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16. Abstract

In June of 1989, the Texas Department of Transportation (TxDOT) contracted with the Texas Transportation Institute (TTI) to develop a set of performance specifications for truck mounted attenuators (TMA's). The objectives of this project were to (1) assess the performance of several truck mounted attenuators and then (2) develop and propose the criteria that define an "acceptable" TMA. These criteria will be used by the Equipment and Procurement Division (D-4) of the Texas Department of Transportation in setting minimum performance requirements for TMA's purchased by the Department.

This report is the first of three volumes. The purpose of this report is to detail the work conducted during the course of the study, and to present the study findings, conclusions and recommendations. More specifically, this volume provides an overview of the study, along with the results obtained during crash, vibration and moisture tests on seven different makes and models of TMA's. Comparisons are drawn between the different attenuators that were tested, and a set of performance specifications for TMA certification is proposed.

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AN EVALUATION OF SELECTED TRUCK MOUNTED ATTENUATORS (TMA's) WITH RECOMMENDED PERFORMANCE SPECIFICATIONS

by

Lindsay I. Griffin, III
Richard A. Zimmer
Wanda L. Campise
King K. Mak

August 1991

Safety Division
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

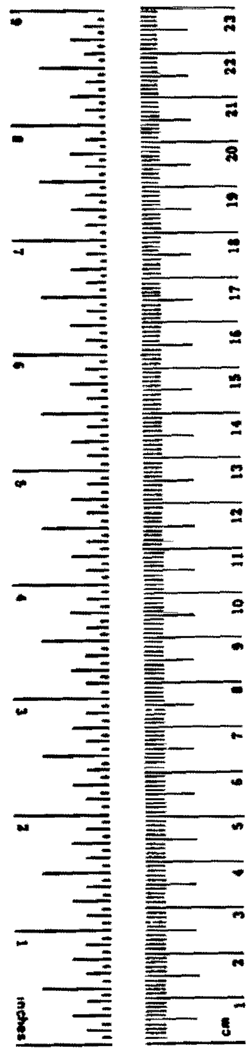
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

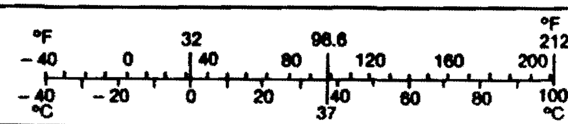
NOTE: Volumes greater than 1000 L shall be shown in m^3.

	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

NOTICE

This report was prepared for the Texas State Department of Highways and Public Transportation (SDHPT) under the provisions of a contract to the Texas Transportation Institute (TTI) of the Texas A&M University System entitled "Development of Performance Specifications for Truck Mounted Attenuators" (Study Number 2-4-89-991). SDHPT assumes no liability for its contents or use thereof.

The contents of this report reflect the views of the authors, who are responsible for the accuracy of the data presented herein. Any conclusions or opinions expressed in this report do not necessarily represent those of TTI, SDHPT or any other political subdivision of the state of Texas.

This report does not constitute a standard, specification or regulation.

ACKNOWLEDGEMENTS

The authors would like to recognize the contributions of Glenn Hagler and David Herrington of SDHPT for their efforts during the course of this study. In addition to overseeing this study on behalf of the Department, they provided insight and information throughout the project. Their assistance was very much appreciated.

The designers and manufacturers of the truck mounted attenuators tested in this study provided numerous comments and suggestions that proved of use. From Energy Absorption Systems, Inc., appreciation is expressed to Mike Essex, Bill Cragy, Barry Stephens, and Elmer Parker; from Hexcel, Inc., Mike Bandak; and from Vanderbilt University (on behalf of the Connecticut DOT), Jack Carney.

The assistance of John Marlow of the California Department of Transportation and George Newman of C&N, Inc. is also acknowledged with appreciation.

PREFACE

In June of 1989, the Texas State Department of Highways and Public Transportation (SDHPT) contracted with the Texas Transportation Institute (TTI) to develop a set of performance specifications for truck mounted attenuators (TMA's). The objectives of this project were to (1) assess the performance of several truck mounted attenuators and then (2) develop and propose the criteria that define an "acceptable" TMA. These criteria will be used by the Equipment and Procurement Division (D-4) in setting minimum performance requirements for TMA's purchased by the Department.

This report is the first of three volumes. The purpose of this report is to detail the work conducted during the course of the study, and to present the study findings, conclusions and recommendations. More specifically, this volume provides an overview of the study, along with the results obtained during crash, vibration and moisture tests on seven different makes and models of TMA's. Comparisons are drawn between the different attenuators that were tested, and a set of performance specifications for TMA certification is proposed.

This first volume is divided into five main parts: (1) Introduction (a brief review of the development and crash testing of TMA's since 1972), (2) TTI Assessment of Individual Makes and Models of TMA's, (3) Summary of Findings of on TMA Performance, (4) Proposed TMA Certification Procedures, and (5) Recommendations.

In the second volume to this study [Comparative Crash Tests Conducted on Seven Different Makes and Models of Truck Mounted Attenuators (TMA's), by Wanda L. Campise], the procedures and protocols employed in the 21 crash tests conducted during the course of this project are presented, along with the ways and means by which test data were collected and analyzed. Results of the tests are presented photographically (before-and-after photographs of the TMA's and impacting vehicles; sequential photographs of the crashes) and graphically (vehicle deceleration by time plots; angular displacements by time plots). Performance measures based upon NCHRP Report 230[1] (occupant impact velocity and occupant ridedown acceleration) and TRB Circular 191[2] (maximum 50 msec average longitudinal acceleration) criteria are provided.

In the third volume [Procedures and Equipment for Conducting Vibration and Moisture Tests on Truck Mounted Attenuators (TMA's), by Richard A. Zimmer], procedures for conducting vibrations and moisture tests on TMA's are discussed. Detailed plans for the construction of the necessary apparatus to conduct these tests is also provided. Test procedures and protocols are documented, and the results of individual vibration and moisture tests are provided.

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[1]Michie, J.D. Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances, National Cooperative Highway Research Program Report 230, Transportation Research Board, National Research Council, Washington, D.C., March 1981.

[2]Transportation Research Circular 191. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. Transportation Research Board, National Research Council, Washington, D.C., February 1978.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The history of the development of the truck mounted attenuator (TMA) in the United States can be traced to the early 1970's when the Texas Transportation Institute (TTI) designed and tested a "crash cushion trailer" (Marquis and Hirsch, 1972). The TTI crash cushion trailer was 22.5 feet long and 5.8 feet wide. The energy absorbing portion of the device consisted of 30, twenty gage, 55-gallon steel drums, three drums wide and 10 drums long. Trailer weight was estimated to be 2,010 pounds (Figure 1).[3]

One crash test was conducted on this crash cushion trailer. In this test a 4,060 pound passenger car impacted the cushion at 63.3 mph, head-on, i.e., zero degrees offset, centerline of car to centerline of crash cushion trailer. The dump truck to which the cushion trailer was attached weighed 9315 pounds. The truck was free standing, in gear, with the parking brake on.

During the collision the dump truck was displaced 20.0 feet. The maximum forward motion of the car was 36.4 feet. The maximum 50 msec average longitudinal acceleration during the collision was approximately 8 g's (estimated from the graph provided as Figure 12 in Marquis and Hirsch, 1972).

Several objections to the use of the TTI crash cushion trailer were raised after its introduction into the field, as quoted below (Hirsch, Nixon, Hustace and Marquis, 1975, page 28):

- Have used system for about six months behind sweepers but jiggle bars caused welds to fail. They have abandoned its usage after several repairs – might be useful if it were more maneuverable and was more substantial.

- Objections to its use are: they can't turn it around, length is prohibitive, requires a storage area when in use and may not be practical in urban areas.

To overcome the operational problems associated with trailering a 22-foot crash cushion, personnel in District 19 (Atlanta, Texas) designed and constructed a true TMA (i.e., a crash cushion suspended from, rather than trailered behind, a service vehicle). This TMA consisted of 16 steel barrels arranged in four longitudinal rows, four barrels per row. Although this TMA was used in the field, full-scale crash tests were never conducted on the system (Figure 2).[4]

In late 1975, the Connecticut Department of Transportation contracted with the University of Connecticut to develop a truck mounted attenuator, i.e., a portable crash cushion that could be suspended or cantilevered off the rear of a dump truck, rather than trailered (Carney 1977, 1979). The attenuator that was developed consisted of four, two-foot diameter steel cylinders (open-ended pipes) attached within a telescoping, box-beam frame. The box-beam frame was, in turn, attached beneath a dump truck. At the rear of the attenuator a vertical, steel

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[3]Additional information on the design of crash cushions trailers can be found in Jung, 1977; Jung and Billing, 1976.

[4]Texas State Department of Highways and Public Transportation (D-10R). The Research Reporter, No. 8-77, November 1977.

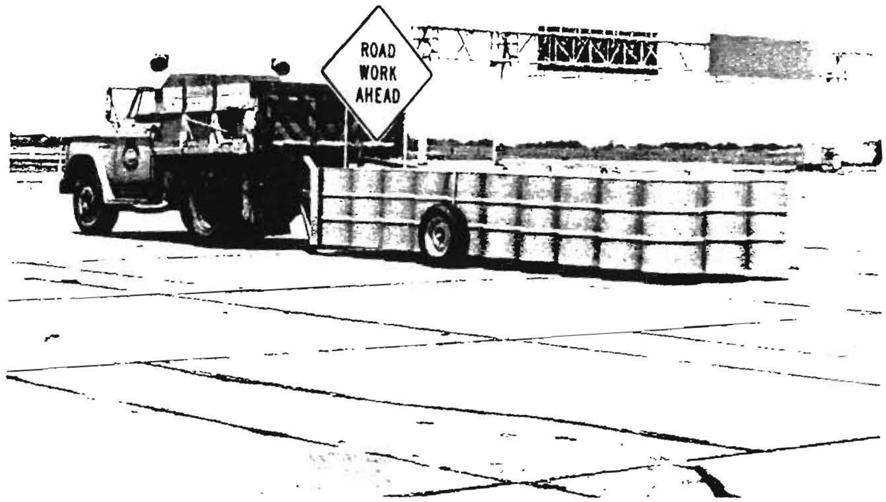

Figure 1(a): TTI Crash Cushion Trailer (Marquis and Hirsch, 1972)

Figure 1(b): TTI Crash Cushion Trailer After Impact by a 4046 lb Passenger Car at 63 mph

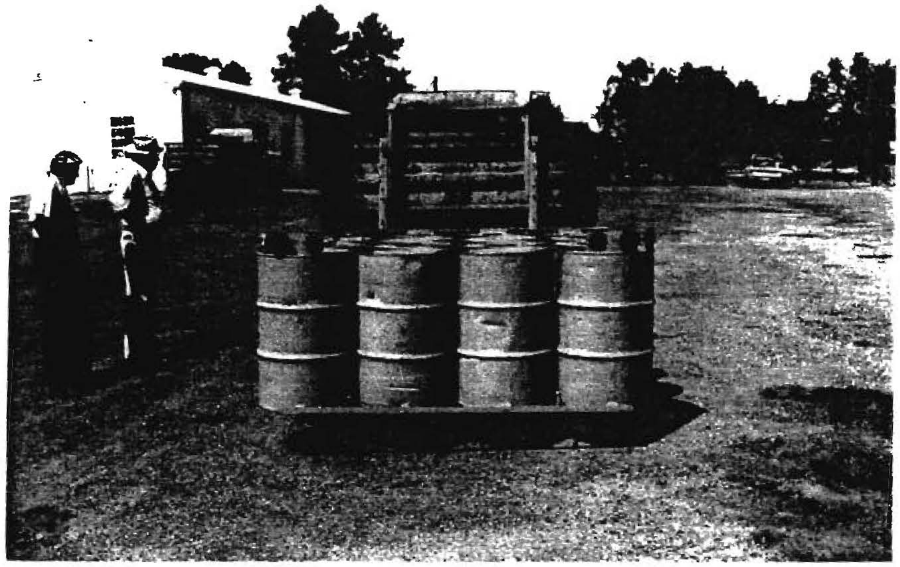

Figure 2(a): Rear View of District 19 Sixteen Barrel TMA

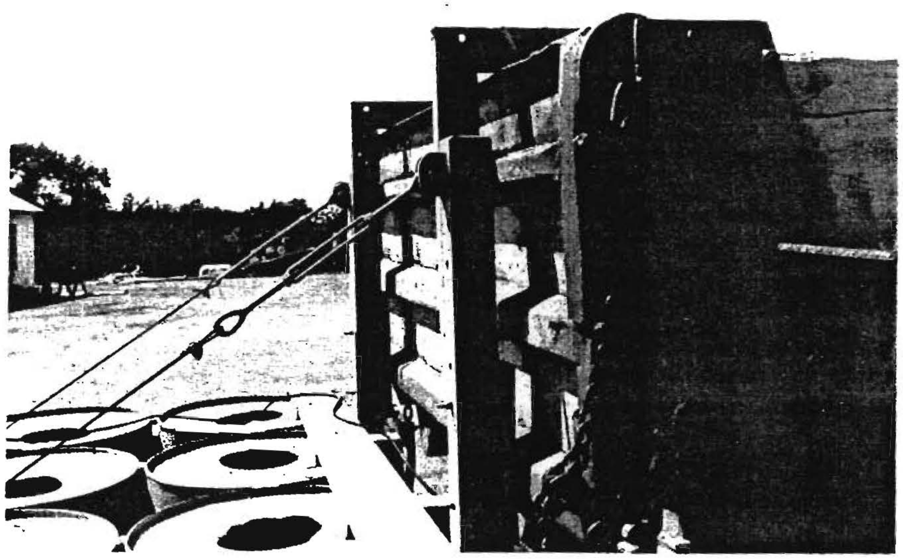

Figure 2(b): Attachment of District 19 TMA (later changed to aluminum) plate was positioned to distribute the load of impacting vehicles across the breadth of the frame. The rear-most portion of the attenuator assembly was suspended from the dump truck by means of chains and turnbuckles (Figure 3).

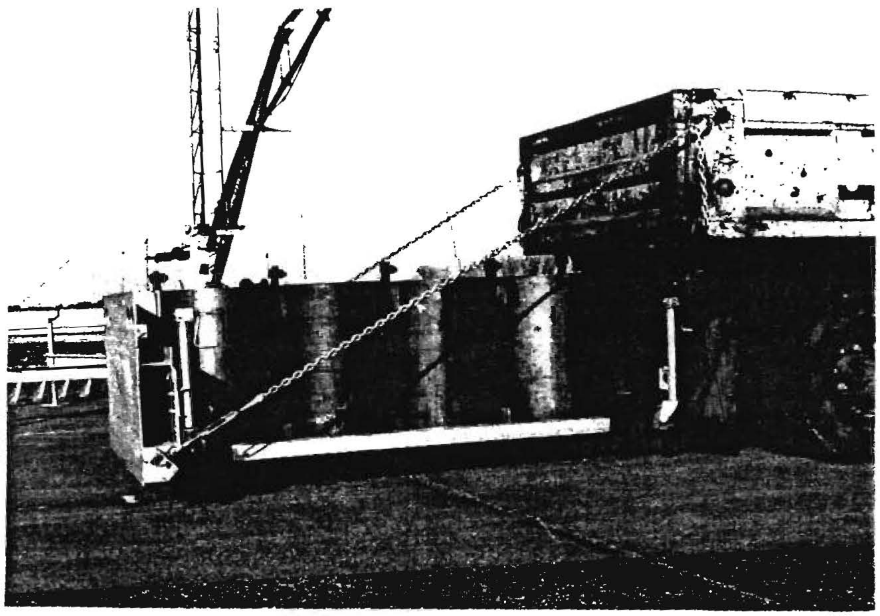

Figure 3: Connecticut Department of Transportation TMA

The overall length of the Connecticut TMA is 8.8 feet. Ground clearance is 6 to 8 in and the height of the system (to the tops of the pipes) is approximately 41 in.

Six crash tests were conducted on the Connecticut TMA before the start of the present project: four tests at Calspan Corporation and two at TTI. The nominal speed at impact in each of these six tests was 45 mph. Vehicle weights fell into two categories: light (about 2,250 lbs) and heavy (about 4,500 lbs). Three tests were conducted head-on, centerline to centerline; three were conducted off center, i.e., the centerline of the striking vehicle was offset from the centerline of the TMA. Further detail on the test conditions is provided in Table 1.

In a 1988 publication, Carney reanalyzed the results of the first six tests on the Connecticut TMA in terms of the evaluation criteria contained in NCHRP Report 230 (Michie, 1981). Figure 4 presents the results of this reanalysis. Using the NCHRP Report 230 criteria, five of the six tests were within acceptable limits, i.e., five of the six tests had longitudinal occupant impact velocities below 40 fps and longitudinal occupant ridedown accelerations between 0 and -20

Table 1: Conditions for the First Six Crash Tests Conducted on the Connecticut TMA (Carney 1977, 1979, 1988)

	TEST NUMBER					
	CAL-1	CAL-2	CAL-3	CAL-4	TTI-1	TTI-2
DUMP TRUCK						
Weight (lbs)	15980	16000	16000	16000	15080	15080
Displacement (ft)	8.3	18.6	16.2	14.8	8.1	11.6
Brake Setting	Off	Off	Off	Off		
Gear Setting	2nd	2nd	2nd	2nd		
STRIKING VEHICLE						
Weight (lbs)	2260	4480	4480	4470	2300	4500
Speed (mph)	45.8	46.5	45.5	45.8	45.9	47.2
Impact Angle (deg)	0	0	0	10	0	10
Impact Offset (in)	0	0	30	30	0	30
TMA						
Wall Thickness of Third Pipe (in)	1/4	3/8	3/8	3/8	3/8	3/8
Impact Plate (lbs)	430	430	430	430	278	278

Note: The pipe next to the impact plate is the first pipe. The pipe next to the dump truck is the fourth pipe. The third pipe is defined accordingly.

g's. The sixth test (TTI-1) was unacceptable, i.e., the calculated longitudinal ridedown acceleration of -23.4 g's exceeded the acceptable limit of -20 g's.[5,6]

In a 1980 report, Stoughton, Stoker and Nordlin give the results of six full-scale crash tests on TMA's that used 84 vermiculite concrete cells to absorb the energy of impacting vehicles. The 84 cells were contained within a plywood box that measured 6 ft long, 8 ft wide and 2 ft high. The plywood box was cantilevered off the back of a dump truck. The overall weight of this TMA was approximately 1,400 lbs.

