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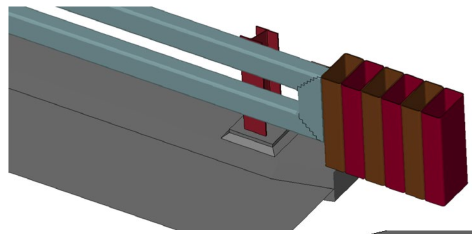

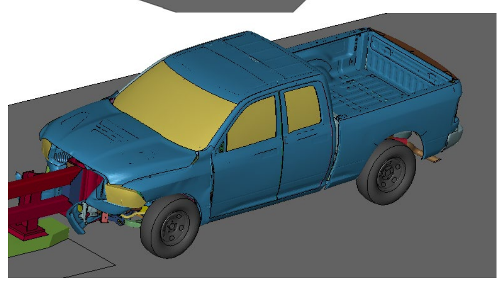

BRIDGE RAIL END TREATMENTS GUIDANCE FOR CONSTRAINED SITES

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16. Abstract

This report provides guidance for the treatment of bridge rail ends on low-speed, low-volume (LSLV) roads at sites with geometric constraints. Based on federal guidelines and supporting research, the installation of end terminals, transitions, or crash cushions is considered risk-beneficial for bridges with posted speed limits above 30 mph. However, conventional systems typically require a minimum installation length of 37.5 feet, which is often impractical in constrained environments.

To address these limitations, the research team collected LSLV-related current practice data from state agencies and conducted a cost-benefit analysis. Using this information, finite element modeling and simulation were employed to develop compact, non-proprietary attenuator designs as short as 36 inches, evaluated under MASH Test Level 1 (TL-1) conditions.

Although full-scale crash testing was not performed, simulation results demonstrated that the proposed designs significantly reduce occupant risk factors compared to blunt-end impacts—particularly in terms of occupant impact velocity and ridedown acceleration.

This report includes design recommendations intended to enhance safety at bridge ends where space and geometry constraints prevent the use of conventional crash-tested end terminals or crash cushions.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units

Chapter 1. INTRODUCTION

1.1. BACKGROUND

Bridge railing ends at constrained sites often face significant challenges in meeting American Association of State Highway and Transportation Officials' (AASHTO's) Manual for Assessing Safety Hardware (MASH) [1] compliance due to site-specific factors such as roadway geometry, steep slopes, adjacent perpendicular driveways, and the presence of sidewalks. These constraints are particularly prevalent in low speed/low volume (LSLV) traffic areas, where traditional transition rails and end treatment systems cannot be feasibly installed. As a result, practitioners are frequently confronted with the difficult decision of either leaving such sites without any protective measures or installing safety products in untested configurations (Figure 1.1). This lack of viable solutions creates a critical gap in safety provisions for these constrained locations, increasing the risk of accidents and compromising roadway safety. Addressing this issue is essential to ensure that adequate safety measures are available for sites where standard crash-tested MASH-compliant systems cannot be installed.

(a) "Do Nothing" approach at short radius turn (b) Bollard end; low-speed parking lot application

Figure 1.1. Examples of Site Constrained Bridge Rail Ends

1.2. OBJECTIVE

This project developed guidance for bridge end attenuation in situations where site-specific constraints—such as low speed, low volume, and challenging roadway geometry—make it difficult to install crashworthy hardware. The primary objective was to design a non-proprietary end treatment suitable for these restrictive conditions. To achieve this, the research team conducted a comprehensive literature review, engaged in outreach to gather current best practices, and performed a risk analysis based on the collected information. Using these insights, an initial design concept was developed and evaluated through finite element (FE) modeling and simulation under MASH Test Level 1 (TL-1) impact conditions. Full-scale crash testing was not included within the scope of this research.

Chapter 2. LITERATURE REVIEW

Bridge end treatments face significant challenges due to various site-specific constraints, including tight roadway geometry, adjacent driveways, steep slopes, and limited right-of-way. These constraints often hinder the installation of MASH compliant transition rails or standard end treatments, particularly in LSLV areas. Existing studies highlight the difficulties practitioners encounter when deciding between leaving such sites unprotected or implementing untested configurations, creating critical safety gaps. This literature review explores existing research on bridge rail end treatment decision flow chart, LSLV volume bridge, and alternative solutions to address these constraints effectively.

2.1. BRIDGE RAIL DESIGN FOR EXTREMELY LOW-VOLUME ROADS [2,3]

US Department of Transportation (US DOT) Published Guide (DOT Guide) [2] and a corresponding report (DOT Report) [3] addressing Bridge Curb/Railing and Approach Treatment for Extremely Low Volume Roads. According to the DOT Guide, extremely low-volume roads are defined as roads with less than 50 vehicles per day (vpd) and posted speed ranges equal to 5-15 mph, 16-30 mph, and 31-45 mph. These roads present unique challenges for bridge rail designs. They often serve agricultural, timber harvesting, and recreational vehicles, necessitating practical and cost-effective solutions tailored to their specific use cases. The Federal Highway Administration's Guide for Bridge Curb/Rail and Approach Treatment emphasizes balancing safety performance goals with the practicality of existing infrastructure. Key considerations include whether existing bridge rails can remain unchanged, the adequacy of associated roadside hardware, and when improvements are warranted. Crashworthy bridge rails are prioritized to reduce the risk of fatal or serious injuries crashes, particularly in scenarios involving passenger vehicles encountering bridge structures. For extremely low-volume bridges, the FHWA guide evaluates factors such as rail height, post spacing, and delineation while accommodating oversized loads common in rural settings. Additionally, it introduces parameters for crash-tested hardware and modified designs like the West Virginia Timber Curb-Type Bridge Rail (WVBR) adapted for lower-strength decks [2]. Through a systematic inspection process and decision matrices, engineers can determine whether existing conditions meet safety goals or require upgrades. This approach ensures that bridge rail systems on these roads align with both safety standards and economic feasibility.

The decision matrix from US DOT Guide [2] provides a workflow to determine practical solutions for reducing the risk of fatal and serious passenger vehicle collisions. Figure 2.1 shows a modified flow chart that was used for this project. The section related to delineation was removed from the original decision matrix, as it is not relevant to the focus of this project, which is to examine the effect of the bridge rail end on fatal and serious injuries resulting from crashes.

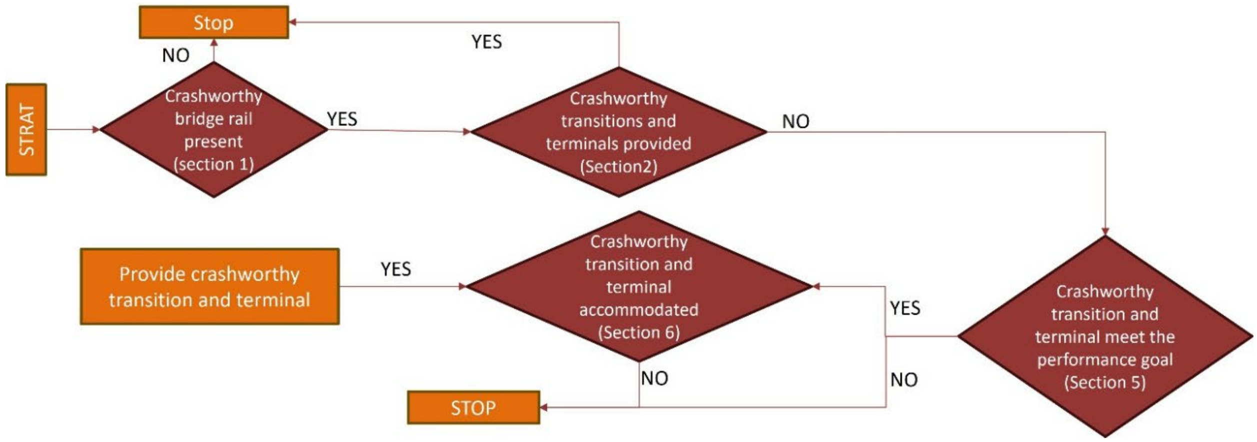


Figure 2.1. Determine Practical Solutions for Reducing the Risk of Fatal and Serious Passenger, Modified Flow Chart [2]

For end treatments, if the posted speed limit is 30 mph or less and the rail is terminated at a post-and-rail system, the installation of new terminals and transitions is generally not considered risk-beneficial, and further analysis is not required. However, if the posted speed limit is greater than 30 mph, the use of crashworthy terminals and transitions is considered risk beneficial and should be evaluated further before proceeding to other design considerations [3].

The crash-tested bridge rail terminal designs are categorized into three types as shown in Figure 2.2, each evaluated under NCHRP Report 350 Test Level 2 (TL-2) standards, as outlined in the DOT Guide [2]. First, the Vermont G1-d W-beam Terminal uses a W-beam rail with steel blocks and steel posts, Figure 2.2(a). It features a W-beam radius end equipped with a buffer. This design features a curved terminal with a radius of 15.75 feet and is typically installed in a tangent configuration. Although the exact length is not specified, such designs commonly require a minimum length of approximately 37.5 feet. Second, the NETC-MELT Guardrail End Terminal consists of a W-beam rail with wood blocks and wood posts, Figure 2.2(b). It incorporates a flared W-beam design with a buffer end and includes a 4-foot flare. Flared terminals generally require more space to accommodate the offset geometry. Based on standard flared configurations, the estimated minimum length is approximately 50 feet. Lastly, The Steel-Backed Timber Guardrail Tangent End Terminal features a timber rail backed by steel plates, with timber blockouts and breakaway posts designed for crash safety as shown in Figure 2.2(c). The steel components are integrated behind the timber to preserve aesthetics while enhancing structural performance. It employs a 90-degree blunt end design. This terminal also follows a tangent layout and requires a minimum length of 37.5 feet for proper installation and performance.

(a) Vermont G1-d W-beam Terminal

(b) NETC-MELT Guardrail End Terminal

(c) Steel Backed Timber Guardrail Tangent End Terminal

Figure 2.2. NCHRP Report 350 TL-2 Compliant Crash-Tested Bridge Rail Terminal

DOT Report [3] evaluates the crash severity associated with approach terminals, transitions, and unshielded bridge rail ends on extremely low-volume roads. As shown in Table 2.1, at lower speeds (5–15 mph), all configurations, including unshielded ends, indicate minimal crash severity. However, as speed increases, crash severity rises significantly, especially for unshielded bridge ends.

As shown in Table 2.1 and Table 2.2, if the posted speed limit is 30 mph or less and the bridge rail system is a post-and-rail type with the rail terminated at a post, installing new terminals and/or transitions is generally not risk beneficial. In this case, no further analysis is needed before proceeding with the delineation decision.

In Table 2.2, “NRB” indicates that a terminal or transition is not risk beneficial for the conditions. However, if the posted speed limit is greater than 30 mph, installing terminals and transitions is risk-beneficial. In this case, these terminals and transitions need to be installed, followed by delineation decisions.

Table 2.1. Crash Severity Proportions for Terminals, Transitions, and Unshielded Bridge Rail Ends at Various Post Speed Limits [3]

Posted Speed Limit (mph)	$KA_{EXPOSED\ END}$	KA_{TERM}	KA_{TRANS}
5 - 15	0.0000	0.0006	0.0000
16 - 30	0.0000	0.0049	0.0000
31 - 45	0.0218	0.0166	0.0024
65	0.0656	0.0500	0.0071

KA_{TERM}: Severity values for terminals crashes;
$KA_{EXPOSED\ END}$: Unshielded;
KA_{TRANS}: Transitions

Table 2.2. RRR for Terminals, Transitions, and Unshielded Bridge Ends on Bridges with Posted Speed Limits of 45 mph or Less and 50 vpd or Less [3]

Posted Speed limit(mph)	Terminals	Transition
5 - 30	NRB	NRB
31 - 45	24%	89%

RRR: Relative Risk Reduction
NRB: Not Risk-Beneficial

2.2. VEHICLE SAFETY SYSTEM TEST

The National Highway Traffic and Safety Administration (NHTSA) requires that passenger vehicles meet the requirements of the Federal Motor Vehicle Safety Standards (FMVSS) [4], which include crash tests such as those outlined in FMVSS 208. This standard requires that vehicles demonstrate occupant protection in a 35-mph full frontal crash into a flat, rigid barrier.

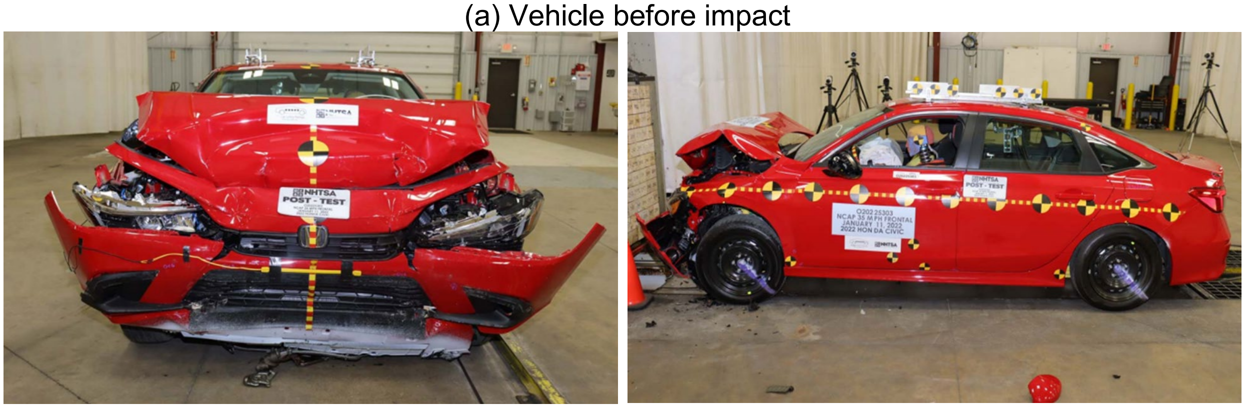
To simulate real-world collisions, NHTSA conducts frontal barrier impact tests at 35 mph using vehicles like the 2022 Honda Civic, 2022 Toyota Tundra, 2023 Acura Integra, and 2023 Chevrolet Colorado. Figure 2.3 shows a frontal crash test using a 2022 Honda Civic conducted by NHTSA, in which the vehicle was impacted at a speed of 35 mph and a 0-degree angle against a flat, rigid barrier. Both vehicle and occupant safety parameters were successfully met.

