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7. Author(s)
LuAnn Theiss and Roger P. Bligh

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16. Abstract
While most transportation agencies are very familiar with truck-mounted attenuators, trailer-mounted attenuators are increasing in popularity. There is a concern for the level of protection that attenuators provide for workers when they are mounted on trailers compared to trucks. This research evaluated and compared the level of protection provided to workers by truck-mounted and trailer-mounted attenuators. No crash testing was conducted; instead, the researchers used existing crash test report data for the comparison. The researchers found that the use of heavier support vehicles for these mobile attenuators provided better protection for workers and recommend that TxDOT maintains the current policy of requiring 20,000 lb support vehicles, regardless of attenuator type. In addition, the researchers found that the concern of trailer-mounted attenuators swinging around may not be justified, given that post-impact trajectories of the impacting vehicles are similar to those reported during truck-mounted attenuator impact testing.

17. Key Words
Truck-Mounted Attenuator, Trailer-Mounted Attenuator, TMA, Mobile Attenuator, Worker Safety, Work Zone

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WORKER SAFETY DURING OPERATIONS WITH MOBILE ATTENUATORS

by

LuAnn Theiss, P.E.
Associate Research Engineer
Texas A&M Transportation Institute

and

Roger Bligh, P.E.
Research Engineer
Texas A&M Transportation Institute

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TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was LuAnn Theiss, Texas P.E. #95917.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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INTRODUCTION

STATEMENT OF THE PROBLEM

Truck-mounted attenuators (TMA) have been in use by transportation agencies for many years. More recently, manufacturers have transferred the energy absorbing technologies of their truck-mounted attenuators to trailer-mounted versions. Although many truck-mounted and trailer-mounted attenuators have been accepted for use on the national highway system, their required testing focused primarily on their structural adequacy, occupant risk for the impacting vehicle, and post-impact vehicular response. For workers that may be located near the attenuators when an impact occurs, the level of protection provided has not been compared. This research compared truck-mounted and trailer-mounted attenuators in terms of worker safety.

BACKGROUND

History of Mobile Attenuators

During construction and maintenance operations, workers must often perform duties close to active travel lanes. Although various techniques, such as channelizing devices, signs, flaggers, and arrow panels, are used to route traffic away from work areas, these measures do not provide positive protection for workers. For various reasons, errant vehicles may enter areas not intended for motorists and where workers are present. The use of shadow vehicles during mobile operations, as well as the use of barrier vehicles in stationary operations, is a common technique for protecting workers from errant vehicles. While this protection provides a benefit for workers, it does not protect occupants in errant vehicles that may strike the shadow vehicle. This led to the development of several impact attenuation devices that were designed to decrease the severity of collisions with the shadow vehicle by errant vehicles. These devices were essentially compact crash cushions attached to the rear of the shadow vehicles and were intended to reduce the accelerations felt by occupants of the errant vehicle. When shadow vehicles and barrier vehicles are used with mobile attenuators, they are referred to as support vehicles.

Early Product Development

In the early 1970s, researchers at the Texas Transportation Institute (TTI) successfully developed and crash tested the first trailer-mounted attenuator and called it the "Texas Crash

Cushion Trailer." This trailer, shown in Figure 1, consisted of several 20-gage 55-gallon steel drums with 8 inch holes in the top and bottom and mounted on a set of wheels and a trailer hitch. The trailer was described as a "workable and easily used implement for the protection of personnel and equipment" during maintenance activities. This device was never commercially available as an assembled unit. However, based on successful crash testing, TxDOT used it extensively in the field. But due to its size, the trailer proved difficult to handle in the field in many situations. With a desire to improve the device, TxDOT eliminated the trailer and attached the drum array directly to the rear of the shadow vehicle using a cantilever-type connection. Although it was never crash-tested, this was probably the first truck-mounted attenuator (*1*, *2*).

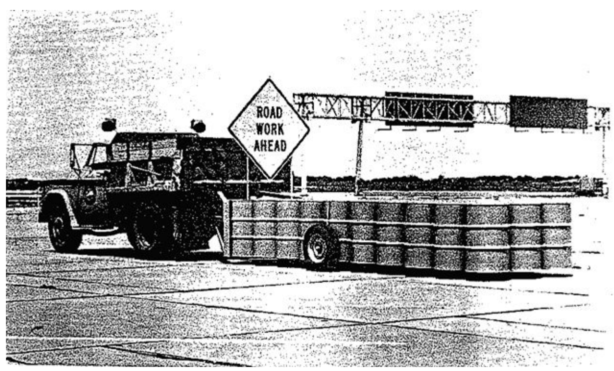

Figure 1. TTI's Texas Crash Cushion Trailer (*1*).

In the mid-1970s and early 1980s, other mobile attenuators were developed. Connecticut Department of Transportation, working in conjunction with the University of Connecticut, developed a truck-mounted attenuator that employed steel cylinders approximately 2 ft in diameter enclosed within a telescoping box-beam frame. This device evolved over time and is still in use today in Connecticut on roadways with posted speed limits of 45 mph or less. The design was not proprietary in nature, and interested agencies may obtain complete sets of fabrication drawings and specifications for the current design (*3*, *4*).

Energy Absorption Systems, Inc. (EASI) played a role in early development of several different truck-mounted attenuator systems. EASI, working in conjunction with California Department of Transportation (CalTrans), developed a mobile attenuator system that used vermiculite concrete, which is a lightweight concrete that has a cushioning effect (*5*). EASI also worked with Hexcel Corporation to develop two other attenuator systems. The first system consisted of polyurethane foam-filled cardboard honeycomb cells (called Hex-Foam) and was introduced in 1981. A second system consisted of formed aluminum sheet metal cartridges and honeycomb cells combined to form the Alpha 1000 mobile attenuator. The Alpha 1000 was introduced in 1986 and was the first truck-mounted attenuator to feature a 90-degree vertical pivot, which allowed the operator to stow the attenuator in an upright position for transport, significantly improving the maneuverability of the support vehicle (*2*). Although routine use of truck-mounted attenuators was not common practice during this time period, the Alpha 1000 was commercially available until the manufacturer recently discontinued the product.

Most of these early mobile attenuators were designed for and tested at moderate impact speeds of 45 mph or less (*6*, *7*, *8*, *9*, *10*). The use of higher impact speeds and heavier impacting vehicles could easily produce attenuators that were too large and impractical to use. As impact attenuating technologies evolved, higher impact speeds were introduced into the development of more compact products.

In 1989, TxDOT contracted with the TTI to develop a set of performance specifications for truck-mounted attenuators. The project was aimed at assessing the performance of several truck-mounted attenuators and developing the criteria for an acceptable product. The information was used by TxDOT's purchasing personnel to establish minimum performance requirements for devices purchased by the agency (*11*).

Evolving Technologies

In the mid- and late-1990s, several new mobile attenuators were designed and tested at speeds above 60 mph. Attenuators are developed using specific technologies that are patented and considered proprietary. Several of these designs were further refined over time to create the products that are commonly used today.

The MPS 350 truck-mounted attenuator, shown in Figure 2, was developed by Syro Steel, Inc. in the mid-1990s. The MPS 350 frame consists of steel C-channel beams, which are connected by an impact face at the rear and cross braces along the length of the frame. The channels have steel face plates across the opening, which creates a box-shaped section. When struck, the rear portion of the frame slides into a cutter assembly, which then shears off the metal plates. This shearing action dissipates the energy of the impacting vehicle. This attenuator was originally accepted for use in June 1996, but design modifications were made later that year in order to accommodate higher impact speeds. By 2003, Trinity Industries, Inc. purchased Syro Steel, Inc. and further modified the MPS 350 by widening the steel frame impact face and strengthening the attachment between the cutter assemblies and the structural supports that keep the device level (*12*, *13*, *14*).

Figure 2. Trinity Industry's MPS 350 Truck-Mounted Attenuator (*15*).

The Safe-Stop truck-mounted attenuator, shown in Figure 3, was also developed in the late 1990s by EASI and consists of two different light-weight aluminum cartridges contained in a steel support frame. When struck, the frame collapses and the energy absorbing aluminum cartridges absorb the energy from the impacting vehicle. The cartridges are replaceable, and the frame may be reusable after impact. A unique feature of this attenuator is the bi-folding articulating nature of the steel support frame, which allows one cartridge to be stowed above the other for transport. This attenuator was originally accepted for use in April 1999, although several design modifications were made by 2005, including changing the release hardware, adding metal guides for the cartridges, adding corner gussets to restrict some rotation, and lengthening some frame arms for improved collapse geometry. In 2006, the design of the tailgate mount was modified, but the general design of the attenuator remained unchanged (*16, 17, 18, 19, 20, 21*).

Figure 3. Energy Absorption's Safe-Stop Truck-Mounted Attenuator.

The U-MAD truck-mounted attenuator, shown in Figure 4 was developed by Albert W. Unrath, Sr. in the late 1990s. The U-MAD truck-mounted attenuator consists of an aluminum box containing eight separate internal compartments filled with variable density energy dissipating material. The top back surface of the aluminum box was slightly tapered. The proprietary material enclosed in the box absorbs the energy from the impacting vehicle. This attenuator also has a lift mechanism, which allows the attenuator to be raised into a vertical position for transport. This attenuator was originally accepted for use in March 2000. By 2006, the ownership rights were transferred to Impact Absorption, who eliminated the taper on the aluminum box, making a fully rectangular enclosure. Ownership rights for the U-MAD truck-mounted attenuator now belong to Barrier Systems, Inc. (*22, 23, 24, 25*).

Figure 4. Barrier Systems' U-MAD Truck-Mounted Attenuator (*26*).

The Scorpion truck-mounted attenuator, shown in Figure 5 was developed by TrafFix Devices, Inc. in the late 1990s. The Scorpion truck-mounted attenuator consists of a curved aluminum tube framework and engineered aluminum cartridge cushioning technology. Crash energy is absorbed by both the aluminum frames and the proprietary energy absorbing contents of the cartridges. The curved design is intended to redirect side angle impacts away from the exposed corner of the truck. This attenuator also has a lift mechanism, which allows the attenuator to be raised into two different vertical positions for transport. This attenuator was originally accepted for use in July 2000 (*27, 28*).

Figure 5. TrafFix Devices' Scorpion Truck-Mounted Attenuator.

The Ram 100K truck-mounted attenuator, shown in Figure 6, was also developed in the late 1990s by Renco, Inc. This attenuator consists of cardboard honeycomb sections housed in a rectangular aluminum box. This device can be raised for transport and was accepted for use in June 2000. There have been no documented design modifications to the original device (*29*).

Figure 6. Renco's Ram 100K Truck-Mounted Attenuator (*30*).

Table 1 gives a summary of the proprietary technologies associated with each of the devices. The technologies consist of very distinct combinations of energy-absorbing materials.

These materials are designed to lower the deceleration rate for the occupants of the impacting vehicle when the vehicle strikes the attenuator. This is their primary purpose in the attenuator design.

Table 1. Proprietary Technologies for Truck-Mounted Attenuators.