Table 2 documents the six crash tests that were conducted on this TMA. All six tests were conducted once again at a nominal speed of 45 mph. Four of the striking vehicles (passenger cars) weighed in excess of 4,000 lbs, two weighed

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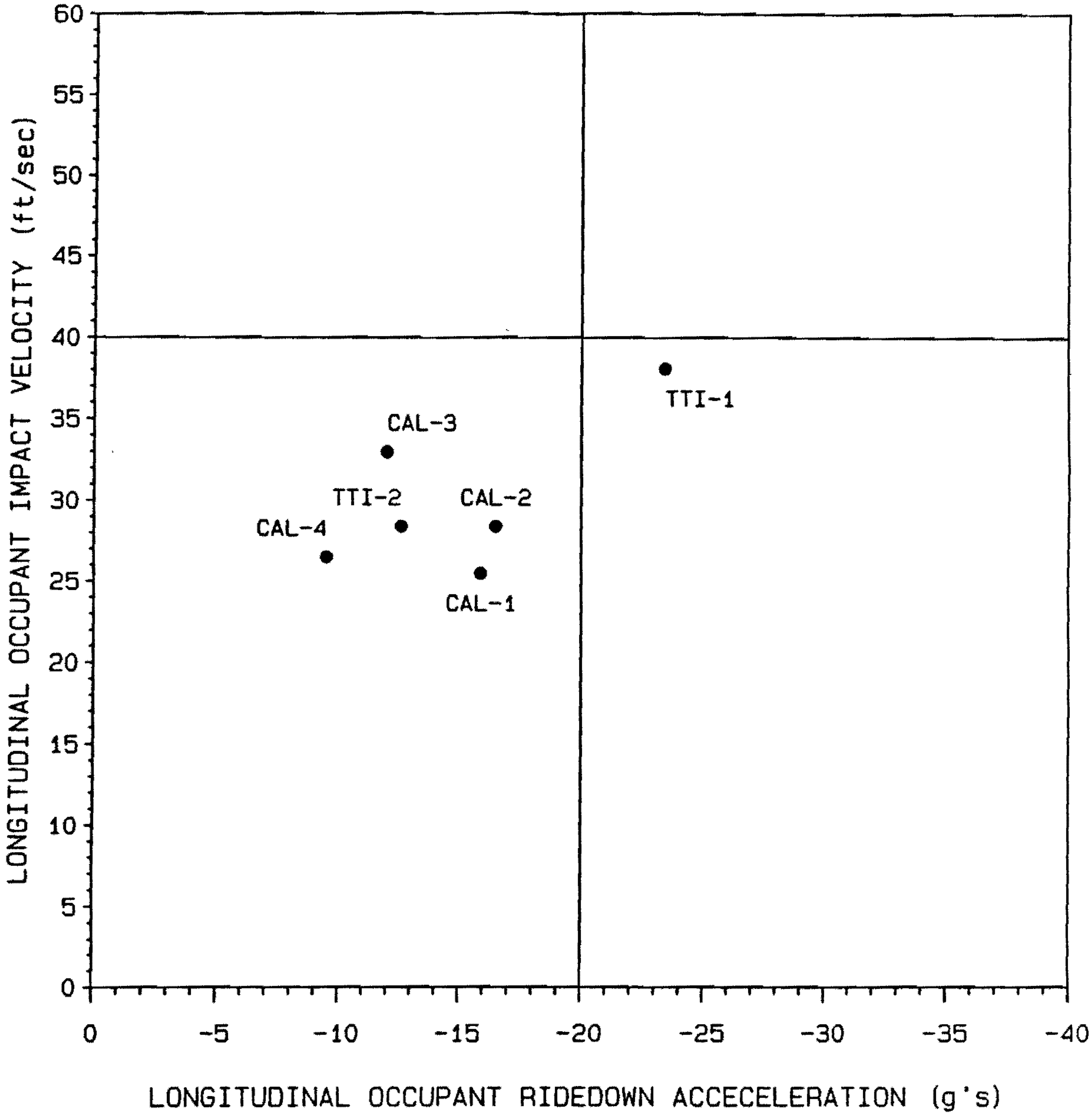
[5]Additional information on occupant impact velocity and occupant ride down acceleration, as defined in NCHRP 230, is provided in Appendix A.

[6]Lateral occupant impact velocities and lateral occupant ride down accelerations were well within the acceptable range, as might have been expected, for all six tests.



Notes:	CAL-1:	2260 lb Car,	45.8 mph,	No Offset,	0 deg
	CAL-2:	4480 lb Car,	46.5 mph,	No Offset,	0 deg
	CAL-3:	4480 lb Car,	45.5 mph,	30 in Off,	0 deg
	CAL-4:	4470 lb Car,	45.8 mph,	30 in Off,	10 deg
	TTI-1:	2300 lb Car,	45.9 mph,	No Offset,	0 deg
	TTI-2:	4500 lb Car,	47.2 mph,	30 in Off,	10 deg

Figure 4: RESULTS OF THE FIRST SIX CRASH TESTS CONDUCTED ON THE CONNECTICUT TRUCK MOUNTED ATTENUATOR

Table 2: Conditions for Six Crash Tests on TMA's Using Vermiculite Concrete Cells for Energy Absorption (Stoughton et al., 1980)

	TEST NUMBER					
	372	373	374	EAS-1	375	376
DUMP TRUCK						
Weight (lbs)	13140	13140	13300	13140	13140	13140
Displacement (ft)	7.9	13.8	2.4	3.7	7.3	3.2
Brake Setting	All	Rear	All	All	All	Rear
Gear Setting	2nd	2nd	2nd	2nd	2nd	2nd
STRIKING VEHICLE						
Weight (lbs)	4400	4420	2140	2250	4360	1890
Speed (mph)	45.0	45.0	45.0	49.0	45.0	44.0
Impact Angle (deg)	0	0	0	0	15	0
Impact Offset (in)	0	0	0	0	36	0

over 2,000 lbs and one weighed 1,890 lbs. Five of the tests were conducted head-on; one was at 15 deg, 36 in from the centerline.

The results of these six crash tests are shown in Figure 5, along with a comparison crash test into an unprotected dump truck, i.e., a dump truck without a TMA (371). By the provisions in TRB Circular 191, three of these tests were acceptable (372, 373 and 375); three were unacceptable (374, EAS-1 and 376). Note that the acceptable tests involved heavier cars (4400, 4420 and 4360 lbs); the unacceptable tests involved lighter cars (2140, 2250 and 1890 lbs).[7]

Schiefferly and Marlow (1983) reported the results of eight crash tests into dump trucks protected by TMA's that used aluminum honeycomb to absorb the energy of impacting vehicles.[8] The aluminum honeycomb was contained within a box that was 7 ft long, 7 ft 8 in wide and 2 ft high.

The conditions for the eight crash tests conducted on this TMA are shown in Table 3. Five of the striking vehicles (passenger cars) weighed in excess of 4,000 lbs; the other three weighed over 2,000 lbs. The first seven tests were head-on tests at a nominal speed of 45 mph. The eighth was conducted at 12 deg, 12 in off center.

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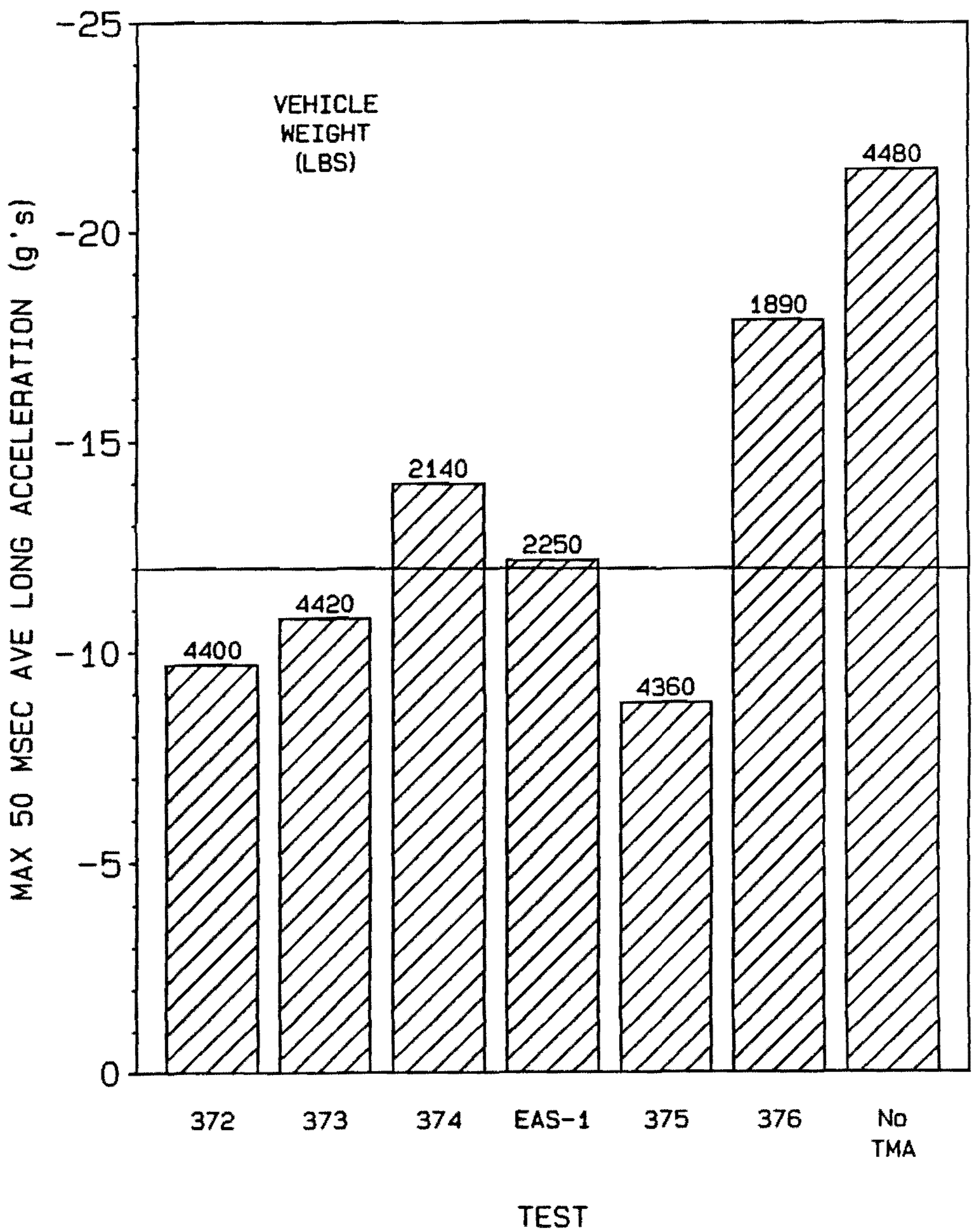
[7]These test results are reported in terms of the applicable standards or guidelines in 1980 – TRB Circular 191. NCHRP 230 was published in 1981. A brief discussion of the TRB 191 "50 msec maximum average longitudinal acceleration" criterion for assessing TMA performance is provided in Appendix A.

[8]Additional crash tests were performed with the aluminum honeycomb TMA attached to a smaller, light-duty truck rather than a dump truck. The results of those tests are not presented here.



Notes:
(1) Impact speeds were nominally 45 mph (see Table 2).
(2) Test 375 was 36 in off center, at 15 deg. All other tests were
0 in off center, 0 deg, i.e., head-on, centerline-to-centerline.

Figure 5: RESULTS OF SIX CRASH TESTS ON TMA's USING VERMICULITE CONCRETE CELLS FOR ENERGY ABSORPTION (from Stoughton, Stoker and Nordlin, 1980)

Table 3: Conditions for Eight Crash Tests on TMA's Using Aluminum Honeycomb for Energy Absorption (Schiefferly and Marlow, 1983)

	TEST NUMBER							
	382	383	384	385	386	387	388	389
DUMP TRUCK								
Weight (lbs)	11000	11000	11000	11000	11000	11000	11000	11000
Displacement (ft)	16.7	6.4	6.1	6.8	17.0	28.7	39.8	14.3
Brake Setting	All	All	All	All	All	All	All	All
Gear Setting	2nd	2nd	2nd	2nd	2nd	2nd	2nd	2nd
STRIKING VEHICLE								
Weight (lbs)	4420	2085	2080	2180	4230	4190	4185	4270
Speed (mph)	43.9	44.7	43.2	44.4	45.1	45.5	46.4	44.8
Impact Angle (deg)	0	0	0	0	0	0	0	12
Impact Offset (in)	0	0	0	0	0	0	0	12

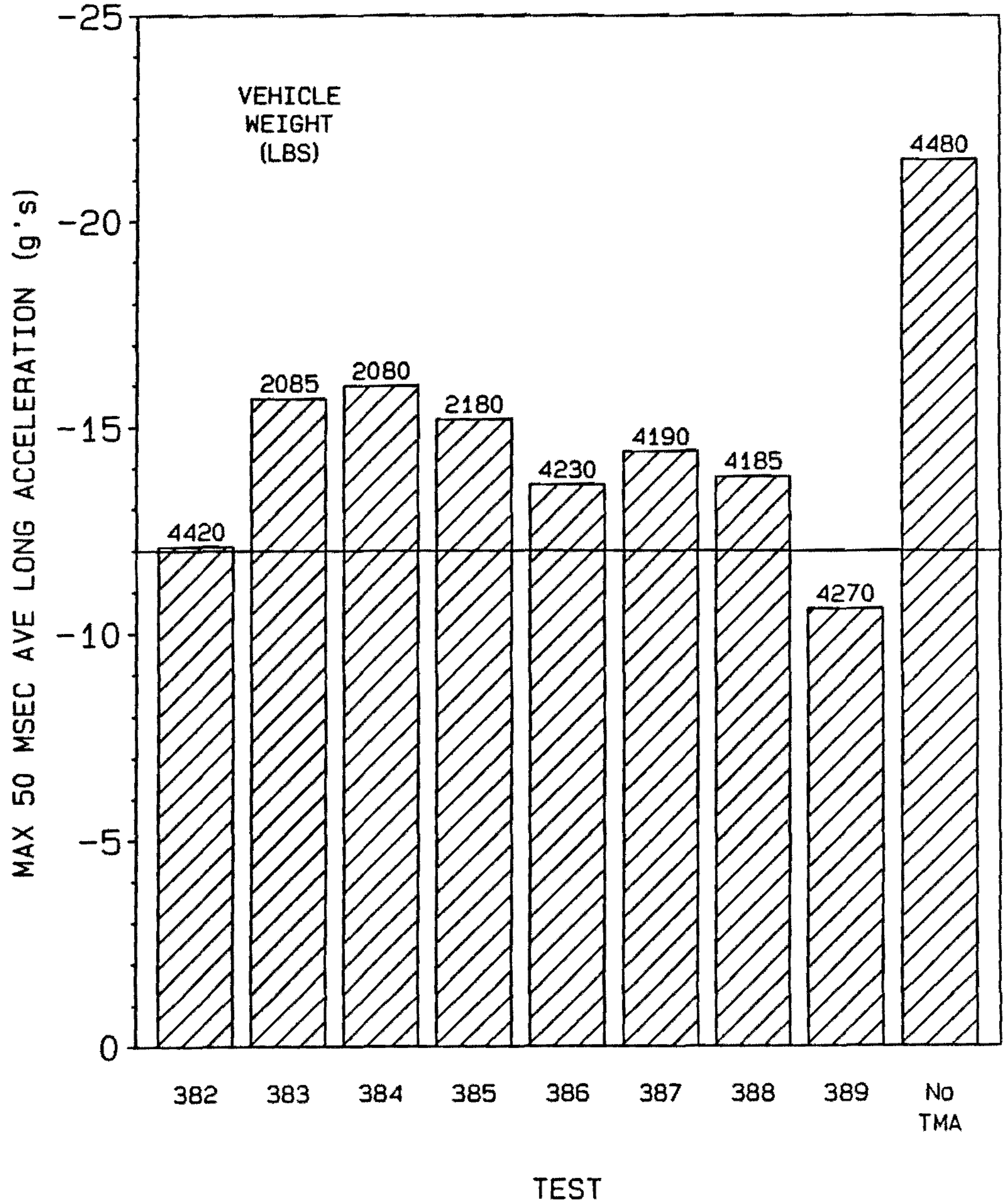
The results of these eight tests are provided in Figure 6, along with the results of a similar test conducted in the absence of a TMA (371). Of the eight tests that were conducted with the aluminum honeycomb material, the first seven were unacceptable by TRB Circular 191. These tests were all head-on tests. The eighth test (12 in off center at 12 deg) was acceptable.

Energy Absorption Systems, Inc (EAS 1987a, 1987b, 1987c) provides data on eleven additional crash tests - four conducted on the EAS Alpha Model TMA and seven conducted on the Hex-Foam Model.[9] Test conditions for the Alpha and Hexfoam tests are shown in Tables 4 and 5, respectively. The results of the four Alpha tests are shown in Figure 7; the results of the Hexfoam tests are shown in Figure 8.

The results of all 11 crash tests depicted in Figures 7 and 8 are acceptable. All longitudinal occupant impact velocities are between 0 and 40 fps; all longitudinal occupant ridedown accelerations are between 0 and -20 g's.

In terms of occupant impact velocity, there seems to be very little difference between the Alpha and Hexfoam models. In terms of occupant ridedown accelerations, however, the Hexfoam model does appear to provide somewhat lower ridedowns than the Alpha model.

[9] The assistance of Energy Absorption Systems, Inc. in resolving several minor discrepancies in these reports is acknowledged with appreciation.



Notes:
(1) Impact speeds were nominally 45 mph (see Table 3).
(2) Test 389 was 36 in off center, at 12 deg. All other tests were 0 in off center, 0 deg, i.e., head-on, centerline-to-centerline.

Figure 6: RESULTS OF EIGHT CRASH TESTS ON TMA's USING ALUMINUM HONEYCOMB FOR ENERGY ABSORPTION (from Schiefferly and Marlow, 1983)

Table 4: Conditions for Four Crash Tests on Energy Absorption System's Alpha Model TMA (EAS 1987a)

	TEST NUMBER			
	103-2	103-3	88-6	88-8
DUMP TRUCK				
Weight (lbs)	12540	12540	12300	12300
Displacement (ft)	16.8	4.2	17.6	12.3
Brake Setting	All	All	All	All
Gear Setting	2nd	2nd	2nd	2nd
STRIKING VEHICLE				
Weight (lbs)	4323	1800	4260	4380
Speed (mph)	46.2	45.1	44.7	49.3
Impact Angle (deg)	0	4.5	0	12.5
Impact Offset (in)	0	0	0	6

Table 5: Conditions for Seven Crash Tests on Energy Absorption System's Hex-Foam Model TMA (EAS 1987b, 1987c)

	TEST NUMBER						
	78-1	78-2	12-10	12-11	109-1	109-4	109-5
DUMP TRUCK							
Weight (lbs)	20000	20000	12000	12000	13250	12800	12800
Displacement (ft)	2.2	11.9	12.3	2.0	31.6	1.9	12.7
Brake Setting	All	All	Rear	Rear			
Gear Setting	Neutral	Neutral	2nd + Chain	2nd + Chain			
STRIKING VEHICLE							
Weight (lbs)	1827	4411	4700	4534	5434	1600	5440
Speed (mph)	48.4	46.0	43.6	46.5	45.0	48.7	44.7
Impact Angle (deg)	0	0	0	15	0	0	12
Impact Offset (in)	0	0	30	36	0	0	0

Notes: (1) In test 78-1 there was a 165-lb dummy in the 1827-lb test vehicle.

(2) In tests 12-10 and 12-11 the parking brake was set on the rear wheels, and the wheels were chained to prevent rotation.

(3) The striking vehicles in 109-1 and 109-5 were pickup trucks. The striking vehicles in all other tests were passenger cars.

