following:

$$S = \frac{(M_I + M_P)\,(V_T)^2}{2\,M_p\,g\,D} \qquad (1)$$

where

S = roll ahead distance, ft (m)
M_I = mass of impacting vehicle, slugs (kg)
M_p = mass of protective vehicle, slugs (kg)
g = gravitational constant, 32.2 fps^2 (9.8 m/s)
D = drag factor of protective vehicle, typically less than full braking
V_T = post impact speed of both impacting vehicle (V_I) and protective vehicle (V_p = 0 for stationary condition), fps (m/s)
V_I = impact speed of impacting vehicle, fps (m/s)

If V_I is impact speed of impacting vehicle and if protective vehicle is assumed stationary at impact, then

TABLE 2
TMA CRASH TEST MATRIX (*15*)

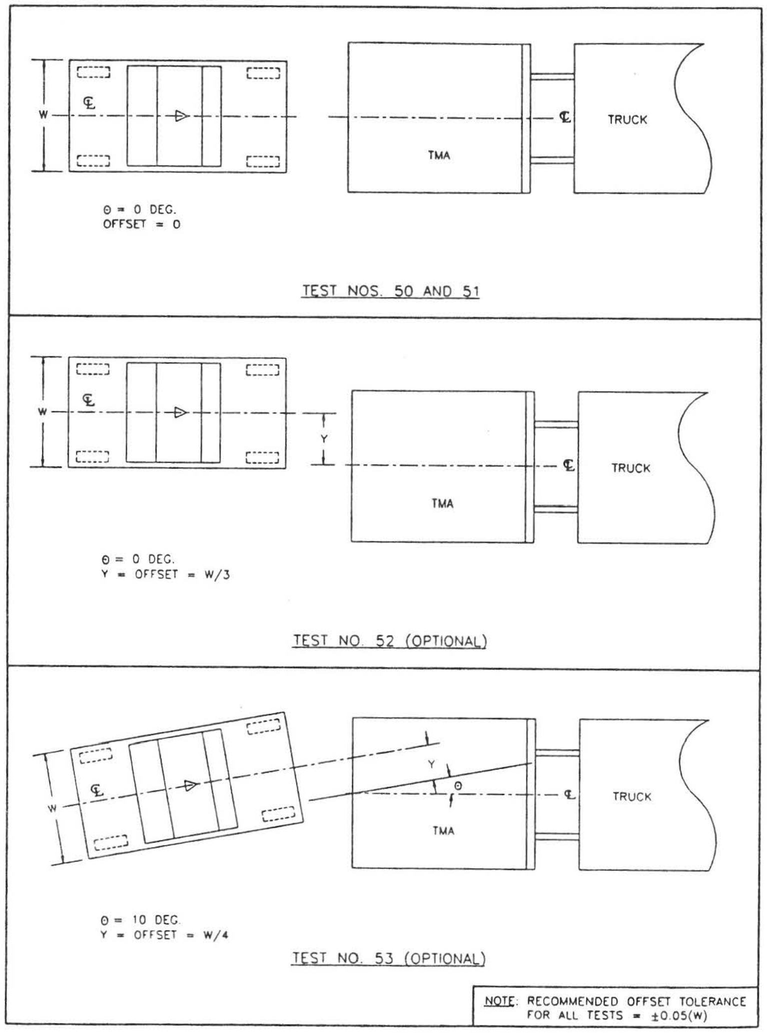
Test Number	Vehicle Type	Vehicle Wt lb(kg)	Impact speed mph(km/h)	Angle (degree)	Impact Point
50	car	4500 (2040)	45 (72)	0	Center of nose
51	car	2250 (1020)	60[a] (97)	0	Center of nose
52	car	1800 (820)	60[a] (97)	0	Center of nose
54	car	4500 (2040)	45 (72)	10-15	0-3 ft offset from center of nose

[a] Most crash tests have been conducted at 45 mph (72 km/h).
Note: TMA truck in 2d gear with rear brakes engaged.

TABLE 3
PROPOSED TMA CRASH TEST MATRIX (*23*)

Test No.	Vehicle	Veh Wt lb (kg)	Impact Speed mph (km/h)
2-50(a)	car	1800 (820)	44 (70)
52-50(a,c)	car	1540 (700)	44 (70)
2-51(b)	pickup	4400 (2000)	44 (70)
2-52(b,c)	pickup	4400 (2000)	44 (70)
2-53(b,c)	pickup	4400 (2000)	44 (70)
3-50(a)	car	1800 (820)	62 (100)
53-50(a,c)	car	1540 (700)	44 (70)
3-51(b)	pickup	4400 (2000)	62 (100)
3-52(b,c)	pickup	4400 (2000)	62 (100)
3-53(b,c)	pickup	4400 (2000)	62 (100)

a) TMA truck - against rigid barrier
b) TMA truck - rear brakes, 2nd gear
c) Optional test



$$V_T = \frac{M_I V_I}{M_I + M_p} \qquad (2)$$

Combining Equations (1) and (2) gives the following

$$S = V_I^2 \frac{(M_I)^2}{2 M_p (M_I + M_p) g D} \qquad (3)$$

From Equation (3), it can be deduced that the roll-ahead distance is reduced by (a) providing a heavy protective vehicle (M_p) and/or (b) maximizing the value of drag by locking the protective vehicle brakes and having the transmission in gear.

Experimental roll-ahead distance data are presented in Table 4 for 15 tests. All tests involved a 4,500-lb (2040-kg) vehicle impacting the protective vehicle at 45 mph (72 km/h) and 0 degrees. Three different truck restraint conditions were reported:

- Truck in second gear and with rear wheels braked;
- Neutral gear and with rear wheels braked; and
- All wheels braked.

An effective drag value was computed for each of the 15 experiments and these are shown in Table 4 and are plotted in Figure 6. It can be seen that the effective drag value ranges from about 0.2 to about 0.7 (usually lying above 0.3) and generally reflects the degree of restraint for a stationary protective vehicle. Using the 0.3 drag factor, theoretical roll-ahead distances are shown in Figure 7 for 45, 55, and 65 mph speeds (72, 89 and 105 km/h) of a 4,500-lb (2040-kg) vehicle impacting with the rear of a stationary protective truck. For reference, roll-ahead data for the 15 experimental tests shown in Table 4 are also plotted in Figure 7.

Protective vehicles as light as pickup trucks have been used in some tests and to a limited degree in operational practice, but this practice is not recommended because of the large roll-ahead

TABLE 4
ROLL-AHEAD DISTANCE FROM CRASH TESTS

Test No.	Ref. No.	TMA type	Truck Mass (lb)	Truck Resistance(1)	Roll-ahead Distance	Point No.(2)	Effective drag factor(3)
388	10	Hexcel	11,700	A	39.8	1	.18
392	10	Hexcel	5,000	B	80.0	2	.36
371	10	n/a	11,600	C	10.3	3	.71
088-06	14	Alpha 1000	12,300	A	17.5	4	.378
103-02	14	Alpha 1000	12,540	A	16.8	5	.382
012-10	11	Hex Foam	12,000	A	12.3	6	.562
078-02	11	Hex Foam	20,000	A	11.9	7	.235
71790-3	21	Renco	15,390	A	10.8	8	.415
9919-05	4	Alpha 1000	14,000	A	14.8	9	.357
9910-4	4	Hex Foam	14,000	A	8.3	10	.637
9919-02	4	Hexcel	14,000	A	9.8	11	.540
9919-04	4	Renco	14,000	A	7.9	12	.67
9919-03	4	Mark & Equip	14,000	A	13.8	13	.383
9910-10	4	CCC	14,000	A	12.6	14	.420
9910-16	4	n/a	14,000	A	10.8	15	.490

Note: All crash tests: 4,500 lb (2040 kg) car at 45 mph (72km/h) and 0 deg
(1) Truck restraint:
A--rear parking brakes, 2d gear
B--rear parking brakes, neutral
C--all wheels braked
(2) Keyed to points plotted in Figures 6 and 7
(3) From equation 3, see text

distance and increased risk to the pickup truck driver compared to the driver of heavier protective trucks.

For a slow- or fast-moving mobile operation, a shadow vehicle will be following a working vehicle, both moving at the same speed, with some minimum safe distance between the two vehicles. If the shadow vehicle, equipped with a TMA, is struck from the rear, it will roll ahead (based on the standard transfer of momentum equation) a distance of:

$$S = \frac{(M_I V_I + M_p V_p)^2}{2 M_p g D (M_I + M_p)} \tag{4}$$

It is assumed that the shadow vehicle drag will be provided only by transmission and rolling resistance, and that the driver's foot is off the gas pedal, but not on the brake pedal during the collision sequence. A reasonable drag factor for this condition would be D = 0.1, which is less than the drag factor if the wheels are braked and not turning where the drag factor is expected to be at least D = 0.3. However, total roll-ahead distance is not the critical distance because it is assumed that the working vehicle will keep moving at a constant speed. The critical distance, then, is the shadow distance or the reduction in distance between the moving shadow and working vehicles. Immediately after impact the shadow vehicle will be accelerated closer to the working vehicle, but will gradually fall back as the drag forces slow it to a stop. This shadow distance is calculated by using the closing speed for V_I in equation (3) (i.e., speed of impacting vehicle less the speed of the protective vehicle).

$$S = \frac{[M_I (V_I - V_p)]^2}{2 M_p g D (M_I + M_p)} \tag{5}$$

In a mobile operation, the longitudinal spacing between the shadow

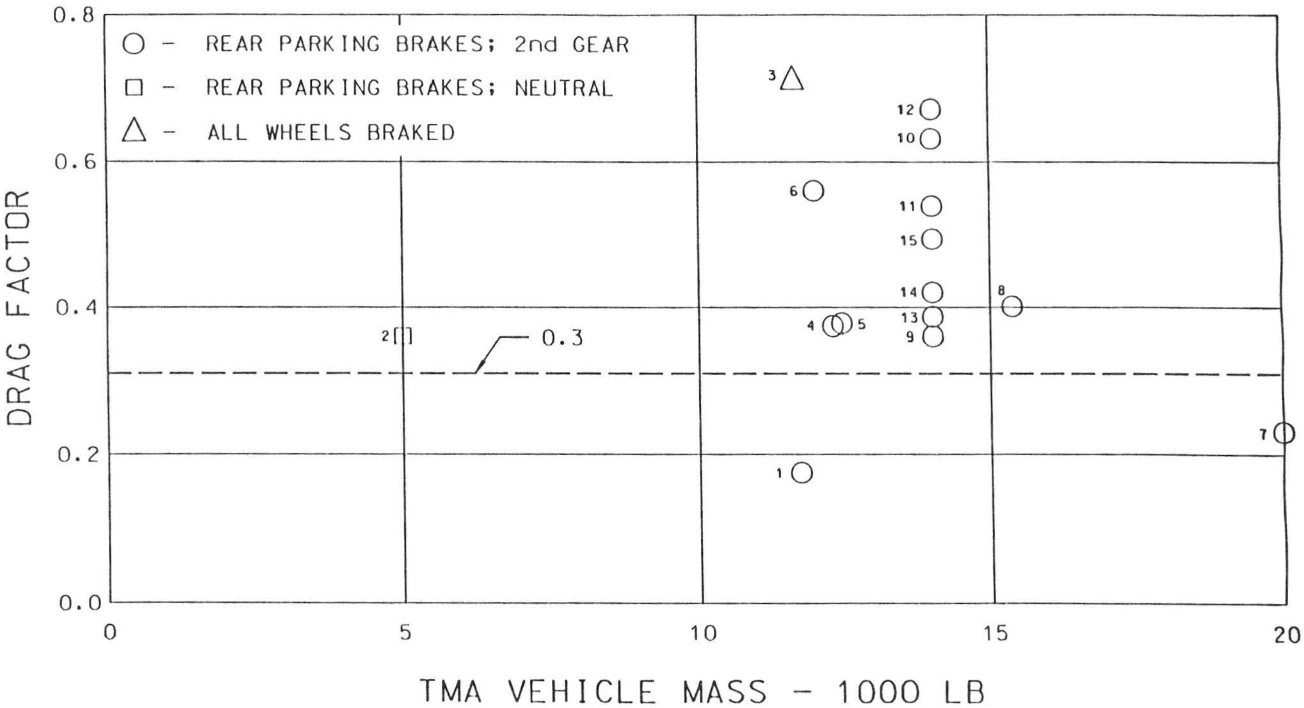


FIGURE 6 Effective drag factors from test data.

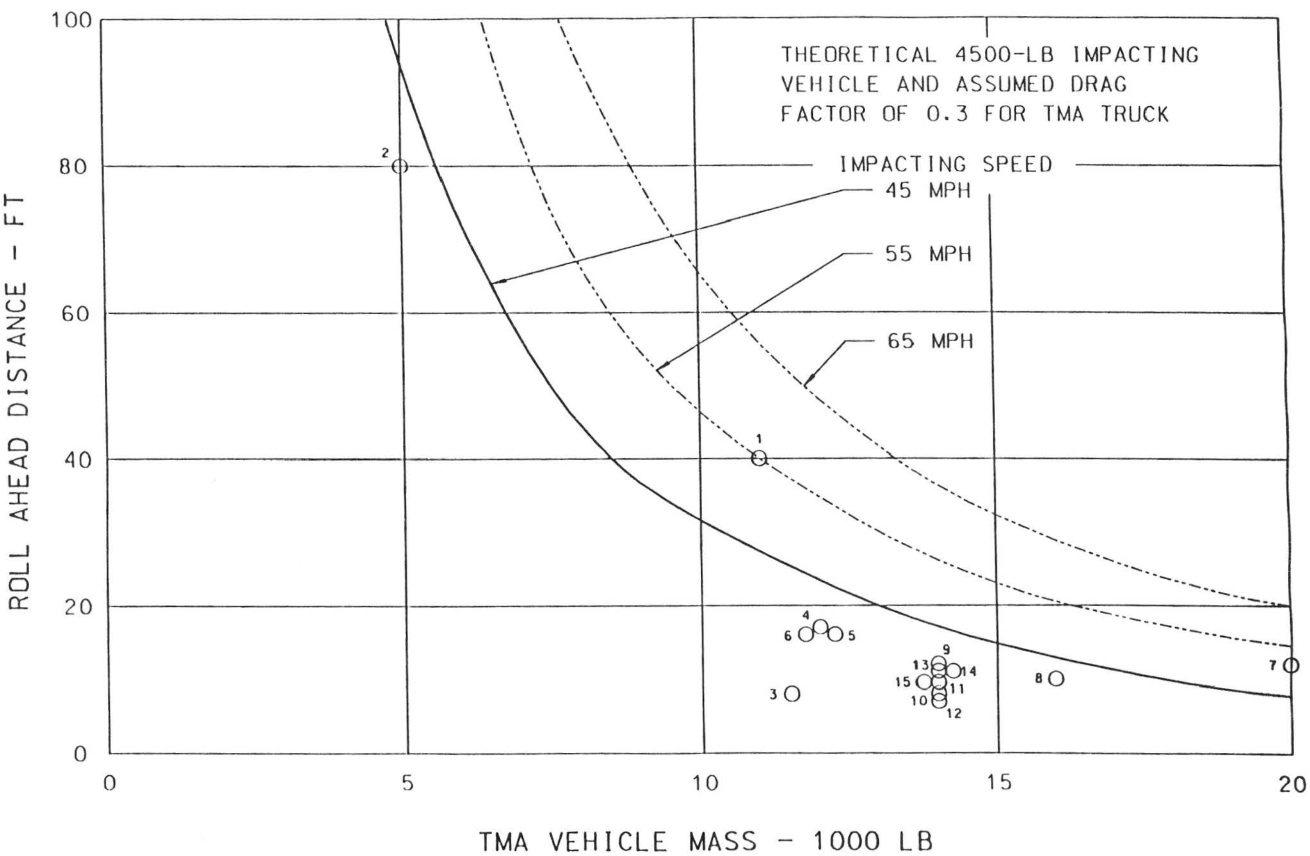


FIGURE 7 Comparison of theoretical and experimental roll-ahead distance for stationary operations.

and working vehicles should exceed the reduction in the spacing caused by the collision, i.e., it should be more than the shadow distance calculated in equation (5).

In Figure 8, reduction in spacing is shown graphically for a range of impact conditions; the impacting vehicle is assumed to weigh 4,500 lb (2040 kg) and the shadow vehicle is assumed to decelerate back to pre-impact speed due to transmission and rolling resistance (but no braking) with a drag factor of 0.1. For example, reduction in spacing would be about 95 ft (25 m) for a 4,500-lb (2040-kg) car traveling at 60 mph (97 km/h) and striking a 10,000-lb (4536-kg) shadow vehicle moving at 15 mph (24 km/h) (i.e., closing speed of 60 minus 15 or 45 mph (72 km/h)). The spacing reduction would be less for a larger mass shadow truck, a lower closing speed, or a larger drag due to shadow truck braking. Other considerations in establishing longitudinal spacing between the shadow and working vehicles involve sight distance and close spacing to deter traffic from entering the space.