These tests evaluate crashworthiness and occupant restraint systems. Vehicles meeting NHTSA standards consistently protect occupants, with driver dummies passing all safety criteria. Since NHTSA standards and the modern vehicle safety systems are designed to protect occupants in collisions up to 35 mph, a terminal is generally not required to shield bridge rail ends on roads with posted speed limits of 30 mph or less.

The Insurance Institute for Highway Safety (IIHS) conducts frontal corner impact tests on passenger vehicles at 40 mph and a 30-degree angle [5-7]. As shown in Figure 2.4, IIHS also conducted a test using 2022 Honda Civic, where the vehicle successfully met both vehicle and occupant safety parameters [5].

The AAA Foundation for Traffic Safety and the Insurance Institute for Highway Safety (IIHS) jointly studied how crash severity and injury risk increase with speed. Researchers conducted three frontal crash tests using a 2010 Honda CR-V EX, chosen to represent the average vehicle age on U.S. roads. Each vehicle was crashed into a fixed aluminum honeycomb barrier, with the impact focused on the driver side to simulate a partial-overlap frontal collision at 0-degree impact angle and three different impact speeds: Test 1 – 40 mph; Test 2 – 50 mph; and Test 3 – 55.9 mph.

(a) Vehicle before impact



(b) Vehicle damage after impact

Figure 2.3. NHTSA Frontal Impact Test Using 2022 Honda Civic [4]

Dummy sensors recorded increasing injury measures with speed. While chest injuries remained minimal, head, neck, and lower body injuries worsened as speed increased to 50 mph. Based on the results of this study, it can be concluded that vehicle safety systems can protect the occupant in a collision on roads with posted speed limits of 40 mph or less. However, since IIHS does not require testing all passenger vehicles, for the purposes of this research project, NHSTA's test outcomes will be applied to a bridge rail end treatment guideline, i.e., a bridge rail end treatment is generally not required to shield bridge rail ends on roads with posted speed limits of 30 mph or less.

(a) Vehicle before impact

(b) Vehicle damage after impact

Figure 2.4. IIHS Frontal Corner Impact Test Using 2022 Honda Civic [5]

2.3. RISK OF FIXED-OBJECT CRASHES IN THE UNITED STATES

Research conducted by Virginia Tech shows that road departure collisions were among the most dangerous types of crashes on U.S. highways [8]. In particular, those involving fixed objects, such as trees, utility poles, and guardrails, pose a significant safety concern, accounting for 41% of all traffic fatalities in 2010. Data from the Fatality Analysis Reporting System (FARS) indicates that trees were the most harmful event in 30.8% of roadway departure fatalities between 2016 and 2018. These crashes often occur at relatively low speeds; for instance, in Figure 2.5, the median Delta-V (change in velocity) for serious tree-related injuries was 22.4 mph. The impact conditions in these cases are comparable to those in our project, which involve crashes into terminals or transitions at bridge ends. Virginia Tech did not record impact speed. However, in impacts with rigid objects, delta-V was an excellent surrogate for impact speed. Addressing tree-related crashes should remain a top priority in efforts to reduce fatalities and injuries associated with fixed-object collisions.

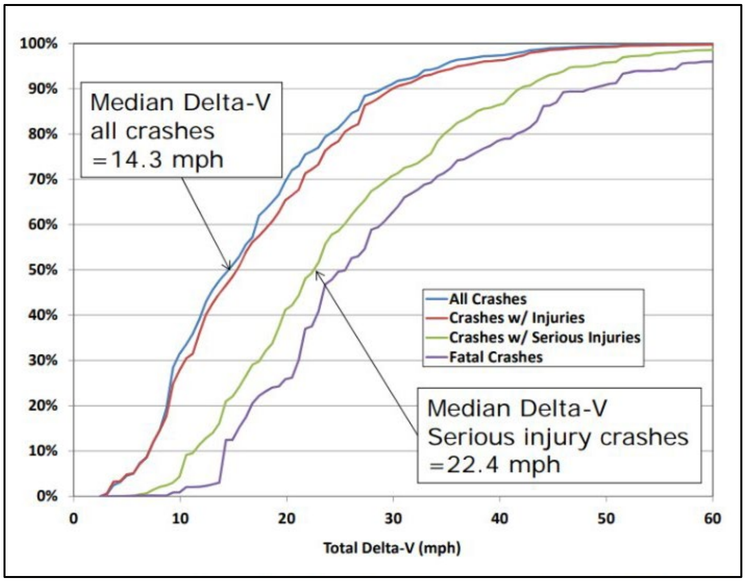


Figure 2.5. Distribution of Total Delta-V in Tree Crashes (NASS-CDS 1997-2008) [7]

Chapter 3. OUTEREACH

To identify and categorize critical factors influencing high-priority situations in a low-speed/low-volume (LSLV) bridge rail end treatment, the research team conducted a survey through a set of questions. The survey was sent to all Roadside Safety Pooled Fund Program members and 19 state agencies provided responses, with some states providing more than one responses, for a total of 27 responses.

3.1. QUESITONNAIRE AND RESPONSES

The survey broadly addressed each state's definition of LSLV bridge, along with the corresponding types and test level of bridge rail ends.

3.1.1. Maximum Speed Limit (or Definition) of a Low-Speed Bridge

Figure 3.1 presents survey results regarding the maximum speed limits used to define low-speed bridges across various states. The most frequently reported range was 40–45 mph, cited by 38% of respondents. Other defined ranges included 45–50 mph (12%), 30–35 mph (8%), and 25–30 mph (4%). Additionally, 38% of responses were categorized as "Other," which encompassed states without an official definition (23%), those applying variable speed limits based on road type (8%), and a small subset identifying low-speed bridges as those with limits either exceeding 65 mph or below 25 mph (4% each).

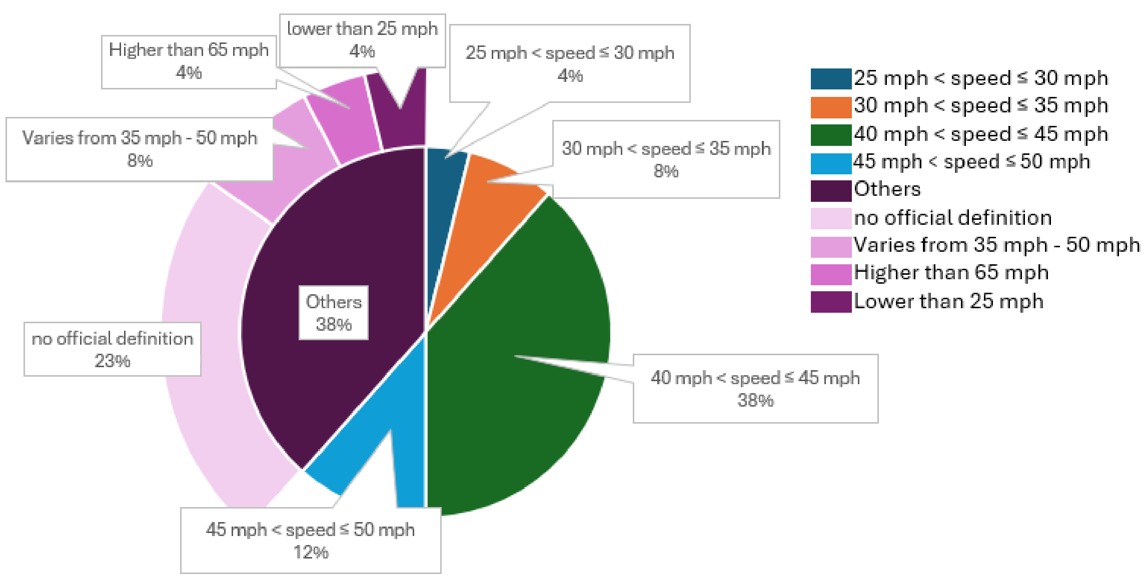


Figure 3.1. Maximum Speed Limits of a Low-Speed Bridge

3.1.2. Definition of a Low-Volume Bridge

Figure 3.2 illustrates the variability in how different states define low-volume bridges, using vehicles per day (VPD) as the primary metric. The most frequently cited threshold was 400 VPD, reported by 35% of respondents. Additional thresholds included 2,000 VPD (18%), and 4% each for 1,000, 500, 200, and 150 VPD. Notably, 31% of responses fell into an “Other” category, which encompassed states without a formal definition (17%), those applying supplementary criteria such as lane count or roadway classification (9%), and a small subset defining low-volume bridges as those carrying 50 or fewer vehicles and 10 or fewer trucks per day (4%).

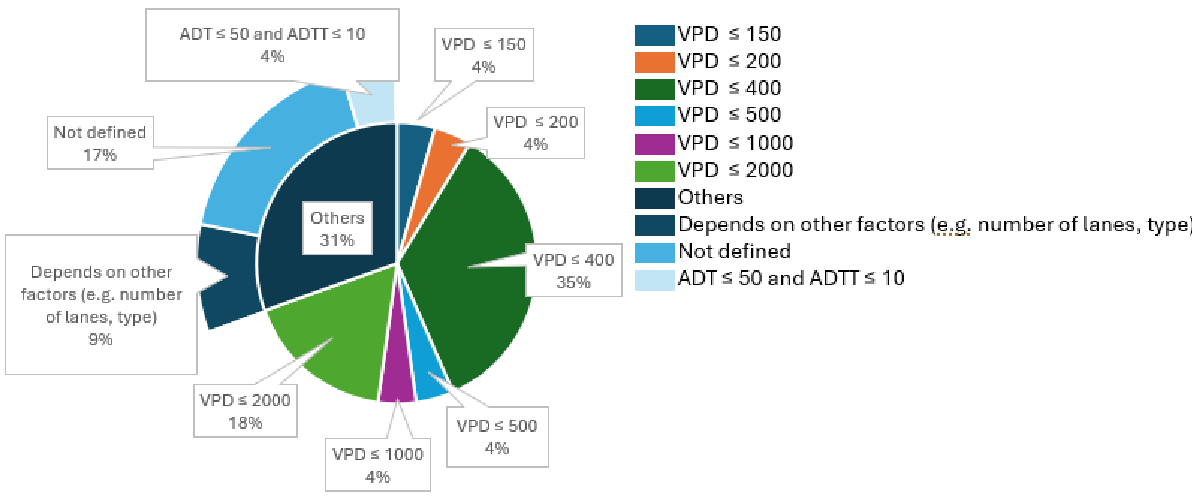


Figure 3.2. Definition of a Low-Volume Bridge in Terms of VPD

3.1.3. Type of Bridge Rail Used on LSLV Bridges

Figure 3.3 summarizes the types of bridge rails utilized on LSLV bridges, based on survey responses that allowed multiple selections. Concrete rails appeared as the most commonly used bridge rail type, cited by 72% of respondents, followed by steel rails at 48%, and wood rails at 16%. A small portion (4%) reported using none of these rail types. Additionally, 32% of responses fell under the “Other” category, which included various comments. Several respondents noted the frequent use of thrie-beam rails, particularly on older or remote low-volume bridges where timber structures remain prevalent. Some respondents noted that regardless of traffic speed or volume, concrete and steel rails are generally preferred for new installations. It was also noted that the Colorado Department of Transportation (CDOT) does not currently maintain MASH TL-1 or TL-2 bridge rail standards; instead, TL-4 rails are mandated for new bridge construction. In California, TL-2 combination rails—such as solid concrete barriers or post-and-beam—may be employed. Timber bridge construction is typically limited to local roads not maintained by the Michigan Department of Transportation (MDOT), and often incorporates wood railings.

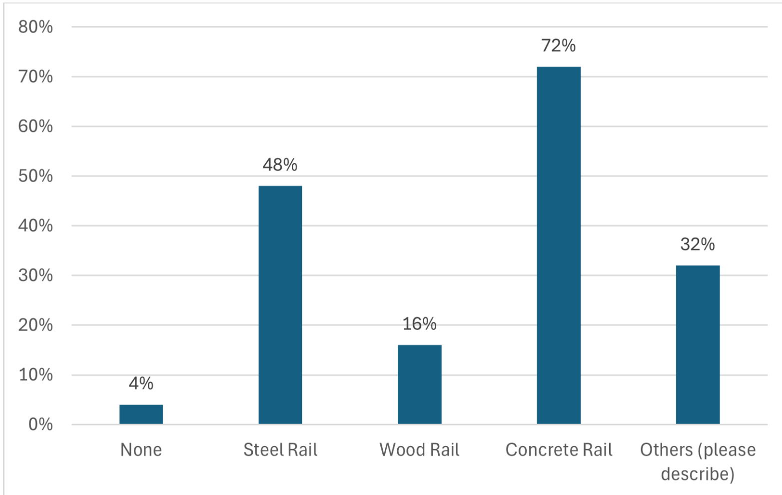


Figure 3.3. Type of Bridge Rail Used on a LSLV Bridges

3.1.4. Test Standard and Test Level Used for Testing LSLV Bridge Rail

Figure 3.4 presents survey findings on the testing standards applied to LSLV bridge rails, based on a multiple-choice question. NCHRP Report 350 emerged as the most commonly referenced standard, selected by 63% of respondents. MASH testing was reported by 33%, while 8% indicated that their bridge rail systems had not evaluated by any formal testing. The 29% of respondents selected “Other” category, which included references to PL-1 standards. Several respondents noted that all new or retrofit bridge installations are required to meet MASH criteria. Additionally, Tennessee Department of Transportation (TDOT) does not use MASH guidelines to evaluate the bridge rails, with TL-2 barriers deemed acceptable for roadways with posted speeds of 45 mph and average daily traffic volumes exceeding 2,000 vehicles.