Attenuator	**Proprietary Energy-Absorbing Technology**
Alpha 100K	Cartridge of energy absorbing lightweight aluminum sheet metal of various thicknesses
MPS 350 III	Steel C-channel beams connected by an impact face and a series of steel cross-braces, which are torn apart by a cutter assembly upon impact
SAFE-STOP 180	Two types of lightweight aluminum energy absorbing cartridges on a bi-folding articulated steel frame assembly
U-MAD Cushion 100K	Aluminum box containing eight separate internal compartments filled with variable density energy-dissipating material
Scorpion C10000	Three aluminum boxes with energy absorbing aluminum honeycomb supported by curved tubular aluminum frames
Ram 100K	Cardboard honeycomb sections housed in a rectangular aluminum box

Trailer-Mounted Attenuators

Many of the truck-mounted attenuators require special mounting hardware in order to attach to the rear of the support vehicle. Each mounting assembly is structurally designed to support the weight of the energy absorbing component, or cushion, of the attenuator in a cantilevered position behind the support truck. In addition, many truck-mounted attenuators have hydraulic controls that allow workers to lower the attenuator into the deployed position and raise it into the transport position. Most hydraulic systems and their controllers are not interchangeable. Figure 7 shows the Safe-Stop truck-mounted attenuator tailgate mount and hydraulic controls that are used to support the device with a standard dump truck.

Figure 7. Safe-Stop Truck-Mounted Attenuator Tailgate Mount and Hydraulic Controls.

In the late 1990s and early 2000s, several manufacturers designed trailer-mounted versions of their existing truck-mounted attenuators. In most cases, special mounting hardware was no longer needed because the trailer axle provided support for the cushion. The trailer-mounted attenuators were connected to the rear of the support vehicle by way of a simple pintle hook and could be towed just like a normal trailer. Since most trailer-mounted attenuators do not need to be raised for transport, hydraulic lift controls were not needed. While several trailer-mounted attenuators were simply modified truck-mounted attenuator designs, others were originally developed as trailers and entered the market during this same time period.

The Scorpion Trailer Attenuator is a trailer-mounted version of the Scorpion truck-mounted attenuator developed by TrafFix Devices, Inc. It utilizes the same curved aluminum tube framework and engineered aluminum cartridge cushioning technology as the truck-mounted version. It has a pintle hook connection and an axle located near the rear of the trailer. It also incorporates a Telescoping Anti-Rotation System (TARS), which is designed to prevent the attenuator trailer from rotating about the pintle hook at the rear of the support vehicle. Although it was accepted for use in March 2007, the Scorpion Trailer has had several design modifications that have resulted in a mass reduction of 162 kg (435 lb). In addition, the Scorpion Trailer Attenuator was impact tested with a variety of different support vehicle masses, ranging from 4500 kg (9920 lb) to 10,000 kg (20,046 lb) (*31, 32, 33*).

Figure 8. TrafFix Devices' Scorpion Trailer-Mounted Attenuator.

The Safe-Stop SST Trailer, shown in Figure 9, is a trailer-mounted version of the Safe-Stop 180 truck-mounted attenuator developed by Energy Absorption Systems, Inc. (EASI). There were two basic modifications made to the Safe-Stop 180 truck mounted attenuator. First, the upward folding mid-frame elements and hydraulic lift system were replaced with a rigid frame and incorporates a suspended axle and wheels. Second, a pintle hook connection was added to the front of the unit along with a damper system that allows the trailer to articulate like a normal trailer, but locks to prevent trailer rotation during offset or angled impacts. The Safe-Stop SST Trailer was also impact tested with an arrow panel mounted to the trailer (*34, 35*).

Figure 9. Energy Absorption's Safe-Stop Trailer-Mounted Attenuator (*36*).

The TTMA-100 trailer-mounted attenuator, shown in Figure 10, was developed by Safety by Design Company. It was a new design that was not based on a prior truck-mounted style attenuator. This design was based on a bursting tube technology originally developed for the energy-absorbing box-beam guardrail. Energy from the impact is absorbed when the inner square tubing is forced into the outer tubing, splitting the corners of the outer tubing. The TTMA-100 was modified and the new design was accepted by FHWA in July 2011. Ownership rights were transferred first to Safety Trailers, Inc. and are now owned by Gregory Industries, Inc. (*37, 38, 39*).

Figure 10. Gregory Industries' TTMA-100 Trailer-Mounted Attenuator.

The UMAD Trailer, shown in Figure 11, is a trailer-mounted version of the U-MAD truck-mounted attenuator developed by Albert W. Unrath, Sr. and further refined by Impact Absorption, Inc. The ownership rights now belong to Barrier Systems, Inc. The U-MAD energy absorbing cartridge of the truck-mounted attenuator was mounted to a steel fabricated trailer with an anti-rotational mechanism that activates upon impact (*40, 41*).

Figure 11. Barrier Systems' U-MAD Trailer-Mounted Attenuator (*42*).

The Vorteq trailer-mounted attenuator, shown in Figure 12, was developed by Energy Absorption Systems, Inc. (EASI). This trailer-mounted attenuator did not originate as a truck-mounted attenuator. The long frame tubes are the primary energy absorbing feature of this attenuator. When an impact occurs, the frame tubes curl inward as the impact head is forced forward. The work performed during the curling of the frame absorbs energy from the impact. After being accepted for use in February 2008, this trailer-mounted attenuator was impact tested with an arrow panel in place using U.K. testing standards (*43*, *44*).

Figure 12. Energy Absorption's Vorteq Trailer-Mounted Attenuator (*45*).

Table 2 summarizes the proprietary energy absorbing technologies for each of the trailer-mounted attenuators presented in this report. For the Scorpion trailer, Safe-Stop SST trailer, and the U-MAD trailer, the technologies are simply transferred from related truck-mounted attenuator. The technologies found in the TTMA-100 trailer and the Vorteq were new, since no truck-mounted counterpart existed at the time of their development. Again, the primary purpose of the energy-absorbing materials in the trailer design is to lower the deceleration rate for the occupants of the impacting vehicle when the vehicle strikes the attenuator.

Table 2. Proprietary Technologies for Trailer-Mounted Attenuators.

Attenuator	Proprietary Energy-Absorbing Technology
Scorpion Trailer	Trailer-mounted version of Scorpion C10000 TMA with anti-rotational feature on the steel trailer tongue
SAFE-STOP SST	Trailer-mounted version of SAFE-STOP 180 TMA with locking anti-rotational dampeners
TTMA-100 Trailer	Bursting tube technology assembly (similar to a box-beam guardrail) mounted on a tubular steel frame
U-MAD 100k Trailer	Trailer-mounted version of U-MAD Cushion 100K with anti-rotational feature.
Vorteq Trailer	Steel frame tubes that curl upon impact

Devices Approved by Texas Department of Transportation

TxDOT's *Compliant Work Zone Traffic Control Devices List* (*46*) contains products that have been evaluated and determined to be acceptable traffic control devices for use in work zones on TxDOT roadways. These devices are shown in Table 3. Test Level 3 (TL-3) devices are approved for use on all TxDOT roadways, while Test Level 2 (TL-2) devices are approved only for use on roadways with regulatory speed limits of 45 mph or less. Within each device category, the devices are listed in alphabetical order by manufacturer of record.

Table 3. TxDOT-Approved Mobile Attenuators.

Test Level	Type of Mount	Device	Manufacturer of Record
3	Truck	U-MAD Cushion 100K	Barrier Systems, Inc.
		Alpha 100K	Energy Absorption Systems, Inc.
		SAFE-STOP	Energy Absorption Systems, Inc.
		SAFE-STOP 180	Energy Absorption Systems, Inc.
		Ram 100K	Renco Supply, Inc.
		MPS 350 III	Trinity Highway Products, LLC
		Scorpion C10000	TrafFix Devices, Inc.
	Trailer	U-MAD 100k	Barrier Systems, Inc
		SAFE-STOP SST	Energy Absorption Systems, Inc.
		Vorteq	Energy Absorption Systems, Inc.
		Scorpion	TrafFix Devices, Inc.
		TTMA-100	Safety Trailers
2	Truck	Alpha 70K	Energy Absorption Systems, Inc.
		Ren-Gard 815	Renco Supply, Inc.
		Scorpion A 10000	TrafFix Devices, Inc.
	Trailer	U-MAD 70k	Barrier Systems, Inc

The TL-2 mobile attenuators shown on the *Compliant Work Zone Traffic Control Devices List* are typically smaller and lighter versions of their TL-3 counterparts. TxDOT no longer purchases TL-2 devices, but continues to allow contractors to use these devices in appropriate circumstances. The TL-3 devices, which may be used on all roadways, offer more utility than the TL-2 devices, which are limited to lower-speed roadways.

The possibility does exist for workers to inadvertently deploy TL-2 devices on higher speed roadways. This is an undesirable situation in terms of both motorist and worker safety. If the TL-2 device were to be impacted by an errant vehicle at a higher speed than it is designed for, the motorist may be subjected to higher decelerations, which may increase bodily injury risk. In addition, a worker located inside the support vehicle would be subjected to higher accelerations. Since TxDOT no longer purchases the TL-2 devices, the opportunity for this type of event to occur is diminished significantly.

UTILITY OF MOBILE ATTENUATORS

The researchers sought to identify any differences in the utility of truck-mounted attenuators and trailer-mounted attenuators in terms of their physical characteristics and maneuverability. To accomplish this, the researchers tabulated the physical dimensions of each device based on information found in product literature and on the FHWA website. In addition, information obtained from TxDOT workers regarding maneuverability was also considered in the part of the research. The results are given below.

PHYSICAL CHARACTERISTICS

Table 4 shows the approximate weights and dimensions of these mobile attenuators.

Table 4. Dimensions and Masses of Mobile Attenuators.

Device	Length (m) *(ft-in)*	Width (m) *(in)*	Height When Deployed (m) *(in)*	Height When Stowed (m) *(ft-in)*	Mass (kg) *(lb)*
TL-3 Truck-Mounted Attenuators					
U-MAD Cushion 100K	3.277 *10-9*	2.286 *90*	0.762 *30*	*3.785* *12-5*	570 *1256*
SAFE-STOP 90	4.013 *13-2*	2.362 *93*	0.914 *36*	4.013 *13-2*	905 *1996*
SAFE-STOP 180	4.191 *13-9*	2.362 *93*	0.914 *36*	2.083 *6-10*	943 *2080*
MPS 350 III	4.267 *14-0*	1.829 *72*	0.762 *30*	3.81 *12-6*	816 *1800*
Scorpion C10000	3.556 *11-8*	2.438 *96*	0.635 *25*	3.658 *12-0*	632 *1393*
TL-3 Trailer-Mounted Attenuators					
U-MAD 100k Trailer	6.477 *21-3*	2.286 *90*	0.914 *36*	N/A	1266 *2790*
SAFE-STOP SST Trailer	5.867 *19-3*	2.362 *93*	1.143 *45*	N/A	1202 *2650*
Vorteq Trailer	6.934 *22-9*	2.337 *92*	0.787 *31*	N/A	594 *1310*
Scorpion Trailer	5.436 *17-10*	2.438 *96*	0.914 *36*	N/A	785 *1730*
TTMA-100 Trailer	7.163 *23-6*	2.438 *96*	0.940 *37*	N/A	658 *1450*

In terms of length, the truck-mounted attenuators measured between 3.277 m (10 ft 9 inches) and 4.267 m (14 ft), while the trailer-mounted attenuators (which do not fold for transport) measured between 5.436 m (17 ft 10 inches) and 7.163 m (23 ft 6 inches). Interestingly, the bi-fold feature of the Safe-Stop 180 allows it to be folded to an even shorter length of 2.388 m (7 ft 10 inches) when the support vehicle configuration allows. This configuration was successfully impact tested at lower speeds, so this device would provide some attenuation during transport. Overall, the truck-mounted attenuators tended to be shorter than the trailer-mounted attenuators by approximately 2.7 m (8 ft) on average. Longer attenuator lengths may present maneuverability concerns for workers, as they may be more difficult to turn around.