ENVIRONMENTAL DESIGN FACTORS

The TMA will be subject to adverse operational and climatic conditions during its service life attached to the rear of a protective vehicle. To be effective, the TMA must sustain these conditions without compromising the collision-performance capabilities. Although there are several factors that could degrade the TMA's collision performance, the most important have been identified as road-induced vibration fatigue and moisture retention. A third environmental factor is corrosion due to salt spray. California was the first state to develop fatigue, moisture, and corrosion tests to

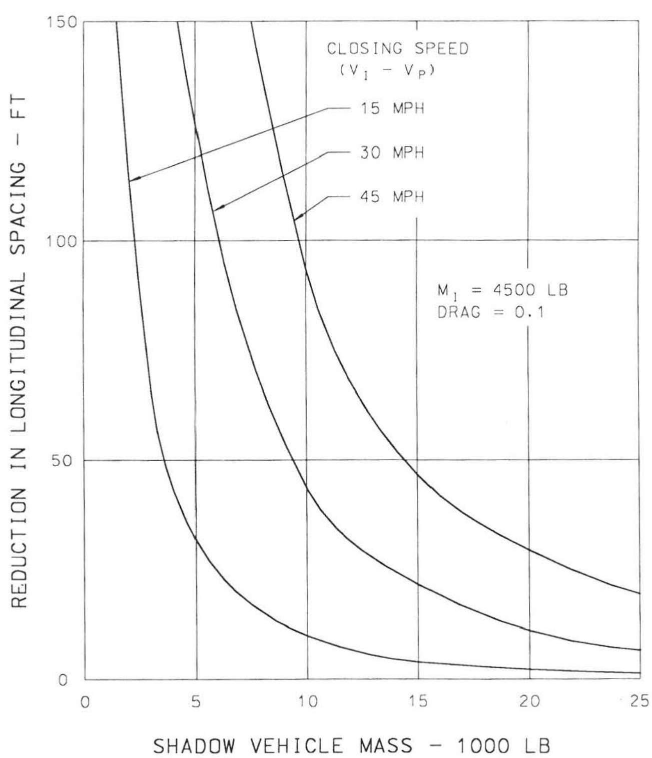


FIGURE 8 Theoretical reduction in spacing between shadow and working vehicles for mobile operations.

evaluate TMAs; these requirements are shown in Caltrans Specification Number 90002-406-91 (*24*). In 1991, the Texas Transportation Institute (TTI) developed modified versions of the Caltrans tests (*25*). A more detailed description of the environmental test is contained in Appendix B.

The relationship between environmental tests and evaluation criteria and TMA in-service failures has not been established conclusively. It is unknown whether these tests are too harsh (i.e., needlessly eliminating some promising TMA systems) or too lax and unable to identify deficient TMA systems. Until such a relationship is established, the highway agency may wish to consider environmental tests, but should exercise caution in interpreting the results.

Fatigue Evaluation

California Vibration Test (*25*)

California vibrates the TMA cushion assembly at a constant frequency between six and eight cycles per second (Hz) and a constant amplitude of 0.60 in. (1.5 cm) (peak-to-peak) in three different orientations: horizontal, 60 degrees, and vertical. Each orientation is evaluated for a duration of 40 hours, about 1 million cycles. At the end of the tests, the unit is inspected and measured for any physical damage or position change greater than 0.50 in. (1.3 cm).

The TMA is attached at the end of a 139-in. (353-cm) long lever with the 0.60-in. (1.5-cm) amplitude controlled at the interface of the TMA cartridge and the back-up support structure. At the rear-end of a typical 84-in. (213-cm) long TMA, the amplitude is increased by the ratio of (139 + 84)/139 or 1.6, giving a 0.96-in. (2.4-cm) peak-to-peak amplitude.

TTI Vibration Test (*4*)

In contrast to the 139-in. (353-cm) pivot arm, the TTI vibration tester moves the TMA vertical mounting plate in a vertical plane through a peak-to-peak amplitude of 0.60 in. (1.5 cm). Thus, assuming a completely stiff TMA, the rear of the TMA also experiences an amplitude of 0.60 in. (1.5 cm). In contrast to the 6 to 8 Hz frequency range in the Caltrans test, TTI has selected a single 7-Hz frequency with only the horizontal TMA orientation being fatigued for a 40-hour duration. At the end of each day and at the conclusion of the 40-hour test, the vibration is interrupted and the TMA is examined for structural damage. In particular, vertical sag measurements between each side of the rear of the TMA are determined and a drop of 0.5 in. (1.3 cm) or more for either side is deemed a failure.

Moisture Tests

California Moisture Test

In the Caltrans test, the TMA assembly oriented in a normal horizontal position is sprayed with water representing a rainfall of 6 in. (15 cm) per hour for a period of 24 hours. The assembly is then inverted and the water spray is repeated for a second 24-hour period. If, at the conclusion of the 48 hours and a one hour drain and dry period, the assembly is deemed to be "free of water," it is judged to have passed the test.

TTI Moisture Test (25)

The TTI test calls for the TMA cushion assembly in a normal horizontal position to be subjected to a water spray representing a 6-in. (15 cm) per hour rain for a test duration of 24 hours. At the end of the test, the TMA assembly is permitted to drain and dry for a period of 1.0 hour. A TMA passes the moisture test if the weight of the unit does not increase by more than 5 percent. For example, a TMA unit weighing 400 lbs (181 kg) cannot retain more than 20 lbs (9 kg) of water.

Corrosion Tests

Corrosion evaluation generally concerns the degradation of the cushion material due to a salt spray, with any visible damage noted at the conclusion of 24 hours being reason to reject the candidate TMA. The American Society for Testing and Materials B 117-73 *Method of Salt Spray (Fog) Testing* is the most referenced state procedure. Not all state agencies require the corrosion test.

CHAPTER THREE

OPERATIONAL FACTORS

This chapter presents operational experience of state agencies with TMAs, principally over the past six years. Other TMA users, such as city and county agencies, toll-road authorities, and contractors were not surveyed, although the findings from state agencies, the predominant TMA users, may be useful to other agencies.

Of 51 highway agencies surveyed, 39 returned completed questionnaires; these are denoted by either L (low user) or H (high user) in Table 5. Information gathered in a phone survey conducted by Syro Steel Company provided the number of TMAs in service (P) for 10 of the remaining 12 states; two states did not respond.

Each of the 14 high-user (H) agencies reported at least 30 TMA units in use in 1991, with an aggregate total of 2,077; this number represents about 85 percent of all units currently in state agency use. In 1985, these same 14 agencies had 641 units or about 98 percent of the total. It appears that 14 of the 51 state agencies had a majority of the TMAs in service over the past six years. These 14 agencies, identified by H in Table 5, were selected as a basis for the analyses presented in this chapter.

The survey questionnaire and responses from the selected 14 state highway agencies are contained in Appendix C.

INITIAL INSTALLATION AND MAINTENANCE

More than half (59 percent) of TMAs are attached to a dedicated truck. Typically, state personnel attach the mounting assembly to a truck using a manufacturer's design fixture. This attachment involves welding the framework to the understructure of the protective truck and requires about two persondays of effort. Generally, the material cost of the attachment fixture is included in the purchase price of the TMA.

Routine Attachment and Detachment of TMAs

Although the reported time and personnel required to attach and detach a TMA ranged from one person/ten minutes to two persons/one hour, the majority of reported practice required about one person for fifteen minutes to either attach or detach a TMA from a protective truck.

TMA Maintenance

Eleven of 14 states, representing 72 percent of the total 2,077 TMAs (1,500 units), indicated that less than one personhour was spent each month in maintaining each TMA; no particular type of maintenance problem was identified by this group. Two states indicated spending between one and four personhours per month to maintain each TMA; one maintenance problem was the replacement of cylinders in the Connecticut Crash Cushion (CCC) unit. One state required more than four personhours per month in maintaining each TMA with principal problems involving the lifting mechanism and operational damage.

Protective Trucks

Nearly all (90 percent) of protective vehicles are dump trucks with gross vehicle weight capacity (GVW) ranging from 22,000 to 38,000 lb (10 000 to 17 000 kg); the operational mass of these vehicles is typically in the 12,000- to 16,000-lb range (5440 to 7250 kg). The remaining protective vehicles are flat bed trucks (8 percent) and others (2 percent).

More than half (58 percent) of protective trucks are dedicated to carry a TMA. The personhour requirement of 0.25 hr to attach and detach a TMA is small and provides flexibility for scheduling even dedicated TMA protective trucks for non-TMA related activities.

Lift Mechanism

Most states now use TMAs that can be rotated upward to facilitate truck maneuvering in restricted space and over rough terrain and to minimize storage space requirements. The lift mechanisms have either a manual latch or a hydraulically operated latch in the truck cab and at the unit to lock the raised or lowered unit in position. These systems should only be lowered from the back of the truck to prevent injuries to motorists or personnel behind the unit.

Currently the CCC unit does not have this tilt-up capability, in contrast to the EASI and Hexcel designs.

At least one state, Texas, has an established policy that TMAs should be in the "down" or "horizontal" position whenever the TMA-equipped truck is operating in traffic, regardless of whether or not the truck is on station or moving to or from the job site. This policy was believed to have been developed due to concerns of unnecessary liability exposure of TMA trucks during transit with the TMA unit in the non-active "up" mode. This practice is also recommended by at least one TMA manufacturer.

USAGE

TMAs are used in mobile operations, either for moving or intermittent activities, by all of the 14 states highest in TMA usage. The predominant use is for pavement striping, crack pouring, sweeping, chemical spraying, and luminaire relamping operations. Six states use TMAs in stationary activities including guardrail, median barrier, and glare-screen repairs. Two experimental applications of TMAs are shown in Figures 9 and 10. In Figure 9, a TMA used

TABLE 5
NUMBER OF TMAs IN SERVICE

		1991 NCHRP Survey TMA Units				Other Surveys TMA Units	
		High Users		Low Users			
	Response (1)	1985	1991	1985	1991	1991	
Alabama	L	-	-	1	25	-	
Alaska	L	-	-	0	1	-	
Arizona	L	-	-	0	1	-	
Arkansas	L	-	-	0	2	-	
California	H	430	580	-	-	-	
Colorado	L	-	-	5	6	-	
Connecticut	H	12	60	-	-	-	
Delaware	L	-	-	0	3	-	
Florida	P	-	-	-	-	154	
Georgia	H	20	36	-	-	-	
Hawaii	L	-	-	0	0	-	
Idaho	P	-	-	-	-	-	
Illinois	H	2	30	-	-	-	
Indiana	N	-	-	-	-	-	
Iowa	H	6	63	-	-	-	
Kansas	P	-	-	-	-	4	
Kentucky	H	0	62	-	-	-	
Louisiana	L	-	-	0	2	-	
Maine	L	-	-	0	2	-	
Maryland	L	-	-	0	8	-	
Massachusetts	L	-	-	0	2	-	
Michigan	P	-	-	-	-	-	
Minnesota	H	11	44	-	-	-	
Mississippi	L	-	-	0	5	-	
Missouri	H	0	228	-	-	-	
Montana	L	-	-	0	1	-	
Nebraska	L	-	-	0	17	-	
Nevada	L	-	-	0	14	-	
New Hampshire	L	-	-	1	1	-	
New Jersey	H	32	110	-	-	-	
New Mexico	P	-	-	-	-	2	
New York	H	40	220	-	-	-	
North Carolina	P	-	-	-	-	23	
North Dakota	L	-	-	0	5	-	
Ohio	P	-	-	-	-	25	
Oklahoma	P	-	-	-	-	2	
Oregon	L	-	-	1	15	-	
Pennsylvania	H	0	256	-	-	-	
Rhode Island	L	-	-	0	1	-	
South Carolina	L	-	-	0	2	-	
South Dakota	P	-	-	-	-	4	
Tennessee	H	33	38	-	-	-	
Texas	H	45	89	-	-	-	
Utah	L	-	-	8	8	-	
Vermont	L	-	-	0	0	-	
Virginia	H	10	261	-	-	-	
Washington	L	-	-	0	15	-	
West Virginia	P	-	-	-	-	8	
Wisconsin	N	-	-	-	-	-	
Wyoming	L	-	-	0	1	-	
Puerto Rico	L	-	-	-	0	-	TOTAL
	Year: 1985	641		16			657
	%	98		2			100
	Year: 1991		2077		137	225	2439
	%		85		6	9	100

(1)L-less than 30 units in 1991; H - more than 30 units in 1991; P - oral partial response to survey; N - no response

with a salt-spreader truck, was evaluated in the Strategic Highway Research Program (SHRP) (*26*). In Figure 10, a TMA is attached to a sweeper.

Virginia has required use of TMAs since 1990 on all limited-access highways and on all four- or more lane highways with speeds in excess of 45 mph (72 km/h) for the following operations: pavement marking, stationary lane closures, other mobile maintenance operations occupying all or part of a lane, and other situations where the district or traffic safety engineer feels such protection is warranted.

Several states provided traffic-control plans in which TMAs are used for both advance-warning and shadow trucks in contrast to prior applications in which only the shadow truck is TMA-equipped. This dual use immediately doubles the TMA inventory requirements for an agency and may be cost beneficial, although this determination has not been addressed in the literature.

The more prevalent situation is where a highway agency has a limited number of TMAs necessitating that they be assigned to activities where they will be most effective. Humphreys and Sullivan (*27*), developed a ranking method for assigning TMAs based

FIGURE 9 TMA Application with salt-spreader vehicle. (Courtesy SHRP)

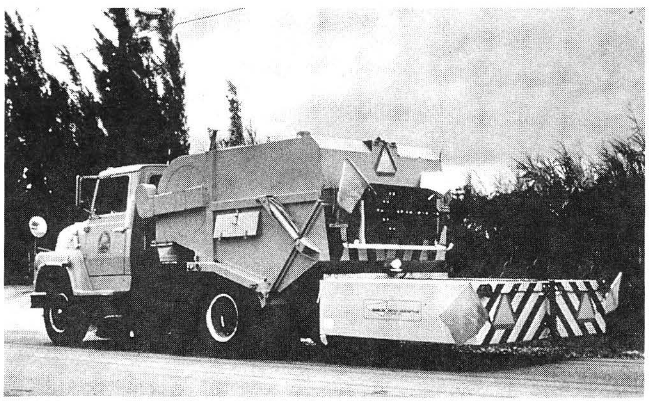


FIGURE 10 TMA Application with sweeper. (Courtesy EASI)

on type of maintenance activity, highway class, and speed limit; a summary of their findings is presented in Table 6. Basically, work zone activities are divided into mobile or stationary and shoulder or lane closure. The alphanumeric ranking gives priority first for need of a protective vehicle and second for the need of a TMA. More frequent use of TMAs than is indicated in Table 6 may be beneficial.

In 1990, Minnesota DOT (*28*) developed guidelines for TMA applications based on analysis of 32 collisions. The MnDOT priority array is a function of types of highway and operation and traffic volume. According to the guidelines, TMAs should be used with:

- Trailing or shadow vehicles used for moving operations on all multilane divided highways.
- Trailing or shadow vehicles used for mobile operations on all multilane divided highways.
- Barrier vehicles for all lane closures on multilane divided routes with 30,000 or greater average daily traffic (ADT).
- Barrier vehicles for all lane closures on multilane divided routes with 10,000 to 29,999 ADT.
- Barrier vehicles for all lane closures on multilane routes with 2,000 to 9,999 ADT.

Minnesota's recommendations (*28*) were the only ones to use ADT as an application guide.

TRAFFIC-CONTROL PLANS

Along with their survey responses, several state highway agencies submitted their standards for traffic-control plans using TMAs. The TxDOT traffic-control plans for moving operations were revised in 1991 [i.e., TCP(3-1,-2,)-91] and provide guidance for the more prominent TMA applications. Excerpts taken from these standards (*29,30*) are presented in Figures 11 and 12; terminology of the excerpts has been modified so that definitions of trail and advance warning vehicles are consistent with the glossary of terms in this synthesis.

Four- or More Lane Divided Highway

In Figure 11, the number and spacing of protective vehicles is illustrated for mobile activities on divided multilane highways. A mobile traffic-control plan is shown in Figure 11a for a four-lane configuration and in Figure 11b for a six- or more lane highway. The shadow truck is positioned about 60 to 100 ft (18 to 30 m) behind the working truck. This distance should equal or exceed the collision roll-ahead distance of the shadow truck. However, this spacing should be kept to a minimum to discourage traffic from moving around the shadow truck and in behind the work truck.

For the four-lane divided highway (Figure 11a) an advance-warning truck is spaced about 1,500 ft (460 m) behind the shadow truck; this distance varies during a work operation based on sight distance, speed limit, and entrance ramps. Where adequate shoulder width is available, the advance-warning truck should drive fully on the shoulder. On high-speed roadways, a third protective vehicle or trail vehicle may be used. In this case, the shadow vehicle would be in the closed lane, the trail vehicle would straddle the edge line and the advance-warning vehicle would be on the shoulder. However, the straddling vehicle may be more susceptible to offset impacts.

For a six- or more lane divided highway, a mobile traffic-control plan is shown in Figure 11b. In this case, work is being performed on an interior lane with traffic being routed to the inside and outside lanes. In addition to the shadow truck and advance-warning truck, a trail vehicle is illustrated.

Two-Way Roadway

In Figure 12, number and spacing of protective vehicles are shown for a two-way roadway with paved shoulders. Spacing between the working and shadow vehicles is maintained between 60 and 100 ft (18 and 30 m). An advance-warning truck is spaced about 1,500 ft (460 m) from the shadow truck. When work is performed on the travel lane, a lead vehicle may be positioned about 60 to 100 ft (18 to 30 m) in advance of the working vehicle to provide advance warning for opposing traffic; need for the lead vehicle is optional and is based on prevailing roadway conditions, traffic volume, and sight-distance restrictions.