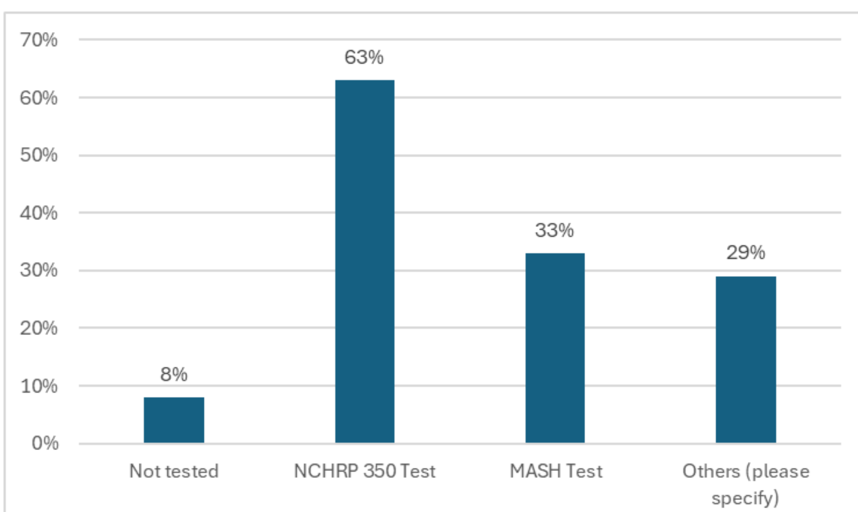


Figure 3.4. Test Standard Used for Testing LSLV Bridge Rail

Following the previous question, Figure 3.5 summarizes survey responses regarding the test levels applied to LSLV bridge rail systems. Respondents were allowed to select multiple options. Test Level 2 (TL-2) was the most frequently cited standard, selected by 67% of participants. TL-3 was reported by 42%, while TL-4 accounted for 38% of responses. A smaller portion of respondents indicated the use of TL-1 (8%), and 4% reported that their bridge rails had not undergone any formal testing.

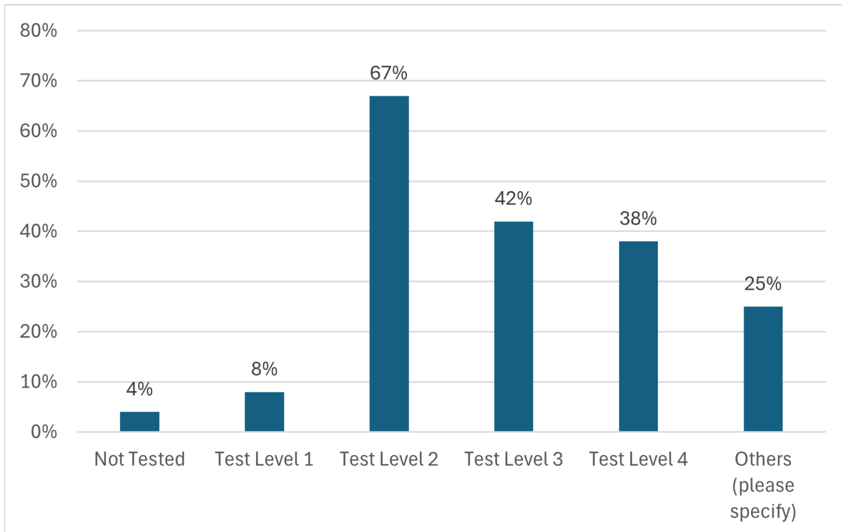


Figure 3.5. Test Level Used for Testing LSLV Bridge Rail

3.1.5. Bridge Rail End Treatment Devices Used for LSLV Bridges

Figure 3.6 displays survey responses regarding the types of bridge rail end treatment devices used on LSLV bridges. Respondents were allowed to select multiple options. Proprietary devices were reported by 75% of participants, while 54% indicated the use of non-proprietary devices, and 17% stated that no end treatment devices were employed. Among those utilizing proprietary systems, 46% reported the use of crash cushions, 43% employed terminals, and 11% referenced alternative device types – such as modified transition rails or approach guardrail transition (AGT).

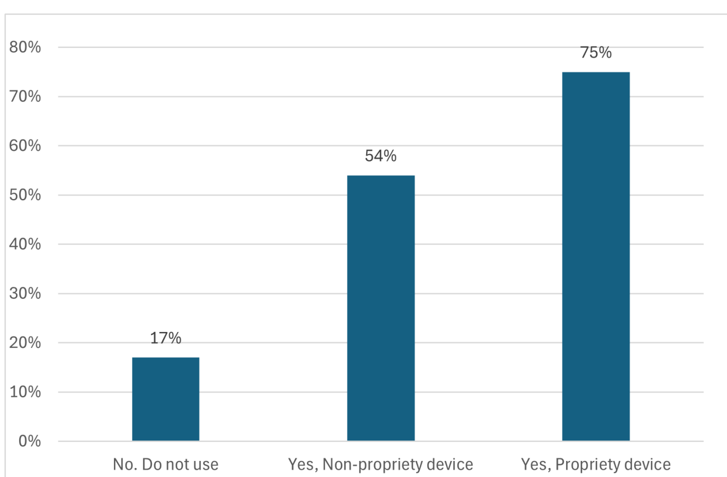


Figure 3.6. Bridge Rail End Treatment Devices Used for LSLV Bridges

3.1.6. Test Standard Used for Testing Bridge End Treatment Devices

Figure 3.7 shows survey responses regarding the testing standards applied to non-proprietary bridge rail end treatment devices. Respondents were allowed to select multiple options. A majority (60%) reported using devices evaluated under MASH standards, while 35% indicated the use of alternative testing protocols. Additionally, 20% of respondents stated that their devices had not been tested, and 15% referenced testing through NCHRP Report 350 standards.

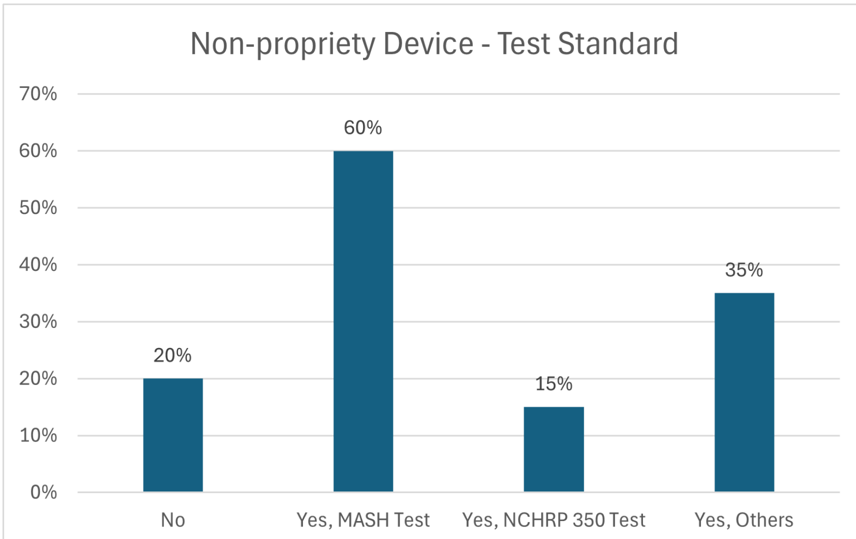


Figure 3.7 Non-Propriety Device-Test Standard

Following the discussion on testing standards for non-proprietary devices, Figure 3.8 presents survey data on the test levels applied to bridge rail end treatments. Respondents were allowed to select multiple options. Test Level 3 (TL-3) was the most frequently reported, accounting for 65% of responses. TL-2 was the second most common, selected by 35% of participants. Both the “Not Tested” and “Others (please specify)” categories were each cited by 15% of respondents. TL-4 had the lowest adoption rate, reported by 5% of participants.

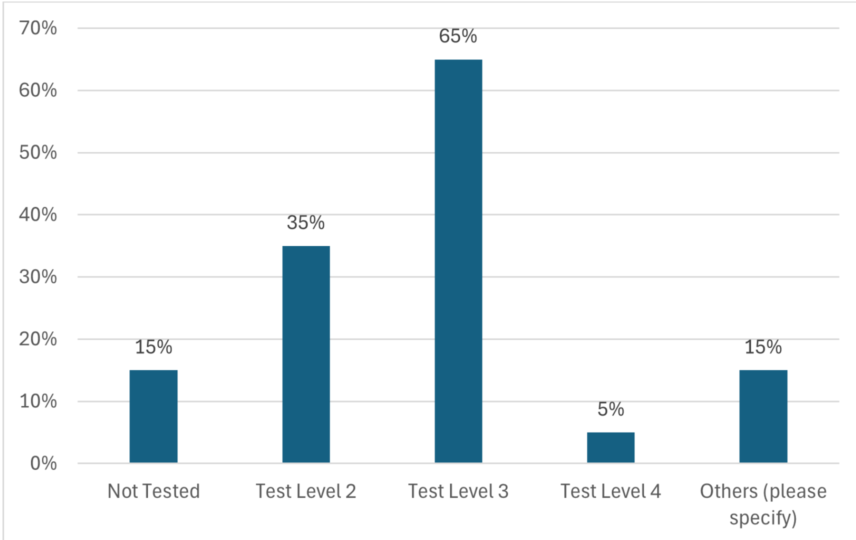


Figure 3.8. Test Level for the End Treatment Devices

3.1.7. Site Constraints

Survey respondents were asked to rank site-specific constraints that limit the effectiveness or feasibility of installing bridge rail end treatment devices on LSLV bridges. A prioritization scale from 1 (highest priority) to 5 (lowest priority) was employed. Constraints related to curved roadways with tight radii were identified as the most critical, followed by right-of-way limitations. Clear zone or horizontal clearance restrictions were ranked third, while steep terrain gradients were placed fourth. Proximity to adjacent infrastructure — such as facilities, parking areas, or other roadside features — was ranked fifth. Miscellaneous site-related challenges, grouped under the "Other" category, were ranked sixth and included factors such as driveways, intersections, existing rail compatibility, curved approach alignments, nearby streets, and budgetary limitations. Design-related considerations, particularly aesthetic constraints that hinder the integration of crash cushions or terminals, received the lowest priority ranking.

Table 3.1. Site Constraints Limiting Rail End Treatment Devices

Rank	Site constraints
1	Curved roadway- short radius
2	Right of way
3	Clear zone/ horizontal clearance
4	Steep slopes
5	Proximity to facility/parking/feature
6	Others 1 (please specify)
7	Aesthetic features make it hard to attach a crash cushion or terminal

3.2. SURVEY CONCLUSION

This chapter presents results of the survey conducted on bridge rail end treatments for LSLV bridges. Most states define low-speed bridges as those with speed limits between 40–45 mph and low-volume bridges as those with fewer than 400 vehicles per day. On most LSLV bridges, concrete and steel rails are commonly used, and proprietary end treatments are widely used. The bridge rails and end treatments were tested based on NCHRP Report 350 and MASH, and with the most common test level being TL-2. Key constraints to installing end treatments included tight curves, limited right-of-way, and steep slopes. Results of this survey guided the research team in the selection of bridge and bridge rail types for the design task.

Chapter 4. ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP) ANALYSIS

This chapter presents a benefit-cost evaluation using the Roadside Safety Analysis Program (RSAP) [10] to assess the efficiency of implementing a bridge rail end treatment. The analysis incorporates key input variables, including average daily traffic (ADT), traffic speed, and roadway characteristics such as highway classification and terrain type.

4.1. RSAP

RSAP is an encroachment-based software tool designed to evaluate the cost-effectiveness of roadside safety improvements. It uses a structured analytical model to assess roadside safety interventions through four interconnected modules: encroachment analysis, crash prediction, severity estimation, and benefit-cost evaluation. By estimating the frequency of vehicle encroachments, predicting crash likelihood and severity, and comparing the costs of safety improvements against their benefits, RSAP enables transportation engineers to make informed decisions about roadside safety designs. The program is particularly useful for analyzing the feasibility of safety features such as guardrails or crash cushions, ensuring that resources are allocated efficiently to reduce crash risks and improve public safety. RSAP has undergone multiple iterations, with the latest version (RSAPv3) incorporation enhanced algorithms and user-friendly interfaces, making it accessible to transportation agencies and researchers worldwide. Its ability to perform detailed benefit-cost analyses has established RSAP as a critical tool for optimizing roadside safety investments.

4.2. RSAP VARIABLES

In this study, an Alaska LSLV 2-steel tube bridge was selected for analysis. Site specific parameters were provided by the Alaska state agencies, while default RSAP values were used where applicable.

4.2.1. Traffic Information

The Alaska LSLV steel bridge has an ADT for 400 vehicles. A default annual traffic growth rate of 1.0 % was applied.

The default distribution of vehicle types on the roadway was assumed as follows: 60% of small car; 20% of pickup trucks; 14% of light tractor trailers; 6% average tractor trailers; and other vehicle types, such as motorcycles, heavy tractor trailers, etc., were neglected.

The posted speed limit for the roadway was set at 45 mph. Based on outreach data, when defining the low-speed bridge, the speed ranging from 40 to 45 mph was the most widely used posted speed limit. However, since the program does not support the posted speed limit lower than 45 mph, a speed of 45 mph was selected as the representative posted speed limit at the low-speed bridge.

4.2.2. Ground Characteristics

The roadway was classified as Type “U,” an undivided roadway since there is no median barrier on the bridge, and the flat terrain type was selected, which represented as “F.”

4.2.3. Percent of Traffic in Primary Direction

The RSAP default values were used for the proportion of traffic traveling in the primary direction, which is set at 50%. The value assumes an even distribution of ADT across both directions of an undivided roadway.

4.2.4. Percentage of Traffic Encroaching Right

The RSAP default value of 50% was also applied for the percentage of traffic encroaching to the right. This parameter should be within a range of 0% to 100%. A value of 0% means all encroachments occur on the left side of the roadway, while 100% indicates all encroachments occur on the right. The 50% default reflects an assumed equal distribution of encroachment directions.