With the exception of the MPS 350 III, which is 1.829 m (72 inches) in width, most attenuators are 2.286 to 2.438 m (90 to 96 inches) in width. A typical support truck, such as a standard dump truck, is 2.438 m (96 inches) in width. None of the attenuators (regardless of type) exceed this width, so width is not expected to be an impediment to maneuverability.

When examining the tabulated heights, these values include the ground clearance under the device when deployed. Most attenuators (regardless of type) are typically around 0.9 m (36 inches) in height in their deployed position. For truck-mounted attenuators that are lifted and/or folded up for transport, height becomes a consideration. Figure 13 shows a Safe-Stop 90 truck-mounted attenuator in the upright position for transport. In this configuration, the device is approximately 4 m (13 ft 2 inches) in height. This can be a concern if workers inadvertently drive under awnings, entry gates, or other overhead obstructions without checking for clearance. Although the development of the Safe-Stop 180 was based on design improvements to the Safe-Stop 90, there are many Safe-Stop 90 attenuators still in use today in the field. In addition, other truck-mounted attenuators in their transport positions are almost as high, and can be just as concerning, given that a typical attenuator support vehicle (a standard dump truck) is approximately 2.438 m (96 inches or 8 ft) high.

Figure 13. Safe-Stop 90 in Upright Position for Transport.

MANEUVERABILITY

In the early evaluations of mobile attenuators, researchers found that TxDOT workers had some concerns about their use. They felt that the effects of the mobile attenuators on support truck maneuverability were detrimental. In addition, the support vehicle used for the attenuator had limited maintenance utility, since it was not available to perform other functions. Finally, the need for another worker to drive the support vehicle was often seen as a waste of manpower (*47*).

As mentioned earlier, longer attenuator lengths, particularly with trailer-mounted attenuators, may impact maneuverability. For example, if workers are on a two-lane roadway in a rural area, there may be limited opportunities to turn around. Some TxDOT crews have reported having to travel several miles away from the work area to find a suitable place to turn around while towing trailer-mounted attenuators.

With the limited resources available in today's transportation environment, TxDOT has shown an interest in combining functions when feasible. One such idea involves eliminating the use of a shadow vehicle during herbicide application operations if the herbicide application truck could carry or tow its own attenuator. This would reduce the number of workers and vehicles required to perform herbicide application. Unfortunately, the loss of maneuverability is significant when either truck-mounted or trailer-mounted attenuators are attached to work vehicles. Truck position is critical during herbicide application operations and TxDOT workers must be careful to position the sprayer truck such that sprayer nozzles reach the appropriate areas to be treated. This typically requires significant maneuvering of the work vehicle during the operation, and the restricted maneuverability due to the attenuator makes this scenario difficult, if not impossible to achieve.

SUMMARY

As mentioned in the previous section, many of the attenuators require some type of modification to the rear bumper area of support vehicles to accommodate the carrying or towing of the attenuator. Because these fleet vehicles cannot perform both attenuator support vehicle functions and work functions at the same time, TxDOT districts typically dedicate certain vehicles to carry or tow attenuators and the vehicle is specifically set up solely for that purpose. Approximately 150 TxDOT fleet trucks are primarily used as attenuator support vehicles. Thus, the loss of utility of support vehicles noted in earlier research is still prevalent today (*47*).

While each device is unique in size and shape, truck-mounted attenuators tend to provide more height challenges for workers in terms of maneuverability, while trailer-mounted attenuators may be more difficult to turn around. These challenges associated with their utility do not appear to be any greater for one type of device over the other.

CRASHWORTHINESS

Before newly developed roadside safety hardware products can be used on the national highway system, they must meet certain criteria established by the Federal Highway Administration (FHWA). Mobile attenuators must be crash tested using full-scale vehicle impact testing. The impact testing evaluated the performance of the attenuator in terms of the hazards to which occupants of the impacting vehicle would be exposed, the structural adequacy of the attenuator, the hazard to workers and pedestrians located nearby due to debris resulting from the impact, and the post-impact behavior of the test vehicle. FHWA prescribes specific impact conditions for the testing, including vehicle mass, speed, approach angle, and the point on the attenuator to be hit. In addition, FHWA prescribes acceptable measurement tolerances and techniques for each element of the testing. Proper documentation of the impacting testing data, including a comprehensive report, must be submitted to FHWA for review.

FHWA reviews the documentation to determine if it meets crash performance criteria. If the criteria are met, FHWA issues an acceptance letter. While the acceptance letter typically states that use of the attenuator on the national highway system is acceptable, it addresses only the crashworthiness characteristics of the attenuator. It does not address moisture, vibration, and durability testing, nor does it address other agency approvals that are typically required prior to deployment. Table 5 lists the acceptance letters issued by FHWA for mobile attenuators that are currently on the *TxDOT Compliant Work Zone Traffic Control Devices List* (*46*).

Table 5. FHWA Acceptance Letters for Mobile Attenuators (*48*).

Device	Manufacturer of Record	FHWA Acceptance Letter
TL-3 Truck-Mounted Attenuators		
U-MAD Cushion 100K	Barrier Systems	CC-64, CC-64A, CC-64D, CC-64G
Alpha 100K	Energy Absorption Systems	CC-39
SAFE-STOP	Energy Absorption Systems	CC-59, CC-59A, CC-59B
SAFE-STOP 180	Energy Absorption Systems	CC-78, CC-78A, CC-78B
Ram 100K	Renco	CC-67
MPS 350 III	Trinity	CC-34, CC-34A, CC-34B
Scorpion C10000	TrafFix	CC-65, CC-65A
TL-3 Trailer-Mounted Attenuators		
U-MAD 100k	Barrier Systems	CC-99, CC-103
SAFE-STOP SST	Energy Absorption Systems	CC-78C, CC-78D
Vorteq	Energy Absorption Systems	CC-104, CC-104A
Scorpion	TrafFix	CC-65B, CC-65C, C-65E
TTMA-100	Safety Trailers (now Gregory Industries)	CC-90, CC-90A
TL-2 Truck-Mounted Attenuators		
Alpha 70K	Energy Absorption Systems	CC-32
Ren-Gard 815	Renco	CC-20, CC-20A
Scorpion A 10000	TrafFix	CC-65F
TL-2 Trailer-Mounted Attenuators		
U-MAD 70k	Barrier Systems	CC-64B, CC-64E, CC-64F, CC-64G

The requirements for full-scale impact testing have recently changed. These changes were intended to more accurately reflect changes in the vehicle fleet. Vehicles have increased in size and light truck bumper heights are increasing. A brief discussion of the current and previous test criteria are presented in this section.

MASH TESTING

The current crashworthiness testing requirements for mobile attenuators are defined in the *Manual for Assessing Safety Hardware* (*49*), commonly referred to as MASH. As of January 1, 2011, all new products must be tested using MASH test criteria. Retesting of devices that were already accepted under the previous test criteria is not required. Changes to the test vehicle masses found in MASH were intended to make the impacting vehicles used in the testing more representative of the modern vehicle fleet. The recommended MASH impact test matrix for mobile attenuators is given in Table 6 and is illustrated in Figure 14.

Table 6. MASH Test Level 3 Impact Tests for Mobile Attenuators (49).

<table>
<tr><td colspan="2" rowspan="2">Test Conditions</td><td colspan="4">MASH Test Number</td></tr>
<tr><td>3-50</td><td>3-51</td><td>3-52</td><td>3-53</td></tr>
<tr><td rowspan="2">Impacting Vehicle</td><td>Mass (kg)
(lb)</td><td>1100
2420</td><td>2270
5000</td><td>2270
5000</td><td>2270
5000</td></tr>
<tr><td>Speed (km)
(mph)</td><td>100
62</td><td>100
62</td><td>100
62</td><td>100
62</td></tr>
<tr><td rowspan="2">Impact Conditions</td><td>Impact Point</td><td>Centerline</td><td>Centerline</td><td>Offset (W/3)</td><td>Offset (W/4)</td></tr>
<tr><td>Alignment</td><td>Head-On (0 deg)</td><td>Head-On (0 deg)</td><td>Head-On (0 deg)</td><td>Angled (10 deg)</td></tr>
<tr><td rowspan="5">Support Vehicle Criteria</td><td>Mass</td><td>Heaviest Allowable</td><td>Heaviest Allowable</td><td>Heaviest Allowable</td><td>Lightest Allowable</td></tr>
<tr><td>Engine</td><td>Off</td><td>Off</td><td>Off</td><td>Off</td></tr>
<tr><td>Transmission</td><td>2nd gear</td><td>2nd gear</td><td>2nd gear</td><td>2nd gear</td></tr>
<tr><td>Parking Brake</td><td>On/Set</td><td>On/Set</td><td>On/Set</td><td>On/Set</td></tr>
<tr><td>Restraint</td><td>Rigid/Blocked in lieu of Heaviest Available</td><td>Rigid/Blocked in lieu of Heaviest Available</td><td>Rigid/Blocked in lieu of Heaviest Available</td><td>No external restraint</td></tr>
</table>

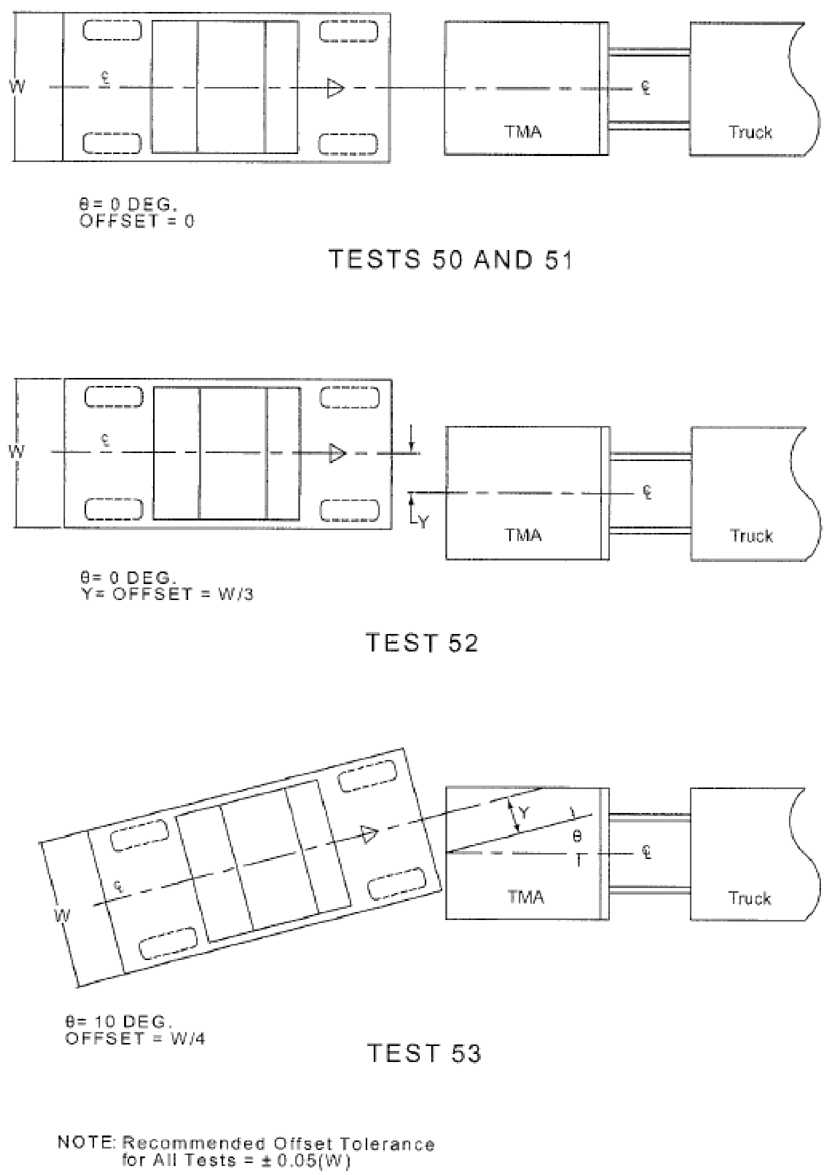

Figure 14. MASH Impact Tests for Mobile Attenuators (*49*).