General information that is provided with Figures 11 and 12 includes the following notes (*29, 30*):

1. The Engineer will determine if the LEAD VEHICLE and/or TRAIL VEHICLE are optional based on prevailing roadway conditions, traffic volume, and sight distance restrictions.
2. All traffic control devices shall be in accordance with the *Manual on Uniform Traffic Control Devices*, latest edition.

TABLE 6
SUGGESTED PRIORITIES FOR THE APPLICATION OF PROTECTIVE VEHICLES AND TRUCK-MOUNTED ATTENUATORS (*20*)

Closure/Exposure Condition	Examples of Typical Construction/ Maintenance Activities	Ranking*			
			Non-Freeway with Speed Limit		
		Freeway	≥50 mph	40-45 mph	≤35 mph
Mobile Activities:					
No Formal Lane Closure					
Shadow Vehicle for Operation Involving Exposed Personnel	Crack pouring, patching, utility work, striping, coning	A-1	A-2	A-3	A-4
Shadow Vehicle for Operation Not Involving Exposed Personnel	Sweeping, chemical spraying	E-1	E-2	E-3	E-4
No Formal Shoulder Closure					
Shadow Vehicle for Operation Involving Exposed Personnel	Pavement repair, pavement marking, delineator repair	B-2	B-3	C-3	C-3
Barrier Vehicle for Operation Not Involving Exposed Personnel	Open excavation, temporarily exposed bridge pier	E-2	E-3	E-4	E-5
Stationary Activities:					
Formal Lane Closure					
Barrier Vehicle for Operation Involving Exposed Personnel	Pavement repair, pavement marking	B-2	B-3	C-4	D-5
Barrier Vehicle for Condition Involving Significant Hazard	Open excavation	E-2	E-3	E-4	E-5
Formal Shoulder Closure					
Barrier Vehicle for Operation Involving Exposed Personnel	Pavement repair, pavement marking, guardrail repair	C-3	C-4	D-5	D-5
Barrier Vehicle for Condition Involving Significant Hazard	Open excavation	E-3	E-4	E-5	E-5

*The ranking letter indicates the priority assigned to the use of a protective vehicle. The use of protective vehicles:
A - is very highly recommended
B - is highly recommended
C - is recommended
D - is desirable
E - may be justified on the basis of special conditions encountered on an individual project when an evaluation of the circumstances indicates that an impact with a protective vehicle is likely to result in less serious damage and/or injury than would impact with a working vehicle or the hazard

*The numerical rank indicates the level of priority assigned to the use of a TMA on an assigned protective vehicle. The use of a TMA under the defined conditions:

1 - is very highly recommended
2 - is highly recommended
3 - is recommended
4 - is desirable
5 - may be justified on the basis of special conditions encountered on an individual project

3. The use of blue and/or yellow rotating beacons or strobe lights on vehicles is optional unless otherwise stated elsewhere in the plans.

4. The use of TMA on the SHADOW VEHICLE, TRAIL VEHICLE or ADVANCE WARNING VEHICLE is optional unless otherwise stated elsewhere in the plans.

5. Flashing Arrow Panels shall be Type B or Type C. The panel operation shall be controlled from inside the vehicle.

6. Each vehicle shall have two-way radio communication capability.

7. Vehicle spacing between ADVANCE WARNING VEHICLE and TRAIL VEHICLE or SHADOW VEHICLE will vary depending on sight distance restrictions. Motorists approaching the work convoy should be able to see the ADVANCE WARNING VEHICLE in time to slow down and/or change lanes as they approach the ADVANCE WARNING VEHICLE.

The traffic-control plans contained in this section are for illustration only and are not suggested guidelines or standards.

APPLICATION INSTRUCTIONS

For training personnel in proper use of TMAs, four techniques are employed by the states: classroom instructions, written manu-

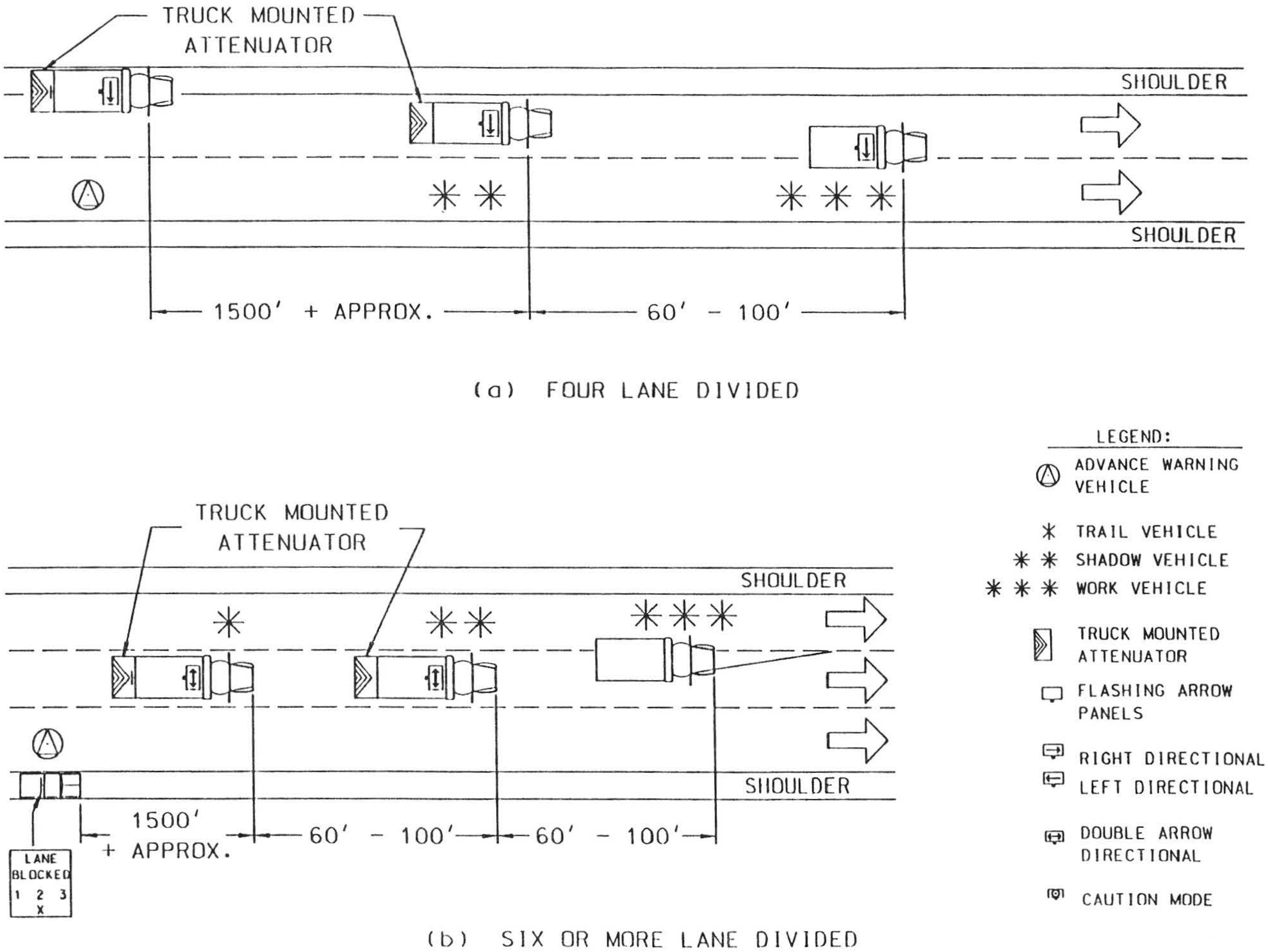


FIGURE 11 Traffic control plan for mobile activities on divided multilane highway (from *29*).

als, video tapes and oral instructions, and on-job training (OJT). Four of the 14 states with highest TMA usage applied all four techniques. Responses from nine of the other states indicated that, in various combinations, six provide OJT, five use classroom instruction, four show video tapes, and three provide manuals. The states that use video are California, Illinois, Iowa, Kentucky, Minnesota, Pennsylvania, and Texas. One of the 14 used only oral instructions. These responses indicate that most of the 14 states use some type of formal instructions for implementing TMAs into their operations.

The Texas Department of Transportation has developed interim operating recommendations for TMAs. As an example of how one state provides guidance to personnel, these recommendations are reproduced in Appendix D.

Roll-Ahead/Shadow Distance

The roll-ahead or shadow distance is the space between the protective vehicle and the work activity and provides for a relative roll-ahead, post-collision movement of the protective vehicle. When a trail vehicle is used, the roll-ahead distance is a factor in spacing the trail vehicle behind the shadow vehicle. This distance is typically a compromise between anticipated roll-ahead movement and excessive space that would permit traffic to move into the space. Other factors that must be considered are the horizontal and vertical highway alignment and traffic speed. Some states report this roll-ahead or shadow distance as ranging from 50 to 200 ft (15 to 60 m).

Driver Protection Procedures

The TMA vehicle operator should receive adequate training for TMA inspection and operational recommendations, pre-crash and "ridedown" recommendations, and warning recommendations. The operator should be alerted to expect the following if the TMA vehicle is rear-ended: sudden and unpreventable TMA forward movement, and a crash duration of about 0.2 seconds plus time to stop the TMA vehicle. TxDOT's recommendations suggest that the TMA operator should be prepared at all times for an unexpected rear-end collision by:

- Having the seat belt properly buckled,
- Maintaining head alignment with the head restraint,
- Maintaining proper rear view mirror adjustment,
- Being aware of the probable effects of a collision, and

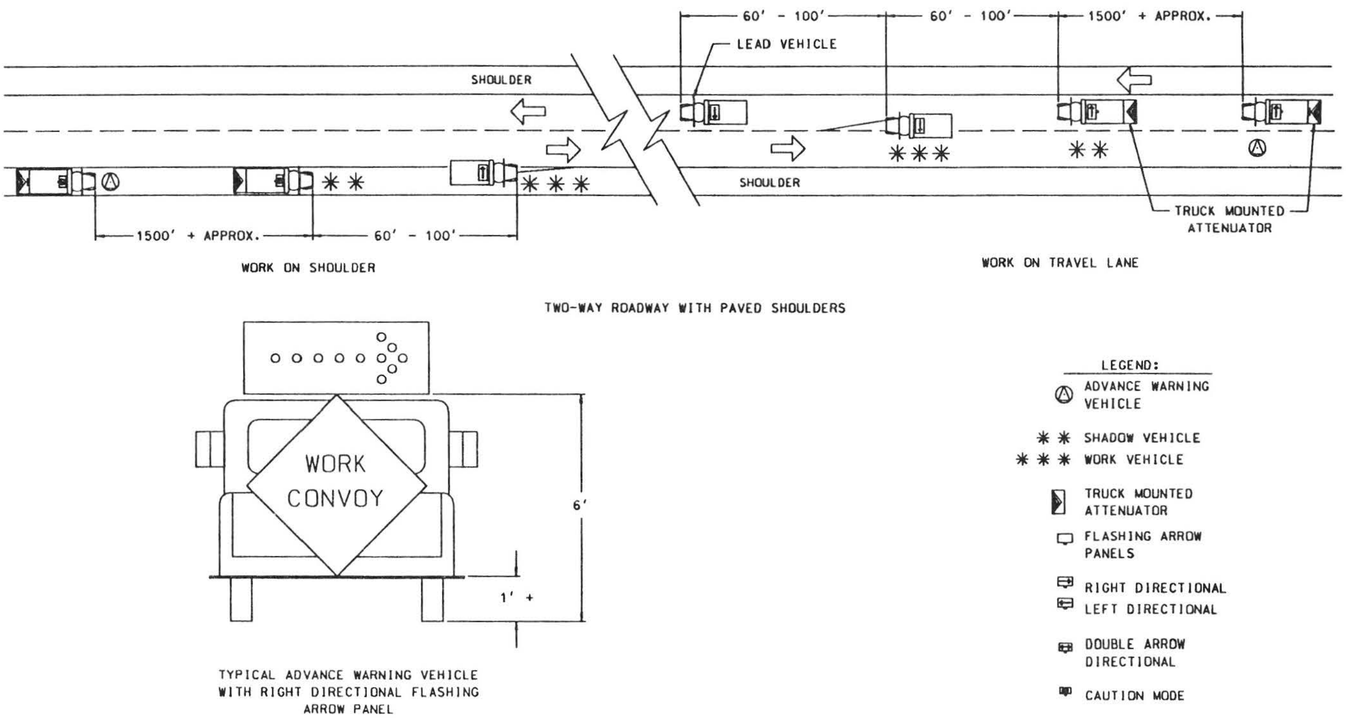


FIGURE 12 Traffic control plan for mobile activities on two-way, two-lane highway (from *30*).

• Being aware of the need to immediately regain control over the TMA vehicle after impact and then bring it to a safe stop.

Of course, it is important for the TMA vehicle driver to be alert at all times to conditions and events in the work zone, as well as to approaching traffic. If there is advance warning of an impending collision from the rear, TxDOT advises the TMA vehicle operator to:

• Alert co-workers by sounding the horn,
• Position head against the head restraint,
• Take foot off the accelerator,
• Position foot over the brake pedal in preparation for braking after impact, and
• Remain alert and attentive to the need for control of the TMA vehicle during and after impact.

For stationary operations, the TMA-equipped truck should not be occupied or the driver positioned anywhere within the roll-ahead space. Truck drivers following these guidelines are at low risk of being involved in a collision. The parked vehicle should have the engine off, the transmission in second gear, rear axle in lowest range, and the emergency brake applied. A TMA-equipped truck is shown in Figure 13 for a stationary operation; note that front wheels are turned to the left away from traffic. Turning the front wheels should be based on specific conditions at the site such that the after-impact trajectory is into a safe area.

In moving operations, drivers of shadow vehicles bear minimal risk of being injured in a rear-end collision. This risk is moderated by (a) the rear-end nature of the collision and the support and protection provided by the truck bed and seating structure and (b) the relative massiveness of the protective truck, typically in the 22,000-lb (10 000-kg) GVW range or higher. Nevertheless, the driver who is seated at time of collision, whose head is positioned against a properly adjusted headrest and who is properly restrained by lap and shoulder harness will reduce even this small risk of injury.

Delineation

Hanscom and Pain (*32*) reported a large variation in the methods states use to provide delineation for protective vehicles and in the degree of effectiveness of the various methods. They expressed concern with this lack of uniform treatment and the possible confu-

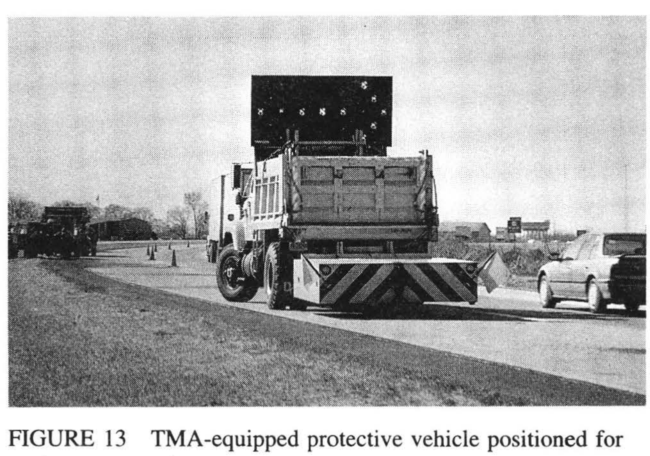


FIGURE 13 TMA-equipped protective vehicle positioned for stationary operation.

sion caused to interstate motorists and suggested that this area should be addressed by the MUTCD. One of the findings of the study conducted by Hanscom and Pain is that the arrow board is effective in alerting and conveying the message to approaching motorists, but that overuse of arrow boards might reduce their effectiveness.

Of the 14 states with high TMA usage, 10 use arrow boards on the protective truck. Three states use chevron markings for both up and down positions of the TMAs. Other methods include flasher lights, lights and reflective markings, and flags and signs, in various combinations.

With regard to the TMA, the manufacturers have encouraged a standardized color scheme—yellow with black hash marks. The delineation patterns are illustrated in Figures 1, 2, 3, and 4. Black and orange- or black and yellow-striped markings are the most common. A manufacturer reports that about 50 percent of the states use their standard yellow with black striping pattern as shown in Figures 14 and 15. The treatment of the underside of a TMA has considerably more variation. While most states did not specify, it is presumed that the standard vehicle running lights are on when the TMA is in either the up or down mode.

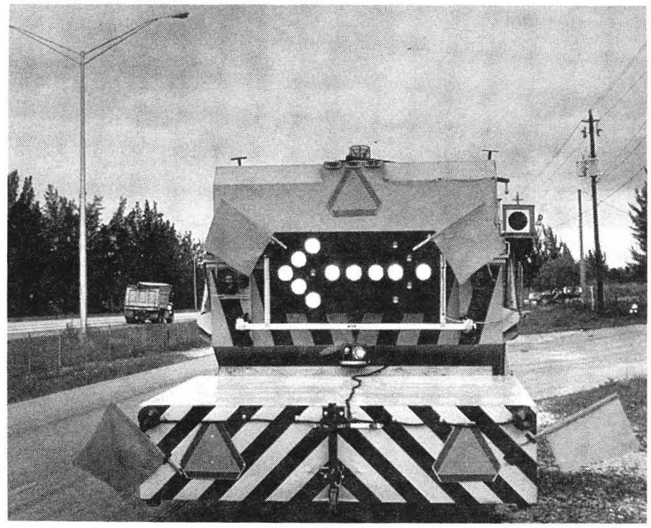


FIGURE 15 TMA delineation with arrow board.