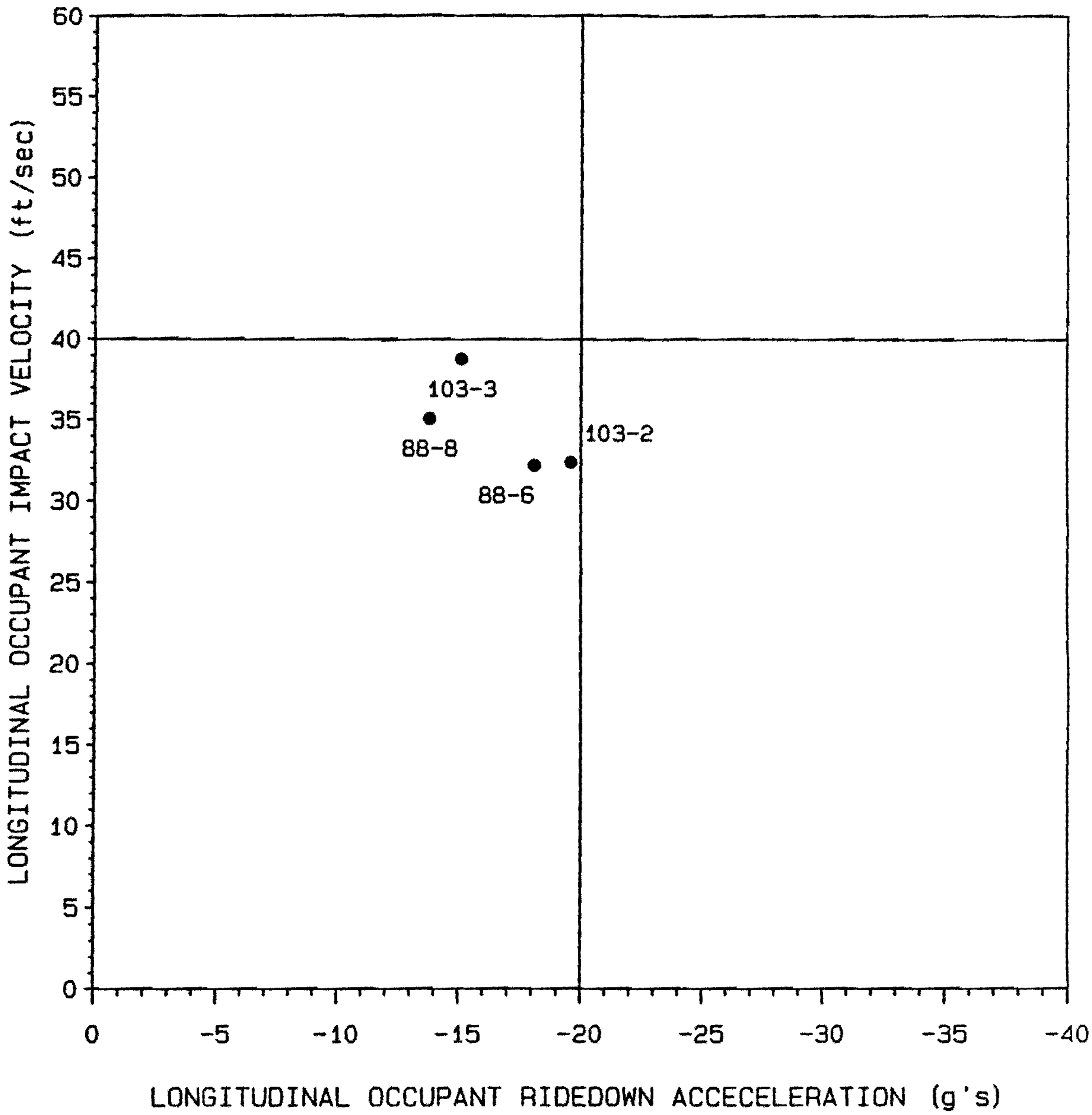


Figure 7: RESULTS OF FOUR CRASH TESTS CONDUCTED ON ENERGY ABSORPTION SYSTEM's ALPHA MODEL TMA (from EAS 1987a)

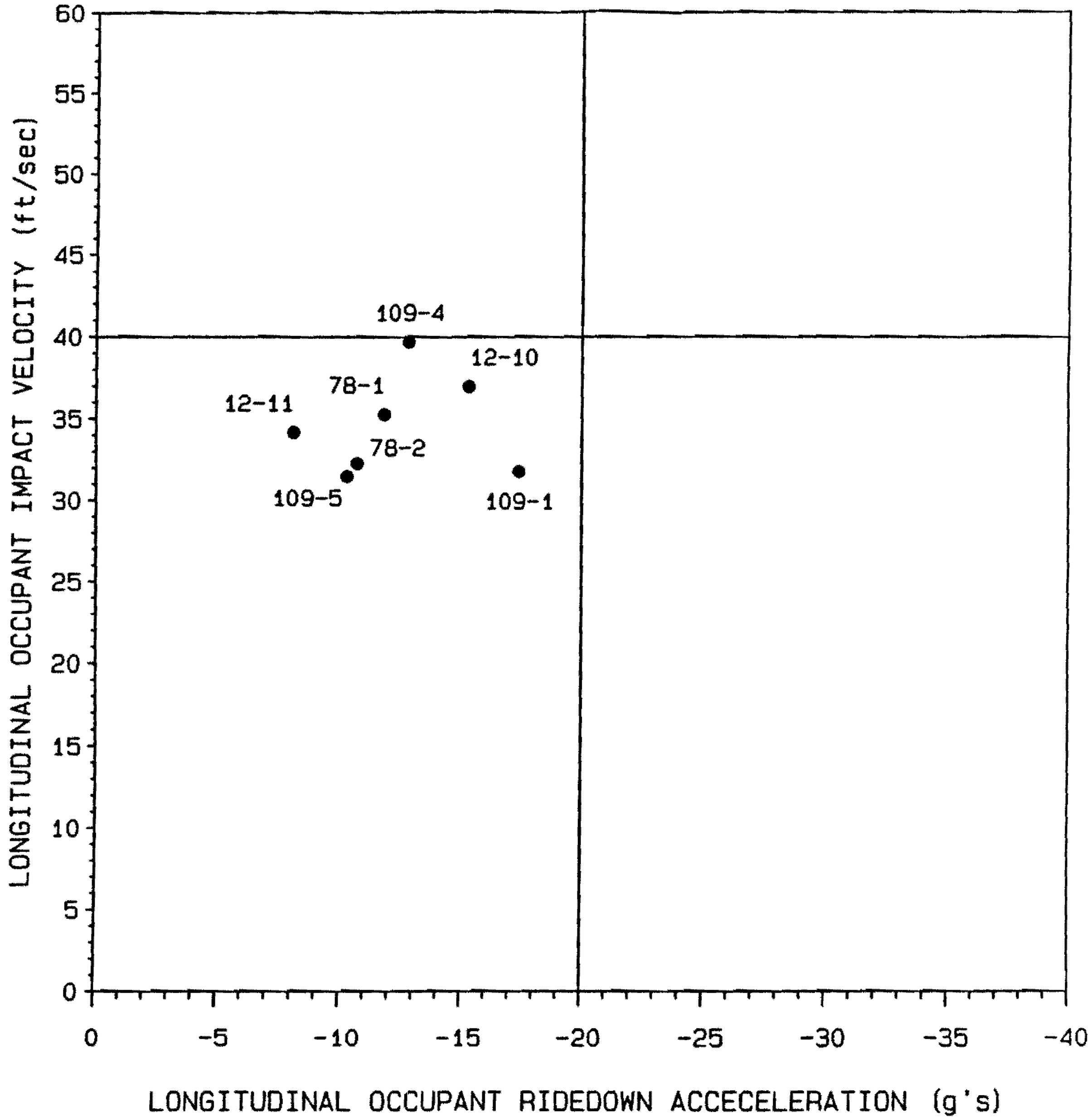


Figure 8: RESULTS OF SEVEN CRASH TESTS CONDUCTED ON ENERGY ABSORPTION SYSTEM's HEX-FOAM MODEL TMA (from EAS 1987b, 1987c)

TTI ASSESSMENT OF INDIVIDUAL MAKES AND MODELS OF TMA's

At the outset of this study the decision was made by SDHPT and TTI to evaluate a candidate set of TMA's currently on the market (or under development) on three basic performance criteria. Although other criteria might have been considered in evaluating the performance of TMA's (e.g., flammability), the three criteria listed below were thought to be of primary importance:

(1) **Crashworthiness:** (a) How much protection is afforded drivers of vehicles that impact TMA's? (b) To a lesser extent, how much protection is afforded drivers of the dump trucks to which TMA's are attached?

(2) **Fatigue:** How well do TMA's "hold up" in real-world operations? How well do TMA's withstand vibrations typical of in-service usage over protracted periods of time?

(3) **Moisture Resistance:** How susceptible are TMA's to collecting moisture during inclement weather - particularly if the collection of moisture might reasonably be expected to denigrate the crashworthiness of the TMA?

In order to conduct the crash, vibration and moisture tests discussed in this section, TTI was provided with seven different makes and models of TMA's (three units per make/model). The specific makes and models provided are listed below. Photographs of each of these seven TMA's are provided in Figures 3 and 9-14.

	Figure
1. Energy Absorption Alpha Model TMA	9
2. Energy Absorption Hexfoam Model TMA	10
3. Hexcel Current Model TMA	11
4. Hexcel Developmental Prototype TMA	12
5. Renco TMA	13
6. Markings and Equipment Corporation TMA	14
7. Connecticut DOT TMA	3

CRASH TESTING

During the course of this study, 21 different crash tests were conducted. These tests served (1) to assess the overall benefit of TMA's (relative to similar tests in which no TMA's were used) and (2) to compare the performance of individual makes and models of TMA's with respect to one another.

The TMA's being evaluated were mounted on a 24,000-lb (GVWR) dump truck that had been ballasted to 14,000 pounds prior to the attachment of the TMA. Each test was conducted in general accordance with guidelines presented in NCHRP Report 230. The 21 crash tests were divided into four test series:

Test Series 1: Eight tests were conducted using a 4,500-lb passenger car impacting the TMA head-on at 45 mph with the dump truck in a free-standing position, parked in second gear with the parking brake on. For purposes of comparison, an additional (ninth) test was conducted under the same impact conditions in the absence of a TMA.

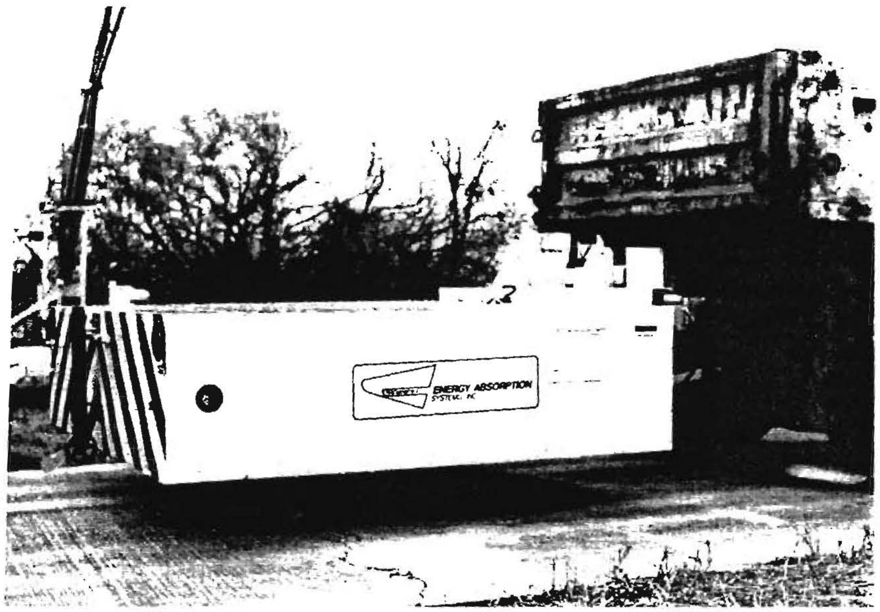


Figure 9: Energy Absorption System Alpha Model TMA

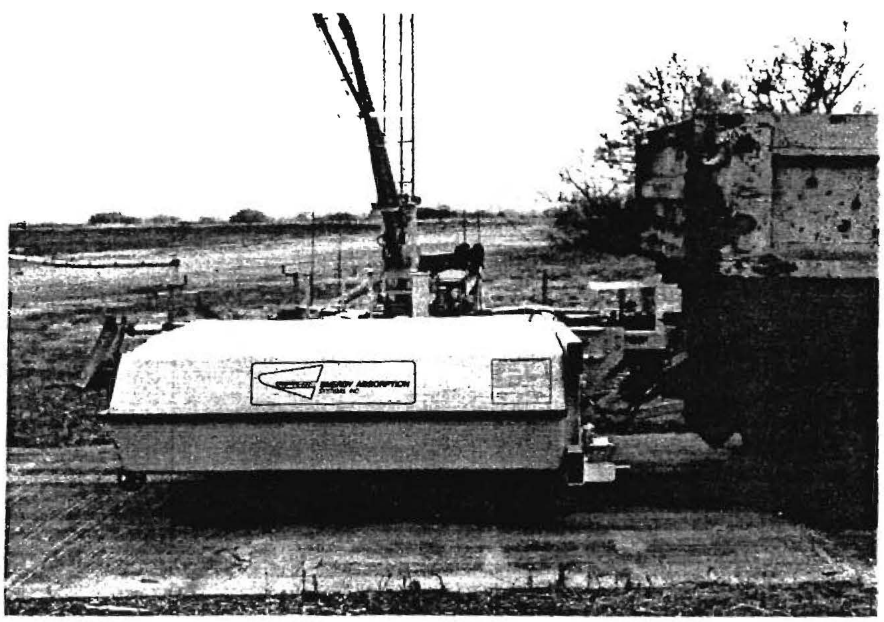


Figure 10: Energy Absorption System Hex-Foam Model TMA

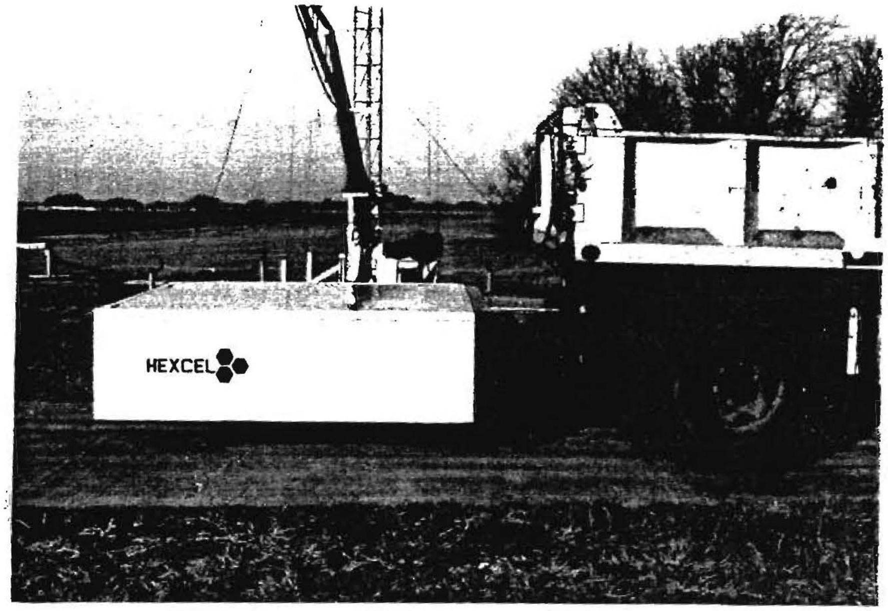


Figure 11: Current Model Hexcel TMA

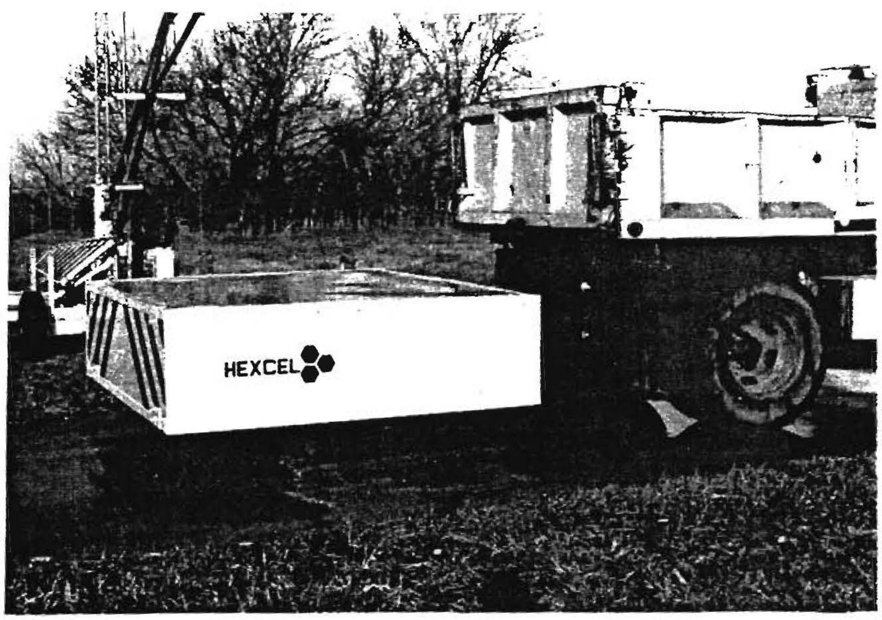


Figure 12: Developmental Prototype TMA by Hexcel

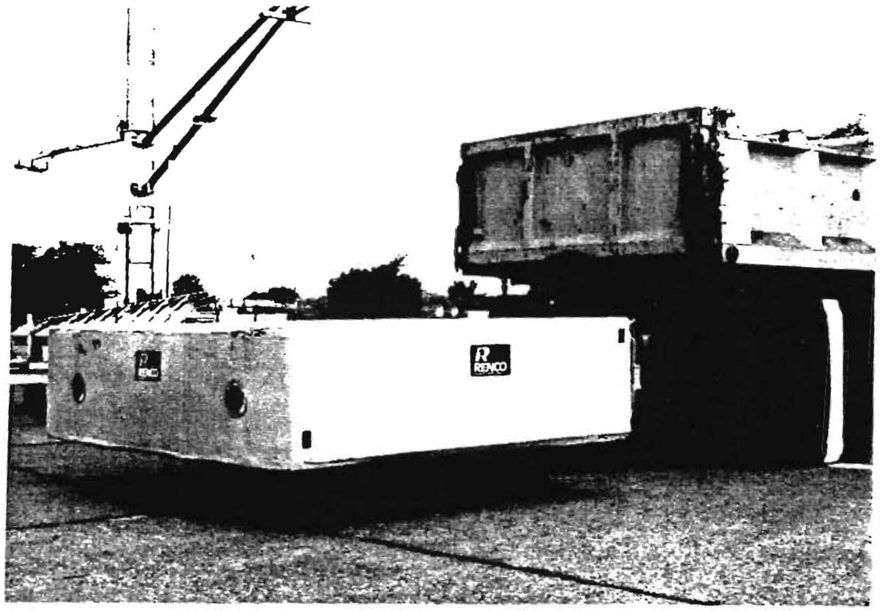


Figure 13: TMA Provided by Renco, Inc.

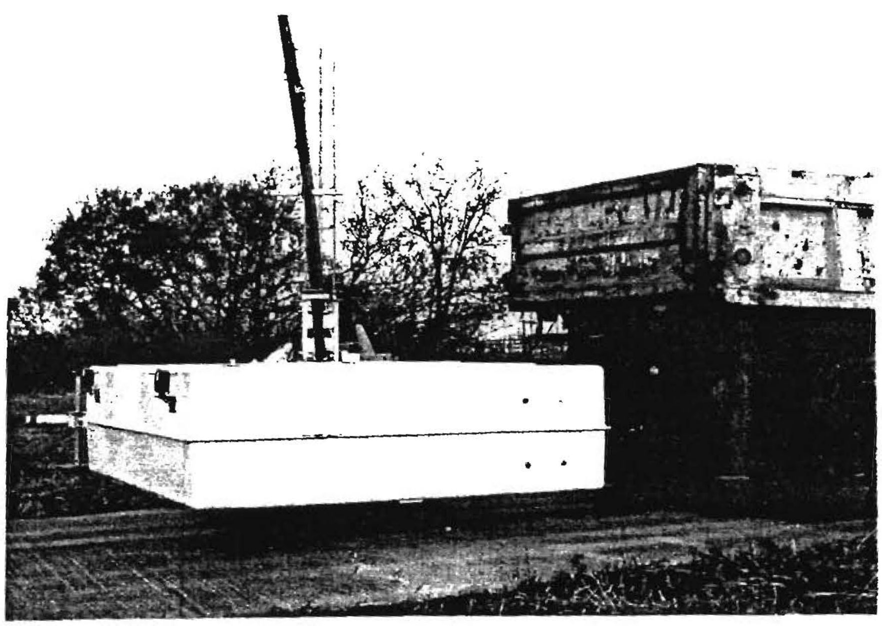


Figure 14: TMA Provided by Markings and Equipment Corporation

Test Series 2: Seven tests were conducted using an 1,800-lb passenger car impacting the TMA head-on at 45 mph with the dump truck in a fixed position (parked with its front bumper against a rigid wall). For purposes of comparison, an additional (eighth) test was conducted under the same impact conditions in the absence of a TMA.

Test Series 3: Three tests were conducted using a 3,500-lb passenger car impacting the TMA head-on at 55 mph with the dump truck in a free-standing position, parked in second gear with the parking brake on. Two of the three TMA's used in these tests had previously been subjected to the vibration and moisture tests discussed in volume 3 to this report.

Test Series 4: One test was conducted in this series. The conditions for this test were equivalent to the conditions in Test Series 1, except that the striking vehicle was a 4,500-lb pickup truck instead of a 4,500-lb passenger car.

The specific crash tests conducted on the different makes and models of TMA's are outlined in Table 6. The overall results of these 21 crash tests are summarized in Table 7.