4.2.5. User Encroachment Adjustment

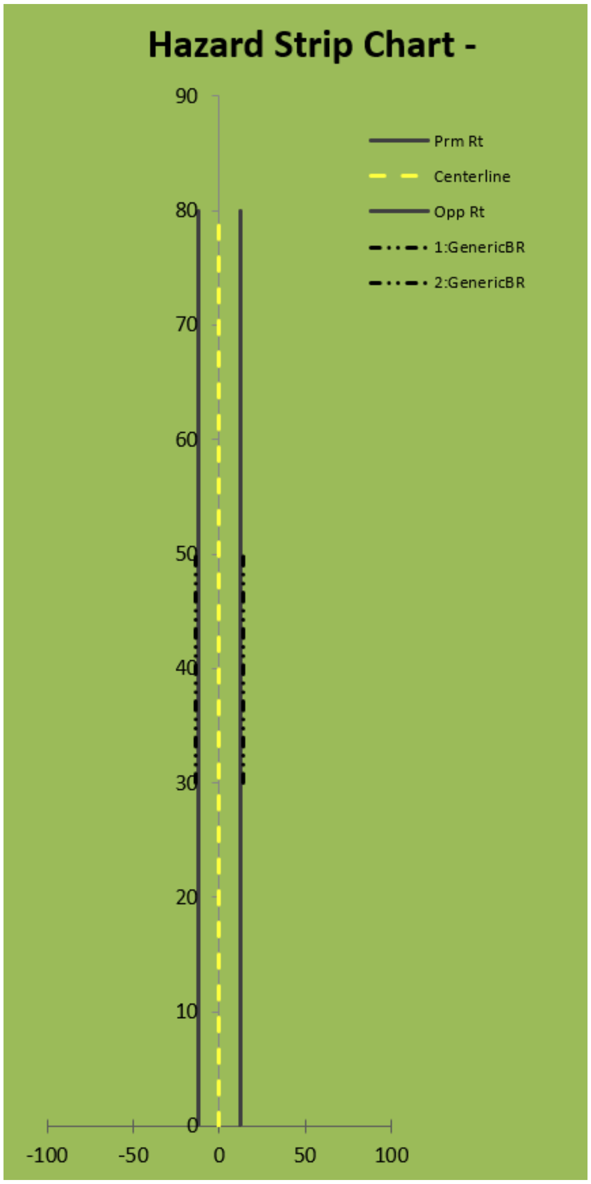
The default adjustment factor of 1 was retained for the User Encroachment Adjustment factor. This factor is a standard parameter in the software and remains unchanged unless adjustments are needed for specific modeling scenarios.

4.2.6. Highway Characteristics

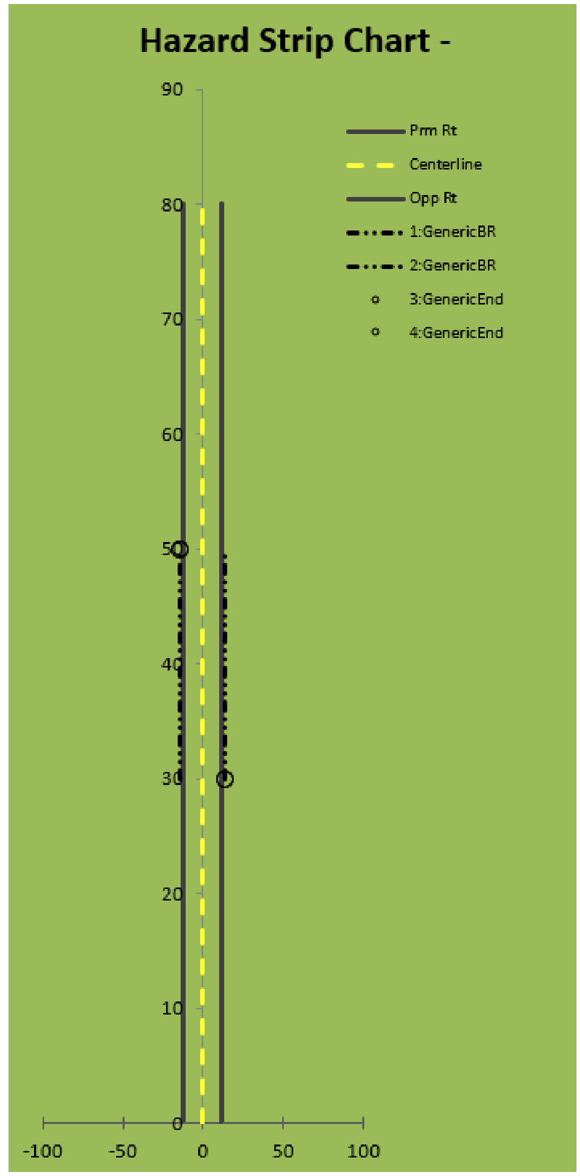
The default RSAP values were used for stationing, access density, and lane configuration. The start station indicates the location where the lane begins, while the end station marks the end of that roadway. For the Alaska bridge and roadway, the length of the bridge was set as 20 ft. Access density is the number of access points in the road. “Lanes total” represents the total number of lanes in both directions of the roadway.

4.2.7. Alternatives

In this research, two alternatives were defined: (a) the one with a 20 ft 2-steel tube bridge rail; and (b) the other with installing a bridge rail end treatment at the end of the same 2-tube bridge rail. Since one of the research objectives is to develop a low-cost and easy maintenance bridge rail end treatment, the estimated construction cost and maintenance costs were defined without a significant cost difference. The costs were estimated and calculated based upon the budgets including labor fees and material costs for existing bridge rails provided by Alaska DOT&PF agency. Figure 4.1 shows the strip chart for both alternatives, which demonstrates the schematic view of the roadways on LSLV bridges and bridge rails. Each lane has 12 ft and 2 ft offsets (shoulder width).



(a) Alternative 1: Do Nothing
(no rail end treatment)



(b) Alternative 2: Adding BRET device
(installing rail end treatment at the bridge rail)

Figure 4.1. Strip Chart for Alternatives from RSAP

4.3. RESULTS AND DISCUSSION

Figure 4.2 shows the RSAP benefit-to-cost analysis result for two alternatives. For the LSLV 2-steel tube bridge rail, RSAP did not provide a result saying one alternative would be beneficial to the other alternative, which means whatever put as Alternative 1 was chosen as the best benefit-cost choice in RSAP as shown in Figure 4.2. This is because RSAP analyzes data by mainly using the crash risk analysis method. In the case used in this study, the program regards such a low volume road with 400 ADT as a road with very low crash possibility, approximately 0.2% of crash probability. In addition, the program is designed to analyze highways rather than low-speed roadways with posted speed limit under 45 mph. Therefore, using RSAP is not recommended for analyzing a low-speed and/or low-volume roadway, since the program would not provide reliable results.

			Decision Point Benefit-Cost Ratio:				1.1
			Alternative Choice				
			1	2			
With Respect to Alternative	Alternative No.	ALTERNATIVE NAMES	Do Nothing	BRET Dvice			
	1	Do Nothing	1.00	0.00			
	2	BRET Dvice		0.00			

Best Benefit-Cost Choice is:	Do Nothing
ADT:	453 vpd
Percent Trucks	20 %

(a) Adding device as Alternative 2

			Decision Point Benefit-Cost Ratio:				1.1
			Alternative Choice				
			1	2			
With Respect to Alternative	Alternative No.	ALTERNATIVE NAMES	BRET Device	do nothing			
	1	BRET Device	1.00	0.00			
	2	do nothing		0.00			

Best Benefit-Cost Choice is:	BRET Device
ADT:	453 vpd
Percent Trucks	20 %

(b) Adding device as Alternative 1

Figure 4.2. RSAP Benefit-to-Cost Analysis Result

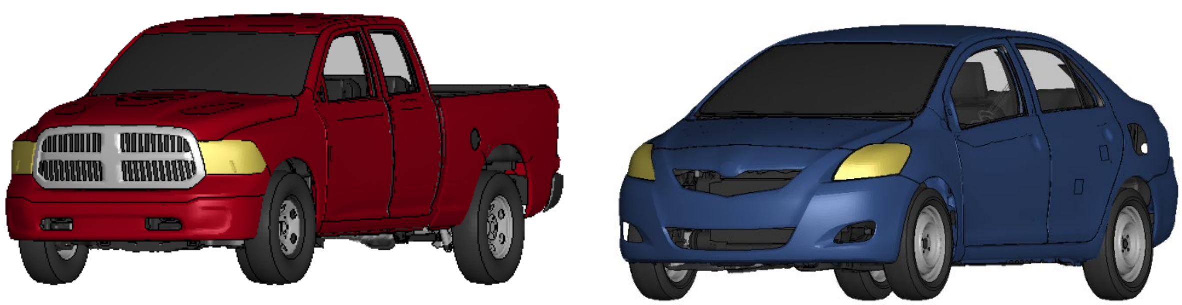
However, as aforementioned in Chapter 1, the RRR value for a posted speed between 31 mph and 45 mph is 24%, even for bridges with a traffic volume of 50 VPD or less. Therefore, the research team recommends adding a bridge rail end treatment to bridges with a posted speed limit greater than 30 mph, as this would be risk beneficial.

Chapter 5. BRIDGE RAIL END TREATMENT DESIGN AND SIMULATION ANALYSIS

This chapter presents the simulation analysis conducted to develop and evaluate the performance of bridge rail end attenuators. Initial design concepts were derived from blunt-end impact simulation results. Considering constructability, ease of maintenance, and stakeholder preferences, specific designs were selected for further investigation. These selected designs were then modeled and evaluated for crashworthiness through vehicle impact simulations. All simulations were performed using LS-DYNA [11], a commercially available finite element (FE) software.

5.1. FINITE ELEMENT MODEL DEVELOPMENT

The research team developed various concepts of bridge end attenuators and evaluated their crashworthiness by developing detailed FE models and performing vehicle impact simulations. For the vehicle impact simulations, the research team used a 2018 Dodge Ram pickup truck model and a 2010 Toyota Yaris small passenger car model [12, 13], which are publicly available and were developed by the Center for Collision Safety and Analysis (CCSA) at George Mason University. These vehicle models have been further improved by TTI researchers over the course of various research projects to achieve greater validation and robustness. Figure 5.1 shows the pickup truck and small passenger car models, which represent the MASH 2700P and 1100C design vehicles, respectively.



(a) 2018 Dodge Ram – MASH 2270P model (b) 2010 Toyota Yaris – MASH 1100C model

Figure 5.1. FE Vehicle Models.

To evaluate an attenuator attached to a bridge rail end, a MASH compliant Alaska 2-tube bridge rail system was modeled and used as an example of a steel bridge rail. The design was selected because it has a narrow blunt end, which was considered to be more critical than some of the other bridge rail designs considered under the project. Key design details of the 2-tube bridge rail system are shown in Figure 5.2 and the bridge rail end details are shown in Figure 5.3. The bridge rail posts were anchored on a 10 inch tall curb with a 4-inch thick overlay of grout, resulting in a 6-inch tall curb profile on the traffic side face. The curb was 18 inches wide at the base, and 17 inches wide at the top, with the traffic side face sloping 1 inch toward the field side. The fabricated steel posts were longitudinally spaced on 10 ft centers, beginning 24 inches from the end of the concrete curb. Two steel rectangular HSS rails spanned the posts and extended past them at each end of the installation. The top of the two rails were located 24 inches and 38 inches above grade.

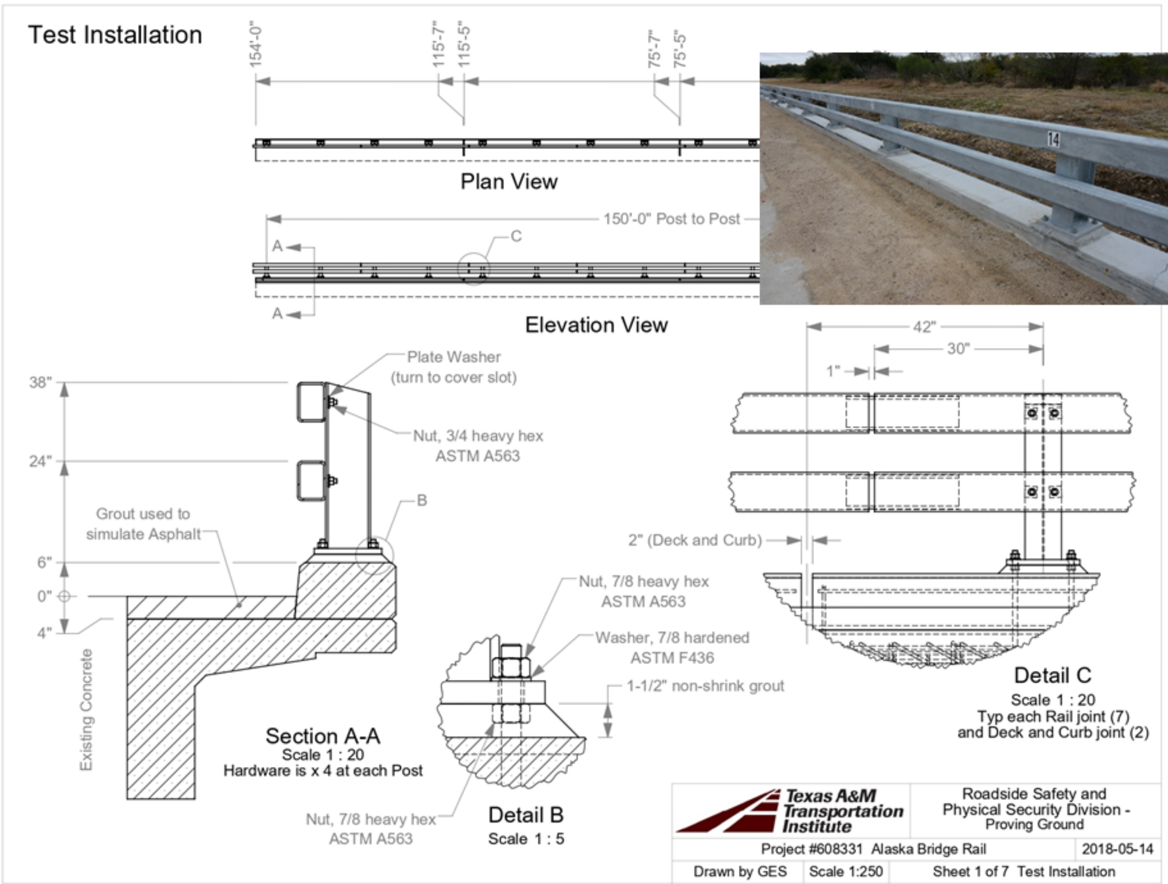


Figure 5.2. Details of Alaska 2-Tube Bridge Rail

At the end of bridge rail, the 2-tube rails were connected with the same size tube as shown in Figure 5.3.

In the FE model of the bridge rail system, the bridge rail and the rail end were modeled as thick shell elements. The model incorporated elastic-plastic steel material representation for the rail parts, which included the HSS tube rails, steel posts, guardrail bolts, etc. The concrete elements and the ground surface were modeled with rigid material representation since movement or deflection of these parts was expected to be insignificant. The FE model of the bridge rail is shown in Figure 5.3.