COLLISION EXPERIENCE

Based on the survey, reported collision experience with TMAs includes no fatalities with respect to the public, truck drivers, or workers outside the truck; FHWA has reported one such fatality. This synthesis contains information on reported accidents and collisions only; the actual number of these events may be much higher than indicated.

California has documented TMA collision experience in depth, dating from 1983 (*10*). A 1991 California Department of Transportation review of these records indicates that rear-end collisions with TMAs, even at high speeds, resulted in fewer fatalities and less severe injuries than lower speed impacts with non-TMA vehicles. The data on high-speed accidents may indicate that TMAs are being used in higher risk locations and operations. Typical TMA/vehicle damage from a 45 mph (72 km/h) impact test is shown in Figure 16. In summary, it appears that the TMAs have been effective in reducing injury severity, especially at high-risk locations.

COSTS

Cost is a major factor in selecting a TMA. Purchase considerations should extend beyond an initial purchase price and include factors such as (1) replacement cost, (2) inventory support, and (3) operational problems that may occur when dealing with two or more TMA systems. The benefits to the agency, including reduced severity of collisions or reduced number of injuries, should also

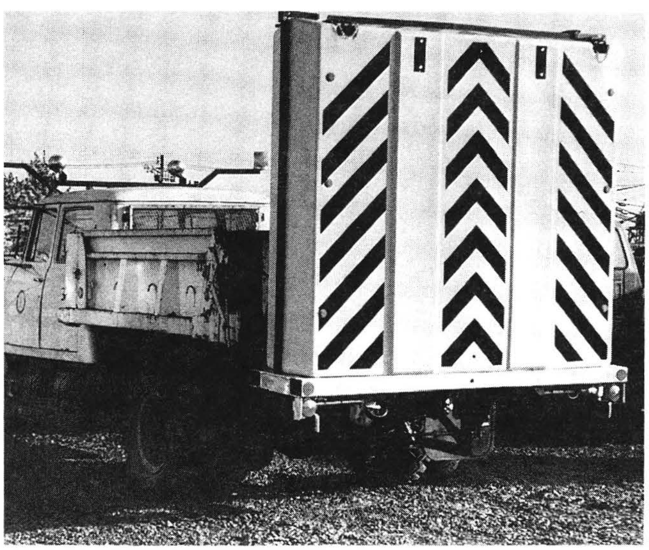


FIGURE 14 Delineation for underside of TMA.

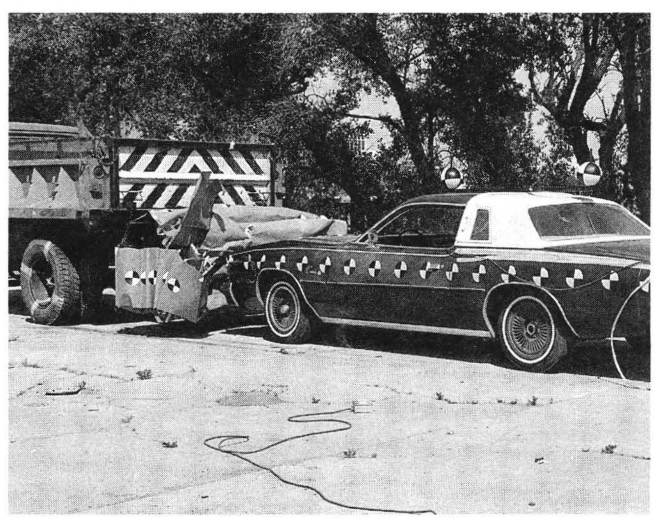


FIGURE 16 Typical TMA/vehicle damage from 45-mph impact.

be considered. What appears to be a high initial cost may actually result in a savings to highway agencies.

Initial and replacement costs for several TMA systems purchased over a ten-year period varied from less than $4,500 to $9,200 per unit. Recognizing that purchase price is sensitive to purchase quantity, delivery schedule, transportation charges, spare parts, special features, delineation schemes, and time of purchase, a more detailed comparison of individual TMAs would be difficult and the findings probably misleading.

Replacement cost ranged from a low of $3,400 to $5,800, representing about 75 percent of the initial purchase price. The small variation between initial and replacement costs may be attributed to the fact that the TMA, exclusive of the attachment mechanism to the protective truck, is consumed in a typical collision. In fact, in the most severe collisions, this attachment frame may also be heavily damaged and require extensive repair or replacement.

Delivery schedule for replacement cushions ranges from one to twelve weeks, with an average period of five weeks. The number of spare cushions in an agency's inventory to prevent "down-time" after a TMA has been damaged is dependent on the number of TMAs in use in a geographical region and the extent of traffic exposure. Accordingly, each agency will need to determine the appropriate number of spare cushions. As an interim guide, a ten percent spare cushion inventory might be adequate, although one state reported an inventory of ten spare cushions for 40 active TMAs.

CHAPTER FOUR

SELECTION GUIDELINES

At this time, evolution of the TMA has progressed to a stage where the different systems are exhibiting similar appearance, geometry, collision performance capability, and operational characteristics. This chapter includes guidelines that a state may consider in selecting the appropriate TMA for its highway safety needs.

SELECTION FACTORS

Collision Performance

The most important factor in evaluating a TMA is its collision performance. Although numerous in-service accidents have been reported where TMAs have exhibited excellent performance, the data are too few and lacking in sufficient exposure measures to adequately define the capabilities and limitations of the several systems. Accordingly, collision performance capability must be defined during crash test evaluation.

Since 1981, the crash test performance has been defined by *NCHRP Report 230* with the test matrix as shown in Appendix A. With the exception of performing Tests 51 and 52 at 45 mph (72 km/h) rather than the specified 60 mph (97 km/h), all current generation TMAs should have been subjected to the test matrix and the results deemed acceptable according to the *Report 230* assessment criteria. Hence, any TMA system being considered for purchase should comply with these test standards.

As discussed in Chapter Two, revisions to the *NCHRP Report 230* TMA test procedures are included in the update to that publication, *NCHRP Report 350*. A major change is the inclusion of a second severity level of testing, which if adopted, may result in the development of a new generation of TMAs. It is assumed that no present generation TMA design will perform to these more demanding test and evaluation criteria. However, the preliminary test matrix is contained in Appendix A to alert states to the pending change and to provide guidance when the new generation of TMAs becomes available.

Environmental Factors

Two principal conditions that could adversely affect the service life and collision performance of a TMA have been evaluated by several states and manufacturers. The first deals with deterioration of the TMA cushion due to moisture infiltration and the second addresses physical damage to the TMA assembly due to highway travel-induced vibration. Obviously, a moisture test may not be important for TMAs operated in arid areas or the vibration tests may not be critical for TMAs that will be used in a small geographic area.

States that have established TMA environmental test programs include California and Texas, and a summary of the test procedures is presented in Appendix B along with the pass/fail criteria. A state may adopt environmental test procedures, such as presented in Appendix B, and require that candidate TMA systems successfully pass these evaluations.

At this time, the moisture retention and vibration tests have not been extensively validated against in-service performance of TMAs. Although the protocols have been carefully developed to test the service life expectancy within an accelerated time frame, further validation of the tests is necessary.

A crash and environmental test evaluation summary is presented in Table 7 for five TMA systems.

Operational Factors

Although TMA systems are evolving into standard designs with similar operating characteristics, it is most important that new TMA procurements fit within the current inventory and do not cause operational problems. For this reason, a state may wish to standardize on a limited number of systems across the state or at least within a district. This will promote interchangeability of TMA units and trucks and lessen inventory requirements for spare parts and cushions.

Cost Factor

With all previously discussed factors being acceptable, the deciding factor for TMA procurement may be cost. Although initial costs appear to be high, the use of TMAs may actually result in savings to highway agencies through reduced injuries and less severe collisions. Once the decision to invest in TMAs has been made, a difference in pricing among vendors may determine the type of TMA selected. Having two or more manufacturers or suppliers competing for the TMA business provides incentive for reasonable prices. For this reason, a state, especially one with large TMA requirements, may want to consider several different systems in its statewide use.

TABLE 7
EVALUATION OF CRASH AND ENVIRONMENTAL TESTS [1]

	Crash Test Evaluation			Environmental Tests			
	NCHRP Report 230 Tests			Caltrans		TTI	
TMA System	50	52	54	Moisture	Vibration	Moisture	Vibration
HEXCEL TMCC	pass	pass	pass	pass	pass	pass[2]	pass
EASI Alpha 1000	pass	pass	pass	pass	pass	pass	pass
EASI Hexfoam	pass	pass	pass	x	x	x	fail[3]
Renco Ren-Gard	pass	pass	pass	x	x	x[4]	fail[4]
Conn CCC	pass	pass	pass	x	x	x	x

(1) Based on (*4,10,12,14,21,25*)
(2) Water retention was 19.4%
(3) Vibration frequency of 7 Hz is near natural frequency of Hexfoam system; manufacturer reports no similar in-service failures.
(4) Renco model CK-1128, developed since this test, passed the TTI tests. (Zimmer, R.A., *Accelerated Fatigue and Moisture Testing of a Renco CK-1128 Ren-Gard Truck Mounted Attenuator*, Texas Transportation Institute, College Station, April 1992)
x = Not tested to this condition

CHAPTER FIVE

TECHNOLOGY TRENDS

The truck-mounted attenuator is a relatively new highway safety device that has been developed and implemented into nationwide service within the past 15 years. The technology, being promoted by both state highway agencies and proprietary companies, has progressed rapidly and will continue to evolve. Refinement in TMA technology will be in the areas of improved performance requirements and operational procedures.

Performance requirements, both collision and environmental, are also changing as highway agencies gain operational experience with TMAs. Collision test procedures have been established somewhat arbitrarily, although researchers have been guided by procedures used for stationary crash cushions. In the future, as representative accident experience is acquired and documented, more rational test procedures will evolve as critical needs are more clearly defined. Also, as TMAs accumulate years of service, noncollision degradation modes will become more apparent and will serve as the basis for developing new or refining current environmental qualification procedures.

Operational procedures will evolve that will more fully integrate TMAs into maintenance and construction activities. Most of the early applications have centered on moving operations in dense traffic conditions. As agencies gain experience and the inventory of TMAs increases, it is anticipated that the use of TMAs in mobile and stationary operations will increase.

Highway agencies should recognize the developing status of TMA technology and be encouraged to critically appraise all aspects of this technology, to develop requirements for hardware modifications and to devise more advanced methods and procedures for conducting operations with these devices.

In the survey, the state highway agencies were asked to rank four listed areas for needed research or improvement. These four are shown in a descending priority sequence:

1. Less maintenance
2. Mounting designs that permit trucks to be used more easily with TMAs attached
3. Longer TMAs for higher speed impacts
4. Units easier to attach

The first three items were about equal in priority ranking while item 4 had a secondary level of importance. Two states added a fifth area of reducing the costs of replacement cushions.

One recent innovation developed by SHRP is a remote-controlled shadow vehicle (*33*). The control unit is carried by an operator who controls the throttle, brakes, transmission, steering, four-way flashers and lights. The truck can be controlled from 800 ft (240 m) away; top speed is about 5 mph (8 km/h).

Even with rapidly changing technology, the current generation of TMAs has been effectively integrated into typical highway construction and maintenance operations and has clearly demonstrated its injury-reducing capability.

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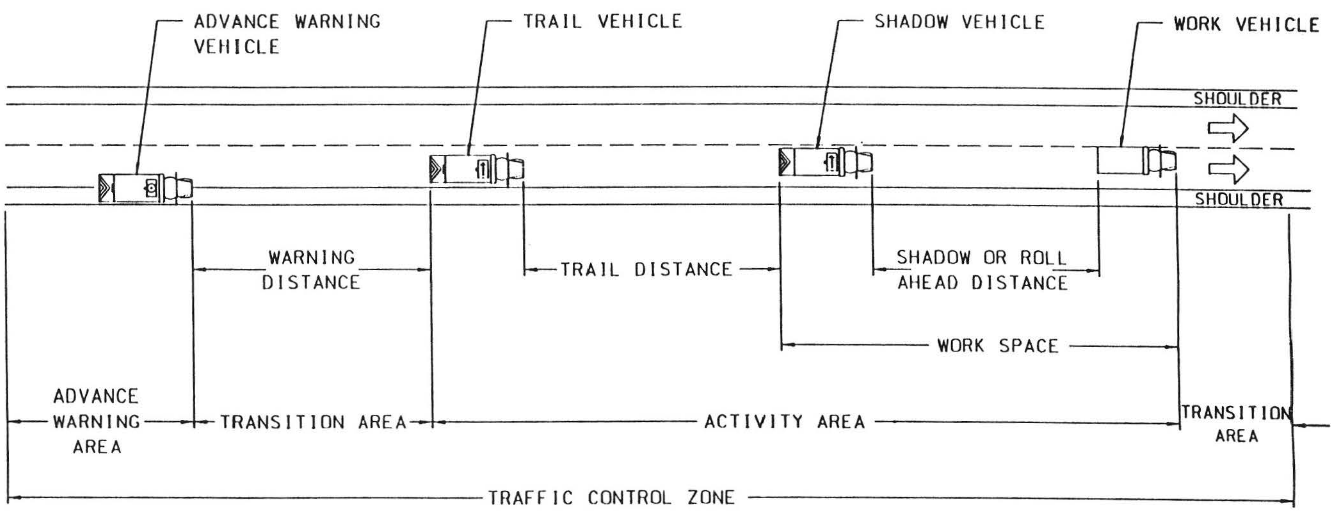

FIGURE 17 Traffic control zone elements for mobile operations.

GLOSSARY

TRUCK-MOUNTED ATTENUATOR (TMA). Device attached to rear end of protective vehicles for the purpose of protecting motorists and workers from consequences of rear end collisions. Major TMA components and properties include:

Cushion. Energy absorbing medium, cartridges, or material together with its housing and protective cover if required.

Latching Mechanism. Feature that locks the TMA in place when it is tilted up or down.

Lift Mechanism. Assembly that provides the TMA with ability to tilt up for greater truck mobility.

Stopping Distance. Distance impacting vehicle travels after impacting TMA. It is typically the sum of the TMA stroke, vehicle front end crush, and the truck roll-ahead distance.

Stroke. Crush distance for a design collision impact into an attenuator. The maximum stroke is achieved when the consumable portion of the cushion is used up and the vehicle "bottoms out" on the more rigid remainder of the TMA/truck assembly.

Support-Frame Assembly. TMA assembly that attaches the cushion to the truck mounting assembly.

Truck-Mounting Assembly. Framework that is attached directly to the protective vehicle by welding or bolting for accommodating the TMA.

PROTECTIVE VEHICLE. Vehicle used in construction or maintenance activities to protect both public and workers from consequences of traffic infringement in a work area. Six types of protective vehicles are:

Advance Warning Vehicle. Vehicle positioned a considerable distance upstream of a mobile or stationary operation. Its purpose is to display information about the hazard ahead and the action needed by the driver to safely traverse the area.

Barrier Vehicle. Vehicle parked in advance of a stationary construction or maintenance operation. It should be unoccupied when parked.

Lead Vehicle. Moving vehicle a short distance downstream from the work vehicle to warn opposing traffic on two-way roadways by signs or flashing arrow panels.

Shadow Vehicle. Moving vehicle a short distance from a work vehicle, giving physical protection from traffic.

Trail Vehicle. Moving vehicle a short distance upstream from the shadow vehicle for added protection in selected multilane divided roadways with high traffic volume.

Working Vehicle. Vehicle used to perform operations such as pavement striping and sweeping.

TRAFFIC CONTROL ZONE. Entire section of roadway over which temporary traffic control related to the work operation is exercised and in which temporary traffic control devices are used (*34*). See Figure 17.

Activity Area. Portion of the roadway in which closure is in effect and where the work is taking place (*34*).

Advanced-Warning Distance. Distance the advance warning vehicle is positioned upstream from the shadow or barrier vehicle.

Roll-Ahead or Shadow Distance. A measure of the distance traveled relative to the work vehicle by a barrier or shadow vehicle after being struck by vehicle from traffic stream. Distance is dependent on vehicle sizes, speed, braking, and other factors.

Trail-Vehicle Distance. Distance trail vehicle is positioned upstream from the shadow vehicle. It is usually the same value as roll-ahead or shadow distance.

Work Space. Portion of the activity area set apart exclusively for workers, equipment, and material storage and is delineated to exclude vehicular and pedestrian traffic (*34*).

STATIONARY OPERATIONS. Maintenance or construction tasks with the following project durations:

Intermediate Term. Activities requiring a few to several days to perform; thus nighttime closures are involved (*34*).

Long Term. Activities in which traffic control zone is in place for several days or longer (*34*).

Short Duration. Activities in which it takes longer to set up and remove the traffic control zone than it does to perform the work; typically the work can be accomplished in 15 minutes or less (*34*).

Short Term (Daytime). Activities that are accomplished during one daylight period (*34*).