Table 6: Crash Test Matrix for 21 Truck Mounted Attenuator (TMA) Tests Conducted at TTI, by Test Condition

	Test Series				
	1	2	3	4	
	45	45	55	45	[Speed (mph)]
	Car	Car	Car	Truck	[Veh Type]
TMA Make/Model	4500	1800	3500	4500	[Wt (lbs)]
EA (Alpha Model)	X	X	X	X	
EA (Hex-Foam Model)	X	X			
Hexcel (Current Model)	X	X	X		
Hexcel (Prototype) [1]	X	X			
Hexcel (Prototype) [2]	X				
Renco	X	X			
Markings and Equipment	X	X			
Connecticut DOT	X	X	X		
None	X	X			

Notes:
1. The truck referred to under Veh Type was a 4500-lb pickup
2. All tests were at 0 degrees, no offset (i.e., head on)
3. TMA's were attached to dump trucks ballasted to 14,000 pounds prior to TMA attachment
4. Under Test Condition 2, the dump trucks were pulled up to a rigid, immovable wall. Under Test Conditions 1, 3 and 4, the dump trucks were "free standing," with the parking brake set and the transmission in second gear.

Table 7: Results of 21, Full-Scale Crash Tests on Selected TMA's

Test Series (1): 4500 Pound Passenger Cars Traveling at Nominal Speeds of 45 mph

TMA	Test Number	Impact Speed (mph)	Longitudinal Occupant Impact Velocity (ft/s)	Longitudinal Occ Ride Down Acceleration (g)	Maximum 50 msec Average Long. Acceleration (g)
EA (Alpha Model)	9919-05	45.9	32.7 (146)	-16.4 (191-201)	-12.6 (151-201)
EA (Hex-Foam Model)	9910-04	44.5	34.2 (133)	-12.4 (136-146)	- 9.8 (78-128)
Hexcel (Current Model)	9919-02	46.3	34.4 (129)	-12.8 (139-149)	-12.1 (111-161)
Hexcel (Prototype) [1]	9919-01	47.3	30.6 (120)	- 8.1 (128-138)	- 9.4 (9- 59)
Hexcel (Prototype) [2]	9910-06	44.5	27.0 (132)	-19.6 (234-244)	-13.4 (203-253)
Renco	9919-04	45.7	33.5 (146)	-15.1 (167-177)	-12.8 (146-196)
Markings and Equipment	9919-03	47.8	30.9 (148)	-18.6 (177-187)	-14.0 (146-196)
Connecticut DOT	9910-10	45.6	28.1 (140)	-19.2 (164-174)	-13.7 (155-205)
None	9910-16	46.8	46.7 (96)	- 9.2 (102-112)	-20.4 (37- 87)

Test Series (2): 1800 Pound Passenger Cars Traveling at Nominal Speeds of 45 mph

TMA	Test Number	Impact Speed (mph)	Longitudinal Occupant Impact Velocity (ft/s)	Longitudinal Occ Ride Down Acceleration (g)	Maximum 50 msec Average Long. Acceleration (g)
EA (Alpha Model)	9910-03	43.9	45.0 (111)	-16.0 (136-146)	-16.0 (76-126)
EA (Hex-Foam Model)	9910-08	44.4	46.5 (93)	-17.8 (126-136)	-16.9 (41- 91)
Hexcel (Current Model)	9910-05	45.2	38.8 (101)	-11.5 (124-134)	-13.2 (31- 81)
Hexcel (Prototype)	9910-07	46.4	38.4 (99)	- 9.3 (142-152)	-14.7 (18- 68)
Renco	9910-02	46.3	34.4 (127)	-28.1 (142-152)	-23.9 (118-168)
Markings and Equipment	9910-01	44.9	30.1 (126)	-24.0 (185-195)	-19.7 (154-204)
Connecticut DOT	9910-09	45.3	37.3 (96)	-13.8 (100-110)	-14.0 (3- 53)
None	9910-15	45.9	58.9 (73)	-11.9 (90-100)	-30.8 (22- 72)

Notes: 1. All tests were at 0 degrees, no offset (i.e., head on).

(notes continue on next page)

Table 7: Results of 21, Full-Scale Crash Tests on Selected TMA's (Continued)

Test Series (3): 3500 Pound Passenger Cars Traveling at Nominal Speeds of 55 mph

TMA	Test Number	Impact Speed (mph)	Longitudinal Occupant Impact Velocity (ft/s)	Longitudinal Occ Ride Down Acceleration (g)	Maximum 50 msec Average Long. Acceleration (g)
EA (Alpha Model)	9910-13	55.5	38.6 (140)	-38.6 (148-158)	-23.8 (112-162)
Hexcel (Current Model)	9910-14	58.0	34.1 (123)	-31.5 (123-133)	-20.5 (110-160)
Connecticut DOT	9910-11	55.8	34.3 (111)	-52.5 (154-164)	-23.7 (119-169)

Test Series (4): 4500 Pound Pickup Traveling at a Nominal Speed of 45 mph

TMA	Test Number	Impact Speed (mph)	Longitudinal Occupant Impact Velocity (ft/s)	Longitudinal Occ Ride Down Acceleration (g)	Maximum 50 msec Average Long. Acceleration (g)
EA (Alpha Model)	9910-12	45.1	35.0 (152)	-14.2 (158-168)	-13.4 (124-174)

Notes:

2. Numbers in parentheses represent the times and durations (in msec after initial impact) from which velocities and accelerations were calculated.

3. The tabulated occupant impact velocities, ridedown accelerations and 50 msec average accelerations have all been adjusted to account for slight differences between impact speed (S) and the nominal, desired test speeds of 45 or 55 mph. This adjustment was made by multiplying the raw occupant impact velocities, ridedown accelerations and 50 msec average accelerations by $(45/S)^2$ or $(55/S)^2$.

4. TMA's were attached to dump trucks ballasted to 14,000 pounds prior to TMA attachment.

5. In Test Series 2, the dump trucks were pulled up to a rigid, immovable wall. In Series 1, 3 and 4, the dump trucks were "free standing," with the parking brake set and the transmission in second gear.

Results of Test Series 1[10]

The tests conducted in this first series might be referred to as "plain vanilla" tests. It was assumed at the outset of this study that commercially available TMA's should, as a minimum, be able to provide reasonable protection in a head-on impact delivered by a 4,500-lb passenger car traveling at 45 mph. Figures 15 and 16 summarize the results of Test Series 1 according to NCHRP Report 230 criteria and TRB Circular 191 criteria, respectively.

By the (a) longitudinal occupant impact velocity and (b) longitudinal occupant ridedown acceleration criteria established in NCHRP Report 230, all seven makes and models of TMA tested were acceptable.[11] All seven TMA tests produced occupant impact velocities of less than 40 fps and occupant ridedown accelerations between 0 and -20 g's. Note, however, that the test conducted with no TMA (9910-16) had an acceptable occupant ridedown acceleration (-9.2 g's) and an occupant impact velocity that was only moderately unacceptable (46.7 fps).

By the "maximum 50 msec average longitudinal acceleration" criterion of TRB Circular 191, only one of the seven TMA's tested proved acceptable, the Energy Absorption Hexfoam Model TMA (9910-04).[12] All other makes and models of TMA (and the test conducted without a TMA) failed, i.e., produced maximum 50 msec average longitudinal accelerations in excess of -12 g's.

Both Energy Absorption tests conducted in this series (Alpha, 9919-05 and Hexfoam, 9910-04) were judged acceptable. NCHRP Report 230 occupant impact velocities and occupant ridedown accelerations were within acceptable limits. It was noted, however, that vehicle underride was more pronounced in the Hexfoam test than in the Alpha test.

In the test conducted with the current model Hexcel TMA (9919-02), damage to the impacting vehicle was minimal, and the performance of the device was en-

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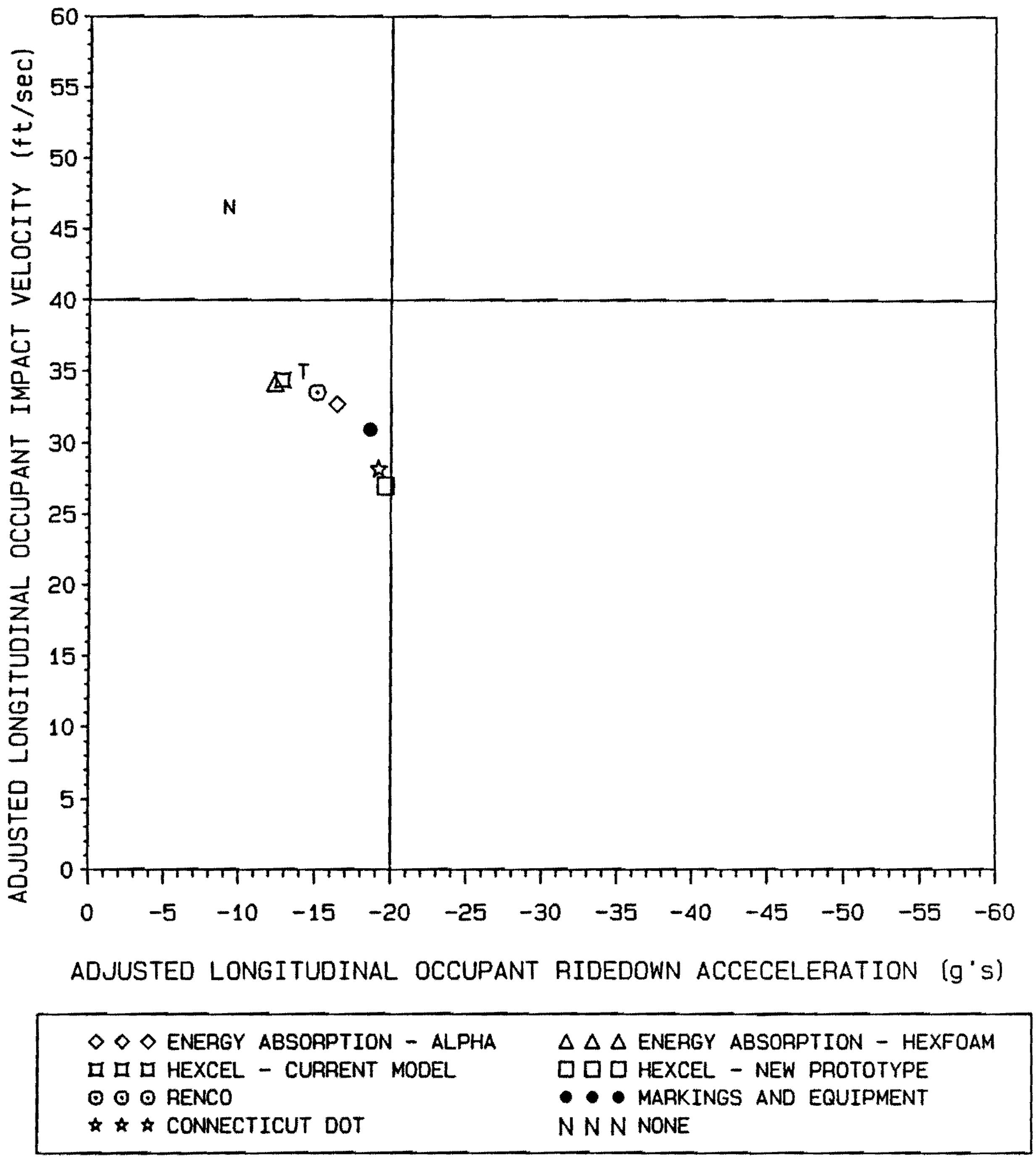
[10]Detailed information on the results of the 21 crash tests conducted in this study may be found in a second, companion volume to this report, Comparative Crash Tests Conducted on Seven Different Makes and Models of Truck Mounted Attenuators (TMA's), by Wanda L. Campise.

[11]The occupant impact velocities and accelerations shown in Figure 15 are longitudinal velocities and accelerations.

The velocities and accelerations recorded during the tests were adjusted to correct for slight deviations from the desired test speed of 45 mph and to assure that comparisons drawn among the different makes and models of TMA were equitable. The correction employed adjusted the data to account for differences in kinetic energy in the various tests. Since the weights of all test vehicles within a test series were equal, adjusted occupant impact velocity (or occupant ride down acceleration) was equated to $(45/S)^2$ times the recorded impact velocity (or ride down acceleration), where S equals the recorded impact speed during the test.

[12]The same kinetic energy correction discussed in the previous footnote was used to adjust the recorded maximum 50 msec average longitudinal accelerations recorded in these tests.

TEST SERIES 1: PASSENGER CAR WEIGHT 4500 POUNDS, SPEED 45 MILES PER HOUR



(Data point "T" from Test Series 4 is provided for comparison)

Figure 15: ADJUSTED OCCUPANT IMPACT VELOCITY AND ADJUSTED OCCUPANT RIDEDOWN ACCELERATION BY MAKE/MODEL OF TMA

TEST SERIES 1: PASSENGER CAR WEIGHT 4500 POUNDS, SPEED 45 MILES PER HOUR

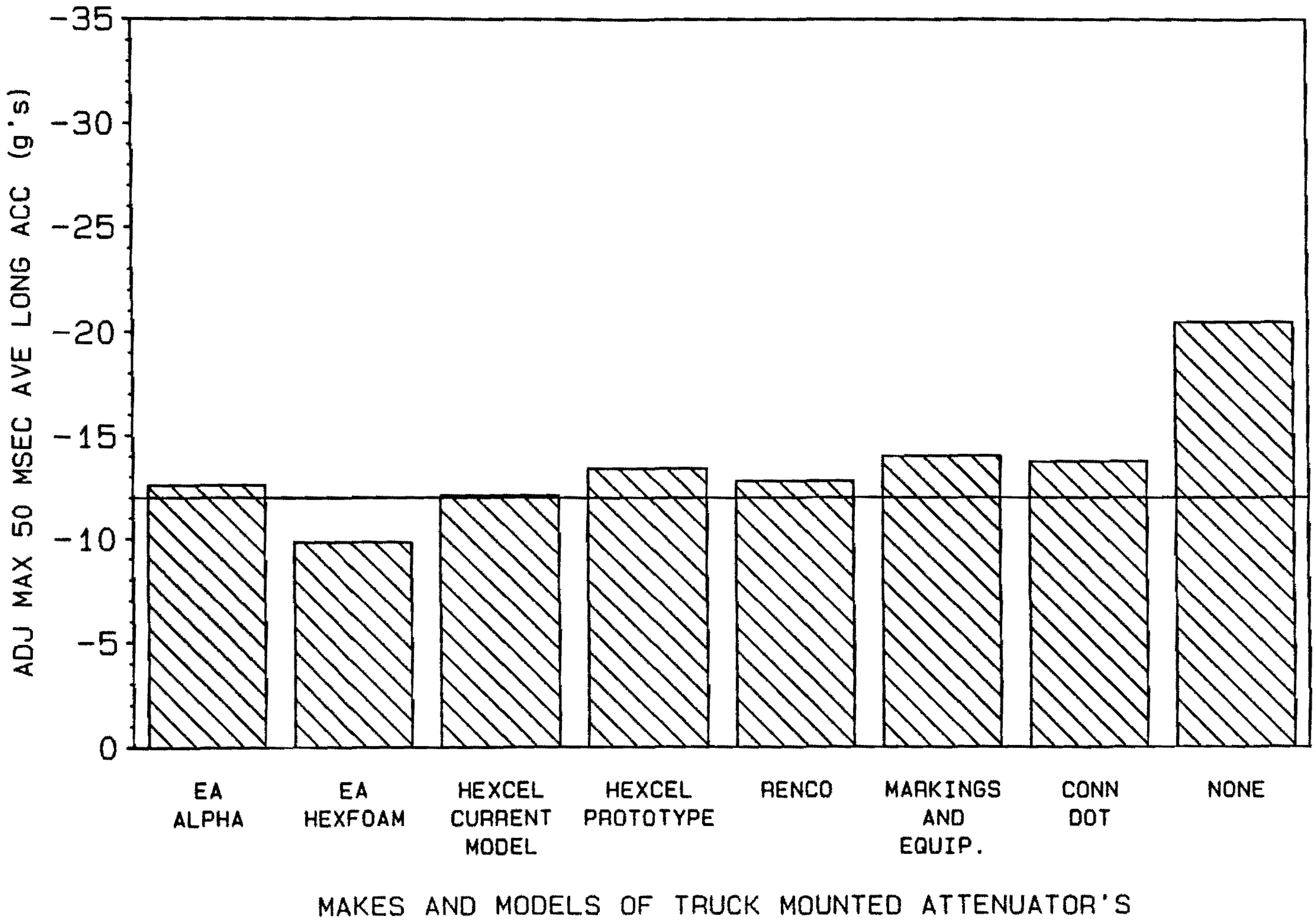


Figure 16: ADJUSTED MAXIMUM 50 MSEC AVERAGE LONGITUDINAL ACCELERATIONS BY MAKE/MODEL OF TMA

tirely acceptable. In the first test of the Hexcel developmental prototype (9919-01), however, the results were somewhat unusual. In this test the dump truck was displaced 22.8 feet, compared to 8 to 15 feet seen in the other tests. More importantly, the dump truck was rolling and not skidding forward. It appears that the parking brake and/or the transmission on the dump truck were insufficient to prevent the truck from rolling forward. Also, truck displacement appears to have been initiated early in the collision sequence. Because of the large displacement of the truck, and the fact that this displacement was initiated early in the collision sequence, the results of this test may not be truly reflective of this TMA's performance.[13]

Analysis of the high-speed films of test 9919-01 revealed that the impacting passenger car was initially forced downward during the collision, with subsequent rebound. During rebound, all four tires appear to have come off the ground. It is difficult to believe that this vertical motion of the impacting vehicle resulted from the displacement of the truck and, therefore, it suggests that this TMA may possibly be too "stiff" - or at least the upper layers of the TMA may be too stiff.

Because of the uncertainties in test 9919-01, and in spite of the fact that this test was acceptable by NCHRP Report 230 and TRB Circular 191 criteria, a second test was run on this device with a new unit provided by Hexcel. In the second test of the prototype (9910-06), the impacting vehicle underrode the TMA. The windshield was broken and deformation to the roof was recorded. Although the occupant impact velocity, occupant ridedown acceleration and maximum 50 msec average longitudinal acceleration for this test were all within the acceptable range, the occupant compartment penetration associated with the broken windshield rendered this test unacceptable.[14]

The results of the tests on the Renco, Markings and Equipment and Connecticut DOT TMA's (9919-04, 9919-03 and 9910-10, respectively) were all acceptable by NCHRP Report 230 criteria. In none of these tests was the occupant compartment of the test vehicle compromised.

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[13]Dump truck displacements and accelerations in Test Series 1:

TMA Make and Model	Test Number	Truck Displacement (ft)	Maximum 50 msec Average Long Accelerations (g's)
EA (Alpha Model)	9919-05	14.8	3.6
EA (Hexfoam Model)	9910-04	8.3	N/A
Hexcel (Current Model)	9919-02	9.8	3.7
Hexcel (Prototype)	9919-01	22.8	3.3
Hexcel (Prototype)	9910-06	13.1	11.5
Renco	9919-04	7.9	3.6
Markings and Equipment	9919-03	13.8	5.2
Connecticut DOT	9910-10	12.6	5.4
None	9910-16	10.8	6.9

[14]In Figures 15 and 16, the results of 9910-06 (not 9919-01) are reported for the Hexcel prototype.

Results of Test Series 2

The second series of crash tests employed 1,800-lb passenger cars striking TMA's head on at 45 mph. In these tests, the dump trucks to which the TMA's were attached were pulled up to a rigid wall that prevented any appreciable forward displacement of the dump trucks during the tests.

Test Series 1 indicated that dump truck displacement was highly variable from test to test. This variation in displacement resulted from at least two factors: (1) the physical characteristics of the TMA being tested and (2) the degree to which the dump truck was rendered immovable (i.e., how tightly the parking brake was set, whether or not the truck may have popped out of gear during the test, etc.). In order to separate the effects of these two factors, and to ensure an equitable comparison of the different makes and models of TMA's being evaluated, the decision was made to immobilize the truck.

It should be noted that by immobilizing the dump truck by pulling it up to a rigid wall, this test series is not appreciably more severe than it would have been had the dump trucks been free standing. For an impacting 1,800-lb passenger car, the critical evaluation criterion (occupant impact velocity) occurs very early in the crash sequence, before sufficient force is developed to displace the dump truck.