Although MASH is the current standard for impact testing, none of the mobile attenuators currently in use have been tested using these protocols. Instead, they were developed while the previous impact testing protocols were still in effect. The test matrix is provided in this report for informational purposes only.

NCHRP 350 TESTING

Prior to the introduction of the MASH testing criteria, mobile attenuators were evaluated using testing protocols that are defined in *National Cooperative Highway Research Program Report 350 Recommended Procedures for the Safety Performance Evaluation of Highway Features* (*50*). This protocol has been in use since 1993.

Mobile Attenuator Test Parameters

It is important to understand that vehicle impact tests are complex experiments and are difficult to replicate because of imprecise controls of test conditions and sometimes random and unstable behavior of dynamic crush and fracture mechanisms. As a result, FHWA is faced with the challenge of making acceptance decisions based on single impact test reports. There is no guarantee that the attenuator will perform in the exact same manner under all conditions found in the field, but impact testing is still the best tool available for evaluating impact performance. For this reason, a considerable effort is made to maintain the uniformity of tests that may be performed by many different testing facilities.

For tests that include the small car (820C), the support vehicle should be placed against a rigid barrier to prevent any forward movement. This effectively maximizes the deceleration of the impacting vehicle and represents the worst case condition for occupants of a small car during a real collision with a mobile attenuator.

For tests that include the pickup truck (2000P), the support vehicle should be placed on a clean, dry, paved surface, such as asphaltic or portland cement concrete surfaces. In addition, the supporting vehicle should be in second gear with the parking brakes on. The front tires of the support vehicle should be aimed directly ahead.

Curb mass is the mass of a test vehicle in its standard manufactured condition, which does not include vehicle occupants or cargo, but all fluid reservoirs are filled. Test inertial mass is the mass of test vehicle and all items including ballast and test equipment that is rigidly attached to the vehicle structure. Mass of test dummies is not included. Gross static mass is the total of test inertial mass and dummy mass combined.

The support vehicle used for mobile attenuator testing should be representative of the type and mass of the vehicle commonly used in service. If different types and masses of vehicles are commonly used, it is recommended that the tests be performed with vehicles at both the lower and upper extremes in terms of mass. In absence of a common support vehicle, it is recommended that mobile attenuator tests be conducted with a support vehicle having a test inertial mass of 9000 ± 450 kg (approximately 19,800 ± 990 lb). For mobile attenuators, the support vehicle is typically a General Motors Corporation (GMC) C7500 tandem axle dump truck, such as the one shown in Figure 15. This dump truck has a gross vehicle weight rating (GVWR) ranging from 11,794 to 14,969 kg (26,001 to 33,000 lb) (*51*).

Figure 15. GMC C7500 T/A Dump Truck (*52*).

The recommended impact test matrix for mobile attenuators is given in Table 7 and illustrated in Figure 16.

Table 7. NCHRP Report 350 Test Level 3 Impact Tests for Mobile Attenuators.

Test Conditions		NCHRP Report 350 Test Number			
		3-50	3-51	3-52	3-53
Impacting Vehicle	Mass (kg) *(lb)*	820 *1800*	2000 *4400*	2000 *4400*	2000 *4400*
	Speed (km) *(mph)*	100 *62*	100 *62*	100 *62*	100 *62*
Impact Conditions	Impact Point	Centerline	Centerline	Offset (W/3)	Offset (W/4)
	Alignment	Head-On (0 deg)	Head-On (0 deg)	Head-On (0 deg)	Angled (10 deg)
Support Vehicle Criteria	Mass (lb)	N/A	N/A	N/A	N/A
	Engine	Off	Off	Off	Off
	Transmission	2nd gear	2nd gear	2nd gear	2nd gear
	Parking Brake	On/Set	On/Set	On/Set	On/Set
	Restraint	Rigid/Blocked	N/A	N/A	N/A

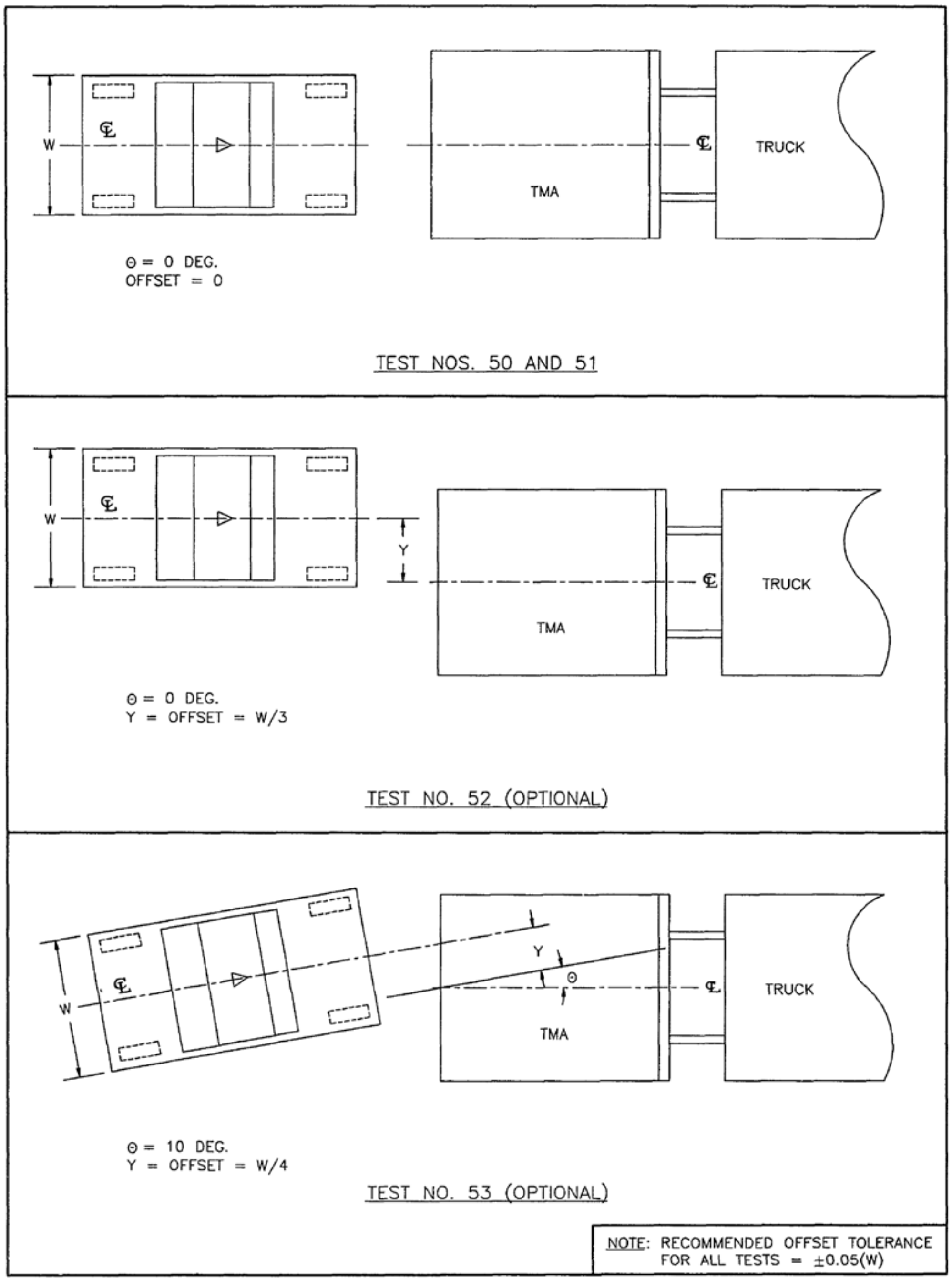

Figure 16. NCHRP Report 350 Impact Tests for Mobile Attenuators (*50*).

Test 3-50 is intended to evaluate risks to occupants of a small car impacting the mobile attenuator. During this test, the 820C (1800 lb) small car strikes the mobile attenuator head on and centered. An instrumented test dummy located in the front seat of the small car collects data during the impact.

Test 3-51 is intended to evaluate structural adequacy of the mobile attenuator, risks to occupants, and the roll-ahead distance of the support vehicle when impacted by the heavy passenger vehicle. Occupant risk is measured in terms of occupant impact velocity and ridedown acceleration. Roll-ahead distance is the distance the support vehicle moves after impact, and it is important to consider when selecting safe separation distances from the support vehicle and workers on foot near the support vehicle.

Test 3-52 is an optional test that is performed with the centerline of the impacting vehicle offset one third of the width of the impacting vehicle. Test 3-53 is an optional test that is performed with the centerline of the impacting vehicle offset one-fourth of the width of the impacting vehicle and at an impact angle of 10 degrees. When these test standards were developed, there was no assurance that any mobile attenuator design could meet the 3-52 and 3-53 test requirements and still be a feasible design. For this reason, these two tests were optional for truck-mounted attenuators, even though the impact conditions for 3-52 and 3-53 are believed to be representative of many collisions that occur with mobile attenuators.

Evaluation/Passing Criteria

The recommended test matrix for mobile attenuators only addresses safety performance during vehicular collisions. It does not address durability, mobility of the support vehicle, road-induced vibration, maintainability, influence of temperature variations and moisture, and other factors. The safety performance is evaluated based on specific evaluation criteria. The evaluation criteria fall into three categories: structural adequacy, occupant risk, and post-impact vehicle response. Impact test results are compared to evaluation criteria to determine acceptable performance of the mobile attenuator.

Structural Adequacy

Mobile attenuator products that satisfy the structural adequacy requirements should stop the impacting vehicle in a controlled manner. This is readily evident from the impact testing. The structural adequacy criteria refer to the structural requirements associated with the impact and do not address structural requirements of wind, ice, and other environmental loads that may occur.

Occupant Risk

Occupant risk relates to the degree of hazard to which occupants of the impacting vehicle are subjected and is primarily measured in terms of (1) occupant impact velocity and (2) occupant ridedown accelerations.

Occupant Impact Velocities. Occupant Impact Velocities (OIV) is the velocity at which a hypothetical point mass occupant impacts a surface of a hypothetical occupant compartment. More simply stated, this is the velocity at which a vehicle occupant's head strikes the interior of the vehicle during a collision. Maximum acceptable longitudinal OIV is 12 m/s (or 39.4 ft/s) and should preferably be limited to 9 m/s (29.5 ft/s) in the longitudinal and lateral directions.

Occupant Ridedown Acceleration. Occupant ridedown acceleration is the highest lateral and longitudinal component of resultant vehicular acceleration averaged over any 10-ms interval for the collision pulse subsequent to occupant impact. This value should preferably be limited to 15 G in the longitudinal and lateral directions, with a maximum of no more than 20 G, where G equals 9.81 m/s^2 (32.2 ft/s^2).