MOBILE OPERATIONS. Work activities that move along the road either intermittently or continuously, thus making it difficult or impractical to use stationary traffic control devices (*34*).

Fast-Moving Operations. Activities in which the speed of operations is in the range of 3 mph to 10 to 15 mph below the posted speed limit. Examples are lane striping and roadway sweeping (*34*).

Intermittent-Stop Operations. Highly mobile activities in which a stop is required to perform the actual work. Examples include pot hole patching, litter pickup, and luminaire relamping (*34*).

Slow-Moving Operations. Activities in which operations generally proceed in a continuously moving fashion, and the speed of travel is less than 3 mph. Examples include spraying herbicides, painting pavement markings using walk-behind equipment and pavement marking removal (*34*).

OCCUPANT RISK CRITERIA. Criteria used to evaluate crash test dynamics for probability of serious injury.

APPENDIX A
CRASH TEST EVALUATION

The crash test matrix for TMAs is presented in *NCHRP Report 230* and contained in Figure A-1. Four of the tests specified for permanent crash cushions are applicable to evaluate TMAs; Test 53 with the large sedan impacting along the side of the energy absorbing device is excluded. Moreover, all tests are performed with the vehicle impacting at 45 mph rather than 60 mph. This is a change from the text, which specifies 60 mph impacts for the two small sedans in Tests 51 and 52.

Safety evaluation guidelines keyed to Figure A-1 are contained in Table A-1; the revised guidelines are shown in Table A-8.

Summaries of vehicle crash tests for the more prevalent TMA systems are presented in Tables A-2, A-3, A-4, A-5, and A-6.

Modification to *NCHRP REPORT 230* Test Matrix

Contained in Table A-7 are the proposed changes to the *Report 230* crash test matrix. Important differences include addition of a second severity level of evaluation, primarily increasing impact speeds from 45 mph to 62 mph (72 km/h to 100 km/h) and fully restraining the TMA truck for Tests 2-50 and 3-50.

It is unknown whether any present TMA hardware will perform adequately for these more severe test conditions and states should continue to use the basic severity level until such hardware has been developed.

CRASH TEST CONDITIONS FOR MINIMUM MATRIX

Test Designation	Vehicle Type	Speed (mph)	Angle$^{(a)}$ (deg)	Target Impact Severity$^{(b)}$ (ft-kips)	Impact Point$^{(c)}$	Evaluation Criteria$^{(d)}$
50	4500S	60	0$^{(e)}$	541-53,+94	Center nose of device	C,D,E,F,H,J
51	2250S	60	0$^{(e)}$	270-26,+47	Center nose of device	C,D,E,F,H,J
52	1800S	60	0$^{(e)}$	216-21,+37	Center nose of device	C,D,E,F,H,J
53	4500S	60	20$^{(e)}$	63-6,+11	Alongside, midlength	C,D,E,H,I,J
54	4500S	60	10-15$^{(e)}$	541-53,+94	0-3 ft offset from center of nose of device	C,D,E,F,H,J

(a) + 2 degrees

(b) IS - 1/2m (v sin θ)^2 where m is vehicle test inertial mass, slugs; v is impact speed, fps; and θ is impact angle for redirectional impacts or 90 deg for frontal impacts, deg

(c) Point on appurtenance where initial vehicle contact is made

(d) See Table A.1 for performance evaluation factors

(e) From line of symmetry of device

A crash cushion attached to the rear of maintenance trucks or trailer-mounted is a special case and is not specifically addressed by the test matrix in the table. However, Tests 50 and 54 with impact speed reduced to 45 mph (72 kph) and Tests 51 and 52 at the 60-mph (97-kph) recommended speed are suggested. Although it is desirable to develop crash cushions for maintenance vehicles for the full 60-mph performance, the state of the art has not advanced to this point at this time. Accordingly, for the interim, the previously noted 45-mph (72-kph) tests are recommended. The truck should be in second gear, and the brakes on the maintenance trailer and/or truck should be locked. In addition to occupant risk requirements for the impacting vehicle, the trailer/truck skid distance should be reported.

FIGURE A-1 TMA crash test procedures (from *15*).

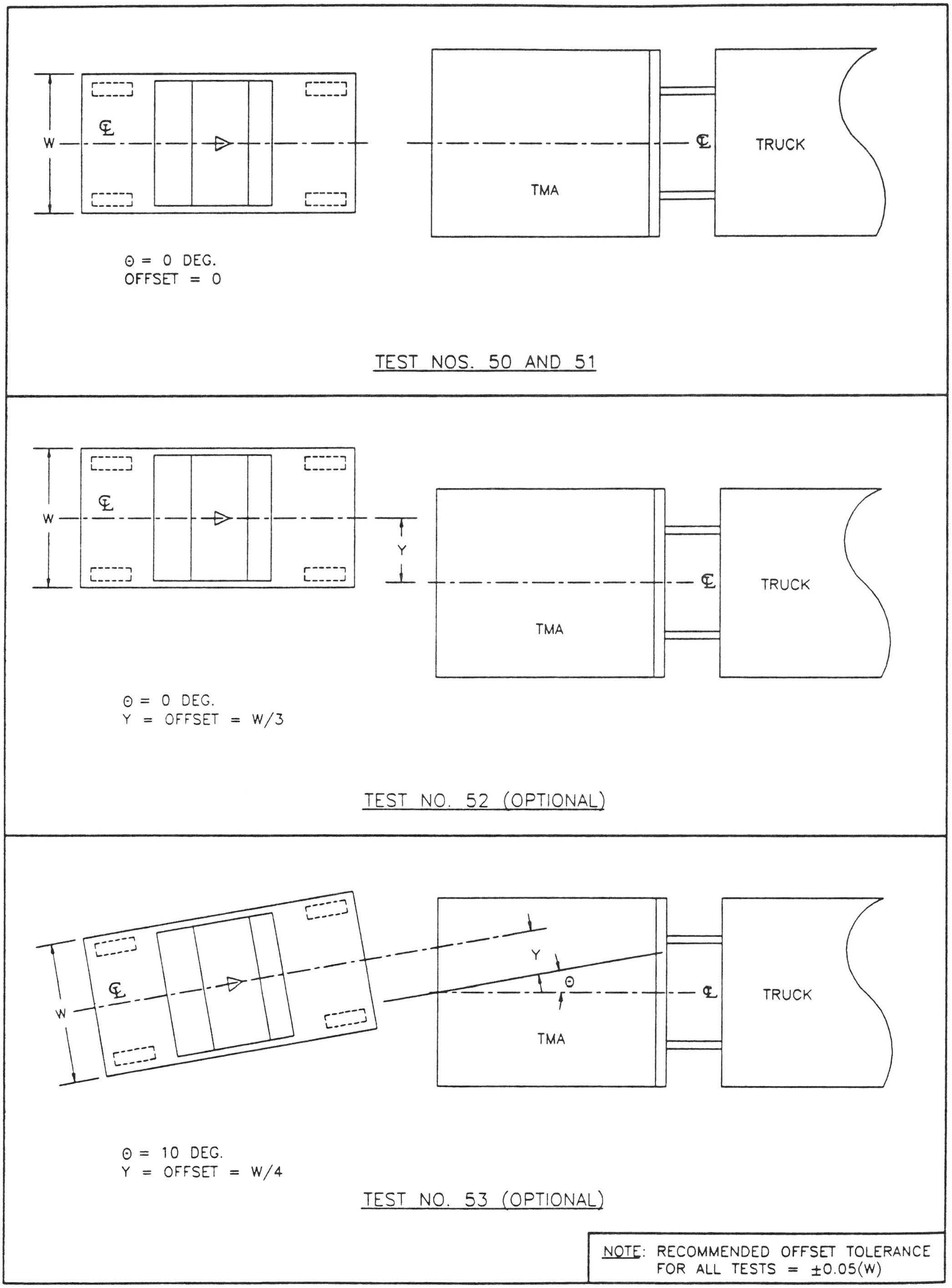

FIGURE A-2 Impact conditions for a TMA (*23*).

TABLE A-1
SAFETY EVALUATION GUIDELINES FOR TMAs

Evaluation Factors		Evaluation Criteria	Applicable to Minimum Matrix Test Conditions
Structural Adequacy	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	50, 51, 52, 53, 54
	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.	All
Occupant Risk	E.	The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	All
	F.	Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 24 in. (0.61m) forward and 12 in. (0.30m) lateral displacements, shall be less than: Occupant Impact Velocity-fps Longitudinal: $40/F_1$ — Lateral: $30/F_2$ and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impact should be less than: Occupant Ridedown Accelerations-g's Longitudinal: $20/F_3$ — Lateral: $20/F_4$ where F_1, F_2, F_3, and F_4 are appropriate acceptance factors.	50, 51, 52, 54
Vehicle Trajectory	H.	After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	All
	I.	In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic 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.	53
	J.	Vehicle trajectory behind the test article is acceptable.	50, 51, 53, 54

TABLE A-2
HEXCEL TMCC VEHICLE CRASH TEST SUMMARY[a]

TMA Description				
Type	Al. Honeycomb	Al. Honeycomb	Al. Honeycomb	Al. Honeycomb
Size	7x7.8x2'	7x7.8x2'	5.5x6.3x2.0'	7x7.8x2'
Weight - TMA	280	280	200	280
Weight - Hardware	420	690	660	420
NCHRP Report 230 Test No.	50	51	52	54
Test No./Ref	388	385	393	389
Test Date	8/27/81	5/7/81	9/15/82	9/24/81
Protective Truck Data				
Model	Ford F750 Dump	Ford F750 Dump	70 Dodge Pickup	Ford F750 Dump
Gross Vehicle Weight, lb	25,000	25,000	3/4 ton	25,000
Test Weight, lb	11,000	11,000	4,305	11,000
Brake Setting	parking, rear wheels	parking, rear wheels	parking, rear wheels	parking, rear wheels
Gear Setting	2nd	2nd	neutral	2nd
Car Data				
Model	72 AMC Matador	72 Ford Pinto	79 Honda Civic	70 Plymouth Belvedere
Gross Weight, lb	4,350	2,345	1,985	4,435
Impact Speed, mph	46.4	44.4	44.8	44.8
Impact Angle	0° centered	0° centered	0° centered	12°, 1' offset
Impact Severity (ft-kips)	313	154	133	
Collision Results				
Occupant Imp Vel (fps)	33.3	35.6	39.0	29.1
Ridedown Accel (g's)	13.8*	15.2*	12.4*	10.6*
Stopping Distance (ft)	-	-	-	-
Roll Ahead Distance (ft)	39.8	6.8	25.0	14.2
TAD/VDI Index - Car	FD5/12FDEW5	FD5/12FDEW5	FD5/12FDEW4	FD4/01FDEW5

(a) Crash test reference: Schiefferly, C. and Marlow, J., "Development of a Lightweight Truck Mounted Attenuator," CALTRANS Final Report on Federal Research Grant D-4-163, Sacramento, CA, July 1983.

* 50 ms average.

TABLE A-3
ENERGY ABSORPTION SYSTEMS ALPHA 1000 VEHICLE CRASH TEST SUMMARY[a]

TMA Description			
Type	Energy Absorption Systems Alpha 1000		
Size	81.5" long, 93" wide, 22.5" high		
Total Weight-TMA and Hardware	750 to 1,200 lbs		
NCHRP Report 230 Test	50	52	54
Test No.-Ref.	088-06	103-03	088-08
Protective truck data			
Model	Dump	Dump	Dump
Gross vehicle wt, lb	22,000	22,000	22,000
Test wt, lb	12,300	12,540	12,300
Brake setting	parking & air	parking & air	parking & air
Gear setting	2d	2d*	2d
Car data			
Model	'77 Chrysler Cordoba	'77 Honda Civic	'75 Ford LTD
Gross wt,lbs	4,260	1,965	4,380
Impact speed, mph	44.7	45.1	49.3
Impact angle	0°	0°	12.5°,centered
Impact Severity(ft-kips)	285	122	358
Collision results			
Occupant imp vel (fps)	32.2	38.8	35.1
Ridedown Accel (*g*'s)	18.1	15.1	13.8
Stopping distance (ft)	23.3	10.4	18.3
Roll-ahead distance (ft)	17.5	4.2	12.3
TAD/VDI index - car	FD2/12FDEW1	FD4/12FDEW2	FD3/01FDEW2

[a]Crash test reference: "Alpha 1000 TMA Crash Test Report," Energy Absorption Systems, Inc., Chicago, IL, June 1987.

TABLE A-4
ENERGY ABSORPTION SYSTEMS HEX-FOAM VEHICLE CRASH TEST SUMMARY[a]

TMA Description			
Type	Hex-Foam		
Size	84" long, 95" wide 26" high Tube wall: 1/4 & 3/8 in		
Total Weight-TMA and Hardware	1,500 lbs		
NCHRP Report 230 Test	50	52	54
Test No.-Ref.	109-01	109-04	109-05
Test Date	3/19/87	7/24/87	8/13/87
Protective truck data			
Model	Dump	Dump	Dump
Gross vehicle wt, lb	22,000	22,000	22,000
Test wt, lb	13,250	12,800	12,800
Brake setting	parking & air	parking & air	parking & air
Gear setting	2d	2d	2d
Car data			
Model	'75 Chevy pickup	'78 Honda Civic	'70 Ford F250 Pickup
Gross wt,lbs	5,434	1,765	5,440
Impact speed, mph	45.0	48.7	44.7
Impact angle	0° centered	0° centered	12°, @ center
Impact severity (ft-kips)	368	140	-
Collision results			
Occupant imp vel (fps)	31.8	39.7	31.5
Ridedown Accel (*g*'s)	17.4	12.8	10.3
Stopping distance (ft)	36.6	5.7	25.9
Roll-ahead distance (ft)	31.6	1.9	12.7
TAD/VDI index - car	FD5/12FDEW4	FD4/12FDEW5	FR4/11FDEW4

[a]Crash test reference: "Hex-Foam TMA Crash Test Report (Addendum)," Energy Absorption Systems, Inc., Chicago, IL, October 1987.

TABLE A-5
CONNECTICUT TMA VEHICLE CRASH TEST SUMMARY[(a)]

TMA Description			
Type	Four 2-ft dia steel cylinders, 34-in long		
Size	Tube wall: 1/4 & 3/8 in		
Total Weight-TMA and Hardware	1,500 lbs		
NCHRP Report 230 Test	50	52	54
Test No.-Ref.	9910-10	9910-09	TTI-2
Protective truck data			
Model			
Gross vehicle wt, lb	24,000	24,000	24,000
Test wt, lb	15,000	15,000	15,080
Brake setting	parking	parking*	off
Gear setting	2d	2d*	2d
Car data			
Model			
Gross wt,lbs	4,500	1,800	4,500
Impact speed, mph	45.6	45.3	47.2
Impact angle	0°	0°	10°, 30" offset
Collision results			
Occupant imp vel (fps)	28.1	37.3	28.4
Ridedown Accel (*g*'s)	19.2	13.8	12.8
Stopping distance (ft)	-	-	-
Roll-ahead distance (ft)	12.6	0	11.6
TAD/VDI index - car	-	-	-

[(a)]Crash test reference: Griffin, L.I., Zimmer, R.A., Campise, W.L., and Mak, K. K., "An Evaluation of Selected Truck Mounted Attenuators (TMAs) With Recommended Performance Specifications," *Final Report*, Study No. 2-4-89-991, Texas Transportation Institute, College Station, August 1991.

*Against rigid wall.

TABLE A-6
RENCO REN-GARD VEHICLE CRASH TEST SUMMARY[a]

TMA Description			
Type	Ren-Gard™ Fibrous Honeycomb TMA		
Size	81.5" long, 95.5" wide, 24" high		
Weight - TMA	550 lb		
Weight - Hardware	570 lb		
NCHRP Report 230 Test	50	52	54
Test No./Ref	71790-3	71790-1	71790-2
Test Date	1/22/91	1/3/91	1/8/91
Protective Truck Data			
Model	81 Ford Dump	81 Ford Dump	81 Ford Dump
Gross Vehicle Weight, lb	24,000	24,000	24,000
Test Weight, lb	15,400	15,400	15,400
Brake Setting	parking on	parking on	parking on
Gear Setting	2nd	2nd	2nd
Car Data			
Model	80 Cadillac	83 Honda Civic	81 Olds Regency
Gross Weight, lb	4,500	1,970	4,500
Impact Speed, mph	45.0	45.1	46.1
Impact Angle	0° centered	0° centered	15°,2-ft offset
Impact Severity (ft-kips)	305	136	-
Collision Results			
Occupant Imp Vel (fps)	32.8	36.7	33.5
Ridedown Accel (g's)	13.8	11.9	11.4
Stopping Distance (ft)	-	-	-
Roll Ahead Distance (ft)	10.75	3.0	14.3
TAD/VDI Index - Car	12FD1/12FDEW1	12FD3/12FDEW2	12FD3/12FDEW2

(a) Crash test reference: Campise, W.L., Griffin, L.I., "Crash Testing and Evaluation of a New, Truck Mounted Attenuator (TMA) For Renco, Inc.", Texas Transportation Institute, College Station, Texas, February 1991.