Figure 17 summarizes the results of Test Series 2 in terms of occupant impact velocity and occupant ridedown acceleration. Two TMA's (Renco and Markings and Equipment) are associated with occupant ridedown accelerations in excess of -20 g's. The two TMA's manufactured by Energy Absorption (Alpha and Hexfoam) are associated with occupant impact velocities in excess of 40 fps. Three TMA's (the current and developmental models provided by Hexcel and the Connecticut DOT TMA) were found to be acceptable by NCHRP Report 230 criteria.

For the comparison test conducted with no TMA (9910-15), occupant ridedown acceleration was acceptable (-11.9 g's), but occupant impact velocity was excessive (58.3 fps).

By the provisions of TRB Circular 191, none of the TMA's tested are acceptable. All seven are associated with maximum 50 msec average longitudinal accelerations in excess of -12 g's (Figure 18).

In terms of the occupant impact velocity and occupant ridedown acceleration requirements of NCHRP Report 230, both Energy Absorption System tests (9910-03 and 9910-08) were judged unacceptable. In a comparison between the Alpha and Hexfoam TMA's, the high speed photographs show that the impacting vehicle in the Alpha test remained fairly level during the collision while the impacting vehicle in the Hexfoam test pitched downward and underrode the TMA. The maximum 50 msec average vertical acceleration in Test 9910-03 was -0.8 g's; in Test 99-08 the corresponding figure was -4.4 g's.

In the first Hexcel test (9910-05), some pitching of the impacting vehicle and underriding of the TMA was observed during the collision. Nevertheless, this test was acceptable. In the second test on the Hexcel developmental prototype (9910-07), however, the pitching of the impacting vehicle was more pronounced, and the underride more profound. The maximum 50 msec average vertical acceleration was -5.6 g's. In this test (9910-07), substantial damage to the

TEST SERIES 2: PASSENGER CAR WEIGHT 1800 POUNDS, SPEED 45 MILES PER HOUR

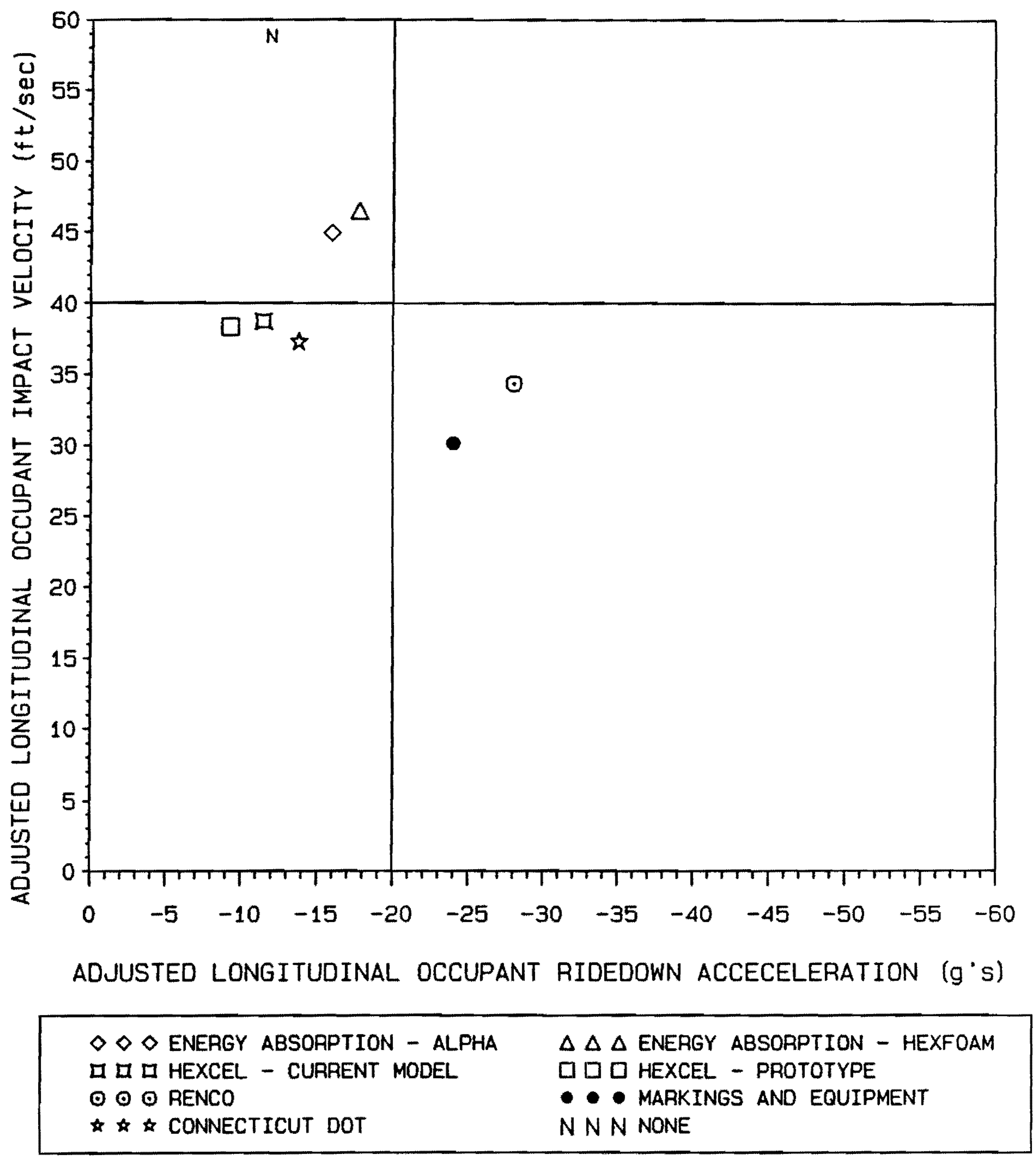

Figure 17: ADJUSTED OCCUPANT IMPACT VELOCITY AND ADJUSTED OCCUPANT RIDEDOWN ACCELERATION BY MAKE/MODEL OF TMA

TEST SERIES 2: PASSENGER CAR WEIGHT 1800 POUNDS, SPEED 45 MILES PER HOUR

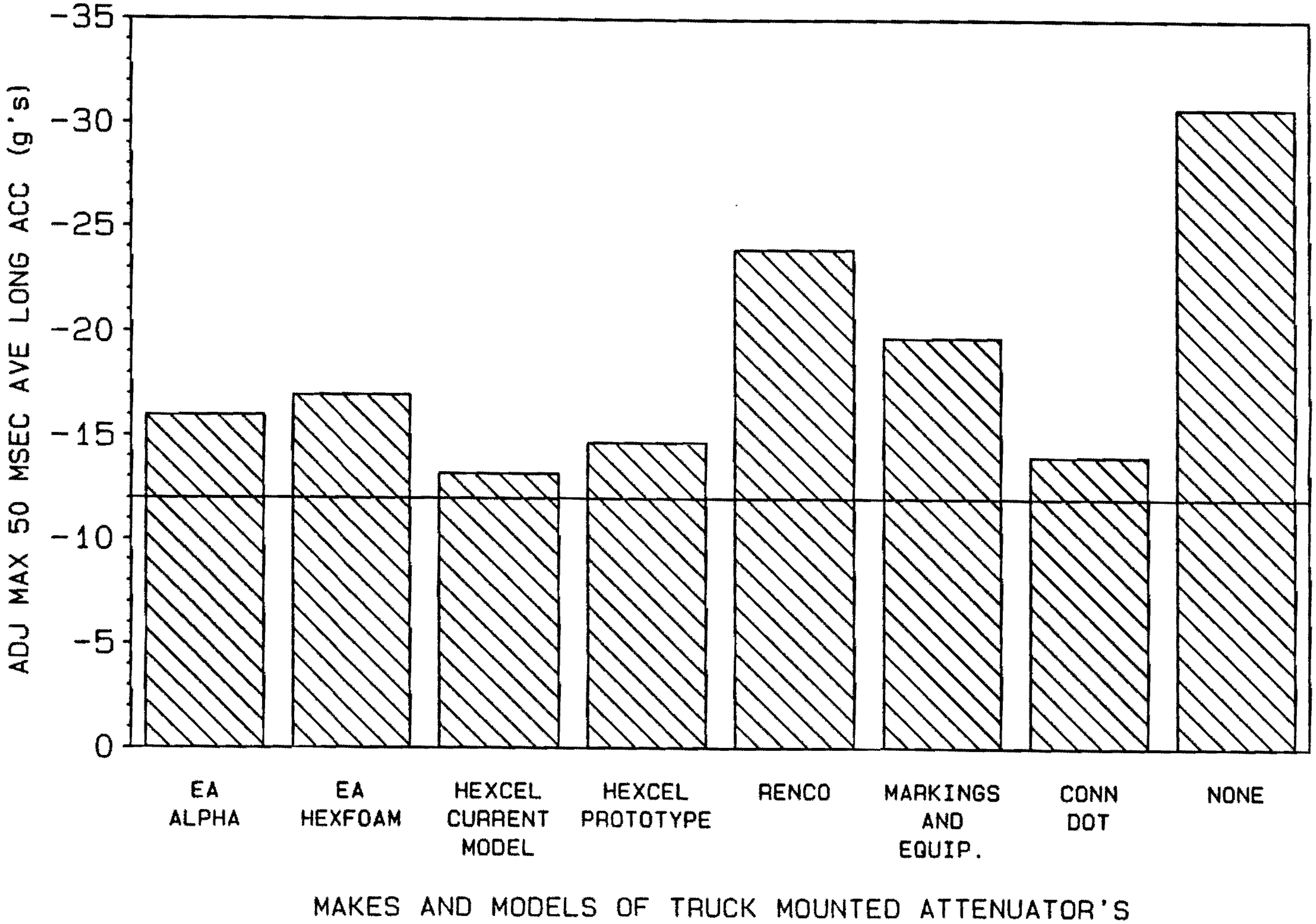

Figure 18: ADJUSTED MAXIMUM 50 MSEC AVERAGE LONGITUDINAL ACCELERATIONS BY MAKE/MODEL OF TMA

front of the car was sustained. The hood was peeled away and deposited atop the windshield and roof of the car. The windshield was broken and the roof deformed due to impact from the TMA and/or frontal portions of the car. In spite of an acceptable occupant impact velocity and an acceptable ridedown acceleration, this test was judged unacceptable due to occupant compartment intrusion.

In the Renco test (9910-02) and the Markings and Equipment test (9910-01), the TMA's did not sufficiently retard the forward motion of the impacting vehicles during the collision. In both cases, the test vehicles "bottomed out" and produced unacceptable longitudinal occupant ridedown accelerations: -28.1 g's for Renco and -24.0 g's for Markings and Equipment Corporation. It should also be noted that in the Renco test, the test vehicle sustained a shattered windshield and a crushed roof. Neither the Renco test not the Markings and Equipment test were judged acceptable.

The test of the Connecticut DOT TMA (9910-09) was acceptable. The longitudinal occupant impact velocity was 37.3 fps and the longitudinal occupant ridedown acceleration was -13.8 g's. No occupant compartment intrusion to the impacting vehicle was observed.

Results of Test Series 3

In the third test series, three TMA's were evaluated (Energy Absorption Alpha Model, 9910-13; Hexcel current model TMA, 9910-14; and the Connecticut DOT TMA, 9910-11). The Energy Absorption and Hexcel TMA's had successfully completed 40 hours of vibration testing and 24 hours of moisture testing prior to these crash tests.[15]

The test conditions for this third series of tests were severe: a 3,500-lb passenger car striking a TMA attached to a 14,000-lb dump truck (with its parking brake set and its transmission in second gear) head on at 55 mph.

From the outset of this study it was believed that none of the makes and models of TMA made available for testing would meet TRB Circular 191 or NCHRP Report 230 performance criteria under the conditions of Test Series 3. The purpose of these tests was to determine the relative standing of several competing TMA's - to determine which TMA's produce the lowest occupant impact velocities, occupant ridedown accelerations and maximum 50 msec average accelerations.

As expected, none of the TMA's tested in this series were able to meet the NCHRP Report 230 occupant ridedown acceleration criterion (Figure 19). Nor did any of the three successfully meet the TRB Circular 191 maximum 50 msec average

[15]Additional information on the vibration and moisture tests conducted by TTI during this study are provided in the next two sections and in a companion volume, Procedures and Equipment for Conducting Vibration and Moisture Tests on Truck Mounted Attenuatrors (TMA's), by Richard A. Zimmer.

TEST SERIES 3: PASSENGER CAR WEIGHT 3500 POUNDS, SPEED 55 MILES PER HOUR

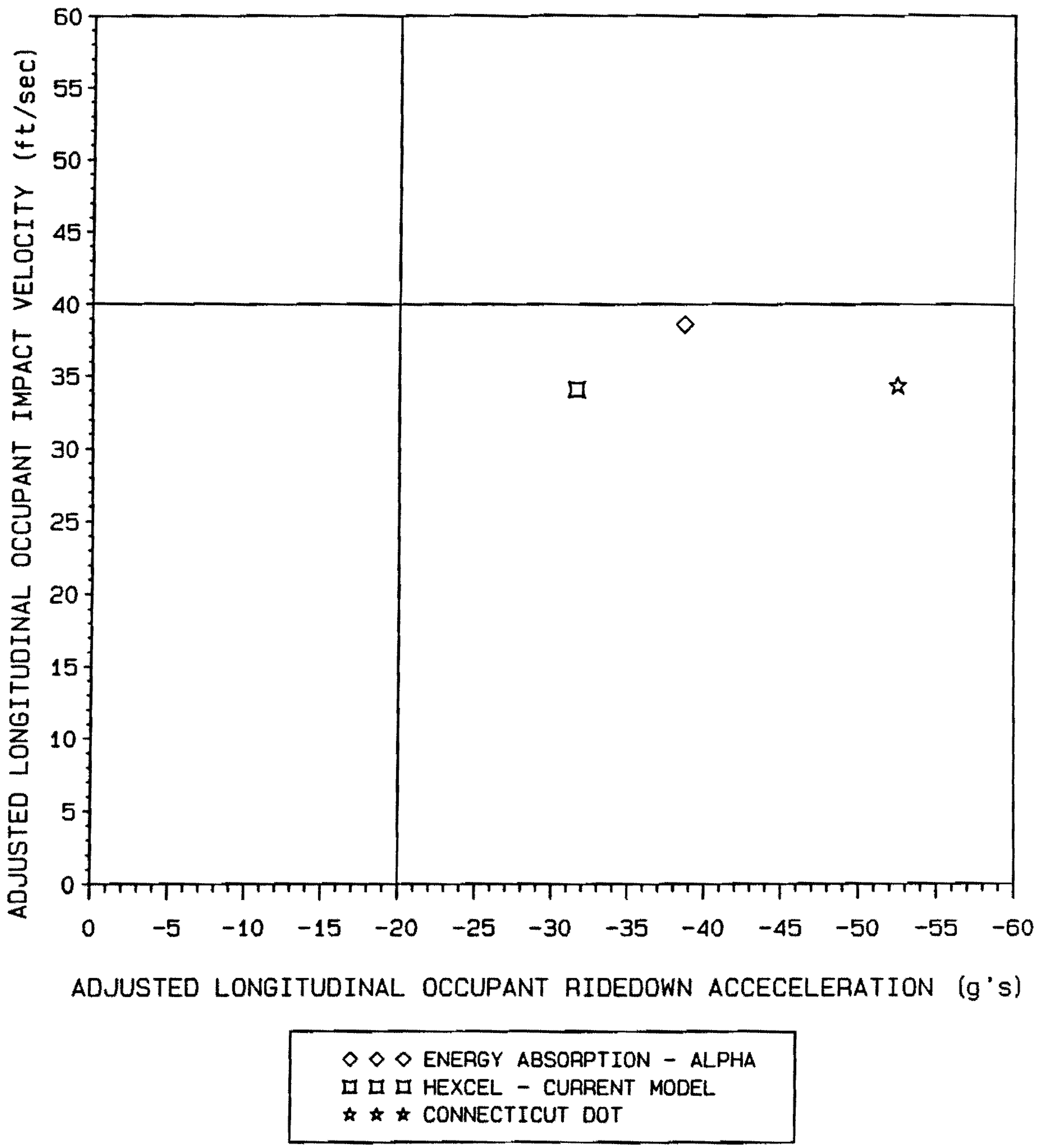

Figure 19: ADJUSTED OCCUPANT IMPACT VELOCITY AND ADJUSTED OCCUPANT RIDEDOWN ACCELERATION BY MAKE/MODEL OF TMA

TEST SERIES 3: PASSENGER CAR WEIGHT 3500 POUNDS, SPEED 55 MILES PER HOUR

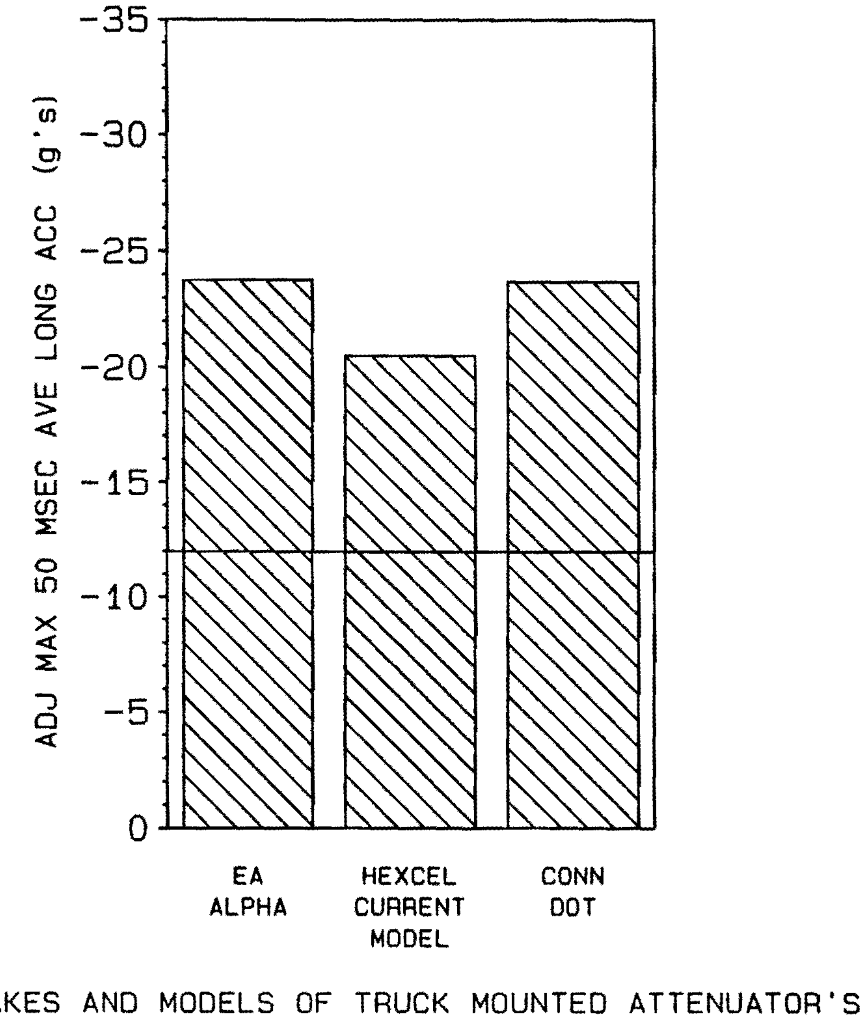

Figure 20: ADJUSTED MAXIMUM 50 MSEC AVERAGE LONGITUDINAL ACCELERATIONS BY MAKE/MODEL OF TMA

longitudinal criterion (Figure 20).[16]

Results of Test Series 4

In the final test series, only one test was conducted: a 4,500-lb pickup truck traveling at 45 mph and striking a TMA (Energy Absorption Alpha Model) head on. The purpose of this test to assess the interaction of a "higher-silhouette" vehicle (i.e., a 4,500-lb pickup truck instead of a 4,500-lb passenger car) with a TMA. The choice of the Energy Absorption Alpha Model was a matter of convenience.