Other Factors. Other aspects of occupant risk relate to detached elements, fragments, or other debris from the mobile attenuator, which should not penetrate or show potential for penetrating the occupant compartment of the impacting vehicle, nor should it present an undue hazard to other traffic, pedestrians, or workers. In addition, deformation of the occupant compartment, or intrusion into the occupant compartment, that may cause serious injuries should not be permitted. Finally, the impacting vehicle should remain upright during and after the collision. Moderate roll, pitching, and yawing are acceptable. Figure 17 illustrates the concepts of roll, pitch, and yaw with the recommended sign conventions for test records. Roll data capture the tipping motion of the impacting vehicle about an imaginary horizontal axis through the center of the vehicle and aligning with the vehicle travel path. Pitch data capture the bucking motion of the impacting vehicle about an imaginary lateral axis through the center of the vehicle. Finally, yaw data capture the spinning motion of the impacting vehicle about an imaginary vertical axis through the center of the vehicle. Higher values of roll, pitch, and yaw may indicate undesirable conditions for the occupants of the impacting vehicle.

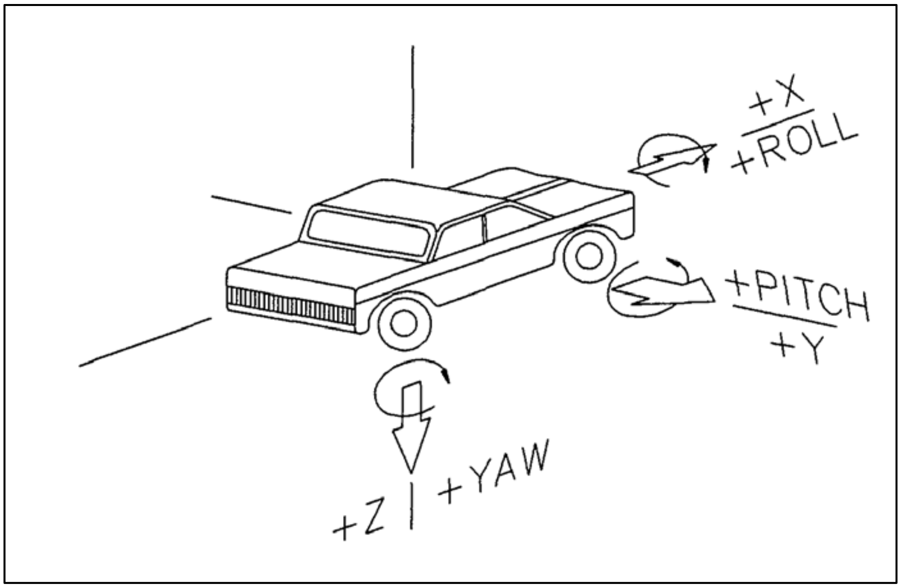

Figure 17. Sign Conventions for Measuring Roll, Pitch and Yaw (*50*).

Post-Impact Vehicle Trajectory

Post-impact vehicle response is a measure of the potential interaction of the impacting vehicle with other traffic after the crash. A subsequent multivehicle crash can subject occupants of other vehicles to undue hazard. NCHRP Report 350 indicates that it is preferable that the vehicle's trajectory not intrude into adjacent lanes and that and the impacting vehicle's final stopping position intrude a minimum distance, if at all, into adjacent or opposing traffic lanes.

TXDOT TESTING CRITERIA AND EVALUATION

Mobile attenuators that are currently in use by TxDOT have received letters of acceptance from FHWA based on testing performed under NCHRP Report 350. There is no deadline for states to switch over to MASH-tested hardware, since all hardware tested under NCHRP Report 350 may remain in place and may continue to be manufactured and installed (*49*).

TxDOT Specification No. 550-42-09 (*53*) dated June 2010 describes purchasing requirements for truck-mounted attenuators. Table 8 shows the design and performance requirements for Test Level 3 mobile attenuators described in this specification.

Table 8. TxDOT TL-3 Impact Testing Requirements per Specification 550-42-09 (*53*).

Test Conditions		Test Number			
		3-50	3-51	3-52	3-53
Impacting Vehicle	Mass (kg) *(lb)*	820 *1800*	2000 *4400*	N/A	N/A
	Speed (km) *(mph)*	100 *62*	100 *62*	N/A	N/A
Impact Conditions	Impact Point	Centerline	Centerline	N/A	N/A
	Alignment	Head-On (0 deg)	Head-On (0 deg)	N/A	N/A
Support Vehicle Criteria	Mass (kg) *(lb)*	8550 to 9450 *18,849 to 20,833* Single Axle Dual Rear Tires	8550 to 9450 *18,849 to 20,833* Single Axle Dual Rear Tires	N/A	N/A
	Engine	Off	Off	N/A	N/A
	Transmission	2nd gear	2nd gear	N/A	N/A
	Parking Brake	On/Set	On/Set	N/A	N/A
	Restraint	N/A	N/A	N/A	N/A

The specification requires only Tests 3-50 and 3-51, which were the only required tests for truck-mounted attenuators under NCHRP Report 350 when the specification was published. Tests 3-52 and 3-53 were determined by NCHRP Report 350 to be optional for truck-mounted attenuators and thus, were not included in the TxDOT specification. The specification requires that a support vehicle with a mass of 8550 to 9450 kg (18,849 to 20,833) lb should be used during the impact testing. TxDOT does not currently have a specification for the purchase of trailer-mounted attenuators.

The truck-mounted attenuator specification gives the recommended passing criteria for truck-mounted attenuators, and these are shown in Table 9.

Table 9. TxDOT Passing Criteria for Impact Testing.

Passing Criteria	**Limits**
Maximum Occupant Impact Velocity Longitudinally	Not to exceed 39.4 fps
Maximum Occupant Ridedown Acceleration Longitudinally	Not to exceed 20 G
Impact Vehicle Rollover	Not permitted
Impact Vehicle Lane Intrusion	Stopped within its lane
Impact Vehicle Passenger Compartment Integrity	Reasonably Safeguarded
Impact Acceleration of Stationary Support Vehicle	Minimized
Roll-Ahead Distance	Minimized

Although the specification reasonably follows the requirements of NCHRP Report 350, the Impact Vehicle Lane Intrusion requirement that the vehicle is stopped within its lane may be too stringent for most mobile attenuators.

The *Compliant Work Zone Traffic Control Devices List* (*46*) provides a list of crashworthy products for contractors to use, purchase or rent for use on TxDOT projects. It includes both truck-mounted and trailer-mounted attenuators. This document has specific language regarding the required mass for support vehicles used for mobile attenuators during work operations on TxDOT roadways:

> *The supporting vehicle shall have a gross (i.e., ballasted) vehicular weight of 20,000 ± 1000 lb unless another weight is recommended by the TMA [Truck Mounted Attenuator] manufacturer. If a contractor chooses to use a lighter vehicle to mount the TMA, then the contractor is responsible for following the TMA manufacturer's recommendations and for being aware of the effect that a lighter vehicle will have on the roll-ahead distance and on the driver of the shadow vehicle. Attachment of TMA shall be in accordance with manufacturer's recommendations.*

WORKER SAFETY ASSESSMENT

COLLISION DYNAMICS

To understand impact testing, one must understand the basic principles of collision dynamics. When two vehicles collide, the interaction follows the principle of conservation of momentum. Momentum is the product of vehicle mass and velocity. The sum the vehicle momentum just prior to the impact equals the sum of the momentum of the vehicles just after impact, as shown in the following equation:

$$M_I V_I + (M_S + M_A) V_S = (M_I + M_S + M_A) V_T$$

Where:

M_I=mass of impacting vehicle, kg (slugs).

V_I=impact speed of impacting vehicle, m/s (fps).

M_S=mass of support vehicle, kg (slugs).

M_A=mass of attenuator, kg (slugs).

V_S=impact speed of support vehicle and attenuator (V_S=0 for stationary condition), m/s (fps).

V_T=post impact speed of impacting vehicle (V_I), support vehicle and attenuator (V_S), m/s (fps).

The support vehicle speed (V_S) is applicable to both the support vehicle and the attenuator because they are connected. Although the attenuator is crushed in the impact, it has the same mass, but it is simply more compact. Interestingly, other than contributing mass, the energy absorbing properties of the attenuator are not applicable in this equation. With all other elements known, V_T can be calculated. Using Test 3-50 and 3-51 data obtained from the FHWA acceptance letters for each attenuator, the researchers calculated values for V_T for each of the mobile attenuators. The results are shown in Table 10 and Table 11, respectively. Under crash test conditions, V_S=0.

Table 10. Post Impact Speeds Calculated from 3-50 Test Data.

Attenuator	Type	M_I (kg) *(lb)*	V_I (m/s) *(mph)*	M_S (kg) *(lb)*	M_A (kg) *(lb)*	V_T (m/s) *(mph)*
U-MAD Cushion 100K	Truck	820 *1808*	27.8 *62.2*	9183 *20,245*	570 *1257*	2.2 *4.9*
SAFE-STOP 180	Truck	903 *1991*	27.1 *60.6*	8550 *18,850*	940 *2072*	2.4 *5.4*
Ram 100K	Truck	896 *1975*	26.4 *59.1*	8849 *19,509*	427 *941*	2.3 *5.1*
MPS 350 III	Truck	915 *2017*	27.8 *62.2*	9000 *19,842*	640 *1411*	2.4 *5.4*
Scorpion C10000	Truck	883 *1947*	27.8 *62.2*	9632 *21,235*	632 *1393*	2.2 *4.9*
Vorteq	Trailer	885 *1951*	27.7 *62.0*	N/A*	594 *1310*	N/A
TTMA-100	Trailer	897 *1978*	26.7 *59.7*	9659 *21,294*	659 *1453*	2.1 *4.7*

*support vehicle blocked from forward movement

Table 11. Post Impact Speeds Calculated from 3-51 Test Data.

Attenuator	Type	M_I (kg) *(lb)*	V_I (m/s) *(mph)*	M_S (kg) *(lb)*	M_A (kg) *(lb)*	V_T (m/s) *(mph)*
U-MAD Cushion 100K	Truck	2000 *4409*	27.8 *62.2*	9183 *20,245*	570 *1257*	4.7 *10.5*
SAFE-STOP 180	Truck	1998 *4405*	26.8 *59.9*	8550 *18,850*	940 *2072*	4.7 *10.5*
Ram 100K	Truck	2000 *4409*	27.9 *62.4*	8849 *19,509*	427 *941*	4.9 *11.0*
MPS 350 III	Truck	2041 *4500*	27.8 *62.2*	9000 *19,842*	640 *1411*	4.9 *11.0*
Scorpion C10000	Truck	1961 *4323*	27.5 *61.5*	9632 *21,235*	632 *1393*	4.4 *9.8*
U-MAD 100k	Trailer	2242 *4943*	27.0 *60.4*	9884 *21,790*	1148 *2531*	4.6 *10.2*
SAFE-STOP SST	Trailer	2000 *4409*	27.5 *61.5*	8550 *18,850*	1202 *2650*	4.7 *10.5*
Vorteq	Trailer	1999 *4407*	28.3 *63.3*	N/A*	594 *1310*	N/A
Scorpion	Trailer	2034 4484	27.0 60.4	N/A*	701 *1545*	N/A
TTMA-100	Trailer	2012 *4436*	27.6 *61.7*	9659 *21,294*	659 *1453*	4.5 *10.1*

*support vehicle blocked from forward movement

V_T is an important factor in determining post impact movement of the support vehicle. The results indicate very small variations in computed V_T values. Although most of the prescribed impact test parameters (such as M_I and V_I) have small variations, a quick review indicates that variations in the mass of the support vehicle are often much greater. In this case, the U-MAD trailer has the lowest calculated V_T value. This does not mean that the energy absorbing capability of this attenuator is greater than the others. The higher V_T value is due to the greater mass of the support vehicle used in the testing as well as the greater mass of the attenuator. If no attenuator were present (M_A=0), we would not expect to see much difference in calculated values of V_T.