TABLE A-7
PROPOSED TEST MATRIX FOR TRUCK MOUNTED ATTENUATORS (*23*)

Test Level	Test Designation	Impact Conditions			Impact Point	Evaluation Criteria[e,g] (See Table A-8)	Evaluation Criteria[f,g] (See Table A-8)
		Vehicle[c]	Nominal Speed (km/h)[d]	Nominal Angle, θ (deg)			
2 Basic Level	2-50	820C	70	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	S2-50[a]	700C	70	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	2-51	2000P	70	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	2-52[a]	2000P	70	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	2-53[a]	2000P	70	10	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
3	3-50	820C	100	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	S3-50[a]	700C	100	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	3-51	2000P	100	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	3-52[a]	2000P	100	0	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K
	3-53[a]	2000P	100	10	(b)	D,F,H,I,(J),K	C,D,F,I,(J),K

[a] Test is optional.
[b] See Figure A-2 for impact point.
[c] 820C and 700C are 1,800-lb. and 1,550-lb. cars respectively; 2,000P is a 4,410-lb. pickup.
[d] To convert to mph, multiply by 0.62.
[e] For impacting vehicle and its occupants.
[f] For supporting truck and its driver. See discussion in reference *23*, Section 5.3.
[g] Criteria in parenthesis are optional.

TABLE A-8
REVISED SAFETY EVALUATION GUIDELINES (*23*)

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Applicable Tests[a]</th></tr>
<tr><td>Structural Adequacy</td><td colspan="4">A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td></td><td colspan="4">B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td></td><td colspan="4">C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</td><td>30, 31, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td>Occupant Risk</td><td colspan="4">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.</td><td>All</td></tr>
<tr><td></td><td colspan="4">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.</td><td>70, 71</td></tr>
<tr><td></td><td colspan="4">F. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in Criterion G.</td></tr>
<tr><td></td><td colspan="4">G. It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>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]</td></tr>
<tr><td></td><td colspan="4">H. Occupant impact velocities (see reference 23, Appendix A, Section A5.3 for calculation procedure) should satisfy the following:</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Occupant Impact Velocity Limits (m/s)</td><td></td></tr>
<tr><td></td><td></td><td>Component</td><td>Preferred</td><td>Maximum</td><td></td></tr>
<tr><td></td><td></td><td>Longitudinal and Lateral</td><td>9</td><td>12</td><td>10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81</td></tr>
<tr><td></td><td></td><td>Longitudinal</td><td>3</td><td>5</td><td>60, 61, 70, 71</td></tr>
</table>

TABLE A-8 (*Continued*)

<table>
<tr><th>Evaluation Factors</th><th>Evaluation Criteria</th><th>Applicable Tests[a]</th></tr>
<tr><td rowspan="2">Occupant Risk</td><td>I. Occupant ridedown accelerations (see reference 23, Appendix A, Section A5.3 for calculation procedure) should satisfy the following:
<table>
<tr><th colspan="3">Occupant Ridedown Acceleration Limits (G’s)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr>
</table></td><td>10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td>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).</td><td>10, 20, 30, 31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td rowspan="4">Vehicle Trajectory</td><td>K. After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>All</td></tr>
<tr><td>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 reference 23, Appendix A, Section A5.3 for calculation procedure) should not exceed 20 G’s.</td><td>11, 21, 35, 37, 38, 39, 44</td></tr>
<tr><td>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.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N. Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 60, 61, 70, 71, 80, 81</td></tr>
</table>

[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
ENVIRONMENTAL TESTS

Three types of environmental tests are performed on TMA specimens to ascertain their relative durability: vibration, moisture exposure, and salt spray exposure.

VIBRATION

Comparison of Protocols

A comparison of vibration test conditions of five states is shown in Table B-1. While there are similarities among the states, the length of the pivot arm varies widely. California attaches the TMA cushion to the end of a 139-in. (3.53-m) pivot arm; a 0.6-in. (1.5-cm) vertical peak-to-peak displacement measured at this interface is amplified to 0.96 in. (2.4 cm) at the end of an 84-in. (2.1-m) long TMA cushion; a schematic of the Caltrans apparatus is shown in Figure B-1. In contrast, Texas (TTI) moves the end of the TMA cushion in a vertical plane through a peak-to-peak displacement of 0.6 in. (1.5 cm); thus the end of the 84-in. (2.1-m) long TMA cushion also experiences this same 0.6-in. (1.5-cm) displacement.

TTI Vibration Test: Apparatus, Procedure, and Protocol

Apparatus

The TTI vibration device or "shaker" moves the TMA mounting plate in a perfectly vertical plane. This design is shown in Figure B-2. The frame of the shaker is intentionally overdesigned using 6 x 8-in. (15 x 20-cm) steel box beams with $^1/_4$-in. (0.6-cm) wall thickness. This is to preclude any structural fatigue in the testing machine after millions of cycles. The frame is anchored in six places to a 6-in. (15-cm) thick concrete slab with heavy duty expansion bolts.

Ancillary equipment provides for precise monitoring of the amplitude and shape of the motion and total time of the test. Various hydraulic and electronic gauges have also been incorporated to insure the health of the system.

Procedure

The amplitude or severity of the vibration test is measured in terms of the peak vertical acceleration on the TMA at the mounting plane.

The duration of the vibration test is the third element in full scale fatigue testing. Test duration is usually specified in terms of total cycles.

The TTI test is run for 40 hours. If the test is run at seven cycles per second for 40 hours, a total of 1,008,000 cycles are completed.

Protocol

Each TMA cushion assembly is tested in the horizontal position. All testing is done at a frequency of 7 Hz at a null-to-peak displacement of ±0.3 in. (±.8 cm) at the mounting plate. This level of vibration applies a dynamic load of ±1.5 *g*'s to the unit. To pass the test a TMA cushion is required to vibrate at this level for a total of 40 hours (approximately one million cycles). The 40 hours of testing is usually completed over a four- to five-day period, eight to ten hours of testing per day.

At the end of each day the TMA is carefully examined for structural damage. Vertical measurements between reference marks at the rear of the TMA and the floor are also taken and compared to pretest values. A drop on either side of more than 0.5 in. (1.3 cm) constitutes a failure.

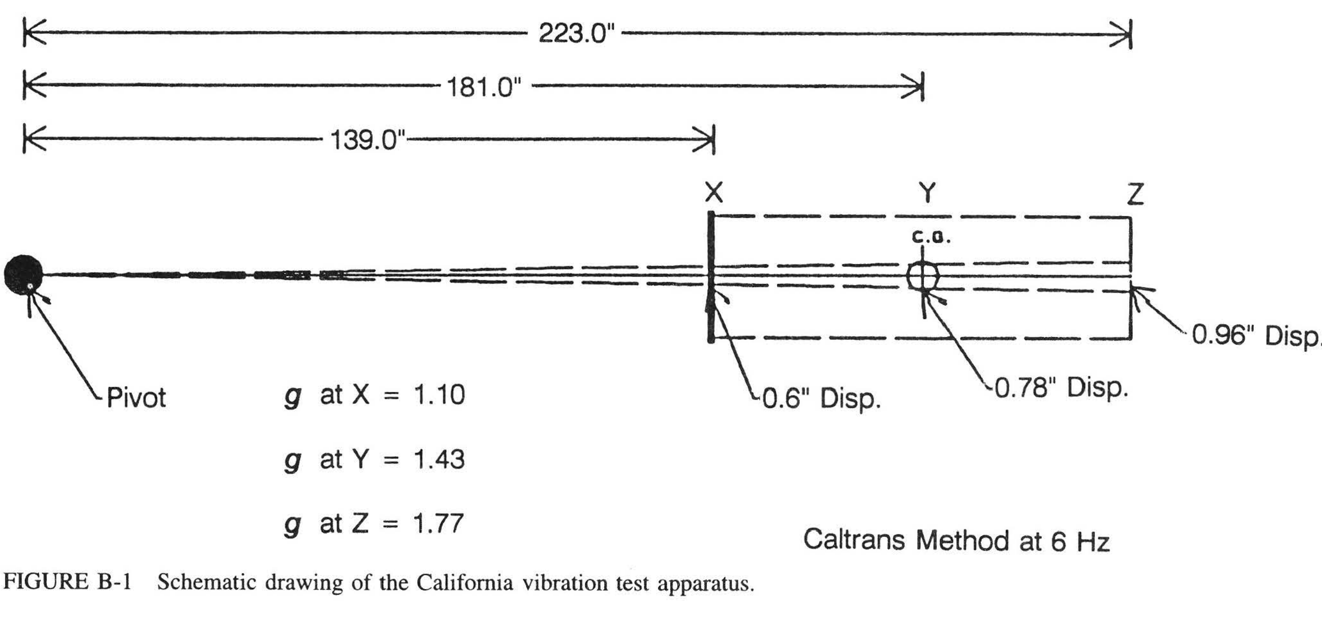

FIGURE B-1 Schematic drawing of the California vibration test apparatus.

TABLE B-1
COMPARISON OF VIBRATION TEST CONDITIONS

State	Pivot to Mounting Surface, in.	Vibration Frequency, Hz	Vibration Amplitude, in.	Duration Hrs	TMA Orientation	Failure Criteria
CA	139	6-8	0.60	40	Horiz, 0°	0.5 in. deviation in any dimension, damage to component
			0.60	40	60°	
			0.60	40	90°	
TX (TTI)	infinite	7	0.60	40	0°	0.5 in. sag
PA	130-140	6-8	0.60	40	0°	0.5 in. sag; damage to energy absorbing cartridge
MO	139	5-8	0.60	40	0°	0.5 in. variance of any component or any damage
			0.60	40	90°	
IL	139	5-8	0.60	40	0°	any evidence of damage
			0.60	40	90°	

TABLE B-2
COMPARISON OF MOISTURE TEST CONDITIONS

State	Test Article	Orientation	Water Spray Rate, in./hr	Test Duration, hr	Drying Time, hr	Failure Criteria
CA MD MO PA	TMA cushion	0°, 180°	6, 6	24, 24	1	cells with any moisture retention
TX	TMA cushion	0°	6	24	1	increase in weight by 5% or more

TABLE B-3
COMPARISON OF CORROSION TEST CONDITIONS

State	Specimen	Test Specification	Cycles	Cycle Duration, hrs Exposure	Cycle Duration, hrs Drying	Failure Criteria
CA	cell material	ASTM B117-73 Salt Spray (fog)	2	24	1	any evidence of corrosion affecting energy absorbing
MO	cell material	ASTM B117-73 Salt Spray (fog)	2	24	1	any evidence of corrosion affecting energy absorbing
MD	4x4x4-in. cell material	ASTM B117-73 Salt Spray (fog)	2	24	1	any evidence of corrosion affecting energy absorbing
PA	cell material	ASTM B117-73 Salt Spray (fog)	1	50	1	any evidence of corrosion affecting energy absorbing

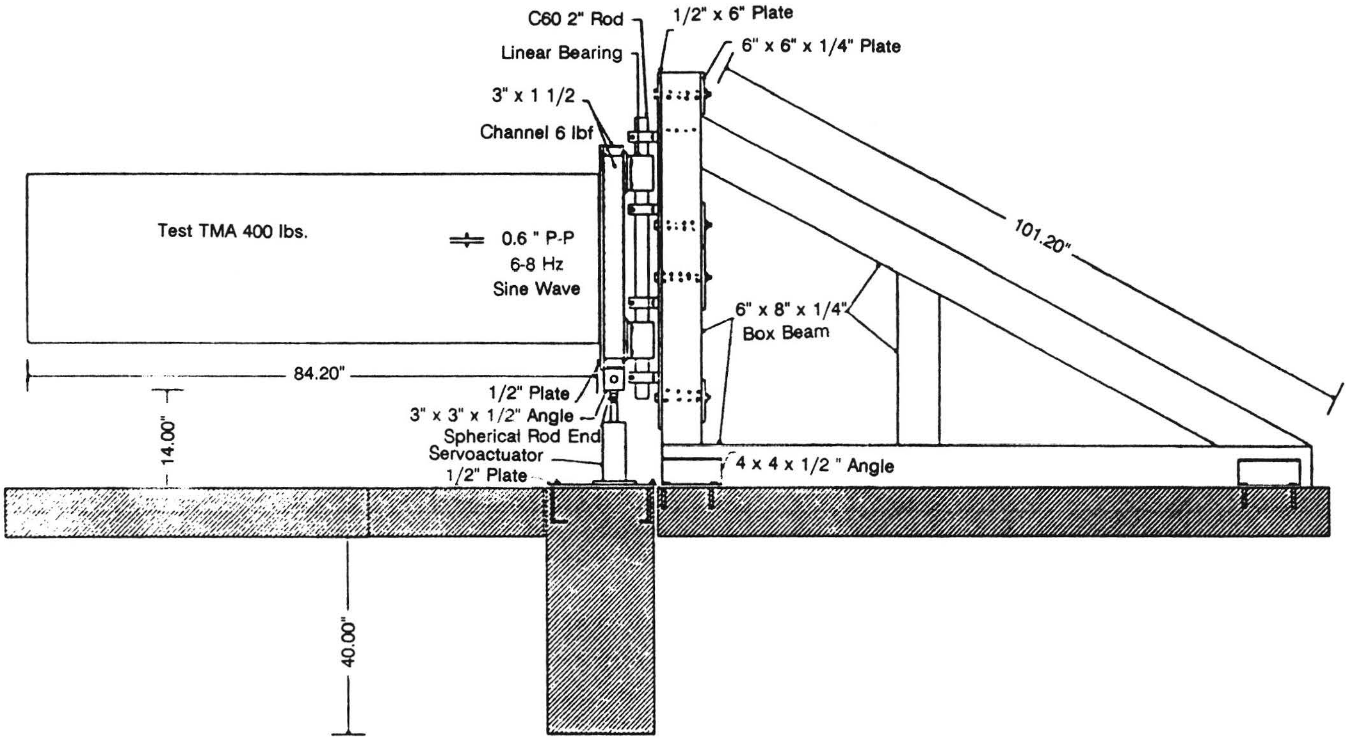

FIGURE B-2 TTI vibration test apparatus, side view (modified).

MOISTURE

Comparison of Protocols

A comparison of moisture test procedures is contained in Table B-2 for four state highway agencies. Each employs the TMA cushion assembly as a test specimen and then subjects the assembly to a water spray that approximates a 6-in. (15-cm) per hour rainfall rate for 24 to 48 hours. The assembly is then permitted to drain/dry for one hour. Water retention is the basis for passing or failing the candidate TMA. It is noted that Texas (TTI) uses an objective weight gain criterion to determine whether the specimen will pass or fail.

TTI Moisture Test: Apparatus, Procedure, and Protocol

Apparatus

The TTI moisture test facility is designed to produce an uninterrupted water spray over the top and sides of TMAs for 24 hours. The TMA is positioned on metal rails over the water tank. Water is pumped from the tank, through a flow-control valve, through the spray nozzles onto the TMA and returned to the tank. The nozzles are of special design to provide a solid cone of droplets with a 90° divergence. The eight nozzles are positioned so that the spray cones overlap and cover the entire surface of the TMA. To contain the overspray and return it to the tank, plastic shower curtains are used. A mechanical flow meter is inserted in the water line just ahead of the nozzles.

Procedure

Each TMA to be moisture tested is weighed, moved to the spray facility, and placed on the tank rails. The TMA is spray tested in its natural condition with no holes or cracks covered. Once in place, the spray and timer are started. By collecting water over several locations on the TMA within a given time period, a valve setting can be found that provides a 6-in. (15-cm) per hour spray. The flow meter reading is set at that rate for use in future tests. After a total spray time of 24 hours, the pump is turned off and the TMA allowed to drain for one hour. At the end of that time it is removed and reweighed just as in the pretest.

Protocol

The weight of the TMA before and after spray testing is considered to be of the utmost importance. The method used to weigh each TMA is to suspend it from an overhead crane by nylon straps. Between the straps and the crane hook is a precision strain gauge load cell. The cell is connected to a digital readout with better than one pound resolution. The difference in the pre- and post-test weights is attributable to the amount of water retained.

A TMA passes the moisture test if, at the end of the one-hour drain period, the weight does not increase by more than 5 percent. For example, a 400-lb (181-kg) TMA cannot retain more than 20 lb (9 kg) of water (2.4 gallons/9.0 L).

CORROSION

Several state agencies provided their test procedure for performing the salt spray corrosion test of cell material specimens. All referenced ASTM B117-73 as the standard that was used. A comparison of four state agencies' procedures is shown in Table B-3.

APPENDIX C
SURVEY FINDINGS

QUESTIONNAIRE

The survey presented in Appendix C was sent to the TRB representative in the 50 state highway departments. A response received from Puerto Rico indicated no current TMA usage.

RESPONSES

As shown in Table C-1, 39 of 50 agencies (14 high usage agencies, plus 25 low usage agencies) completed the questionnaire. Another 12 agencies were contacted by telephone to solicit at least the number of TMAs in use. A few state agencies did not respond, but it is believed that use of TMAs in those states is extremely low.

Accordingly, it is estimated that about 90 percent of the 2,417 TMA units in service in 1991 were represented by the 35 agencies that submitted completed questionnaires.

Moreover, it is determined that of the 35 responding state agencies, 14 states own 2,077 of the formally reported 2,173 TMA units, or about 96 percent.

For convenience, the synthesis findings concentrate on the responses of the 14 states which are and have been the largest users of TMAs. Results of the survey are summarized in Table C-2 for these 14 states.