In this test, longitudinal occupant impact velocity was 35.0 fps and longitudinal occupant ridedown acceleration was -14.2 g's (see Figure 15). Maximum 50 msec average longitudinal acceleration was -13.4 g's. No occupant compartment penetration was sustained by the test vehicle. This test was judged acceptable.

During this test the dump truck was displaced 8.4 feet. The maximum 50 msec average longitudinal acceleration on the dump truck was 4.8 g's.

VIBRATION TESTING

Following crash Test Series 1 and 2, the TMA's manufactured by Energy Absorption Systems, Inc. (Alpha and Hexfoam) and the current model TMA manufactured by Hexcel were judged to be reasonable candidates for further evaluation (i.e., for vibration testing). The TMA's provided by Renco and Markings and Equipment Corporation were judged unacceptable in terms of crashworthiness, but were included in the vibration tests for comparison purposes.

The size and geometry of the Connecticut DOT TMA preclude it from being tested on the California vibration test apparatus, or on the apparatus constructed by TTI during the course of this study. Although it would be desirable to assess the performance of all TMA's currently on the market (or being developed for the market) by means of a standard vibration test, the design of a generic test apparatus that will accommodate all existing and future TMA's is a formidable task. The apparatus developed by TTI, like the apparatus developed in response to the California specifications, is intended for evaluating TMA cushions or cartridges of a "traditional" design.

TTI Vibration Test

In developing the apparatus for assessing the performance of truck mounted attenuators, TTI had the advantage of (1) observing a vibration test device designed to evaluate truck mounted attenuator box assemblies according California

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[16]Dump truck displacements and accelerations in Test Series 3:

TMA Make and Model	Test Number	Truck Displacement (ft)	Maximum 50 msec Average Long Accelerations (g's)
EA (Alpha Model)	9910-13	8.5	5.8
Hexcel (Current Model)	9910-14	10.6	4.7
Connecticut DOT	9919-11	9.0	7.0

specifications[17] and (2) discussing the pros and cons of the California test with personnel familiar with the test requirements, and the apparatus required to perform the test.

In addition to reviewing the California experience with TMA vibration testing, several supplemental tests were conducted at TTI to determine the "reasonableness" of the frequencies and amplitudes used in the California vibration test.[18] These tests involved driving a dump truck (with a TMA attached) over selected reference surfaces at predetermined speeds and recording frequencies and vertical accelerations at various loci on the truck and TMA.

The vibration test apparatus that TTI finally settled on is, in many ways, very similar to the California test apparatus, as are the input frequencies and amplitudes used in testing.

In the TTI vibration test, TMA cushions are mounted to a vertical, half-inch steel plate. The plate is sinusoidally oscillated up and down at 7 Hz through 0.6 inch for approximately 1,000,000 cycles (40 hrs). The 40-hour vibration test typically takes place over 4 or 5 days of testing, 8 to 10 hours per day. Photographs of the TTI vibration test device are provided in Figure 21.

TTI Vibration Test vs California Vibration Test

In the California vibration test, TMA's are sinusoidally oscillated through a distance of 0.6 in at 6 to 8 Hz. The difference between the TTI procedure and the California procedure is that the California attachment fixture oscillates through a distance of 0.6 in at the end of a 139-in moment arm; the TTI fixture oscillates through 0.6 in linearly (up and down). This seemingly minor difference in motion for the two systems is more significant than might at first be appreciated.

Assume, for the sake of argument, that a TMA cushion is 7 feet long, and perfectly rigid (i.e., it does not deform elastically during testing). On the TTI apparatus, the front edge of the TMA and the rear edge of the TMA are both displaced through 0.6 in (up and down). On the California apparatus, the front edge of the TMA is displaced through 0.6 in, but the rear edge of the TMA is displaced through 0.96 in. Both the TTI procedure and the California procedure hold frequency constant during testing (7 Hz for TTI and 6 to 8 Hz for California). In the TTI vibration test, vertical acceleration on the TMA is constant throughout the length of the TMA. In the California test, acceleration increases from front to rear of the TMA (Figure 22). If the TMA is not perfectly rigid, but deforms elastically during testing, the variation in acceleration on the TMA will be even more exaggerated (from front to rear) in the California vibration test than in the TTI vibration test.

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[17]Specifications for "A Truck Mounted Attenuator Box Assembly" (Specification Number 90002-406-91), State of California, Department of Transportation, Division of Equipment, Sacrament, California.

[18]Details of these supplemental tests are provided in <u>Proposed Truck Mounted Attenuator (TMA) Performance Specifications and Test Results (Vibration Tests and Moisture Tests)</u>, by Richard A. Zimmer]

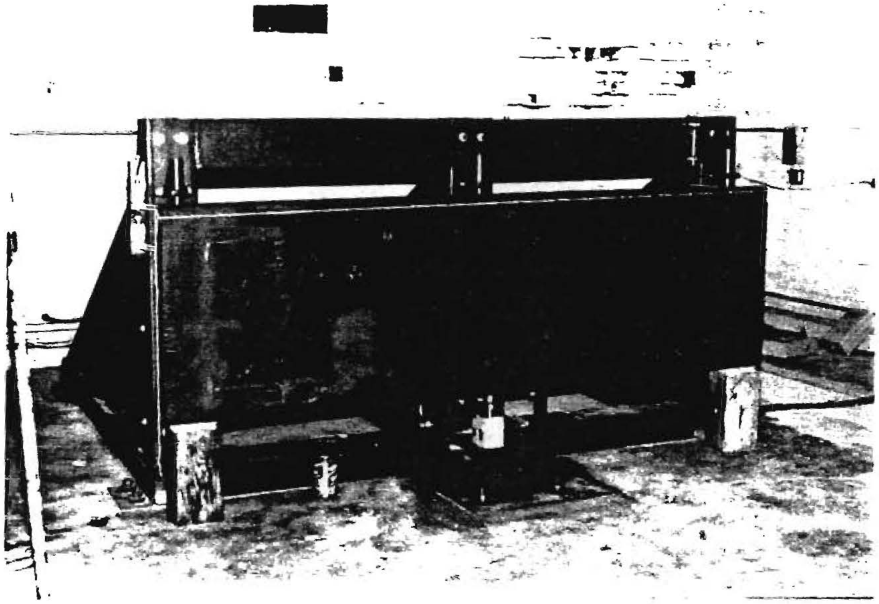


Figure 21(a): TTI Vibration Test Apparatus

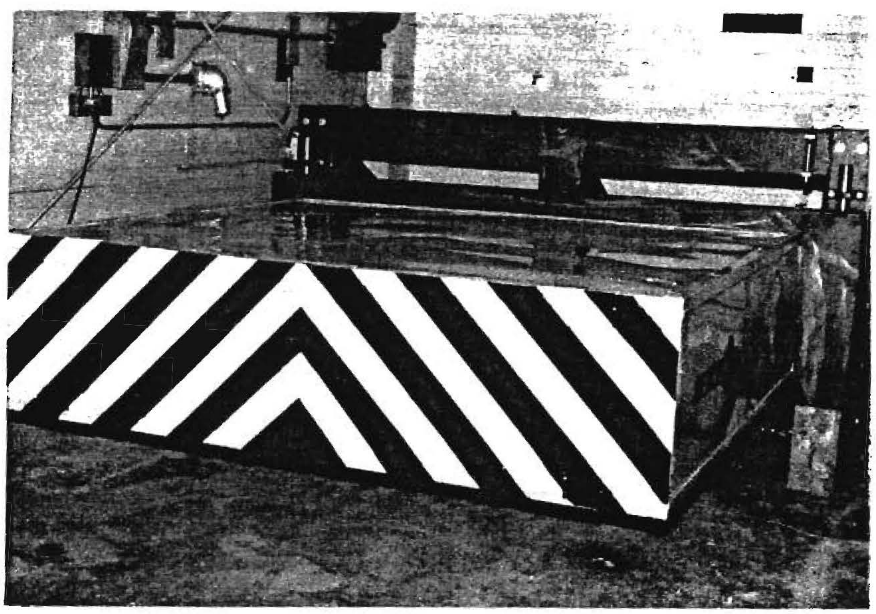
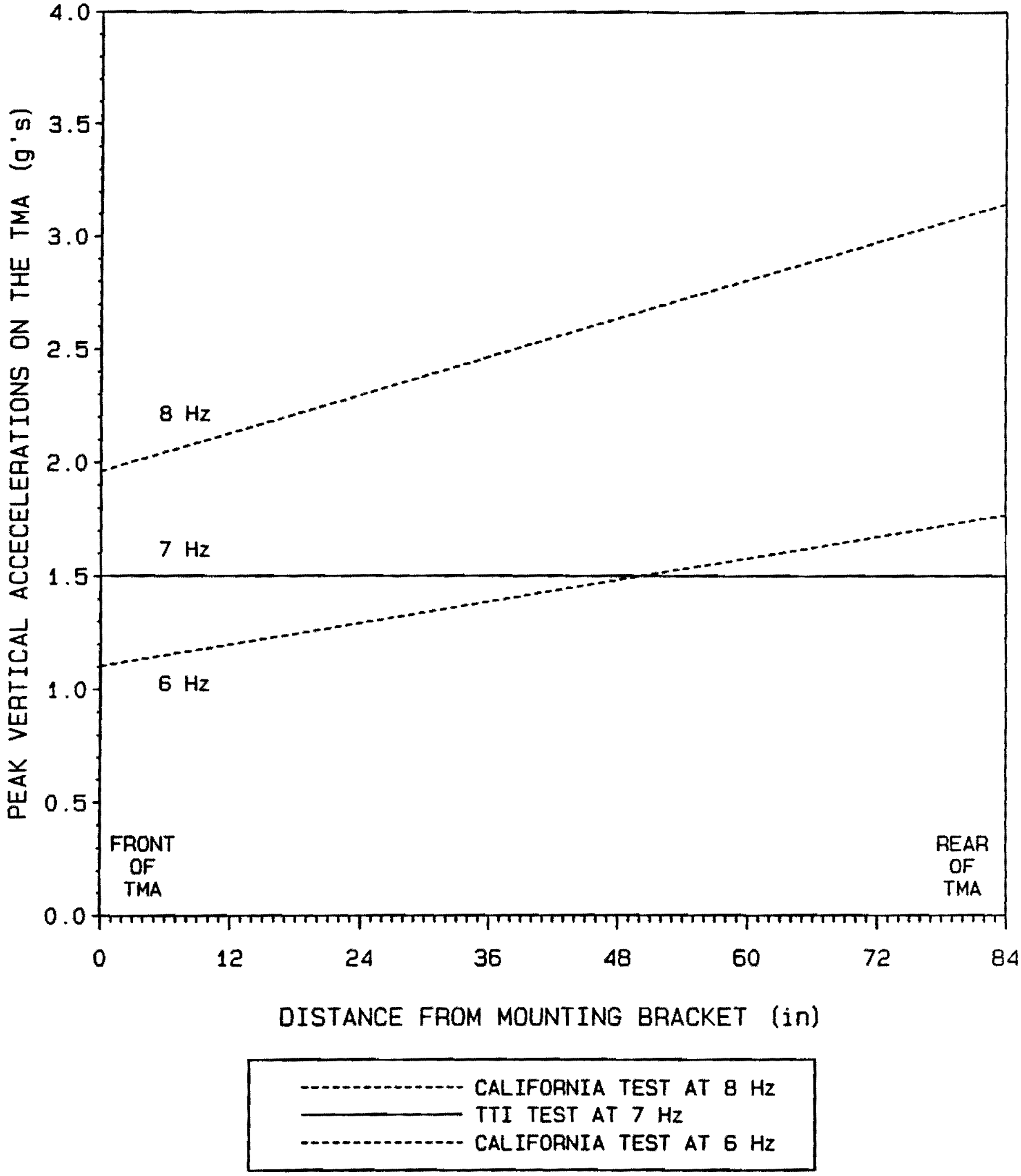


Figure 21(b): Vibration Test Apparatus with TMA in Place



Note: A perfectly rigid TMA is assumed in the calculations on which this figure is based

Figure 22: PEAK ACCELERATION ON THE TMA AS A FUNCTION OF DISTANCE FROM THE MOUNTING BRACKET (in)
(TTI TEST vs CALIFORNIA TEST)

On April 17, 1990 the project staff met with three representatives of Energy Absorption Systems, Inc. and showed them the TTI vibration test apparatus that was then under construction. Energy Absorption expressed concern that the vibration test procedure being developed by TTI was less severe than the California procedure - and perhaps not severe enough. In a follow-up letter the company asserts:

> ... it can be stated that the fixture with a 139 inch arm (Caltrans specification), from pivot point to energy impact point, is approximately 3 times more severe than the vibration that will be induced by the TTI fixture due to variation in geometry.[19]

Energy Absorption's concern is well taken: for a given frequency and amplitude, the California vibration test is more severe than the TTI test, though probably not three times as severe (see Figure 22). Indeed, it might be argued that, other things being equal, the TTI test at 7 Hz is roughly comparable to the California test at 6 Hz.[20]

Results of Vibration Testing

When TMA's are tested on the TTI fixture, they are in a horizontal position.[21,22] After the TMA is attached to the test fixture, it is vibrated for a few minutes to ensure that any slack in the system (i.e., in the TMA or in the connection between the TMA and the test fixture) has settled out. Then a reference point is marked on the left and right rear corners of the TMA cushion. The heights of these points are taken, relative to the ground. At periodic intervals the heights of the reference points are remeasured to determine if the unit is "sagging" due to fatigue or structural failure. An evaluation form is completed each time the reference points are remeasured (Figure 23). In addition, any cracks, fractures, popped rivets, broken bolts or pins, etc. that appear during the course of testing are duly noted and photographed.

Those TMA's that sagged more than 0.5 in during a 40-hour test were tentatively defined as unacceptable. Of the five TMA's subjected to the TTI vibration test procedure, three were judged acceptable by this criterion (Energy Absorption Alpha, Hexcel Current Model, and Markings and Equipment Corporation) and two were judged unacceptable (Energy Absorption Hexfoam Model and Renco).

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[19]Letter from J.M. Essex, Vice President for Sales, Energy Absorption Systems, Inc. to R.E. Flaherty, Head, Equipment and Procurement Division, Texas State Department of Highways and Public Transportation dated May 10, 1990.

[20]This statement assumes that the input amplitude (from peak to peak) is constant for both tests (i.e., 0.6 in).

[21]SDHPT has an established policy that TMA's should be in the "down" or "horizontal" whenever they are operating in traffic, regardless of whether or not they are shadowing (i.e., protecting) a maintenance operation.

[22]The California vibration specifications call for three, forty-hour tests with the TMA in the (1) horizontal position, (2) at 60° with respect to the horizontal, and (3) straight up and down (i.e., 90° with respect to the horizontal).

TEXAS TRANSPORTATION INSTITUTE
TMA VIBRATION TEST

MFG. HEXCELL WEIGHT 323 Lbs.

MODEL TX-3002 LENGTH 84.5 "

SERIAL NO. TTI 002 WIDTH 92.5 "

HEIGHT 24.25 "

INITIAL REF. TEST HEIGHT - RIGHT 20.0 " LEFT 20.0 "

INITIAL TMA TEST HEIGHT - RIGHT 22.0 " LEFT 22.0 "

TEST CONDITIONS - CPS 7 AMP. P-P 0.6 " HOURS 40

DATE	START	STOP	HOURS	R. HT.	L. HT.	DAMAGE	OPR.
7-13-90	1350	1440	0.8	-0.19	-0.13	BOTTOM FRONT BUCK TOP LEFT SPLIT	RaJ
7-13-90	1500	1650	2.0	-0.19	-0.13		RaJ
7-16-90	0800	1225	6.5	-0.19	-0.13		RaJ
7-16-90	1241	1310	7.0	-0.19	-0.13		RaJ
9-17-90	1605	1620	7.3	-0.25	-0.25		RaJ
9-18-90	0810	1630	15.6	-0.25	-0.25	TOP LEFT FRONT SKIN CRACK 4"	RaJ
9-19-90	0750	1320	20.8	-0.31	-0.31		RaJ
9-20-90	0900	1615	27.5	-0.38	-0.38		RaJ
9-21-90	0750	1625	35.7	-0.38	-0.38		RaJ
9-24-90	0830	1245	40.0	-0.38	-0.38	TEST COMPLETE	RaJ

COMMENTS: RECEIVED & TESTED WITH NO TAIL LIGHTS OR JACK

Figure 23: TTI Data Collection Form for Vibration Testing

The Energy Absorption Alpha Model TMA was bolted to the vibration fixture and torqued to 90 foot-pounds, as per the manufacturers instructions. The natural resonant frequency of the TMA cushion (when attached to the vibration apparatus) was then calibrated by "bumping" the TMA with a low amplitude step pulse and measuring the frequency at the rear of the TMA. The natural resonant frequency for this system was determined to be 20 Hz.

At the end of 40 hours, the Alpha Model TMA showed no sag at the left rear corner, and only 1/32 in of sag on the right. Local damage to the TMA was minimal - three rivets popped off during testing and the dolly wheel fell off about six and a half hours into the procedure. This TMA was judged to be acceptable in terms of sag and superficial damage.

The Energy Absorption Hexfoam TMA was mounted to the vibration fixture as previously described for the Alpha Model TMA. The natural resonant frequency of the TMA (when attached to the fixture) was then determined to be 8.6 Hz.

At 0.9 hours into testing, the left rear corner of this cushion had sagged 1/8 in and the right rear corner had sagged 3/16 in. At 5.7 hours, the left rear corner was down 1 3/4 in and the right rear corner was also down 1 3/4 in. At 16.2 hours, the test was terminated. The left and right rear corners were both down 5.0 in. This test was judged unacceptable.

The standard model TMA manufactured by Hexcel completed 40 hours of vibration testing with 3/8 in sag at both the left and right rear corners of the cushion. Although sagging was not a problem with this TMA, buckling and cracking of the aluminum skin encasing the cushion was a problem (Figure 24). Three of the four corners abutting the test fixture showed this failure.

Photographs (provided by SDHPT) of a Hexcel model TMA that has been in use in Texas for three to four years show similar, though less extensive, cracking on the front corners and edges of the cushion. Furthermore, the California Department of Transportation confirms that it too has seen this same type of cracking on the Hexcel model TMA's that it has purchased:[23]

> The HEXCEL truck mounted crash attenuators that we have in our fleet were purchased in 1984, [sic] have experienced deterioration as you illustrated.
>
> We changed the angle from 15 degrees to an angle of 90 degrees when the unit is in the travel position. This has helped the deterioration of the units.

This TMA was judged to be only marginally acceptable. Although the cracks and distortions observed during testing do not appear to adversely affect the crashworthiness of the cushion, they (the cracks and distortions) are,

[23]Letter dated November 21, 1990 from Dale D. Phillips, Chief, Field Operations Branch, Office of Equipment, Division of Equipment, Department of Transportation, Sacramento, California to Robert E. Flaherty, Head, Equipment and Procurement Division, Texas State Department of Highways and Public Transportation, Austin, Texas, in a response to a letter from Mr. Flaherty dated November 6, 1990.