To support this idea, the researchers performed a sensitivity analysis by calculating theoretical values of V_T for a standard set of conditions, assuming: M_I=820 kg, V_I=27.8 m/s (100 km/hr), M_S=9000 kg, and V_S=0 (for stationary condition), while the value for M_A ranged from 0 to 1500 kg. These same calculations were repeated for M_I=2000 kg. In addition, calculated values of V_T from the impact test data were plotted on the same graph with the theoretical data. Figure 18 shows the results.

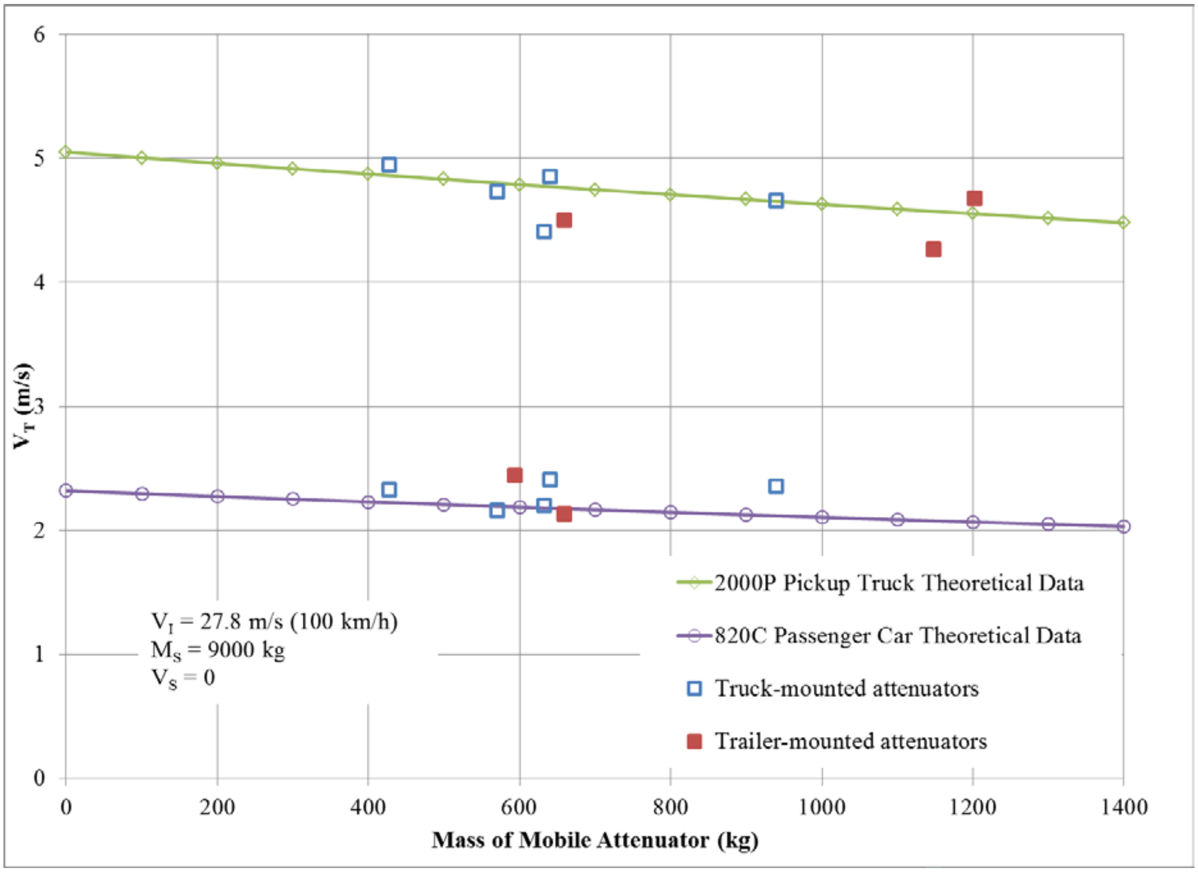

Figure 18. V_T as a Function of M_A.

It appears that the computed values of V_T are well-correlated, regardless of attenuator type. But this graph also tells us that when the mass of the impacting vehicle is significantly increased (from 820 kg to 2000 kg), then the expected value of V_T also increases significantly. To further examine this concept, the researchers computed V_T for various values of M_I (ranging from 820 kg to 36300 kg) and M_S (ranging from 2270 kg to 9000 kg) while assuming an average value of M_A=650 kg. Figure 19 shows the results.

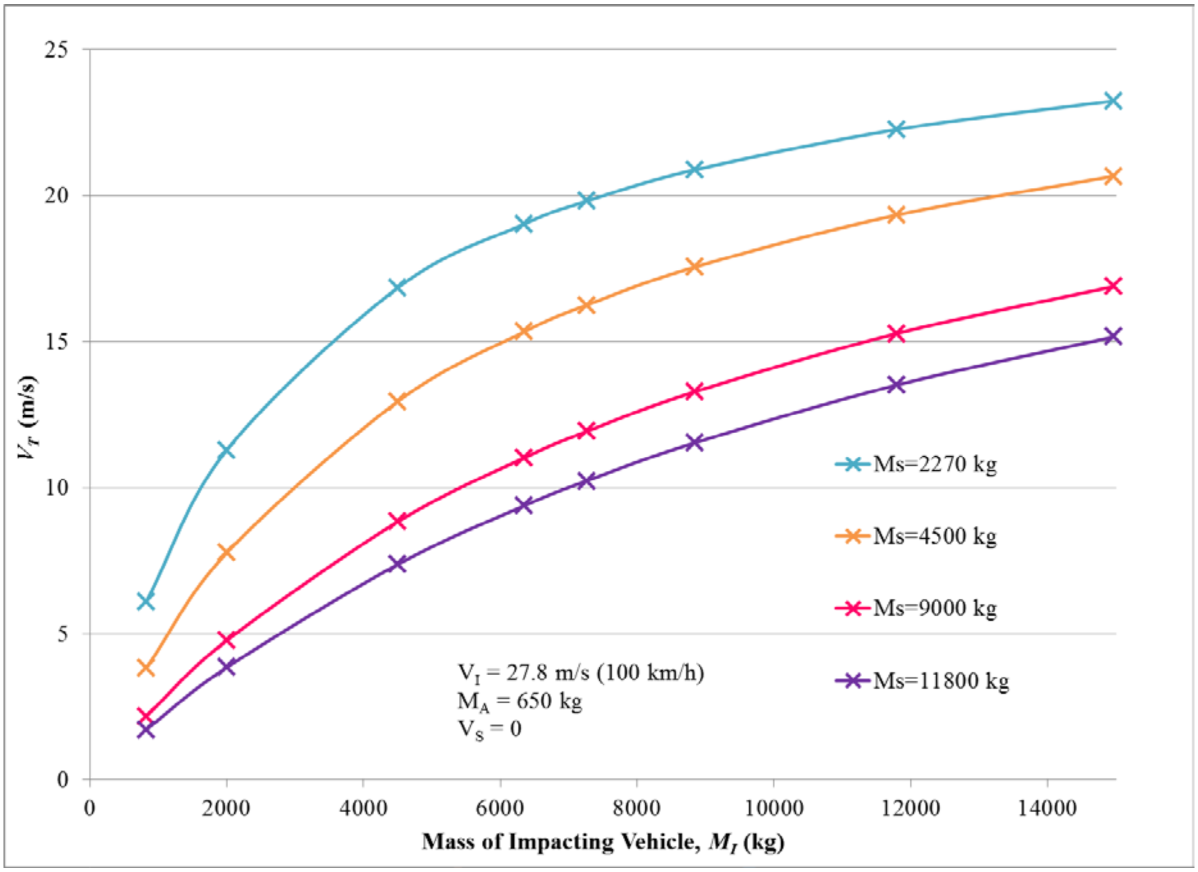

Figure 19. V_T for Various Values of M_I and M_S.

Figure 19 demonstrates that V_T decreases when M_S increases. V_T also decreases when M_I decreases. Lower values of V_T indicate more favorable circumstances for workers. When considering methods that could be used to lower values of V_T during an actual impact, it is important to understand that there is no way to control the mass of the impacting vehicle (M_I) during a random impact. However, the mass of the support vehicle (M_S) is something that can be controlled by strict enforcement of agency policies that require heavier support vehicles.

COMPARISON OF MOBILE ATTENUATOR TYPES

The researchers first examined the impact testing results in terms of safety of the occupants of the impacting vehicle. Occupant impact velocity (OIV) and ridedown acceleration are the two primary indicators of impacting vehicle occupant safety. OIV is the Tests 3-50 and 3-51 are intended to evaluate risks to occupants of a small car and pickup truck, respectively, during mobile attenuator impacts. The researchers plotted OIV against ridedown acceleration for all of the available test data. Figure 20 shows the results.

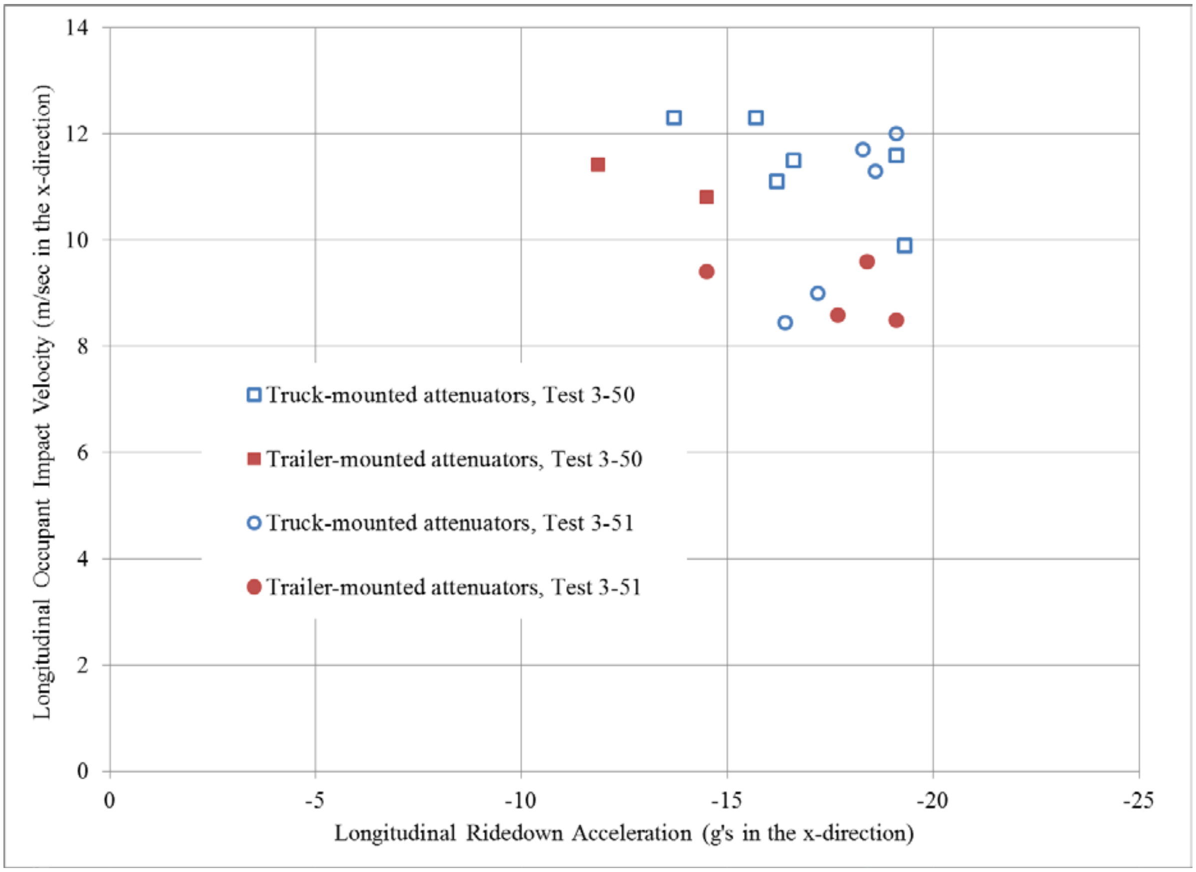

Figure 20. Impacting Vehicle Occupant Safety Indicators.