TABLE C-1
NUMBER OF TMAs IN SERVICE

		1991 NCHRP Survey TMA Units				Other Surveys TMA Units	
		High Users		Low Users			
	Response (1)	1985	1991	1985	1991	1991	
Alabama	L	-	-	1	25	-	
Alaska	L	-	-	0	1	-	
Arizona	L	-	-	0	1	-	
Arkansas	L	-	-	0	2	-	
California	H	430	580	-	-	-	
Colorado	L	-	-	5	6	-	
Connecticut	H	12	60	-	-	-	
Delaware	L	-	-	0	3	-	
Florida	P	-	-	-	-	154	
Georgia	H	20	36	-	-	-	
Hawaii	L	-	-	0	0	-	
Idaho	P	-	-	-	-	-	
Illinois	H	2	30	-	-	-	
Indiana	N	-	-	-	-	-	
Iowa	H	6	63	-	-	-	
Kansas	P	-	-	-	-	4	
Kentucky	H	0	62	-	-	-	
Louisiana	L	-	-	0	2	-	
Maine	L	-	-	0	2	-	
Maryland	L	-	-	0	8	-	
Massachusetts	L	-	-	0	2	-	
Michigan	P	-	-	-	-	-	
Minnesota	H	11	44	-	-	-	
Mississippi	L	-	-	0	5	-	
Missouri	H	0	228	-	-	-	
Montana	L	-	-	0	1	-	
Nebraska	L	-	-	0	17	-	
Nevada	L	-	-	0	14	-	
New Hampshire	L	-	-	1	1	-	
New Jersey	H	32	110	-	-	-	
New Mexico	P	-	-	-	-	2	
New York	H	40	220	-	-	-	
North Carolina	P	-	-	-	-	23	
North Dakota	L	-	-	0	5	-	
Ohio	P	-	-	-	-	25	
Oklahoma	P	-	-	-	-	2	
Oregon	L	-	-	1	15	-	
Pennsylvania	H	0	256	-	-	-	
Rhode Island	L	-	-	0	1	-	
South Carolina	L	-	-	0	2	-	
South Dakota	P	-	-	-	-	4	
Tennessee	H	33	38	-	-	-	
Texas	H	45	89	-	-	-	
Utah	L	-	-	8	8	-	
Vermont	L	-	-	0	0	-	
Virginia	H	10	261	-	-	-	
Washington	L	-	-	0	15	-	
West Virginia	P	-	-	-	-	8	
Wisconsin	N	-	-	-	-	-	
Wyoming	L	-	-	0	1	-	
Puerto Rico	L	-	-	-	0	-	TOTAL
	Year: 1985	641		16			657
	%	98		2			100
	Year: 1991		2077		137	225	2439
	%		85		6	9	100

(1)L-less than 30 units in 1991; H - more than 30 units in 1991; P - oral partial response to survey; N - no response

Survey of Truck Mounted Attenuator Technology for NCHRP Synthesis

1. General Information:

(a) State ______________
(b) Responder ________________________ Title ______________
(c) Phone No. ______________ Address ______________________
____

2. TMA Usage (numbers in inventory):

(a) 1980 ______________
(b) 1985 ______________
(c) Current (1990/91) ______________
(d) Projected 1995 ______________
(e) Highway miles serviced by all TMAs ______________

Percentage of TMA inventory in daily use

(f) During summer __________
(g) During winter __________

Analysis of use (%)

(h) Moving operation (i.e. pavement striping): summer __________ winter __________
(i) Mobile operation (i.e. pothole repair): summer __________ winter __________
(j) Stationary operation (i.e. bridge deck replacement): summer __________ winter __________

Total 100% Total 100%

3. Truck Type Used:

	GVW, lbs	% of All TMA Trucks
(a) Dump	______	______
(b) Flat bed	______	______
(c) Pickup	______	______
(d) Other	______	______
		Total 100%

Percentage of TMAs with dedicated truck ______________

4. TMAs: Approx No. in Inventory

Type A
(a) Manufacturer ______________________
(b) Model No. ______________
(c) Average unit purchase cost (latest) ______________ ________

Type B
(d) Manufacturer ______________________
(e) Model No. ______________
(f) Average unit purchase cost (latest) ______________ ________

Type C
(g) Manufacturer ______________________
(h) Model No. ______________
(i) Average unit purchase cost (latest) ______________ ________

5. Attachment Fixture:

° Initial modification of truck

	Type A	Type B	Type C
Attachment Design			
TMA supplier (Y/N)	(a) ______	(a) ______	(a) ______
State design (Y/N)	(b) ______	(b) ______	(b) ______
Fixture Cost Material (c) ______		(c) ______	(c) ______
State labor	(d) ______	(d) ______	(d) ______
Contractor	(e) ______	(e) ______	(e) ______
Total Cost per Truck	(f) ______	(f) ______	(f) ______

° Routine attachment effort (nondedicated truck)

	Type A	Type B	Type C
Attachment			
Number of personnel	(g) ______	(g) ______	(g) ______
Time, minutes	(h) ______	(h) ______	(h) ______
Detachment			
Number of personnel	(i) ______	(i) ______	(i) ______
Time, minutes	(j) ______	(j) ______	(j) ______

6. Tilt Up Capability:

	Type A	Type B	Type C
Do TMAs tilt up out of the way (Y/N)? If yes, are TMAs	(a) ______	(a) ______	(a) ______
Kept up by hydraulic pressure only	(b) ______	(b) ______	(b) ______
Manual latching by operator	(c) ______	(c) ______	(c) ______
Hydraulic latch through push-button control from cab	(d) ______	(d) ______	(d) ______
Hydraulic latch though push-button at unit	(e) ______	(e) ______	(e) ______
Both (d) and (e)	(f) ______	(f) ______	(f) ______

7. TMA Maintenance Experience (non-collision):

° Manhours required per TMA unit (check one)

	Type A	Type B	Type C
More than 1 manhour per week	(a) ______	(a) ______	(a) ______
Less than 1 manhour per week, more than 1 manhour per month	(b) ______	(b) ______	(b) ______
Less than 1 manhour per month	(c) ______	(c) ______	(c) ______

	Type A	Type B	Type C
• Typical maintenance problem			
Cartridge	(d)____	(d)____	(d)____
Frame/mounting structure	(e)____	(e)____	(e)____
Lifting mechanism	(f)____	(f)____	(f)____
Other (specify)____	(g)____	(g)____	(g)____
	100%	100%	100%
• Estimate of non-collision life of a TMA (yrs)	(h)____	(h)____	(h)____

8. Delineation - describe standards for marking, arrow board, etc. for both truck and TMA:

9. Training for State Personnel (check one or more):

(a) Instructional ____
(b) Training Manual ____
(c) Video ____
(d) Word of mouth ____

10. Collision Experience:
Reported incidents, number
Vehicle less than 4500 lb (a)____
Vehicle more than 4500 lb (b)____
Total (c)____

	Injuries	Fatalities
Severity		
Workers inside truck	(d)____	(e)____
outside truck	(f)____	(g)____
Public	(h)____	(i)____

(Please provide reports if available)

11. Please provide following information:

(a) Procurement specifications
(b) TMA attachment designs
(c) Operating instructions including shadow distance, buffer space, driver protection, etc.

12. If TMAs are selectively used, what is the warranting criteria based on? ADT? Traffic speed? Type of operation? Etc? Please provide warranting criteria:

13. Operational Problems encountered with TMAs:

14. State reasons you prefer one type of TMA over another type:

15. Do you require contractors to use TMAs (Y/N)? (a) ____
If so, when? (b) ____

If so, does the contractor

(c) use state TMAs? ____ (d) purchase/lease own? ____

If contractor's specifications differ from states, please provide.

16. Are TMAs typically included in Traffic Control Plans?
(yes/no/occasionally) ____

	Type A	Type B	Type C
17. Replacement cartridge			
Delivery time	(a) ____	(a) ____	(a) ____
Cost	(b) ____	(b) ____	(b) ____

18. Rank-order needs for future research (1 for highest need, 2 for next highest, etc):

Longer TMA's for higher speed impacts ____
Less maintenance ____
Units easier to attach ____
Trucks that can be used more easily with TMA's attached ____
Other (specify)____ ____

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

Name ____
Address ____

Telephone ____

20. Provide pertinent comments keyed to questions on reverse side of forms.

Please return to: Sally D. Liff
Transportation Research Board
2101 Constitution Ave, NW
Washington, DC 20418

TABLE C-2
SUMMARY OF SURVEY RESPONSE FROM MAJOR USERS OF TMAs

	State Highway Agencies														
	CA	CT	GA	IL	IA	KY	MN	MO	NJ	NY	PA	TN	TX	VA	Total
1. TMA Units															
1985	430	12	20	2	6	0	11	0	32	40	0	33	45	10	641
1990/91	580	60	36	30	63	62	44	228	110	220	256	38	89	261	2077
2. Daily Use															
Summer (%)	90	100	100	50	50	-	90	-	50	100	40	25	95	-	
Winter (%)	60	100	50	0	25	-	5	-	30	10	15	25	75	-	
Operation															
Moving (S/W)	100/54	50/30	60/30	15/0	5/0	-	30/40	-	10/10	25/0	25/10	50/50	95/95	-	
Mobile (S/W)	-	50/30	20/30	60/0	95/100	-	70/60	-	30/40	65/15	50/65	50/50	5/5	-	
Stationary (S/W)	-	20/20	20/40	25/0	-	-	-	-	60/50	10/10	25/25	-	-	-	
3. Truck (%/KGVW)															
Dump	90/(22-33)	-	90/26.5	50/(24-32)	100/32	100/26	70/34	-	90/(27-33)	90/(72)	98/38	25/31	98/24	-	
Flatbed	5/20	-	10/23.5	50/(28-50)	-	-	20/21	-	10/(22-35)	10/(25)	2/27.5	75/(19-28)	2/24	-	
Other	5/20	-	-	-	-	-	10/60	-	-	-	-	-	-	-	
Dedicated (%)	50	-	50	80	0	100	0	10	100	100	69	100	-	100	
4. TMA Type - No.															
HEXCEL-TMCC	430	-	-	-	40	-	-	54	58	80	-	2	1	157	
Cost	-	-	-	-	$8000	-	-	$4700	$6000	$5500	-	$7000	$4436	$4495	
EASI-ALPHA 1000	150	-	10	-	17	63	-	136	-	140	256	-	21	97	
Cost	$5840	-	$5840	-	$7100	$4697	-	$4700	-	$5130	$4610	-	$4697	$4495	
EASI-HEX FOAM	-	-	25	29	6	-	44	38	52	-	-	31	15	-	
Cost	-	-	$8060	$8500	$9200	-	$8900	$5500	$6000	-	-	$8900	$10,000	-	
CONN-CIAS	-	60	-	1	-	-	-	-	-	-	-	-	-	7	
Cost	-	$3500	-	$6300	-	-	-	-	-	-	-	-	-	$7000	
5. Attach. Fixture															
Mfg Design	-	-	X	X	X	-	X	X	X	X	X	-	X	X	
State Design	X	X	-	X	-	-	X	-	-	-	-	-	-	-	
Att - Men/Time	1/15 min	2/16	2/10	2/120	1/15	-	2/120	1/(5-10)	-	-	2/30	-	1/15	-	
Det - Men/Time	1/15 min	2/5	2/10	2/120	1/15	-	2/60	1/(5-10)	-	-	1/15	-	1/15	-	
6. TMA Tilt Up	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	-	yes	no/yes	
7. Maintenance															
Time-Hour/Mo	1	2	1	1	1	1	1	1	1	1	4	1	1	2	
Problem	-	D	A,B,C	-	-	-	A	F	-	-	A,C,G	-	C,H	-	

TABLE C-2 (*Continued*)

	CA	CT	GA	IL	IA	KY	MN	MO	NJ	NY	PA	TN	TX	VA
*8. Delineation	A		A	A,B	A,B	A	A,B	A,B,C	A,B	A,B	A,B		E	A,D
**9. Training	A,B,C,D	A,D	A,D	A,B,C,D	C,D	B,C	C,D	D	A,B,D	A,B	A,B,C,D	A	A,B,C,D	A,B
10. Collision Exp														
Less Than 4500 lb	8	-	12	4	12	-	0	28	20	8	11	0	-	-
More Than 4500 lb	1	-	3	2	3	-	3	0	1	1	3	8	-	-
Total	9	-	15	6	15	-	3	28	21	9	14	8	-	-
Severity (PDO/I/F)														
Public	8/1/0	-	0/3/0	0/2/0	15/0/0	4/0/0	-	8+/20/0	21/0/0	0/9 (minor)	-	-	-	-
Truck Driver	-	-	-	0/2/0	0/0/0	-	-	23/5/0	-	7/2 (minor)	-	0/8/0	-	-
Worker	9/0/0	-	0/1/0	0/0/0	15/0/0	4/0/0	-	0/0/0	1/1/0	9/0/0	-	-	-	-
11. Provided Specs	yes	-	-	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
12. TMA Warrants														
ADT, Speed	-	-	-	X	-	-	-	-	-	-	-	-	-	-
Moving, Short, IH	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Comprehensive	X	-	-	-	-	-	X	X	X	X	X	-	-	X
H. Speed, Mult Lane	-	X	-	X	-	-	-	-	-	-	-	-	X	-
All Moving, IH	-	-	X	-	-	-	-	-	-	-	-	X	-	-
Divided Hwys	-	-	-	-	X	X	-	-	-	-	-	-	-	-
13. TMA Choice	-	cost	-	-	-	cost	-	cost	-	oper	-	-	-	-
14. Req'd Use by Contractor	yes	yes	yes	yes	yes	no	no	-	yes	yes	no	no	no	yes
15. TMA in Traffic Control Plan	-	no	no	-	-	-	no	no	yes	yes	no	-	-	yes
16. Replace Cartridge														
Cost	-	-	$3455/4500	$4300	$4300/5800	$4500/4995	$4800	$3400/5000	$5000/5400	$3700/3600	$3400	$7000	$3800/4420	-
Delivery	-	-	-	2-4 wks	1-4 wks	2-4 wks	12 wks	2-3 wks	8 wks	6 wks/4 wks	2 wks	-	1-6 wks	8 wks
17. Research Needs														
Higher Speed Design	-	1	4	3	2	1	4	-	4	-	2	1	1	-
Less Maintenance	-	4	3	4	4	2	2	-	2	3	4	4	2	-
Easier to Attach	-	3	1	1	1	2	1	-	1	2	1	2	3	-
Trucks - Easier Use	-	2	-	2	3	2	3	-	3	1	3	3	4	-
Lower Cost	-	-	-	5	-	-	-	-	-	-	-	-	-	-

*Code:

A - Arrow board on truck
B - TMA yellow w/black chevrons
C - Flasher lights
D - Lights/refl markings

A - Instructional
B - Training Manual
C - Video
D - Word of mouth

APPENDIX D
INTERIM TMA OPERATING RECOMMENDATIONS FROM THE TEXAS STATE DEPARTMENT OF TRANSPORTATION

1. The TMA supporting vehicle should:

   A. Be a truck having a minimum gross vehicle weight rating of 24,000 lbs., and
   B. Have the tailgate or payload restraint closed and secured, and
   C. Be equipped with:

      1. Seat belts, and
      2. Head restraint(s) , and
      3. Warning lights, arrow boards, and/or strobes, and
      4. Inverted V striped reflective red and white chevrons on the tailgate

2. The TMA should:

   A. Be in the horizontal (WORKING) and locked position during working operations. However, certain vehicle maneuvers will require the TMA to be raised temporarily.
   B. Have warning lights activated.

3. The TMA vehicle operator should:

   A. Receive adequate training for:

      1. TMA inspection and operational recommendations, and
      2. Pre-crash and "Ride down" recommendations, and
      3. Warning recommendations

   B. Follow these procedures for MOVING operations:

      1. Maintain a minimum buffer space of fifty (50) feet between the front of the TMA vehicle and the work area or next vehicle, and
      2. Wear the seat belt at all times, and
      3. Align with the head restraint, and
      4. Display the appropriate warning lights, arrowboard, and/or strobes, and
      5. Be prepared to warn co-workers in the event of an impending crash, and
      6. Be prepared to follow the pre-crash and "Ride Down" recommendations in the event of collision.

   C. Follow these procedures for PARKED operations:

      1. Maintain a minimum buffer space of fifty (50) feet between the front of the TMA vehicle and the work area or next vehicle, and
      2. Park the TMA vehicle with:

         a. Engine off, and
         b. Transmission in SECOND gear, and
         c. Rear axle in LOWEST range, and
         d. Emergency brake applied.

PRE-CRASH AND "RIDE-DOWN" RECOMMENDATIONS

Should the Truck Mounted Attenuator (TMA) be rear ended, the TMA operator should be prepared to experience the following:

1. Sudden and unpreventable TMA vehicle forward movement, and,

2. A crash duration of approximately 0.2 seconds, plus the time required to stop the TMA truck, and

3. A crash impact force of approximately 1/5 that of the striking vehicle.

The TMA operator should be prepared at all times for an unexpected rear end collision by:

1. Having the seatbelt properly buckled.

2. Maintaining head alignment with the head restraint.

3. Maintaining proper rearview mirror adjustment.

4. Being aware of the probable effects of a collision.

5. Being aware of the need to immediately regain control over the TMA vehicle after impact and then bring it to a safe stop.