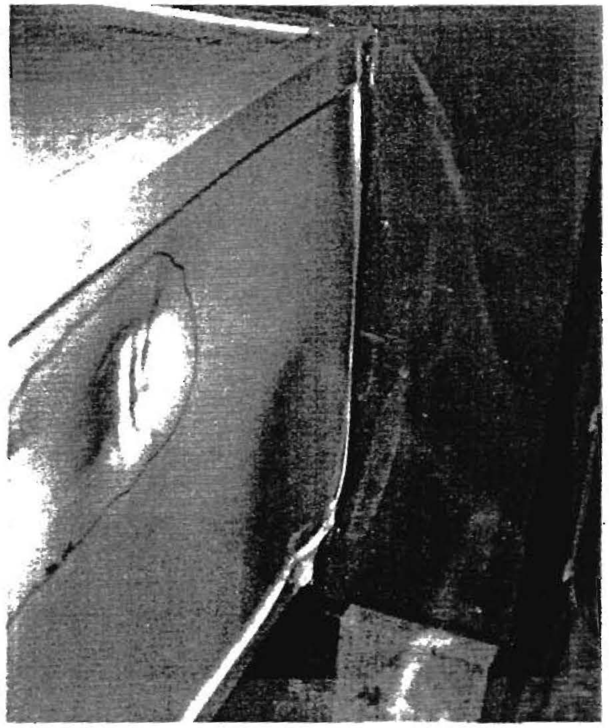

Figure 24(a): Cracks and Distortions to the Hexcel TMA (Right Front Corner)

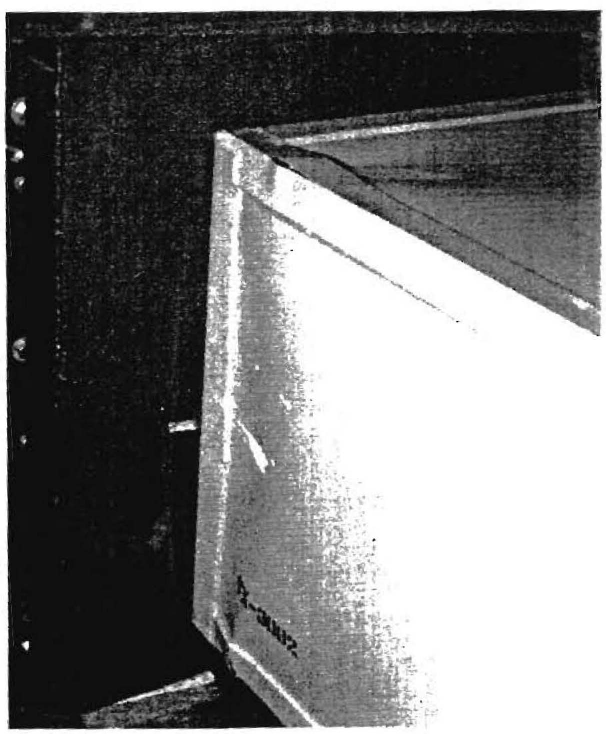

Figure 24(b): Cracks and Distortions to the Hexcel TMA (Left Side - Front) nonetheless, both (1) unsightly and (2) a potential source of lacerative injury to operational personnel.

The Renco TMA was tested for 4.1 hours. Shortly after testing began on this unit, a split developed on the top surface of the unit. At the end of two hours, this split (approximately one foot back from the front edge of the TMA) had propagated completely across the cushion. At this time (2 hours) the cushion had sagged 7/16 in at the left corner and 9/16 at the right corner. At the end of 4.1 hours, the left corner had dropped 1 1/16 in; the right corner 11/8 in. This test result was judged unacceptable.[24]

The last of the five TMA's to undergo vibration testing was the unit manufactured by Markings and Equipment Corporation. This unit was vibrated for 40 hours with only an eighth inch sag at both the left and right rear corners. Superficial damage during testing included the left tail light falling off (18 hours), one rivet popping out (30 hours) and some of the aluminum trim cracking (39 hours). This TMA test was judged acceptable.[25]

MOISTURE TESTING

The three TMA's that were judged acceptable in the vibration test were next subjected to a standard moisture test. Of the three TMA's that were tested for moisture, only one was judged acceptable.

Test Apparatus

The moisture test facility consists of a water-filled reservoir (12 ft wide by 12 ft long by 12 in high) surrounded by clear plastic curtains. A steel "bed" or platform standing in the reservoir is used to support the TMA cushion being tested in a horizontal position, approximately 17 in above ground level. The water in the reservoir is recirculated through 8 nozzles (2 on each side of the reservoir) plumbed in series at a rate of flow to simulate a 6 in per hour rain. The nozzles are positioned 64 in above ground level (approximately 2 ft above the top of the TMA being tested) and oriented to deliver cone-shaped sprays covering the top and sides of the test cushion (Figure 25).

Test Procedure

In the TTI moisture test, the TMA cushion is first weighed. Then it is placed on the "bed" (i.e., the support structure) inside the test chamber and sprayed with water for 24 continuous hours. At the end of 24 hours, the spray is turned off and the TMA is allowed to drain for one hour. The TMA is then reweighed. The weight gain recorded for the TMA serves to define "moisture retention." The tentative criterion for an acceptable weight gain during this

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[24]The natural resonant frequency for the Renco TMA was 10 Hz.

[25]The natural resonant frequency for the Markings and Equipment Corporation TMA was 8 Hz.

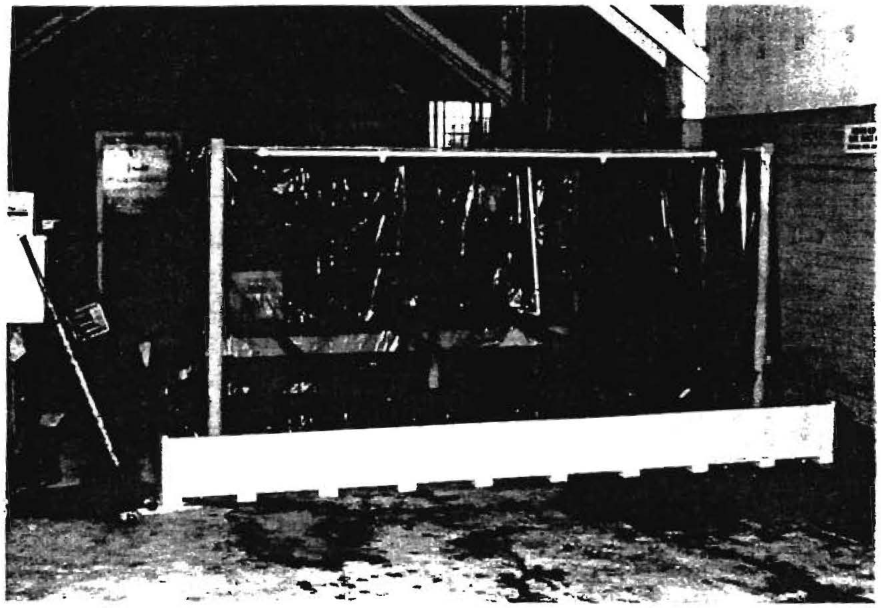

Figure 25(a): View of the TMA Moisture Testing Facility

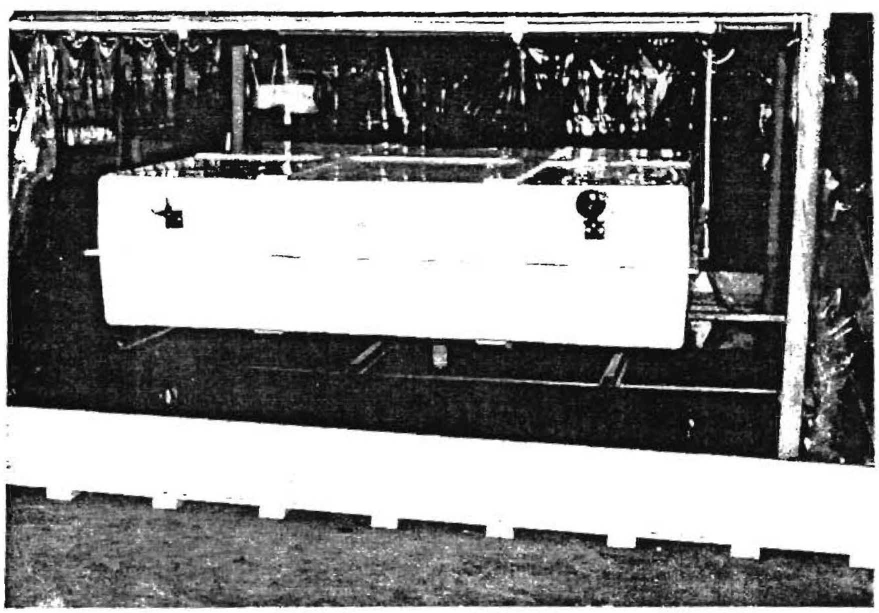

Figure 25(b): View of TMA Moisture Testing Facility with a Unit in Place test was set at 5 percent of the initial weight of the cushion.[26]

Test Results

The Energy Absorption Alpha Model TMA weighed 346 lbs before it was tested. After testing the unit weighed 350 lbs, a 1.2 percent increase. This TMA was judged acceptable in terms of moisture retention.

The Hexcel TMA weighed 323 lbs before testing and 386 lbs after testing, and increase in weight of 63 lbs (19.5 percent). This weight gain was judged unacceptable.

The Markings and Equipment Corporation TMA weighed 391 pounds before testing and 605 pounds after testing. This gain in weight of 214 lbs (54.7 percent) was judged unacceptable.

SUMMARY OF FINDINGS ON TMA PERFORMANCE

Based upon the literature review provided in the introduction to this report, and the testing and evaluation conducted at TTI, the following performance summaries are offered:

ENERGY ABSORPTION (ALPHA MODEL)

This TMA is judged acceptable. In crash Test Series 1 and 4 (head-on tests at 45 mph with a 4,500-lb passenger car and a 4,500-lb pickup truck, respectively), this attenuator was within NCHRP Report 230 performance specifications; in Test Series 2 (a head-on test at 45 mph with an 1,800-lb passenger car), this attenuator was acceptable in terms of longitudinal occupant ridedown acceleration, and only moderately out of bounds on adjusted longitudinal occupant impact velocity (45.0 fps vs the limit of 40 fps).[27] All three test vehicles, i.e., the 4,500-lb passenger car, the 4,500-lb pickup truck and the 1,800-lb passenger car, were fairly stable throughout the collision sequence. Pitching of the test vehicles was moderate; underriding of the cushion was minimal. Occupant compartment intrusion was not observed in these tests, nor was the potential for intrusion manifest.

The Alpha Model TMA also successfully completed 40 hours of vibration

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[26]In the California moisture test, TMA cushions are subjected to 48 hours of testing in a simulated 6-in per hour rain – 24 hours with the TMA right side up, and 24 hours up side down. At the end of this time, the top is removed from the TMA and the energy absorbing material contained within the cushion examined. If this material is "moisture free," and if the material has retained 100 percent of its energy absorbing capability, the unit is acceptable. (From California Department of Transportation Specification Number 90002-406-91) See Footnote 17.

[27]In crash Test Series 3, which involved a 3,500-lb passenger car impacting the Alpha Model TMA at 55 mph, the adjusted longitudinal occupant impact velocity and ridedown acceleration were 38.6 fps and -38.6 g's, respectively. These readings are somewhat better than the test results for the Connecticut DOT TMA, but poorer than the results obtained with the Hexcel (current model) TMA.

testing. Sagging of the cushion was trivial, and superficial damage to the TMA was of minor consequence.

Finally, of the three TMA's that underwent moisture testing, the Alpha was the only cushion to be judged acceptable in terms of the five-percent-weight-gain criterion.

ENERGY ABSORPTION (HEXFOAM MODEL)

The Hexfoam Model TMA is judged unacceptable. In crash Test Series 1 (a head-on test at 45 mph with a 4,500-lb passenger car mph), this cushion was judged acceptable in terms of adjusted longitudinal occupant impact velocity and adjusted longitudinal occupant ridedown acceleration. In Test Series 2 (a head-on test at 45 mph with an 1,800-lb passenger car), adjusted longitudinal occupant ridedown acceleration was acceptable, but adjusted longitudinal occupant impact velocity was moderately out of bounds (46.5 fps vs the limit of 40 fps).

Table 8 is a direct comparison between the performance of the Alpha and Hexfoam model TMA's manufactured by Energy Absorption Systems, Inc.

Table 8: A Comparison of Two TMA's manufactured by Energy Absorption Systems, Inc.

Test Series	Adjusted Longitudinal Occupant Impact Velocity (fps)		Adjusted Longitudinal Occupant Ridedown Acceleration (g's)	
	Alpha Model	Hexfoam Model	Alpha Model	Hexfoam Model
1	32.7	34.2	-16.4	-12.4
2	45.0	46.5	-16.0	-17.8

Although the Alpha and Hexfoam TMA's are similar in terms of occupant impact velocity and ridedown acceleration, under comparable test conditions, the Hexfoam cushion appears more susceptible to vehicle underride than the Alpha, and potentially more susceptible to occupant compartment intrusion (Figures 26 and 27). In reviewing the crash tests previously conducted on the Hexfoam TMA with small cars, this propensity of the cushion to deflect the impacting vehicle downward during the collision (with resultant occupant compartment penetration) was found in two other tests:

(1) In test number 78-1 conducted by Energy Absorption System, Inc. on December 7, 1983, a 1,827-lb passenger car containing a 165-lb dummy was directed head on into a Hexfoam TMA attached to 20,000-lb dump truck (including the weight of the TMA) at 48.4 mph. The parking brakes on the truck were set, but the transmission was in neutral. During the test the truck was displaced 2.2 ft. Longitudinal occupant impact velocity was 35.3 fps; longitudinal occupant ridedown acceleration was 11.8 g's. From the photographs, it is clear that the test vehicle underrode the TMA and that the windshield was broken through impact. Had this test been conducted at TTI during the course of this project, it would have been judged

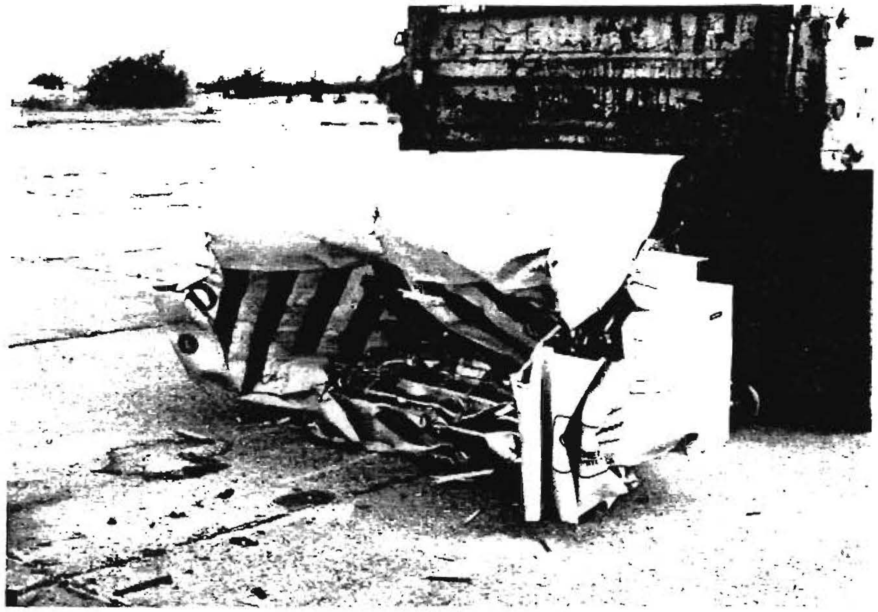

Figure 26(a): Alpha Model TMA After Being Struck by a 4,500-lb Passenger Car at 45.9 mph (9910-05)

Figure 26(b): Hexfoam Model TMA After Being Struck by a 4,500-lb Passenger Car at 44.5 mph (9919-04)

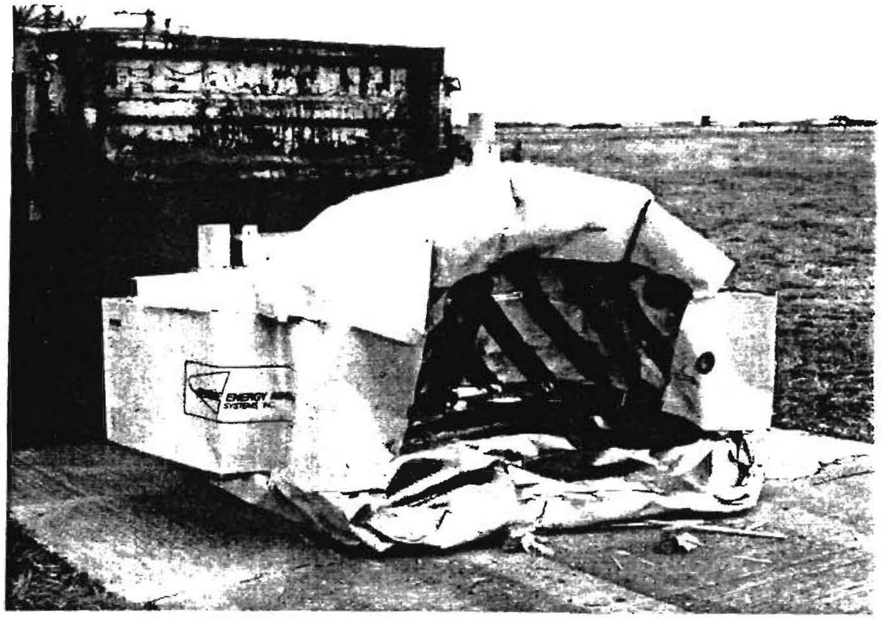

Figure 27(a): Alpha Model TMA After Being Struck by
an 1,800-lb Passenger Car at 43.9 mph (9919-03)

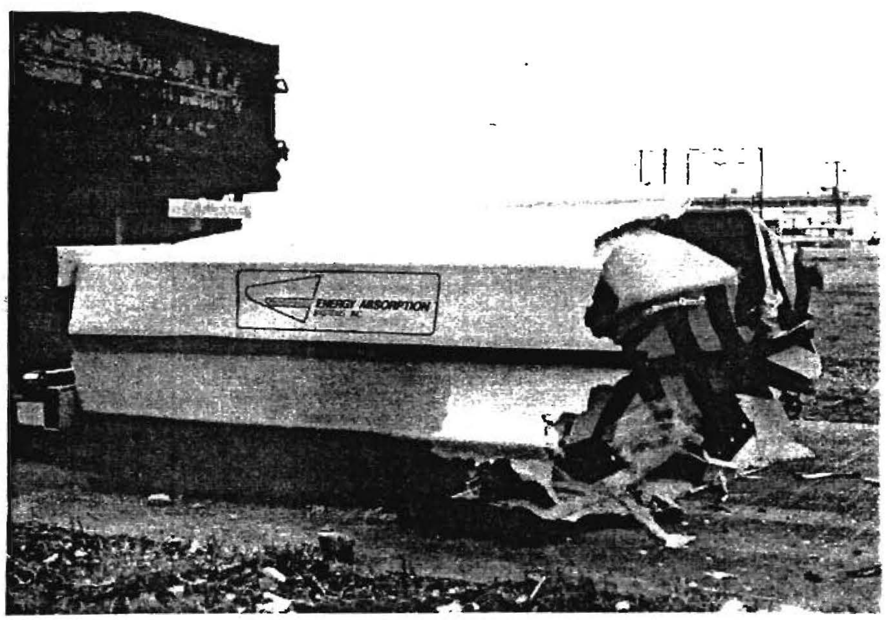

Figure 27(b): Hexfoam Model TMA After Being Struck by
an 1,800-lb Passenger Car at 44.4 mph (9910-08)

unacceptable due to occupant compartment intrusion. (EAS 1987b)

(2) On July 24, 1987, Energy Absorption conducted another crash test on the Hexfoam TMA with a small car (109-4). In this test, a 1,600-lb passenger car containing a 165-lb dummy impacted a Hexfoam TMA (attached to a 12,800-lb dump truck) head on, at 48.7 mph. The dump truck was displaced 1.9 ft during the collision. The longitudinal occupant impact velocity was 39.7 fps; the longitudinal occupant ridedown acceleration was 12.8 g's. Although this test was acceptable in terms of the quantitative criteria of NCHRP Report 230, once again, the photographic record of this crash indicated that the test vehicle underrode the TMA and its windshield was broken in the process. This test too would not have been acceptable, had it been conducted at TTI during the course of this project. (EAS 1987c)

In the vibration test conducted on the Hexfoam, sagging of the cushion was judged to be unacceptable.[28] After 5.7 hours on the vibration test apparatus, the cushion had sagged 1 3/4 in.

Since the Hexfoam was judged unacceptable on the vibration test, it was not subjected to moisture testing, but returned to Energy Absorption Systems, Inc. upon request by the manufacturer, and at the direction of the Department.

HEXCEL (CURRENT MODEL)

The Hexcel TMA is judged acceptable. The performance of this TMA was judged acceptable (i.e., within the performance specifications in NCHRP Report 230) in crash Test Series 1 and 2 (i.e., in head-on collisions at 45 mph with both 4,500-lb and 1,800-lb passenger cars). Furthermore, of the three TMA's tested at 55 mph with a 3,500-lb passenger car (Test Series 3), this cushion produced the lowest adjusted longitudinal occupant impact velocity and ridedown acceleration.