Several of the trailer-mounted attenuators were never subjected to test 3-50, so there are few data points for comparison of this scenario. Nonetheless, no distinct pattern exists. Based on the impacting vehicle occupant safety indicators, there does not appear to be a clear difference between the two types of mobile attenuators. The primary differences, such as attenuator connection type and the addition of an axle, would not be expected to significantly impact OIV values.

WORKER PROTECTION

The researchers sought to determine if any differences exist between the data for the two types of mobile attenuators in terms of worker safety. The primary indicators of worker safety are support vehicle occupant ridedown acceleration and support vehicle roll-ahead distance. To a lesser extent, post-impact vehicle trajectory and flying debris should also be considered.

Support Vehicle Occupant Ridedown Acceleration

When a mobile attenuator impact occurs, there is some risk of injury to the driver of the support vehicle. Most mobile attenuator impacts are unidirectional (head-on) in nature and cause the support vehicle to be accelerated forward. Initially, the driver will not move forward, but is restrained from flailing rearward by the support of the seat and headrest. Rearward occupant movement is generally less dangerous than forward movement. Ridedown acceleration of the support vehicle is the recommended criteria for the assessment of the risk of injury to the driver of the support vehicle (*50*). Unfortunately, detailed impact crash data are not available for this calculation and are not required to be reported from impact testing. However, researchers know that support vehicle accelerations will be significantly less than accelerations measured on the impacting vehicle if the support vehicle weighs significantly more than the impacting vehicle (*47*). Therefore, the use of a heavier support vehicle reduces the risk of injury for the driver of the support vehicle.

Support Vehicle Roll-Ahead

One of the major safety concerns with the used of mobile attenuators is roll-ahead distance. Roll-ahead distance defined as the longitudinal displacement of the support vehicle when impacted by an errant vehicle. Table 12 and Table 13 show the expected roll-ahead distances for moving and stationary operations, respectively, as a function of impact speed, support vehicle mass, and impacting vehicle mass. These tables are based on procedures developed over two decades ago by Humphries and Sullivan (*55*). These values are rounded up to the nearest 25-ft increment.

Table 12. Roll-Ahead Distances for Stationary Operations (55).

Weight of Barrier Vehicle (stationary)	Prevailing Speed (mph)	Weight of Impacting Vehicle to be Contained[a]			
		4,500 lbs	10,000 lbs	15,000 lbs	24,000 lbs
10,000 lbs	60-65	50 ft	100 ft[b]	150 ft	200 ft
	50-55	25 ft	75 ft[b]	100 ft	150 ft
	≤45	25 ft	50 ft[b]	75 ft	100 ft
15,000 lbs	60-65	25 ft	75 ft	100 ft	150 ft
	50-55	25 ft	50 ft	75 ft	100 ft
	≤45	25 ft	25 ft	50 ft	75 ft
24,000 lbs	60-65	25 ft	50 ft	75 ft	100 ft
	50-55	25 ft	25 ft	50 ft	75 ft
	≤45	25 ft	25 ft	25 ft	50 ft

Table 13. Roll-Ahead Distances for Mobile Operations (55).

Weight of Shadow Vehicle (moving)[b]	Prevailing Speed (mph)	Weight of Impacting Vehicle to be Contained[a]			
		4,500 lbs	10,000 lbs	15,000 lbs	24,000 lbs
10,000 lbs	60-65	100 ft	175 ft[c]	225 ft	275 ft
	50-55	100 ft	150 ft[c]	175 ft	200 ft
	≤45	75 ft	100 ft[c]	125 ft	150 ft
15,000 lbs	60-65	75 ft	150 ft	175 ft	225 ft
	50-55	75 ft	125 ft	150 ft	175 ft
	≤45	50 ft	100 ft	100 ft	100 ft
24,000 lbs	60-65	75 ft	100 ft	150 ft	175 ft
	50-55	50 ft	75 ft	100 ft	150 ft
	≤45	50 ft	75 ft	75 ft	100 ft

As explained previously, the laws of conservation of momentum apply to attenuator impacts. Thus, the roll-ahead distance of a support vehicle is a function of the mass of the impacting vehicle (M_I) and the mass of the support vehicle (M_S). The equation for roll-ahead distance during a stationary operation is:

$$S = \frac{(M_I + M_S)(V_T)^2}{2M_S g D}$$

Where

S=roll-ahead distance, m (ft).

M_I=mass of impacting vehicle, kg (slugs).

M_S=mass of support vehicle, kg (slugs).

g=gravitational constant, 9.8 m/s (32.2 fps^2).

D=drag factor of support vehicle, typically less than full braking (unitless).

V_T=post impact speed of both impacting vehicle (V_I) and support vehicle (V_P=0 for stationary condition), m (ft).

V_I=impact speed of impacting vehicle, m/s (fps).

The equation for V_T was established earlier in this report and is shown below:

$$V_T = \frac{M_I V_I}{M_I + M_s + M_A}$$

By solving the roll-ahead equation for D and substituting the V_T equation, the new equation is:

$$D = V_I^2 \frac{(M_I)^2}{2\, M_S\, (M_I + M_s + M_A)\, g\, S}$$

When impact testing is performed with the support vehicle in second gear and the parking brake(s) set, test results usually state the measured roll-ahead distance. With the impact speed and all other masses known, the effective drag factor, D, can be calculated. Using impact test data available at the time for a variety of truck-mounted attenuators, Humphreys and Sullivan found that the effective drag values ranged from 0.2 to 0.7. They assumed an effective drag factor of 0.3, which is on the lower end of the range (*55*). Using a more conservative (lower) value for the effective drag factor in computations will result in slightly higher theoretical roll-ahead distances.

The methodology used by Humphreys and Sullivan can be useful in computing roll-ahead distances for mobile attenuators that are available today. Typically, Test 3-51 is performed with the support vehicle in second gear and the parking brake(s) set, and the test results give the measured roll-ahead distance. In some cases, Test 3-51 was performed with the support vehicle blocked against forward movement, so the roll-ahead distance is not known.

The researchers computed values for D from test data in order to validate the assumed value of 0.3 for effective drag. Based on the results shown in Table 14, the researchers concluded that 0.3 is a reasonable value for effective drag.

Table 14. Calculated Values for Effective Drag Factor Based on 3-51 Test Data.

Attenuator	Type	M_I (kg) *(lb)*	V_I (m/s) *(mph)*	M_S (kg) *(lb)*	M_A (kg) *(lb)*	S (m) *(ft)*	D (-)
U-MAD Cushion 100K	Truck	2000 *4409*	27.8 *62.2*	9183 *20,245*	570 *1257*	6.2 *20.3*	.235
SAFE-STOP 180	Truck	1998 *4405*	26.8 *59.9*	8550 *18,850*	940 *2072*	4.0 *13.1*	.372
Ram 100K	Truck	2000 *4409*	27.9 *62.4*	8849 *19,509*	427 *941*	4.3 *14.1*	.370
MPS 350 III	Truck	2041 *4500*	27.8 *62.2*	9000 *19,842*	640 *1411*	4.0 *13.1*	.390
Scorpion C10000	Truck	1961 *4323*	27.5 *61.5*	9632 *21,235*	632 *1393*	5.6 *18.4*	.225
U-MAD 100k	Trailer	2242 *4943*	27.0 *60.4*	9884 *21,790*	1148 *2531*	9.9 *32.5*	.120
SAFE-STOP SST	Trailer	2000 *4409*	27.5 *61.5*	8550 *18,850*	1202 *2450*	N/A	N/A
Vorteq	Trailer	1999 *4407*	28.3 *63.3*	N/A	594 *1310*	N/A	N/A
Scorpion	Trailer	2034 *4484*	27.0 *60.4*	N/A	701 *1545*	N/A	N/A
TTMA-100	Trailer	2012 *4436*	27.6 *61.7*	9659 *21,294*	659 *1453*	N/A	N/A

For most of the trailer-mounted attenuators, Test 3-51 was performed with the support vehicle blocked from forward movement. If the effective drag was assumed to be 0.3, the theoretical roll-ahead distances can be calculated. Due to the relatively small masses of the trailer-mounted attenuators, any drag associated with the trailer wheels was assumed negligible.

Table 15. Calculated Values for Roll-Ahead Based on 3-51 Test Data and Drag Factor=0.3.

Attenuator	Type	M_I (kg) *(lb)*	V_I (m/s) *(mph)*	M_S (kg) *(lb)*	M_A (kg) *(lb)*	D (-)	S (m) *(ft)*
U-MAD 100K	Trailer	2242 *4943*	27.0 *60.4*	9884 *21,790*	1148 *2531*	0.3*	3.9 *12.9*
SAFE-STOP SST	Trailer	2000 *4409*	27.5 *61.5*	8550 *18,850*	1202 *2450*	0.3*	5.1 *16.7*
Vorteq	Trailer	1999 *4407*	28.3 *63.3*	9000* *19,842*	594 *1310*	0.3*	5.2 *17.1*
Scorpion	Trailer	2034 *4484*	27.0 *60.4*	9000* *19,842*	701 *1545*	0.3*	4.9 *16.1*
TTMA-100	Trailer	2012 *4436*	27.6 *61.7*	9659 *21294*	659 *1453*	0.3*	4.4 *14.4*

*assumed value

Because the primary function of a mobile attenuator is to provide protection for occupants in a striking vehicle, NCHRP Report 350 testing requires the heaviest support vehicle or a rigidly blocked support vehicle (i.e., roll-ahead distance equals 0 feet) to be used for several of the required tests. For each crash test performed under NCHRP Report 350, the weight of the support vehicle is specified. In addition, *NCHRP Synthesis 182* describes a method for calculating roll-ahead distance. The method is based on the concept that the mass (M_I) and speed (V_I) of the impacting vehicle and the mass (M_S) and drag resistance (D) of the support vehicle are the primary determinants of roll-ahead distance. Simply stated, using a heavier support vehicle will provide improved protection for workers that may be located near the support vehicle, provided that the vehicle weight falls within any limits described in the FHWA acceptance letter for that particular device.

TxDOT recently amended the Traffic Control Plan (TCP) 6 Series Standard Sheets. The modifications included the specification of a 30 ft [9.144 m] minimum dimension between the work location and the position of the protection vehicle during stationary operations (*56*). Calculated roll-ahead values shown in Table 15 are at or below the minimum dimension prescribed by TxDOT.

The researchers also investigated the potential for an herbicide application truck to carry or tow its own attenuator. This would eliminate the use of a shadow vehicle during herbicide application operations, thus reducing the number of workers and vehicles required to perform herbicide application operations. Figure 21 shows a typical herbicide application truck found in the Corpus Christi District.

Figure 21. Herbicide Truck in Corpus Christi District Fleet.