If the TMA operator has advance warning of an impending collision from the rear, the following actions should be taken:

1. Warn co-workers by sounding the horn.

2. Position head upon the head restraint.

3. Take foot off the accelerator.

4. Position foot over the brake pedal, in preparation to stop safely after the impact.

5. Remain alert and attentive to need for control of the TMA vehicle up to, during, and after the impact.

After impact, the TMA vehicle should be brought to an immediate stop and secured in place, then exit the vehicle and perform site inspection. React appropriately to site circumstances and District emergency instructions.

TMA operators should receive training and instruction on the proper installation and operation of TMA's through the District training programs.

Prior to beginning each work day, a TMA operator should check all hardware of both the vehicle and attenuator. This checklist has been provided to assist you. A few moments of your time now will be a good investment toward the safety of yourself, the work crew, and the traveling public.

All questions should be answered "YES". If you have a "NO" answer, you should contact your supervisor immediately.

VEHICLE:	Yes	No
1. Is the truck a minimum of 24,000 lbs. GVWR?	___	___
2. Is the tailgate closed and the load secured?	___	___
3. Are the warning lights, stop lights, and turn signal lights clean and fully operable?	___	___
4. Is the horn operable?	___	___
5. Are the seatbelts operable and in good condition?	___	___
6. Is the head restraint (headrest) in place and adjusted to the proper height?	___	___
7. Are the rearview mirrors clean and properly adjusted?	___	___
8. Is the emergency brake operable and properly adjusted?	___	___
9. Are the fire extinguisher and first aid kit in place?	___	___
10. Are all tools, books, lunch boxes, or other items in the truck secured in place?	___	___
ATTENUATOR:		
1. Are you familiar with the recommended procedures for TMA inspection, start-up, and operation?	___	___
2. Are the locking mechanisms for both the "up" (transport) and "down" (working) positions undamaged and operable?	___	___
3. Is the TMA's skin undamaged?	___	___

APPENDIX E
EXAMPLE PROCUREMENT SPECIFICATIONS

CRASH ATTENUATOR FOR TRUCK MOUNTING

PART I

GENERAL CLAUSES AND CONDITIONS

1.0 The equipment furnished under these specifications shall be the latest improved model in current production, as offered to commercial trade, and shall be of quality workmanship and material. The bidder represents that all equipment offered under these specifications shall be new. USED, SHOPWORN, DEMONSTRATOR, PROTOTYPE, OR DISCONTINUED MODELS ARE NOT ACCEPTABLE.

2.0 Bidder should submit with the bid, or have on file with the State Department of Highways and Public Transportation, Austin, Texas, the latest printed literature and detailed specifications on equipment the bidder proposes to furnish. This literature is for informational purposes only.

3.0 The unit(s) shall be completely assembled and adjusted, and all equipment including standard and supplemental equipment, shall be installed and the unit made ready for continuous operation.

4.0 All parts not specifically mentioned which are necessary for the unit to be complete and ready for operation or which are normally furnished as standard equipment shall be furnished by the successful bidder. All parts shall conform in strength, quality and workmanship to the accepted standards of the industry.

5.0 The unit(s) provided shall meet or exceed all Federal and State of Texas safety, health, lighting and noise regulations and standards in effect and applicable to equipment furnished at the time of manufacture.

6.0 Any variation from these specifications must be indicated on the bid or on a separate attachment to the bid. This sheet shall be labeled as such.

7.0 It is the intent of this Department to purchase goods and equipment having the least adverse environmental impact, within the constraints of statutory purchasing requirements, departmental need, availability, and sound economical considerations. Suggested changes and environmental enhancements for possible inclusion in future revisions of this specification are encouraged.

PART II

SPECIFICATIONS

1.0 SCOPE: This specification describes a Crash Attenuator for Truck Mounting, used for protecting departmental personnel and equipment and the general public from injury and damage caused when errant vehicles crash into department equipment used in highway operations. Units furnished under these specifications must meet the following:

Developed by Texas Department of Highways, 1991; modified by removing references to proprietary TMA devices.

1.1 DESIGN AND PERFORMANCE REQUIREMENTS: The Truck Mounted Attenuator (TMA) units shall be functionally designed:

1.1.1 To decelerate impacting vehicles traveling at a speed of 45 miles per hour, at weights of both 1,800 and 4,500 pounds, and colliding in an alignment as shown in para. 3.1 without exceeding the following values:

Occupant Impact Velocity: 40 feet per second
Occupant Ridedown Acceleration: 20 Gs; and
(NCHRP 230)

1.1.2 To prevent impact vehicle roll over and limit intrusion into adjacent traffic lanes, and,

1.1.3 To safeguard impact vehicle passenger compartment integrity; and,

1.1.4 To tolerate routine usage under practical operating conditions of road travel vibration and normal rainfall without water absorption or physical deformation exceeding:

5% of the TMA unit's dry weight and
0.5 inches of corner sag; and, (24)

1.1.5 To minimize the impact acceleration and roll ahead distance of a Stationary TMA Support Truck weighing approximately 14,000 pounds.

2.0 UNITS THAT MAY BE FURNISHED: The products which may be furnished to this specification are listed by manufacturer and model as shown below and have been tested in accordance with the report entitled, "Evaluation of Selected Truck Mounted Attenuators (TMAs) With Recommended Performance Specifications", TTI, 1991. Only the units shown below will be acceptable for this purchase.

NOTE: Bidders wishing to have their units considered for future bids should contact the Equipment and Procurement Division of the State Department of Highways and Public Transportation. See paragraph 3.0 for additional information concerning testing and certification requirements.

3.0 TESTING AND CERTIFICATION:

Each new TMA design purchased under this specification shall be pre-tested and certified as being in compliance with the following test criteria and performance requirements by a SDHPT approved independent testing laboratory. The certification shall be made through the seal and signature of a professional engineer licensed and registered by the State of Texas.

3.1 **CRASH TESTING:**

Test Facility Standardization: All testing, measurement, and analysis shall be conducted in strict accordance with the National Cooperative Highway Research Program Report 230 methods and procedures.

Crash Test One:

Impacting Vehicle Weight	=	1,800 pounds
Impacting Vehicle Speed	=	45 miles per hour
Collision Alignment	=	Centerline Head-On Into Rear Of TMA
TMA Support Truck Weight	=	14,000 pounds, Single Axle, Dual Rear Tires
TMA Support Truck Criteria	=	Engine Off, 2nd Gear, Parking Brake On
TMA Support Truck Restraint	=	Rear Wheel Rotation Chain Restraint

Crash Test Two:

Impacting Vehicle Weight	=	4,500 pounds
Impacting Vehicle Speed	=	45 miles per hour
Collision Alignment	=	Centerline Head-On Into Rear Of TMA *
TMA Support Truck Weight	=	14,000 pounds, Single Axle, Dual Rear Tires
TMA Support Truck Criteria	=	Engine Off, 2nd Gear, Parking Brake On
TMA Support Truck Restraint	=	Rear Wheel Rotation Chain Restraint

* **NOTE**: It is the intent of this department in the near future, to require an eccentric crash test in lieu of the centerline head-on crash test collision alignment specified in Crash Test Two. Bidders may elect to certify their units according to the current requirements or may elect to qualify their units according to the eccentric testing criteria in preparation for future certification requirements.

Passing Criteria For Crash Testing:

Maximum Occupant Impact Velocity Longitudinally:	Not To Exceed 40 Fps
Maximum Occupant Ridedown Acceleration Longitudinally:	Not To Exceed 20 Gs
Impact Vehicle Rollover:	None Permitted
Impact Vehicle Lane Intrusion:	Stopped Within Its Lane
Impact Vehicle Passenger Compartment Integrity:	Reasonably Safeguarded

(NOTE: Deformation to the roof/header structure of the impacting vehicle and/or a broken windshield on the impacting vehicle due to impact with the TMA and/or the dump truck to which it is attached is prima facie evidence of an unacceptable test).

3.2 **ENVIRONMENTAL TESTING:**

3.2.1 Vibration Test:

Test Procedure: Vertical sinusoidal oscillation through 0.6 inch amplitude at a 7 Hertz frequency for a duration of 40 hours. (24)

Passing Criteria:

Quantitative: A maximum rear corner sag of 0.5 inches at the end of the 40 hour test period.

Qualitative: No structural failures permitted. No reasonable expectation of impairment of energy absorbing capability permitted. TMA skin may experience minor distortions, minor cracking, and minimal loss of rivet integrity.

3.2.2 Moisture Test:

Test Procedure: Determine TMA dry weight before exposure to moisture testing. Position the TMA within a moisture chamber in the normal horizontal operational position. Subject the TMA to 24 hours of 6 inch per hour simulated rainfall on its top and sides. Allow the TMA to drain and dry in the chamber for one hour. Determine the TMA weight gain in percent of original TMA dry weight. (24)

Passing Criteria:

Quantitative: The TMA weight gain as a result of the moisture test shall not exceed 5% of the original TMA dry weight.

Qualitative: No reduction in energy absorbing capability or structural integrity as a result of moisture testing.

4.0 **CONSTRUCTION:**

4.1 The back-up frame and/or support platform shall be constructed of steel or aluminum.

4.2 The shell housing the compression material shall be constructed of aluminum or fiberglass (exception: Structural Accessories model).

4.3 The rear compression panel shall be constructed of aluminum or plywood.

4.4 The design shall utilize a replaceable compression material cartridge(s) which is constructed of corrosion, mold, and rot resistant material.

4.5 Mounting hardware and fasteners shall be constructed of steel or aluminum and designed for mounting on a single rear axle, standard production 24,000 GVW truck.

5.0 **LEVELING STANDS**: The front of the unit shall be equipped with at least two (2) adjustable caster-wheeled leveling stands to assist in mounting of the unit. At least one (1) caster wheeled, retractable, leveling stand shall be located at the rear of the unit for portability purposes when unit is not mounted.

6.0 **CONFIGURATION**: Units shall meet the following:

6.1 TILT UNITS: (Compression Material)

DIMENSIONS	MINIMUM	MAXIMUM
Attenuator Length	Approx. 80 Inches	Approx. 96 Inches
Attenuator Width	92 Inches	102 Inches
Attenuator Height	Approx 22 Inches	---------
Attenuator Weight When Detached from Truck (with Hydraulics)	Approx. 750 lbs	1,410 lbs

6.1.1 Self-contained hydraulic or electro-mechanical tilt: The unit shall be equipped with a self-contained tilt feature powered by a replaceable fuse-protected link to the 12 volt vehicle electrical system that will allow the rear of the device to be lifted from horizontal to vertical (90 degrees). The controls for activating this operation shall be located in the truck cab, convenient to driver, and at the right rear corner of the truck so as to allow the operator to raise the unit to its full 90 degree tilt position and manually or hydraulically lock the unit in position with a minimum of one (1) each locking pin. The manual or hydraulic locking system shall be designed to allow routine locking of the unit in a minimal amount of time (approximately three (3) minutes).

6.1.2 Mounting: Shall be such that by the removal of a maximum four (4) bolts or lock pins and any necessary electrical plug connectors, the attenuator assembly including hydraulics may be routinely removed within approximately 15 minutes. Any remaining mounting hardware and components must be completely under the truck body or frame in such a manner that when the unit is removed from a dump truck, the full dump capabilities shall be uninhibited.

6.2 NON-TILT UNITS: (Compression Material)

DIMENSIONS	APPROX. MEASUREMENTS
Attenuator Length	104 Inches
Attenuator Width	72 Inches
Attenuator Height	34 Inches
Attenuator Weight When Detached From Truck With Hydraulics	1,400 lbs.

6.2.1 Mounting: A truck mounting undercarriage system shall be furnished for the mounting of the TMA. The undercarriage system shall act as a support and guide system. The undercarriage system shall be composed of telescoping frame work and adjustable mounting plate type brackets. Support chains with turnbuckles and mounting eye brackets shall be furnished for attaching the TMA to the truck dump body. Additional mounting shall be accomplished through three posts and a plate secured to a boxing plate welded to the the rear of the truck frame. An easily removable safety strap type bracket shall be furnished for installing on the front sides of the dump body subframe to the truck chassis frame so as to prevent the dump body from inadvertently raising. The unit shall be easily removable by extending the jack stands, unbolting the unit from the frame boxing plate and driving the truck away from the TMA.

7.0 LIGHTING: The rear of the crash attenuator shall be equipped with a red tail lamp, red stop lamp, turn indicator lamp and a red reflector on each side. These lamps and reflectors may be incorporated into a single unit on each side. A wiring harness shall be provided for connection of the crash attenuator lighting system to that of the vehicle on which the unit is mounted. All wires shall be protected by a replaceable fuse and be color coded or otherwise identified and shall extend the full length of the mounting hardware with enough additional length to enable Department personnel to install a plug compatible with the receptacle on the supporting vehicle. The lighting arrangement on the truck and body shall be in accordance with Texas Motor Vehicle Laws.

8.0 SAFETY PLAQUES OR DECALS: Safety plaques or decals shall be furnished and shall be affixed at the operator's station and at any hazardous area. The plaques or decals shall include necessary warnings and precautions. Permanent plaques are preferred to decals. Necessary warning plaques, stickers or decals for mounting on the vehicle dash or controls shall be delivered with the unit.

9.0 PAINTING: The unit shall be painted an approved manufacturer's standard white color except for glass, rubber and those metallic accessories or fixtures constructed of rust-resistant or plated material not normally painted. Lead-free paint will be accepted. Examples of paint meeting this requirement are:

NOTE: The entire rear portion(s) of the attenuator when in the operating position and in the 90 degree tilt position (on tilt design units), shall be equipped with reflectorized red and white alternating, invertive V-shaped chevron stripes. Each stripe shall be 6 inches wide to provide maximum visibility for the general public.

10.0 MANUALS: One copy each of an illustrated parts book, operator's manual, service manual and installation manual shall be delivered with each unit. The manuals may be combined into one comprehensive manual. These shall include, as a minimum, appropriate manuals for the electrical system and proper maintenance of the unit.

10.1 Manuals for tilt design units shall include the electrical, mechanical, hydraulic system, and controls. Additionally, one set of complete wiring, plumbing and hydraulic schematics shall be delivered with each unit. All schematics shall be clear, legible and indicate the location of each component. Hydraulic schematics shall include the diameter and length of each hose and the manufacturer and part number of each fitting.

10.2 The manuals and schematics supplied shall provide complete and comprehensive information on all equipment, equipment components and accessories, as supplied to comply with this specification.

10.3 Parts manuals shall show the manufacturer of each part and all cross referencing between the vendor and the manufacturers.

10.4 The operator's manual shall include detailed instructions on the proper method of operation of the unit. Necessary warnings and safety precautions shall be included.

10.5 The following additional information shall be provided by the vendor at time of delivery if it is not included in the manuals required above.

10.5.1 Manufacturer's recommended service/preventive maintenance intervals.

10.5.2 Recommended fluids, lubricants, and their SAE equivalents.

11.0 FUTURE UPDATES AND SPECIFICATION REVISIONS: This specification addresses available current state-of-the-art truck mounted attenuators. The Texas State Department of Highways and Public Transportation encourages the market to move toward units capable of providing the same level of protection and meeting the referenced criteria and requirements for vehicles weighing up through 3500 lbs, while traveling at speeds up through 55 mph.

PART III
DELIVERY, ACCEPTANCE AND PAYMENT

1.0 DELIVERY REQUIREMENTS: Delivery of all equipment on this order shall be complete within the number of days bid, as shown on the purchase order. Any units not delivered within this time frame may be cancelled from the purchase order or, at the State's option, an extension may be granted, whichever is in the State's best interest.

1.1 If any units are cancelled for non-delivery, the needed equipment may be purchased elsewhere and the vendor may be charged full increase, if any, in cost and handling.

1.2 Unless a delivery extension is granted, for acceptable reasons due to circumstances beyond the vendor's control, liquidated damages of $20.00 per unit may be deducted from the invoice for every working day after the expiration of the number of days shown on the purchase order until the units are delivered. This provision is not intended as a penalty but as liquidated damages.

2.0 STATEMENT OF INTENT: It is the intent of this Department that equipment be delivered in full compliance with the specifications.

3.0 ACCEPTANCE INSPECTION: All equipment ordered with this request may be subject to acceptance inspection and road testing upon receipt. Acceptance inspection and road testing will not take more than five (5) working days weather permitting. The vendor will be notified within this time frame of any units not delivered in full compliance with the purchase order specification. If any units are cancelled for non-acceptance, the needed equipment may be purchased elsewhere and the vendor may be charged full increase, if any, in cost and handling.

4.0 PAYMENT: Payment will be made within 30 days after the acceptance inspection has been completed and the ordering agency determines that the equipment delivered meets specifications, or the day on which a correct invoice is received, whichever is later.

5.0 WORKING DAY: A working day is defined as calendar day, not including Saturdays. Sundays, or regularly observed State and Federal holidays.

PART IV
WARRANTY

1.0 WARRANTY: The unit of equipment shall be warranted against defects in material and workmanship for a period of not less than twelve (12) months. If the manufacturer's standard warranty exceeds twelve (12) months, then the standard warranty period shall be in effect. Successful bidder shall furnish manufacturer's warranty to the receiving district at time of delivery.

2.0 PARTS AND SERVICE: The manufacturer of the equipment furnished shall have an authorized dealer available to the State of Texas. The authorized dealer shall have factory-trained personnel available for warranty repairs and the performance of service. The dealer shall also maintain an inventory of high-usage parts and a quick source for low-usage parts.

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