In the small car test (Test Series 2), some pitching and underriding of the test vehicle was evident. Such underriding offers the potential for occupant compartment penetration.

In the vibration test to which this TMA cushion was subjected, sagging of the cushion was not a problem. However, superficial damage to the aluminum covering for the unit was excessive. This deficiency needs to be corrected.

During the moisture test performed on this Hexcel unit, an unacceptable weight gain of 63 lbs (19.5 percent) was recorded. This deficiency also needs to be corrected.

HEXCEL (DEVELOPMENTAL MODEL)

The developmental TMA that Hexcel provided for evaluation is judged unacceptable. The performance of this cushion was unacceptable in both crash Test

[28]To date the Hexfoam cushion has not been evaluated by the standard California vibration test above a frequency of 5 Hz. In order to be accepted by California, the required test frequency must be between 6 and 8 Hz.

Series 1 and 2 (i.e., in head-on tests at 45 mph with 4,500-lb and 1,800-lb vehicles). Although adjusted longitudinal occupant impact velocity and ridedown acceleration were within the acceptable range, vehicle underride and occupant compartment penetration were unacceptable.

This TMA was not subjected to either vibration or moisture testing.

RENCO

This TMA is judged unacceptable. In crash Test Series 1 (a head-on collision at 45 mph with a 4,500-lb passenger car), this cushion was judged acceptable, but in Test Series 2 (a head-on collision at 45 mph with an 1,800-lb passenger car), the windshield of the test vehicle was shattered, the roof was deformed and the adjusted longitudinal occupant ridedown acceleration (-28.1 g's vs the limit of -20 g's) was unacceptable.

The vibration test conducted on this unit was also unacceptable. Early in the test procedure, the polyurethane covering for this cushion split, exposing the interior energy absorbing material.

A moisture test was not conducted on this TMA.

MARKINGS AND EQUIPMENT CORPORATION

The TMA provided by Markings and Equipment Corporation is judged unacceptable. Although this cushion was acceptable in crash Test Series 1 (a head-on test at 45 mph with a 4,500-lb vehicle), the adjusted longitudinal occupant ridedown acceleration in Test Series 2 (a head-on test at 45 mph with an 1,800-lb vehicle) was too high (-24.0 g's vs the limit of -20 g's).

During both tests on this TMA, the cushion split in half (horizontally), dislodging and spilling a portion of the energy absorbing material contained within.

The vibration test conducted on this cushion was acceptable, i.e., this cushion was vibrated for 40 hours with no appreciable sagging and with only slight, superficial damage to the exterior of the unit.

Following the moisture test, however, the unit was found to have retained an unacceptable, 25.6 gallons of water, a 214-lb (54.7 percent) gain.

CONNECTICUT DOT

This TMA is judged acceptable. The crashworthiness of this TMA was found to be adequate (i.e., within NCHRP Report 230 performance specifications) in Test Series 1 and 2 (i.e., in head-on collisions at 45 mph with 4,500-lb and 1,800-lb vehicles). The adjusted longitudinal occupant impact velocity and ridedown in Test Series 1 were 28.1 fps and -19.2 g's, respectively; in Test Series 2, 37.3 fps and -13.8 g's.[29]

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[29]In crash Test Series 3, the Connecticut DOT TMA was struck by a 3,500-lb passenger car traveling at a speed of 55 mph. In this test, the adjusted longitudinal occupant impact velocity and ridedown acceleration were 34.3 fps and

It should also be noted that the Connecticut TMA, due to its weight, its low ground clearance and its telescoping box beam frame minimizes the potential for vehicle underride – a phenomenon observed in several tests conducted during the course of this study. By reducing the probability for underride, this TMA also reduces the likelihood of occupant compartment penetration or intrusion.

The Connecticut TMA was not subjected to the vibration or moisture tests developed during this study. Indeed, the apparatus developed for these tests was not designed to accommodate the Connecticut unit. At the outset of the project, the decision was made that the Connecticut TMA was not likely to suffer structural failure as a result of vibrations typical of real-world operations, nor was it likely to suffer any loss of energy absorbing capabilities through exposure to moisture.

PROPOSED TMA PERFORMANCE SPECIFICATIONS

Based upon the work done during this study, future performance standards for TMA's are proposed in three areas: crash testing, vibration testing and moisture testing.

CRASH TESTING

A minimum of two crash tests are proposed for qualifying TMA's for purchase by SDHPT in the future:

Test 1: An eccentric (off-center) test with an 4,500-lb pickup truck or utility vehicle traveling at 45 mph. The centerline of the impacting vehicle would be aligned with a point half way between the centerline of the TMA and the left (or right) side of the TMA.

Test 2: A head-on (centerline-to-centerline) test with an 1,800-lb passenger car traveling at 45 mph.

Test Conditions

In both tests the dump truck should be ballasted to 14,000 lbs before the TMA is attached. The parking brake on the truck should be set and the transmission put in second gear. In addition, the rear wheels on the truck should be prevented from rotating by chaining, or through other means.

In all other respects, both tests should be conducted in accordance with the provisions of NCHRP Report 230.

-52.5 g's.

Since this TMA proved "adequate" for a small impacting car (Test Series 2), and since in Test Series 3 the ridedown acceleration for this unit was somewhat higher than the values recorded for the Energy Absorption System Alpha Model TMA and the Hexcel (current model) TMA, some thought should be given to stiffening the system by returning to a 3/8 in (rather than 1/4 in) wall thickness for the third pipe in the attenuator.

Acceptance Criteria

Occupant impact velocities and occupant ridedown accelerations in both tests should be within stated quantitative limits as proposed in NCHRP Report 230 and reiterated in Table 9. Other applicable qualitative evaluation criteria cited in NCHRP Report 230 and reiterated in Table 10 should also be met.

Table 9: Quantitative TMA Crash Test Evaluation Criteria
(from Evaluation Criterion F, Table 6, page 13, NCHRP 230)

Acceptable Occupant Impact Velocities	Acceptable Occupant Ridedown Accelerations
40 fps Longitudinal	20 g's Longitudinal
30 fps Lateral	20 g's Lateral

Table 10: Qualitative TMA Crash Test Evaluation Criteria
(from Table 6, page 13, NCHRP 230)

Structural Adequacy

C. Acceptable test article performance may be made by redirection, controlled penetration, or controlled stopping of the vehicle.

D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.

Occupant Risk

E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. *Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.* [*emphasis added*]

Vehicle Trajectory

H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.

J. Vehicle trajectory behind the test article is acceptable.

There is a tendency in the crash test literature to emphasize the quantitative evaluation criteria in NCHRP Report 230 – and to give short shrift to the qualitative criteria – when assessing TMA's, and other test articles. From the experience gained in this study, and based upon the test reports contained in the literature, it appears that particular attention should be paid to vehicle underride and occupant compartment intrusion in future evaluations of TMA's.

Rationale

Test 1 (4,500-lb Test Vehicle at 45 mph, Eccentric Impact)

In the first series of crash tests conducted during this study (Test Series 1), 4,500-lb passenger cars traveling at 45 mph were crashed head-on into seven different makes and models of TMA. All seven met the occupant impact velocity and occupant impact ridedown acceleration guidelines specified in NCHRP Report 230. Furthermore, an additional test (9910-16) conducted with an unprotected dump truck (i.e., a dump truck without a TMA) demonstrated acceptable occupant ridedown acceleration (-9.2 g's vs the limit of -20 g's) and only moderately unacceptable occupant impact velocity (46.7 fps vs the limit of 40 fps) in the longitudinal direction.

Because TMA's evaluated in Test Series 1 were all acceptable by the quantitative criteria of NCHRP Report 230, and because an unprotected dump truck very nearly meets the same criteria, this test provides relatively little information about the crashworthiness of a TMA. It is not recommended for standard compliance testing.

Instead of striking the TMA head on with a 4,500-lb passenger car at 45 mph, it is proposed that the alignment between the TMA and the striking vehicle be offset (Test 1). This proposed test is potentially more difficult to pass since the loading on the TMA is not evenly distributed. Nevertheless, the literature suggests that angular and/or off-center crash tests conducted with 4,500-lb cars traveling at 45 mph can meet the quantitative requirements of NCHRP Report 230 (Figure 4: CAL-3, CAL-4, TTI-2; Figure 7: 88-8; Figure 8: 12-10, 12-11).

In discussions with SDHPT personnel, it was determined that many, if not most, real-world collisions with TMA's in Texas are angular collisions. Thus, the eccentric impact conditions specified in Test 1 appear to better approximate the collisions that TMA's are likely to be experience in real-world operations.

Consideration was given to conducting Test 1 at an angle, rather than head-on (i.e., with the longitudinal axes of the TMA and the striking vehicle parallel). In light of the Texas accident experience, it might be argued that an angular test would have more face validity or fidelity. On the other hand, head-on tests can be conducted more consistently with different makes and models of TMA's (and replicated more easily), while still providing a reasonable assessment of the performance of a TMA when subjected to eccentric loading. The benefits of a head-on test (crash test consistency and ease of replication) are believed to outweigh the alleged advantage (fidelity) of conducting this test at an angle.

In Test 1 a 4,500-lb pickup truck or utility vehicle is proposed for use in lieu of the more traditional passenger car. This substitution of test vehicles is primarily a matter of expediency. Relatively few late-model passenger cars weigh as much as 4,500 lbs, but 4,500-lb vehicles in the form of pickup trucks and utility vehicles are fairly common.[30]

In Test Series 1 the dump trucks to which the TMA's were attached were free standing, with parking brakes set and transmissions in second gear. Because of the variance in dump truck displacement (i.e., "roll ahead" and/or "skid ahead" displacements) in Test Series 1, in Test Series 2 the dump trucks were pulled up to a rigid wall to prevent displacement of the truck during the crash.

In future TMA crash testing (i.e., in Tests 1 and 2), it is recommended that the TMA's be attached to dump trucks that have been ballasted to 14,000 lbs (prior to TMA attachment) and that the rear wheels on the trucks be chained or otherwise prevented from rotating during the crash. By this measure, any displacement of the truck during testing should reflect the test conditions and the performance of the TMA, rather than a "slipping" parking brake or a transmission popping out of gear.

Tests 2 (1,800-lb Test Vehicle at 45 mph, Centerline-to-Centerline Impact)

In Test 2, the proposed test vehicle is an 1,800-lb passenger car traveling at 45 mph. Test 2 is a head-on test, centerline to centerline. The purpose of this proposed test is to determine if a TMA can safely decelerate small cars in a head-on collision without allowing the car to underride the cushion.

Of the seven makes and models of TMA tested at 45 mph with 1,800-lb vehicles, only two proved acceptable: The Connecticut DOT TMA and the current model Hexcel TMA. The prototype TMA from Hexcel was judged to be unacceptable due to occupant compartment penetration. The TMA's from Energy Absorption (Alpha and Hexfoam) had occupant impact velocities in excess of 40 fps; the Renco TMA and Markings and Equipment Corporation TMA had occupant ridedown accelerations in excess of 20 g's.

VIBRATION TESTING

The vibration test apparatus, procedures and performance criteria developed during this study appear to provide a reasonable test of how well a TMA will "hold up" in real world operations.

Test Conditions

The cushion portion of a typical TMA is attached to a vertical plate. The plate is then sinusoidally oscillated up and down at 7 Hz through a displacement of 0.6 in (peak to peak). The test is continued for 40 hours - 8 to 10 hours per day over a 4 to 5 day period.

Acceptance Criteria

Quantitatively, a cushion will be judged acceptable if it sags no more than

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[30]In 1989, some 354,647 vehicles were involved in accidents on the Texas Highway System. 75,332 (21 percent) of these vehicles were pickup trucks. [1989 Tabulations of Accidents in the State of Texas (TARE 85), Accident Analysis Division, Texas Transportation Institute, the Texas A&M University System, College Station, Texas, July 1990.]

0.5 in at the left and right rear corners of the cushion after 40 hours of vibration.

Qualitatively, any damage sustained by the unit during testing (e.g., popped rivets, cracks, distortions in sheet metal, etc.) should be minor. If any damage sustained might reasonably be expected to reduce the energy absorbing characteristics of the cushion, the cushion is unacceptable.

Rationale

In developing the vibration test specifications discussed in this report, the California specifications served as a guide. The test that was ultimately developed at TTI is somewhat less severe than the California test, and much shorter (40 hours vs 120 hours).

Three TMA's tested by TTI proved acceptable after 40 hours of vibration: the Energy Absorption Alpha Model, Hexcel (current model) and Markings and Equipment Corporation.[31] It should be noted, however, that the Hexcel TMA sustained a significant amount of distress to the sheet metal covering to the TMA cushion. The sheet metal cracks and distortions seen in testing were similar to, but more severe than, the cracks and distortions seen in units that had been in operation for several years, as reported by the highway departments in Texas and California.

The Hexfoam Model TMA was found to be unacceptable during this study.[32]

MOISTURE TESTING

Test Conditions

The cushion portion of a TMA is placed on a frame inside a 12-ft by 12-ft moisture chamber. The cushion is oriented in the normal, horizontal operational position.

Through eight nozzles positioned approximately two feet above the cushion, water is sprayed onto the top and sides of the unit at a rate determined to simulate a 6 in per hour rain. Spraying is continued for 24 hours.

Acceptance Criteria

The TMA cushion is weighed before it is placed in the moisture chamber and one hour after it is removed from the chamber. If the weight of the unit is increased by more than five percent, this test is unacceptable.

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[31]The Energy Absorption Alpha Model TMA has also successfully passed the California vibration test at 6 Hz. (C&N, 1989)

[32]To date, the Hexfoam TMA has not been tested above 5 Hz on the California vibration test apparatus, i.e., it has not been tested within California's current range of acceptable frequencies, 6 to 8 Hz. The results of the 5 Hz test are reported in C&N, 1988.

Rationale

The energy absorbing properties of some materials used in TMA construction (e.g., untreated paper) can be degraded if they are exposed to water. If the energy absorbing capabilities of a TMA are degraded, obviously, the effectiveness of the unit in a real-world crash is also degraded.

In the California test procedure, the energy absorbing material within the TMA cushion is removed (at the end of the moisture test) to see if it has absorbed any moisture and if it has thereby been rendered less capable of absorbing energy.

The intent of the "five-percent-weight-gain" criterion proposed herein is in keeping with the intent of the California test. If a TMA is designed to allow water to pass through the cushion without being absorbed (i.e., if the interior materials are nonabsorbent and the cushion is well drained), weight gain from the moisture test should be minimal, less than five percent of the weight of the cushion. Similarly, if the TMA is designed to absolutely prevent water from entering the cushion, weight gain will be minimal, less than five percent of the weight of the cushion. Only when water is somehow retained within the TMA will a weight gain of as much as five percent be likely to be observed.

RECOMMENDATIONS

Three recommendations are offered to the Department based upon the work carried out during the course of this study:

(1) As an interim measure, accept three (3) truck mounted attenuators for purchase by the State, namely, the three that were found acceptable in this study:

- Energy Absorption Alpha Model TMA
- Hexcel TMA (current model offered for sale)
- Connecticut DOT TMA

(2) In the relatively near future (say, two or three years hence), require all manufacturers who would sell TMA's to the State (including the three named above) to pass the crash, vibration and moisture tests defined in the previous section.

Between now and the time the new purchase requirements go into effect, a TMA would be deemed acceptable for purchase by the State if it were found to pass the new performance requirements (defined in the previous section) or the performance requirements met by the three (3) makes and models of TMA's (named above) during the course of this study.

(3) The Department should serve notice to the industry that TMA's currently manufactured for sale in this country can be significantly improved, and that in the not too distant future (say, within the next four years), it (the Department) intends to be purchasing such TMA's. Realistically, and within the next four years, the Department should expect to be able to purchase TMA's that adequately protect occupants of 3,500-lb vehicles striking TMA's at 55 mile per hour.

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APPENDIX A

NCHRP REPORT 230 and TRB CIRCULAR 191 CRASH TEST PERFORMANCE CRITERIA

Synopsis of Occupant Impact Velocity and Occupant Ride Down Acceleration as Detailed in NCHRP 230

Occupant impact velocity and occupant ridedown acceleration are fully defined in NCHRP Report 230. Basically, occupant impact velocity is the velocity with which a vehicle occupant's head strikes the interior of the vehicle during a collision. Occupant ridedown acceleration is the maximum average deceleration that a vehicle occupant's head undergoes (over 10 msec), after the occupant's head has come into contact with the interior surface(s) of the vehicle.

Occupant impact velocity and ride down acceleration are calculated (in the longitudinal and lateral directions) based upon vehicular accelerations and simplifying theoretical assumptions (e.g., the vehicle occupant's head moves two feet in a frontal collision before impacting interior surfaces). The equations for making these calculations are provided in NCHRP Report 230. (Note: Neither occupant impact velocity nor occupant ride down acceleration is calculated from accelerations to the heads of anthropomorphic dummies.)

Maximum acceptable limits for occupant impact velocity and occupant ride down acceleration, are shown below:

	Longitudinal	Lateral
Occupant Impact Velocity (fps)	40	30
Occupant Ride down Acceleration (g's) (Max 10 msec ave acc)	20	20

Two Comments on the Performance Criteria of TRB Circular 191

(1) To evaluate crash cushions (including TMA's) it is necessary to calculate "average deceleration." But, there are two methods for calculating average deceleration in TRB Circular 191. In the first, the change in speed of the impacting vehicle is calculated over the stopping distance of the vehicle. In the second, the highest average vehicular deceleration over a 50 msec interval during the collision is calculated. Which method is more appropriate for evaluating TMA's?

In TMA crash tests, vehicle deceleration is not constant throughout the collision. For stiff or heavy TMA's there may be rapid deceleration shortly after the initiation of the collision. For softer, less resistant TMA's, initial decelerations may be relatively small - followed by high terminal decelerations as the impacting vehicle "bottoms out" and strikes the dump truck. When "... the deceleration signal is not fairly constant ... the maximum 50-ms method gives a more conservative result and is recommended." (TRB Circular 191, p 21) (continued . . .)

(2) According to TRB Circular 191, in a frontal collision, the average deceleration on a vehicle striking a crash cushion (i.e., a TMA) must be less than 12 g's in order to be judged acceptable. The phrase "average deceleration" as used in TRB Circular 191 implies "resultant deceleration." Now, obviously, if a crash is <u>purely frontal</u>, "average resultant deceleration" and "average longitudinal deceleration" are identical. However, if the crash is slightly off center, or if the crash is conducted at an angle, lateral decelerations will differ from 0 and resultant deceleration will differ from longitudinal deceleration.

Most TMA crash tests reported in the literature have been frontal tests – or frontal tests at slight angles (0 to 15 degrees) or small offsets (0 to 36 in). The decelerations reported for these tests have typically been <u>longitudinal</u> decelerations, though it should be acknowledged that resultant decelerations for most of these tests would probably not differ appreciably from the reported longitudinal decelerations. Throughout this paper, when TRB Circular 191 evaluation criteria are cited, maximum 50 msec average longitudinal accelerations will be shown. The acceptable threshold for a maximum 50 msec average longitudinal acceleration will be assumed to be 12 g's.

APPENDIX B

STATE OF TEXAS
STATE DEPARTMENT OF HIGHWAYS
AND PUBLIC TRANSPORTATION
EQUIPMENT AND PROCUREMENT DIVISION

SPECIFICATION NO.
SDHPT XXX-XX-XX
REVISED: XXXX XXXX

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:

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,
(Vol. 2, Final Report, TTI)

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.

Manufacturer	Model
Energy Absorption Systems, Inc.	Model Alpha 1000 TMA
Hexcel Structural Products	Model TMCC
Structural Accessories, Inc.	Model Connecticut Crash Cushion

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.
(Vol. 2, Final Report, TTI)

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. (Vol. 2, Final Report, TTI)

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 CONNECTICUT-TYPE/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 <u>**PAINTING**</u>: 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:

Du Pont No. 21667
Ditzler No. Dar 2185
Sherwin Williams No. F8W230

<u>**NOTE**</u>: 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 <u>**MANUALS**</u>: 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 <u>**FUTURE UPDATES AND SPECIFICATION REVISIONS**</u>: 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.