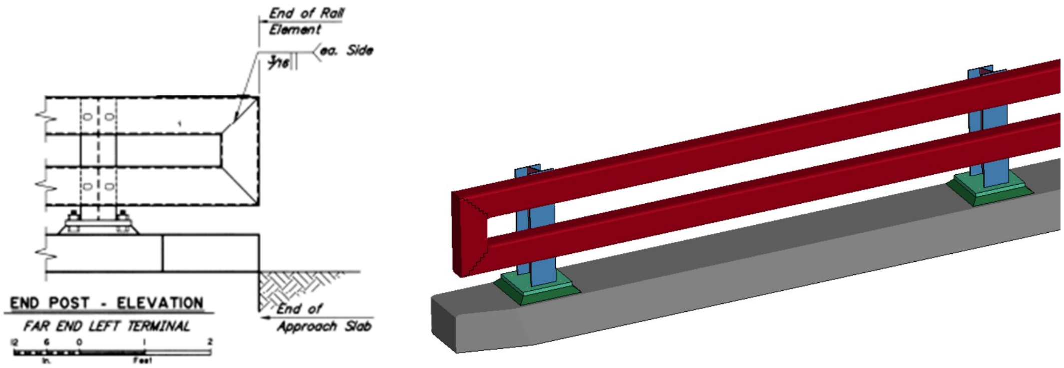


Figure 5.3. Alaska 2-Tube Bridge Rail End Details

5.2. IMPACT CONDITIONS

MASH suggests conducting Tests 30 through 37 for terminal and redirective crash cushion devices. However, in this study, the research team performed only Tests 30, 31, 32, and 33. Figure 5.4 shows the test impact conditions for these tests [1]. Tests 34, 35, 36, and 37, shown in Figure 5.5, were not performed because the attenuator (device) was expected to be short enough to disregard potential for vehicle pocketing that is evaluated through these tests.

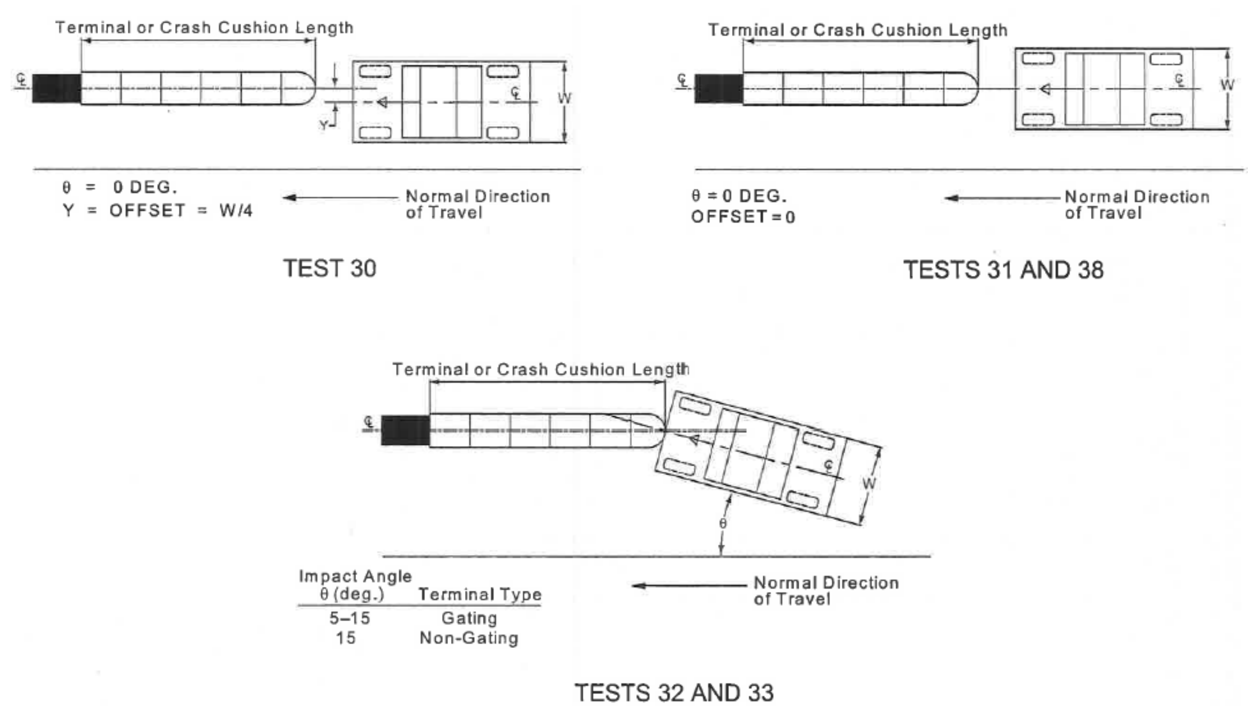


Figure 5.4. Impact conditions for terminal and redirective Crash Cushion Tests [1]

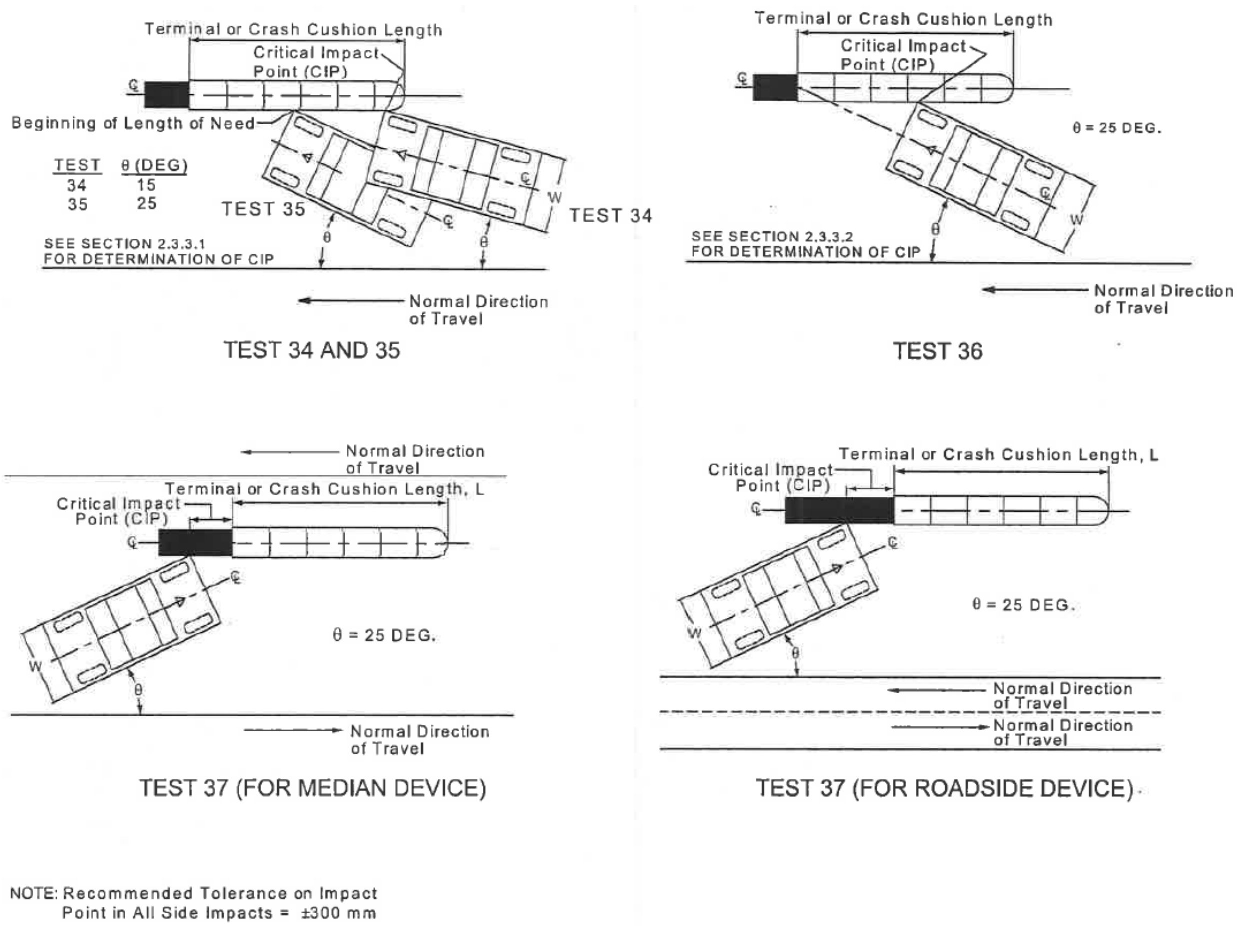
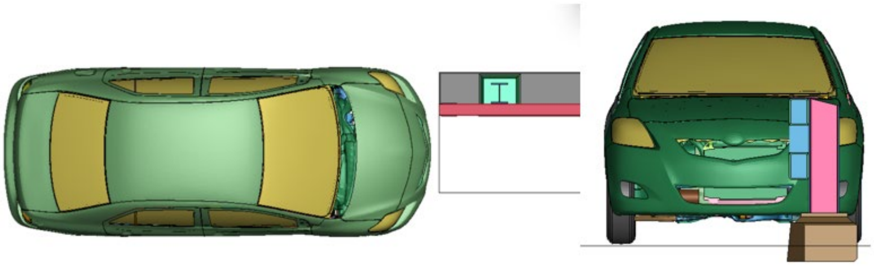


Figure 5.5. Ruled Out Impact Conditions for Terminal and Redirective Crash Cushion Tests [1]

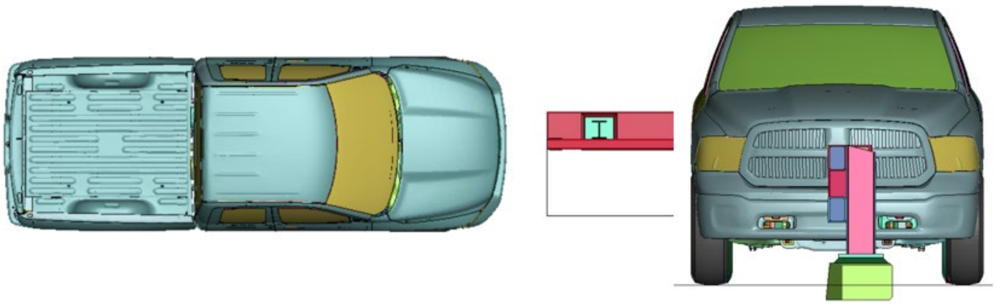
Based on RSAP results and literature review, a bridge rail end treatment for the bridge with the posted speed limit below 30 mph does not provide risk-beneficial outcomes. Terminal systems show RRR of 24% for the road with the posted speed limits between 31 mph and 45 mph. Accordingly, the research team evaluated the attenuator design options at 31 mph, which is impact speed of MASH TL-1.

5.3. BLUNT RAIL END IMPACT SEVERITY UNDER LOW-SPEED

To compare the impact severity, the blunt end impact simulations were performed under MASH Tests 1-30 and 1-31 impact conditions. These involved impacting the bridge rail end with a 2,420-lb small car (Test 30) and a 5,000-lb pickup truck (Test 31) at an impact speed and angle of 31 mi/h and 0 degrees, respectively. The impact on the centerline of the bridge rail end is aligned with the quarter point of the small car and the center of the pickup truck in accordance with MASH requirements (Figure 5.4). Figure 5.6 shows the initial setup for each impact simulation.



(a) Small Car Setup (Test 30)



(b) Pickup Truck (Test 31)

Figure 5.6. Simulation Setup for Blunt End Impact

Figure 5.7 and Figure 5.8 show sequential images for MASH Test 1-30 and Test 1-31 impact simulations, respectively. The bridge rail without a treatment (blunt end) was able to stop both vehicles, but the occupant impact velocities (OIVs) were 44.6 ft/sec and 51.5 ft/sec for the small car and the pickup, respectively, which were higher than the MASH limit of 40 ft/sec. Table 5.1 lists the key occupant risk factors calculated using method described in MASH. The high OIV means that when the vehicle crashes into the blunt end of a bridge rail with an impact speed of 31 mph (or higher), the blunt end may pose a high risk of injury to occupants due to the speed at which they contact the interior surfaces of the vehicle.

Table 5.1. Occupant Risk Factors for Blunt End Impacts

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	44.6	51.5
	Y	5.8	0.5
Ridedown Acceleration (g)	X	9.7	3.0
	Y	7.7	2.4
Max. Angle (degrees)	Roll	4.6	3.2
	Pitch	3.1	3.7
	Yaw	34.7	0.3