This truck is an International 4700 model, which has an empty weight of approximately 11,500 lb (5012 kg). The capacity of the chemical tank is 1235 gallons. Assuming a specific gravity of 1.17 for herbicide chemicals, the weight of the fully loaded tank can be computed as:

$$(1235\ gallons)(1.17)\left(8.34\frac{lb}{gallon}\right) = 12{,}050\ lb$$

Therefore, the fully loaded truck weighs 23,550 lb, which initially meets the TxDOT requirement for a 20,000 lb support vehicle. However, as the chemical is sprayed, the weight of the truck decreases to back down to its empty weight of 11,050 lb, which does not meet the 20,000 lb requirement. Therefore, the researchers concluded that herbicide trucks generally would not meet the minimum weight requirement to carry or tow their own attenuators and do not recommend this practice.

Post-Impact Vehicle Trajectory

Given that most trailer-mounted attenuators are modified versions of their truck-mounted counterparts, which have been in use for years, both will have roughly the same energy absorbing capacity and one would expect similar crash performance. However, the impacts of using a pintle hook, as well as the impacts of anti-rotational features are not known. In all known test cases, the trailer-mounted attenuators remained attached to the support vehicle at the pintle hook. One might expect that effective anti-rotational features would prevent the attenuator from crushing unevenly, as well as mitigate the probability that the impacting vehicle would penetrate adjacent lanes during an attenuator impact. Referring back to Figure 17, the yaw represents the angle that the vehicle spins about an imaginary vertical axis through the center of the impacting vehicle. It is not the angle of deflection of the attenuator. An example of a post-impact yaw value for the Safe-Stop SST trailer is shown in Figure 22. In this case, a 97 degree yaw indicates the potential for the impacting vehicle to intrude into the adjacent (open) lane if the attenuator is located in a lane closure or mobile operation on the left side of traffic.

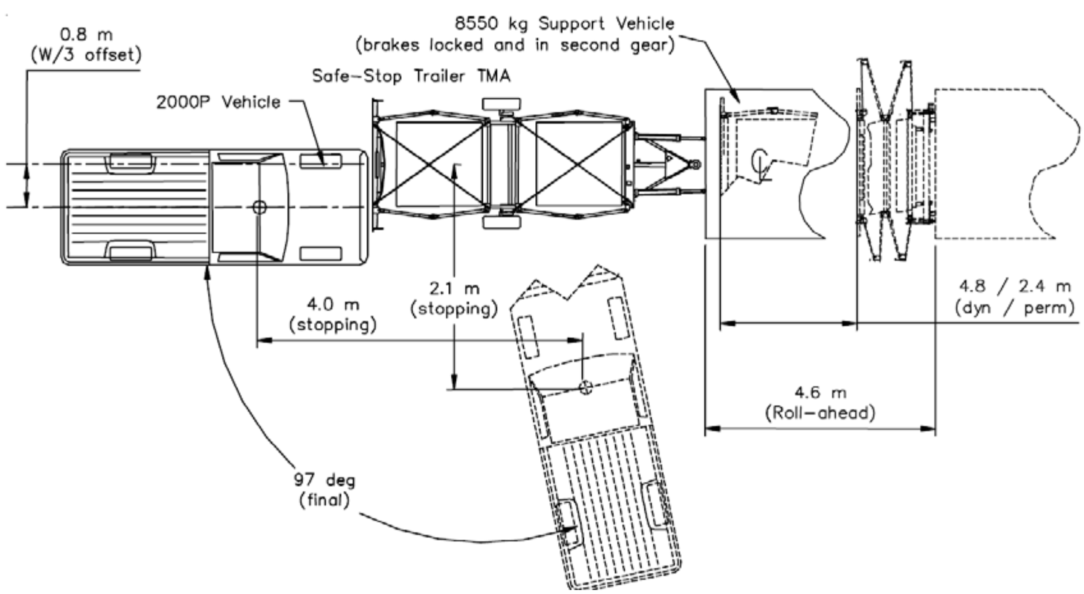

Figure 22. Post-Impact Reported Yaw Value of 97 Degrees during Test 3-52 (*34*).

Less spin (represented by a lower yaw value) is presumed better for the occupants of the impacting vehicle. In addition, less spin indicates a reduced likelihood of the impacting vehicle intruding into the open travel lane and causing a secondary collision (which may result in increased hazard for workers on foot in the area). The researchers tabulated the post-impact vehicle yaw values, shown in Table 16. The angled impacts associated with Tests 3-52 and 3-53 represent the worst cases for which anti-rotational features might be needed. Values of N/A indicate that data are not available for that scenario (i.e., the test was not performed).

Table 16. Post-Impact Yaw of Impacting Vehicles during Angled Tests.

Attenuator	Type	Yaw Value (degrees)	
		Test 3-52	Test 3-53
U-MAD Cushion 100K	Truck	N/A	N/A
SAFE-STOP 180	Truck	-117	-111
Ram 100K	Truck	N/A	N/A
MPS 350 III	Truck	N/A	N/A
Scorpion C10000	Truck	N/A	N/A
U-MAD 100k[1]	Trailer	-46	N/A
SAFE-STOP SST[1]	Trailer	-97	168
Vorteq	Trailer	119	111
Scorpion[1]	Trailer	66	-103
Scorpion (modified anti-rotation system)[1]	Trailer	N/A	-52
TTMA-100[2]	Trailer	140, 135	66

[1]Claims anti-rotational features
[2]Additional test conducted after a design modification

Although only one truck-mounted attenuator was subjected to Tests 3-52 and 3-53, the reported yaw values are comparable to some of the trailers. This may indicate that the concern of trailer-mounted attenuators swinging around upon impact may not be a significantly higher risk than when truck-mounted attenuators are utilized, but there are not enough data to make this conclusion. The Scorpion trailer appears twice in the table because it was re-tested after the manufacturer made modifications to the anti-rotational feature. The Scorpion trailer, Safe-Stop SST trailer, and U-MAD trailers all advertise anti-rotational design attributes, while the Vorteq and TTMA-100 do not. In Test 3-52, the impact is head-on but off center. The Vorteq and TTMA-100 had higher yaw values in Test 3-52 than the trailers with anti-rotational features, suggesting that the anti-rotational features have some benefit during this type of impact. However, these findings are based on a very little test data for each attenuator. Single tests cannot be construed to represent consistent performance in the field. In Test 3-53, the impact is both angled and offset. In terms of yaw, the trailers with anti-rotational features did not appear to perform better than those without, suggesting that anti-rotational features may not effectively reduce post-impact yaw of the impacting vehicle under the angled test conditions.

Flying Debris

When impacted, detached elements, fragments, or other debris from the mobile attenuator should not penetrate or show potential for penetrating the occupant compartment of the impacting vehicle. In addition, any flying debris should not show potential for impacting other vehicles, pedestrians, or workers. Although testing agencies are required to accurately record and report any debris scatter, there are no established limits by which to judge this aspect for each mobile attenuator on a pass/fail basis. In addition, these details are not a part of the data published by FHWA when an acceptance letter is issued.

There is a concern that retrofitting arrow panels to trailer-mounted attenuators may create a debris hazard for workers if the attenuator were to be struck. Only two trailer-mounted attenuators were impact tested with arrow panels in place: the Safe-Stop SST trailer (*35*) and the Vorteq trailer (*44*). However, there are no specific FHWA test criteria that would address the acceptability of attenuator-mounted arrow panels in the impact testing protocols. In the absence of test criteria, the general assumption would be to check that there is no flying debris from the arrow panel and that the panel remains affixed to the support structure. With truck-mounted attenuators, TxDOT has generally mounted the arrow panel to the truck bed when feasible. Attaching the arrow panel to the support vehicle (i.e., to the tailgate in the case of a dump truck) would provide more predictable results during impacts. Figure 23 shows a post-impact view of an arrow panel mounted in this fashion.

Figure 23. Post-Impact View of Arrow Panel on a Safe-Stop Truck-Mounted Attenuator.

When attached to a trailer-mounted attenuator, the integrity of the arrow panel during an impact is a function of the location of the arrow panel and the structural design of the support used to attach it to the trailer. If the arrow panel cannot be mounted on the truck, the more desirable location on the trailer is near the pintle hook. In this case, the crush zone of the attenuator is located between the arrow panel and the impacting vehicle, and the integrity of the arrow panel support structure is not compromised. Figure 24 demonstrates this concept.

Figure 24. Post-Impact View of Arrow Panel on the TTMA-100 Trailer-Mounted Attenuator.

Summary

When attenuator impacts occur, momentum is conserved and the post-impact velocity of the support vehicle can be defined in terms of the vehicle masses and velocities at the moment of impact. Although the energy-absorbing properties of attenuators may change the rate of deceleration of the impacting vehicle, the post-impact velocities do not change. The data show no clear evidence that occupant impact velocities (OIV) and ridedown accelerations are different for truck-mounted attenuators than they are for trailer-mounted attenuators. The impact test data address post-impact conditions for the occupants of the impacting vehicle, but do not specifically address post-impact conditions for the occupant(s) of the support vehicle. However, support vehicle accelerations will be significantly less than accelerations measured on the impacting vehicle if the support vehicle weighs significantly more than the impacting vehicle.

By computations, the researchers demonstrated that roll-ahead distances could be calculated for various impact scenarios. Simply stated, roll-ahead distance is a function of the masses and velocities of the vehicles involved in the collision. The most effective means of reducing roll-ahead distance is to increase the mass of the support vehicle and ensure that the parking brake is set and the vehicle is in 2^{nd} gear. The support vehicle should have a greater mass than the most likely vehicle that would be expected to collide with the attenuator. Again, this is independent of attenuator type.

An analysis of post-impact trajectories from the available impact data indicates that anti-rotational features may have some benefit during offset impacts, but they do not appear to significantly reduce post-impact yaw during angled impacts. There are not enough impact test data available to determine if intrusions into adjacent lanes are more or less likely to occur with trailer-mounted attenuators than with conventional truck-mounted attenuators.

Finally, the preferred position for mounting arrow panels is on the back of the support truck. Although a few trailer-mounted attenuators have been crash tested with arrow panels mounted at the forward end of the trailer, there are not any FHWA test criteria to address their performance during impact testing. A properly designed support structure is essential to keep the arrow panel attached during a collision, regardless of attenuator type.

CONCLUSIONS

RECOMMENDATIONS

Each attenuator has unique features, including proprietary energy-absorbing technologies, physical characteristics, and maneuverability. Crash performance during impact testing has been well documented and made available for public review. Without conducting further impact testing, the researchers were able to use existing data to make inferences regarding the safety of workers while using different types of attenuators.

Based on the research findings, the researchers recommend that TxDOT develop a specification for the purchase of trailer-mounted attenuators. In addition, TxDOT has the option to add MASH testing protocols to supplement NCHRP Report 350 testing protocols, making either one acceptable. The researchers recommend including Test 3-52 and 3-53 as required testing for all attenuators.

The researchers also recommend that TxDOT continue to require 20,000 ±1000 lb support vehicles for attenuators used on TxDOT projects, regardless of attenuator type. The research indicates that the use of heavier support vehicles reduces roll-ahead distance during a collision. The heavier support vehicles also reduce occupant impact velocity and ridedown acceleration for workers in the support vehicle. Heavier support vehicles provide greater protection for workers located in the support vehicle as well as workers on foot located ahead of the support vehicle. In addition, minimum distances between the support vehicle and the location of workers should be maintained at all times during work operations.

Finally, based on the impact testing results, the researchers found no evidence that trailer-mounted attenuators performed worse than truck-mounted attenuators during angled impacts, such as the worst case of Test 3-53 impacts. The researchers recommend that future research include an in-depth examination of actual field impacts to attenuators in order to determine if the devices perform consistently with the limited amount of FHWA impact testing data.

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