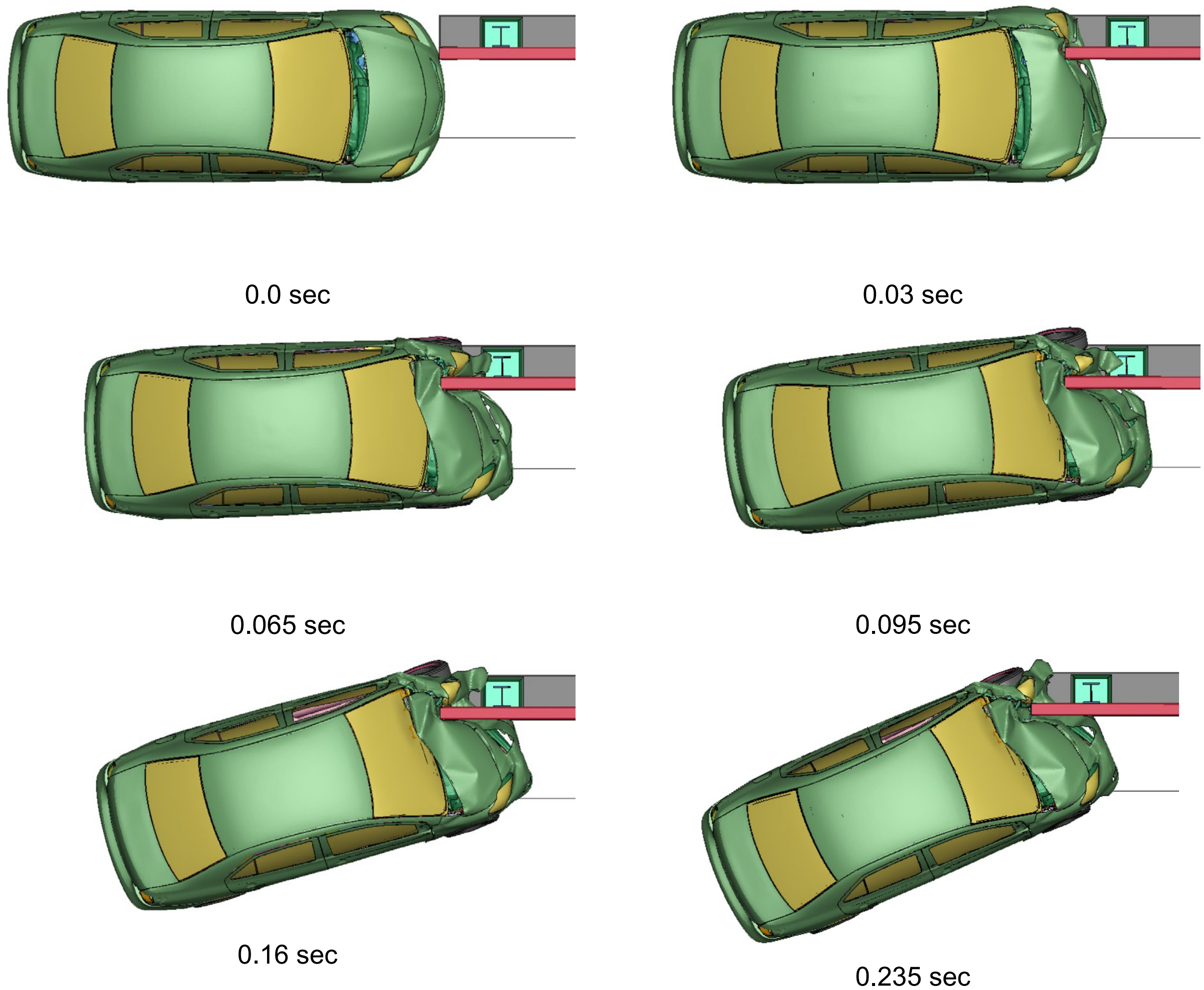


Figure 5.7. Sequential Images Impacting Bridge Rail Blunt End with Small Car

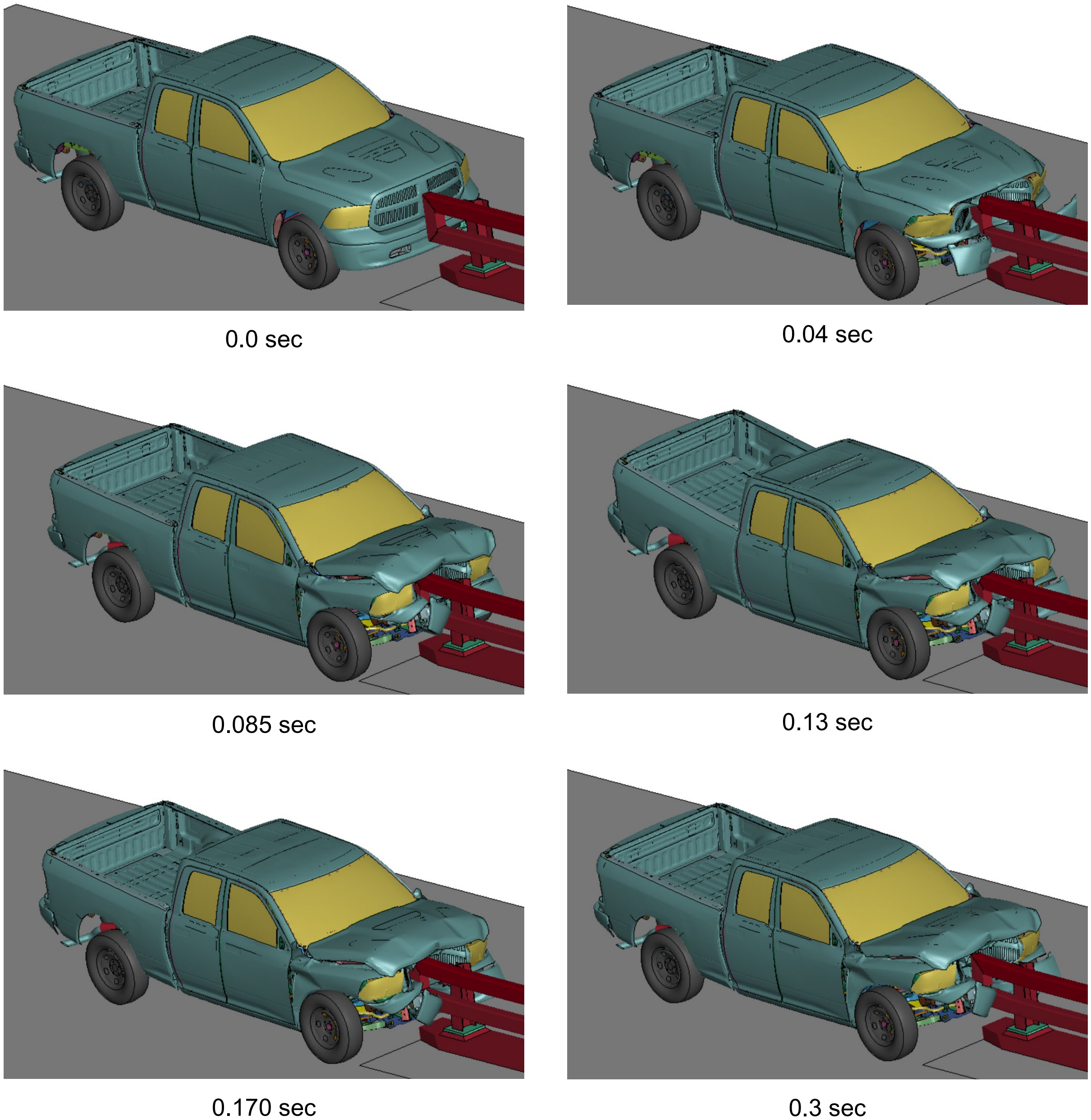


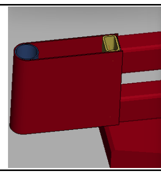
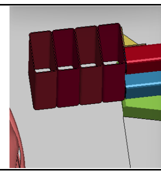
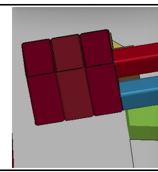
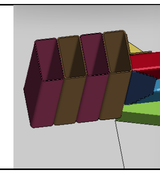
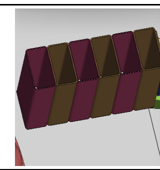
Figure 5.8. Sequential Images Impacting Bridge Rail Blunt End with Pickup Truck

5.4. ATTENUATOR DESIGN OPTIONS

To reduce the occupant risk factors, the research team developed several design concepts of the attenuators. The concepts were developed to be directly attached to the rail end and were kept as simple as possible to minimize the construction and maintenance cost.

Five design options were evaluated using FE impact simulations with MASH TL-1 impact conditions described earlier. Table 5.2 provides key features for each design option. Option 1 utilizes HSS pipes and a steel plate to provide an empty space to reduce some impact energy. Options 2 through 5 use rectangular HSS tubes that crush like an accordion to absorb the impact energy of the vehicle. Adjacent tubes were welded to each other.

Table 5.2. Attenuator Design Options

Attenuator Options	Option1	Option 2	Option 3	Option 4	Option 4-1
Model					
Key Features	HSS Pipes and plate 16 in. long	Four rectangular 12”x6”x3/16” HSS 24 in. long	Three rectangular 12”x8”x3/16” HSS 24 in. long	Four rectangular 12”x6” HSS with different thickness 24 in. long	Six rectangular 12”x6” HSS with different thickness 36 in. long

5.4.1. Option 1 - HSS Pipes and Plate

Figure 5.9 provides the details of the design Option 1 concept. An HSS pipe was located at the front end of the attenuator and a steel plate was wrapped around the pipe and connected to a rectangular HSS tube (5 in. x 3 in. x 0.375 in.). The HSS tube was connected to bridge rail end using anchor bolts.

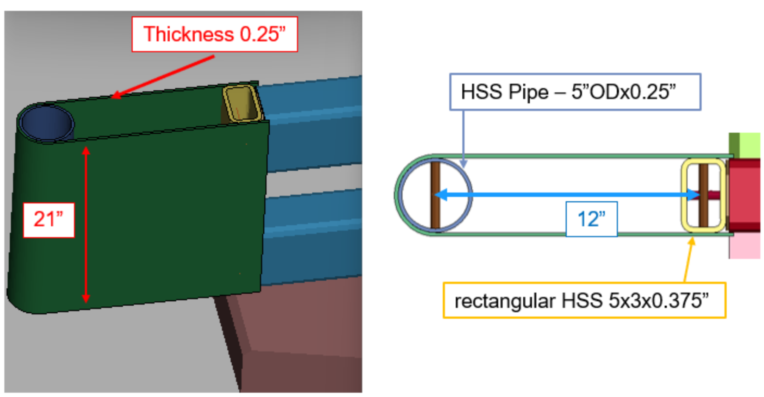


Figure 5.9. Option 1 - HSS Pipes and Plate Concept

Figure 5.10 and Figure 5.11 show sequential images for MASH Test 1-30 and Test 1-31 impact simulations, respectively. The bridge rail with attenuator Option 1 was able to contain and stop both vehicles. The OIV for the small car was reduced to 38.4 ft/sec. The OIV for the pickup truck impact was 44.8 ft/sec, which exceeded the MASH limit. Table 5.3 lists the key occupant risk factors. In the pickup truck impact, the attenuator bent toward the field side, which reduced the energy absorption of the attenuator design.

Figure 5.10. Sequential Images Impacting Attenuator Option 1 with Small Car

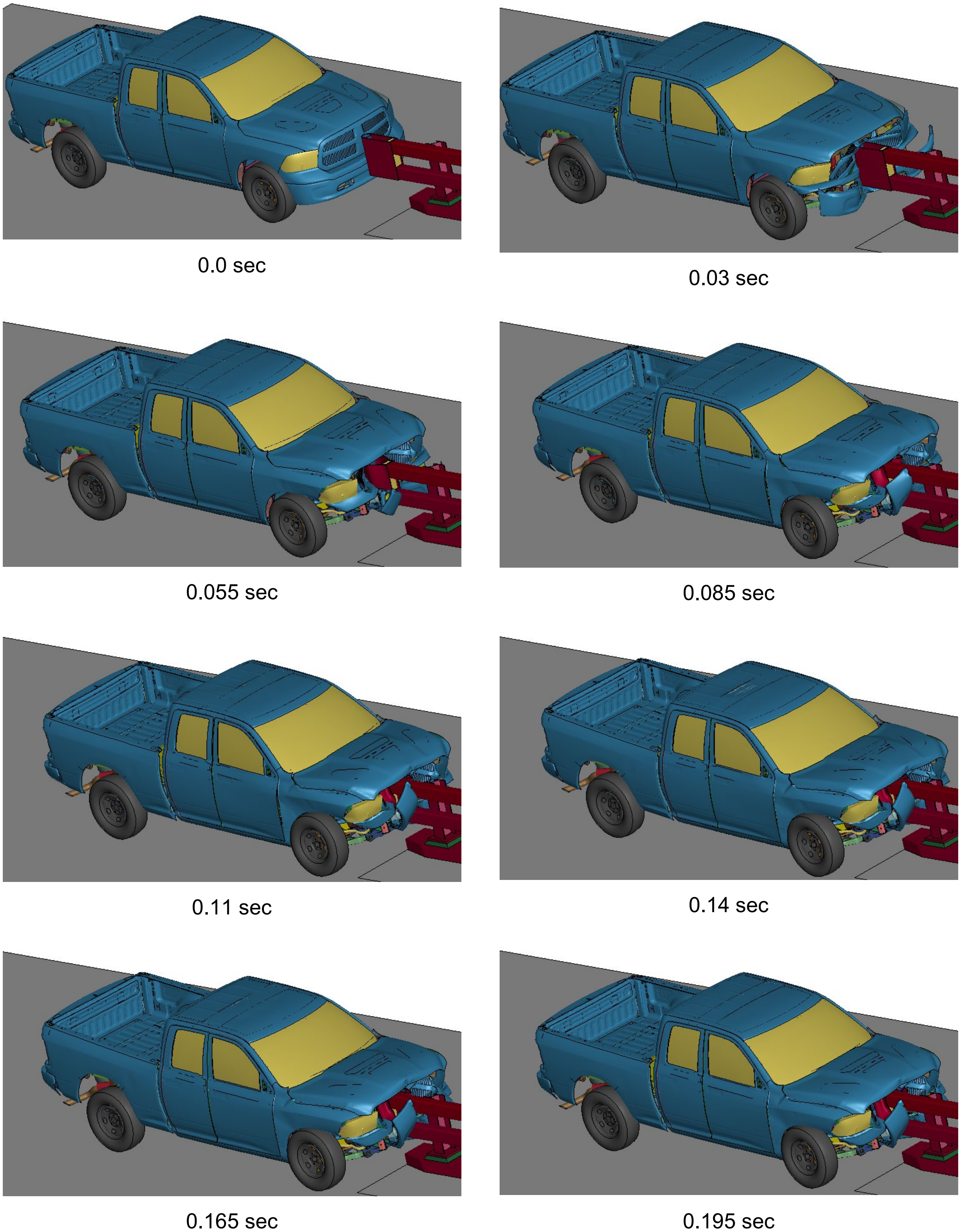


Figure 5.11. Sequential Images Impacting Attenuator Option 1 with Pickup Truck

Table 5.3. Occupant Risk Factors with Option 1

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	38.4	44.8
	Y	7.5	0.7
Ridedown Acceleration (g)	X	13.3	17.7
	Y	4.3	2.0
Max. Angle (degrees)	Roll	5.2	2.3
	Pitch	2.1	1.9
	Yaw	30.6	0.5

5.4.2. Option 2 – Welded four rectangular 12-in. × 6-in. × 3/16-in. HSSs

To overcome the disadvantage of the narrow design of Option 1, Option 2 with a wider design concept, covering more than the rail end was developed. Figure 5.12 shows the details of the Option 2 design concept. To avoid unsymmetric behavior and to absorb energy efficiently, an L-shaped plate and a triangular plate were directly welded on the field side of the bridge rail end (behind the bridge rail). An accordion effect was expected by welding four identical rectangular HSS tubes (12-in. × 6-in. × 3/16-in.) side-by-side, and directly attaching it to the end of the bridge rail.

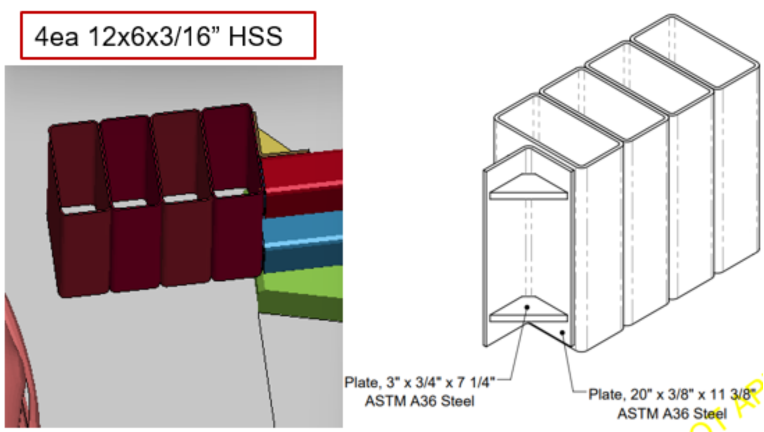


Figure 5.12. Option 2 – Welded Four Rectangular HSSs

Figure 5.13 and Figure 5.14 show sequential images for MASH Test 1-30 and Test 1-31 impact simulations. The attenuator Option 2 was able to contain and stop both vehicles. The OIV for the small car was reduced to 36.1 ft/sec, but the OIV for the pickup truck, 49.4 ft/sec, was still higher than the MASH limit. Table 5.4 lists the key occupant risk factors.

Results showed that stiffer design was needed. Therefore, subsequent design options included more rectangular HSS tubes and/or increased thickness of the HSS tubes.

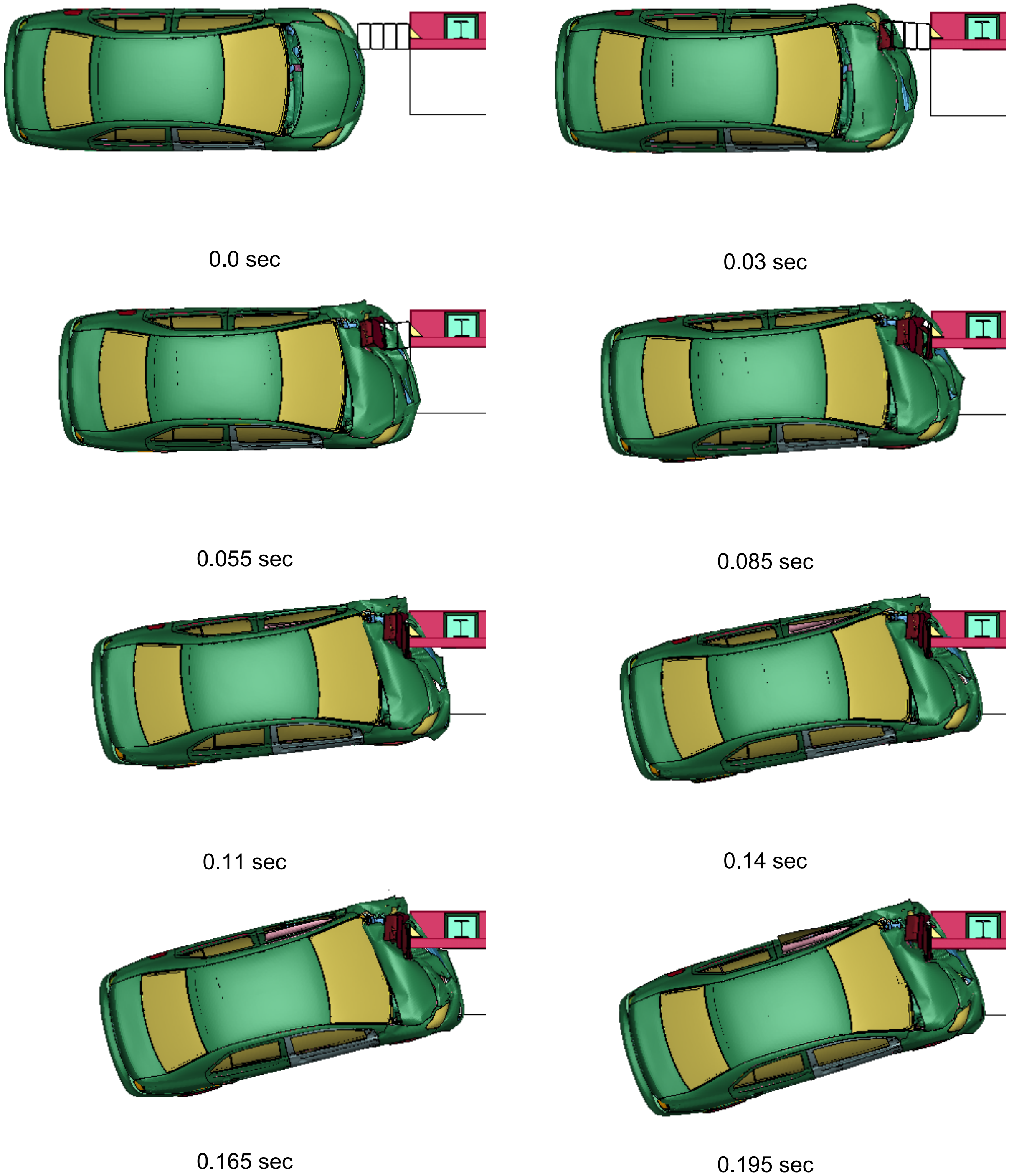
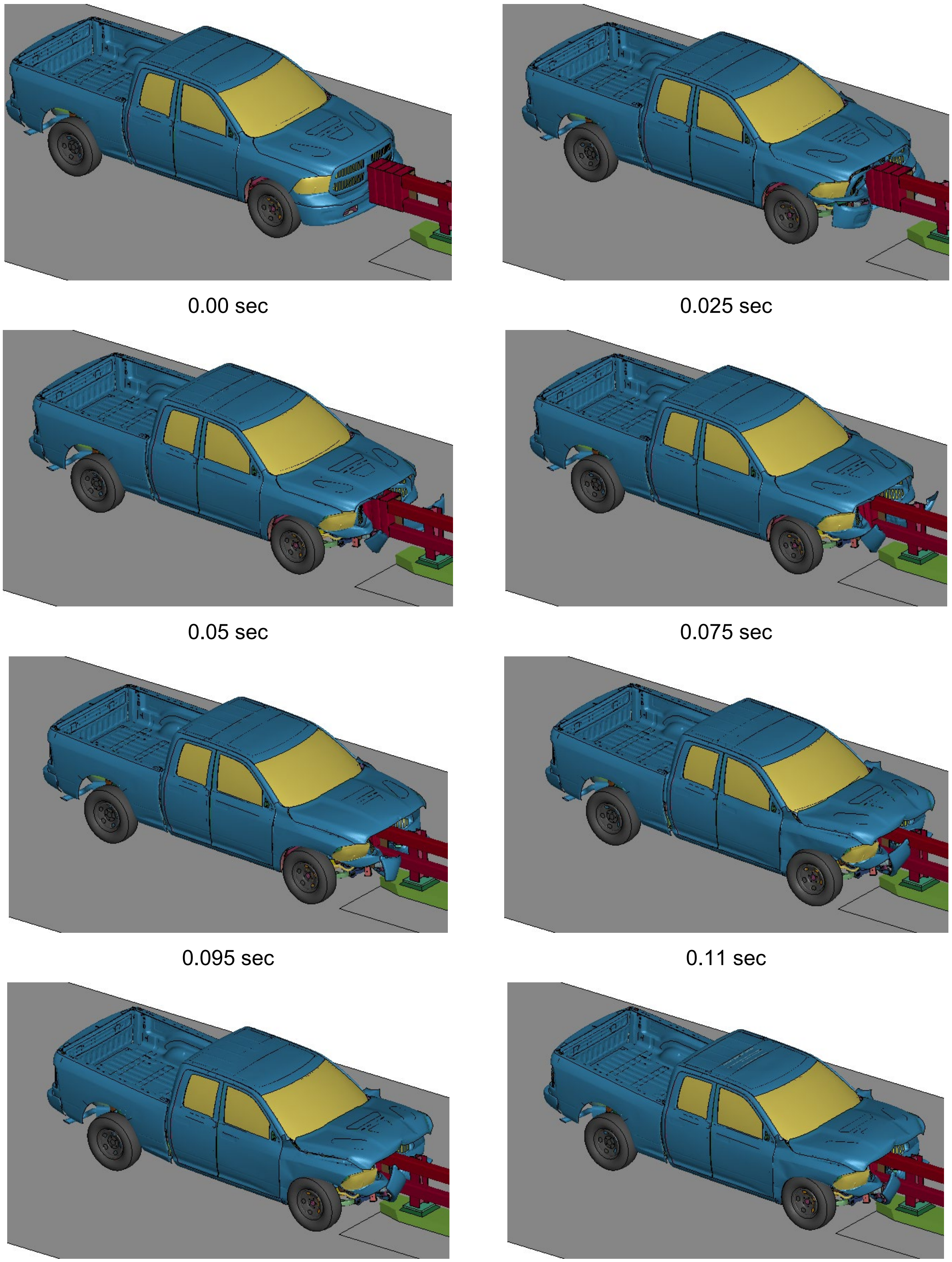


Figure 5.13. Sequential Images Impacting Attenuator Option 2 with Small Car



0.00 sec | 0.025 sec | 0.05 sec | 0.075 sec | 0.095 sec | 0.11 sec | 0.145 sec | 0.17 sec

Figure 5.14. Sequential Images Impacting Attenuator Option 2 with Pickup Truck

Table 5.4. Occupant Risk Factors with Option 2

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	36.1	49.4
	Y	2.0	0.2
Ridedown Acceleration (g)	X	17.7	11.5
	Y	5.7	3.4
Max. Angle (degrees)	Roll	5.9	2.0
	Pitch	3.7	4.2
	Yaw	31.8	1.9

5.4.3. Option 3 – Welded three rectangular 12-in. × 8-in. × 3/16-in. HSSs

Figure 5.15 shows the details of the design Option 3 concept. The number of rectangular HSS sections was reduced to three, while the width of the HSS was increased from 6 in. to 8 in. for the same total length as Option 2. The rectangular sections (12-in. × 8-in. × 3/16-in.) were welded side-by-side and attached directly to the end of the bridge rail.

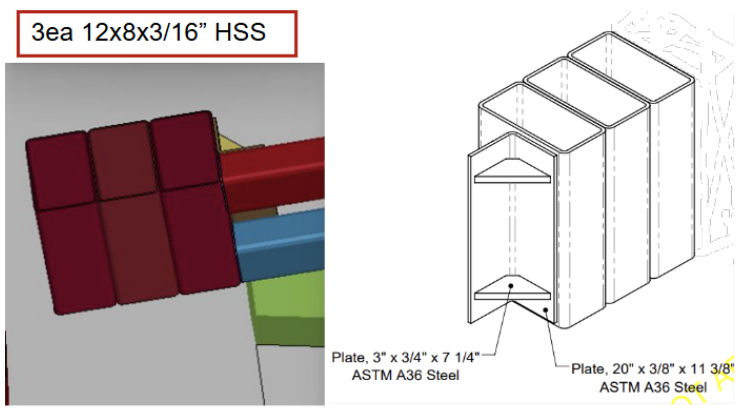


Figure 5.15. Option 3 – Welded Three Rectangular HSSs

Figure 5.16 and Figure 5.17 show sequential images for MASH Test 1-30 and Test 1-31 impact simulations performed with design Option 3. The attenuator was able to contain and stop both vehicles. However, the OIV for both small car (38.4 ft/sec) and pickup truck (48.2 ft/sec) were increased when compared to design Option 2. Table 5.5 lists the key occupant risk factors calculated by using TRAP.

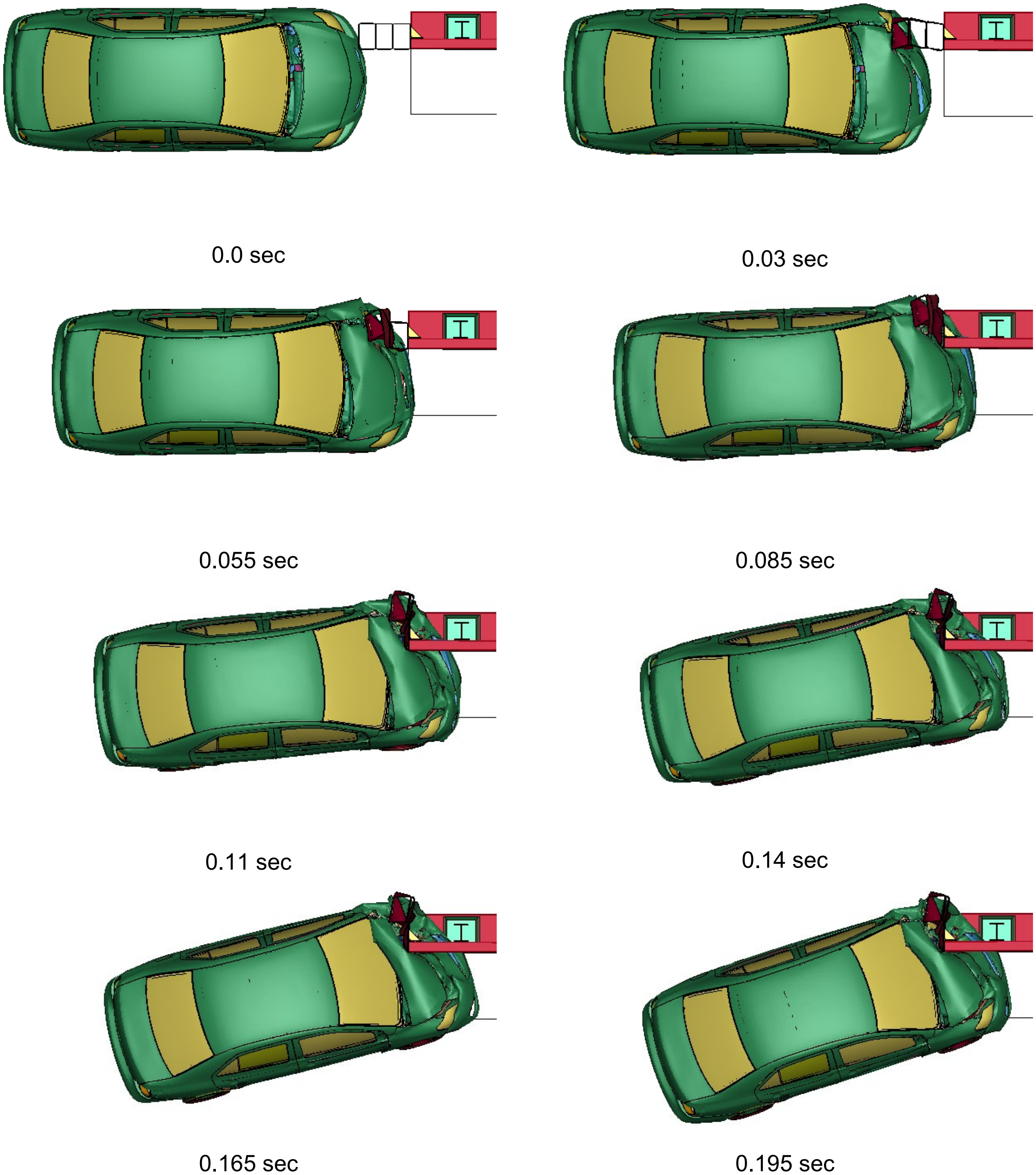
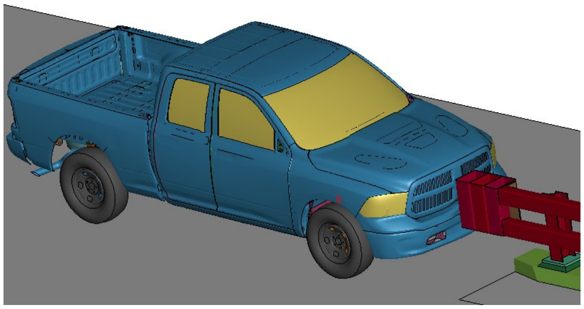


Figure 5.16. Sequential Images Impacting Attenuator Option 3 with Small Car



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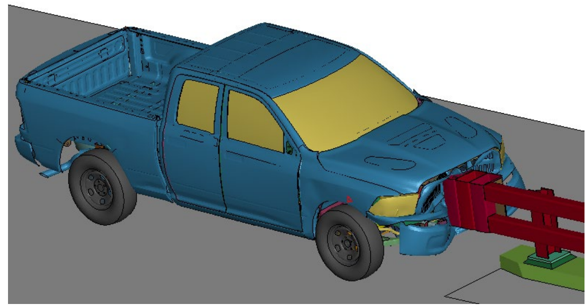

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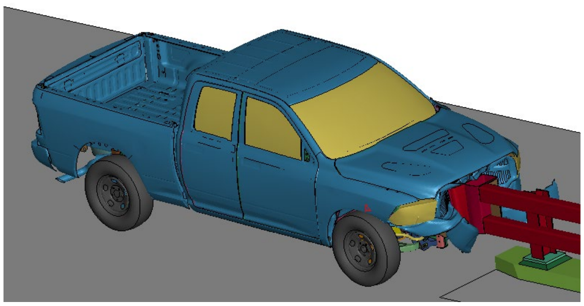

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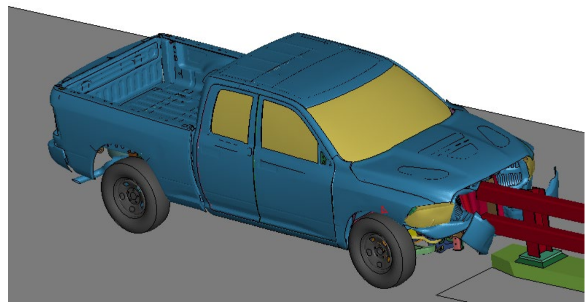

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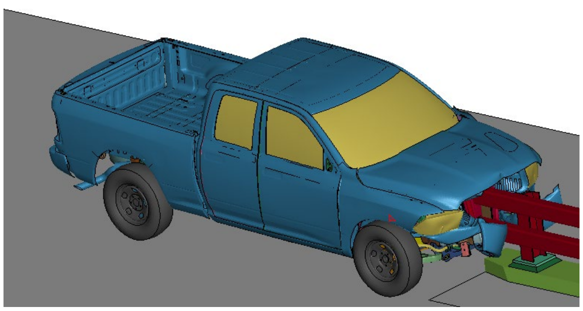

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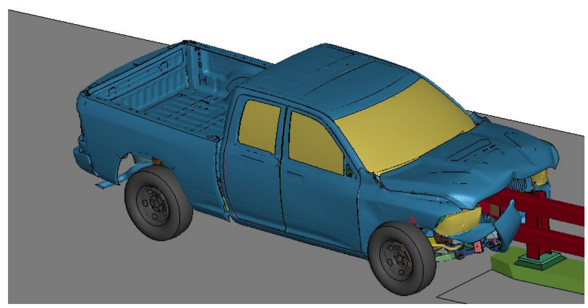

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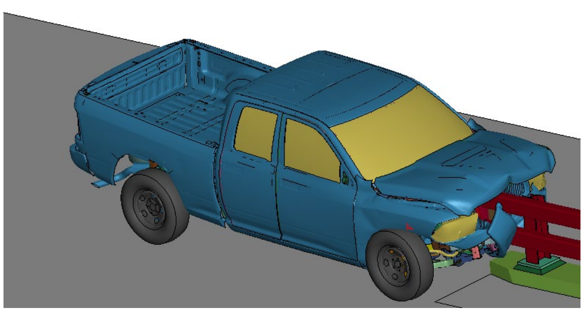

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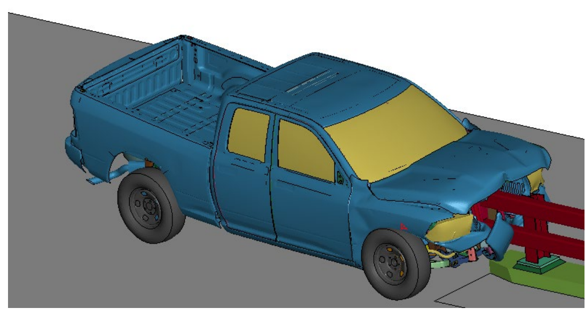

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Figure 5.17. Sequential Images Impacting Attenuator Option 3 with Pickup Truck

Table 5.5. Occupant Risk Factors with Option 3

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	38.4	48.2
	Y	2.4	6.6
Ridedown Acceleration (g)	X	13.8	11.7
	Y	10.2	9.0
Max. Angle(degrees)	Roll	8.3	1.6
	Pitch	4.9	3.8
	Yaw	35.4	1.0

5.4.4. Option 4 – Welded four rectangular 3/16-in. and ¼-in. thick HSSs

Figure 5.18 shows the design Option 4. This option used four 12-in. × 6-in. rectangular HSS tubes, two of which were 3/16-in. thick and two were 1/4-in. thick. The rectangular HSS tubes were welded side-by-side with tubes of differing thickness arranged sequentially. Thicker HSS tube (1/4-in. thick) attached to the rail end and the thinner HSS tube was placed at the end where the vehicle impacted.

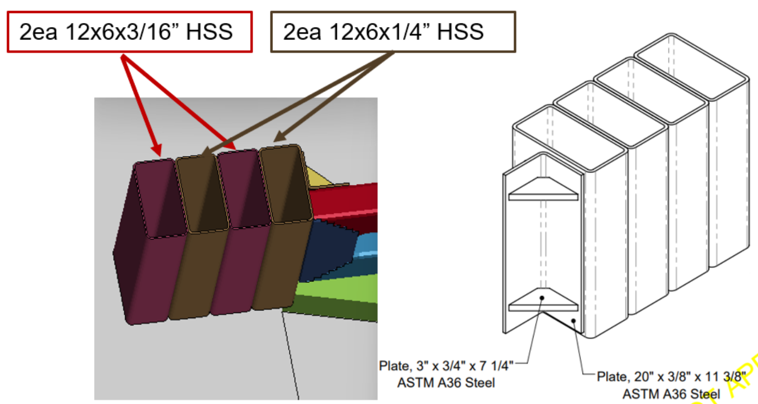


Figure 5.18. Option 4 – Welded Four HSS Tubes with Different Thickness

Figure 5.19 and Figure 5.20 show sequential images of MASH Test 1-30 and Test 1-31 impact simulations. The bridge rail with attenuator Option 4 was able to contain and stop both vehicles. The OIV for small car was increased to 38.6 ft/sec. The OIV for the pickup truck impact was decreased to 46.8 ft/sec. The RA for the pickup, however, increased by 6.5 g when compared to Option 2 with four of 3/16-in. thick HSS tubes. Table 5.6 lists the key occupant risk factors for Option 4.

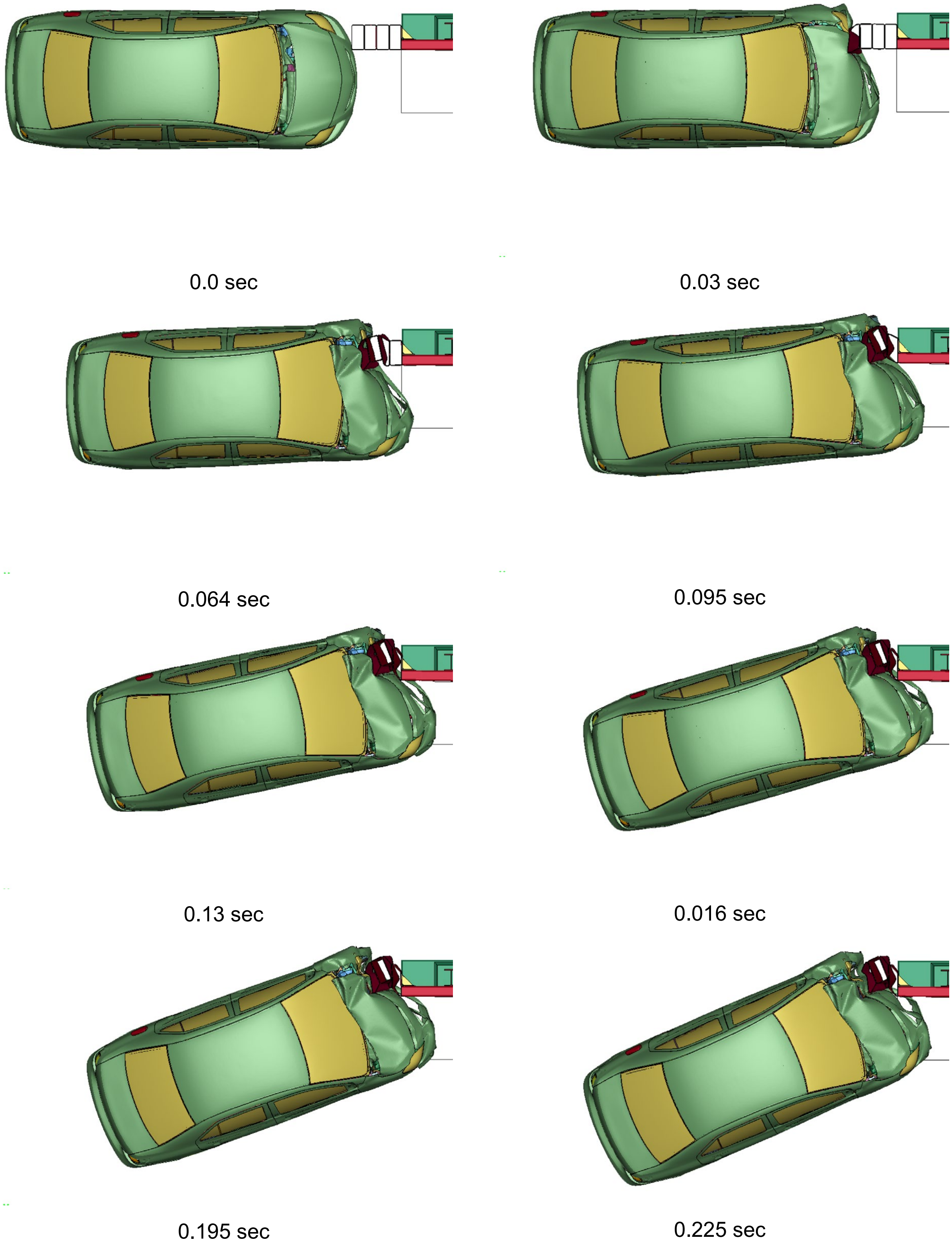
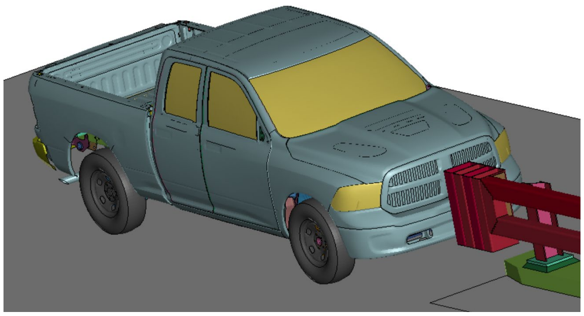


Figure 5.19. Sequential Images of Small Car Impact with Attenuator Option 4



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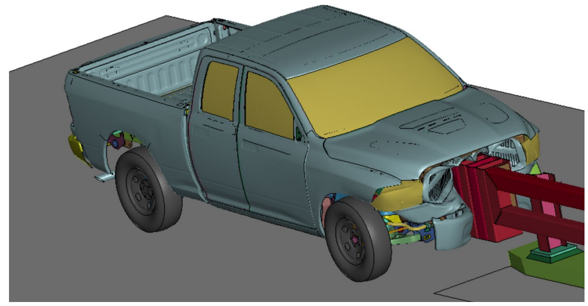

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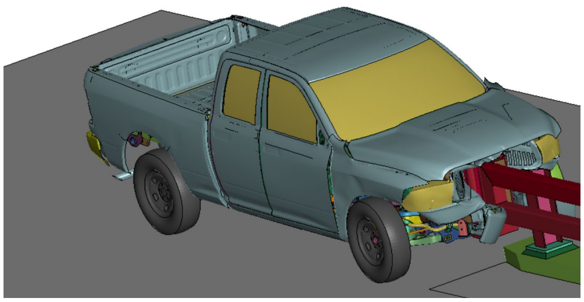

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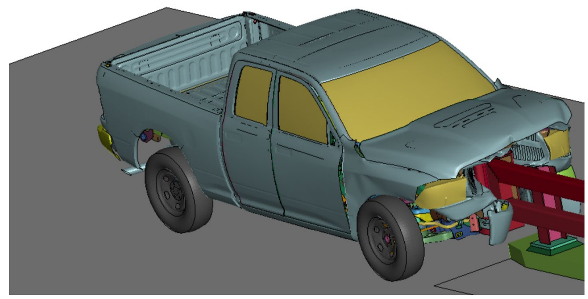

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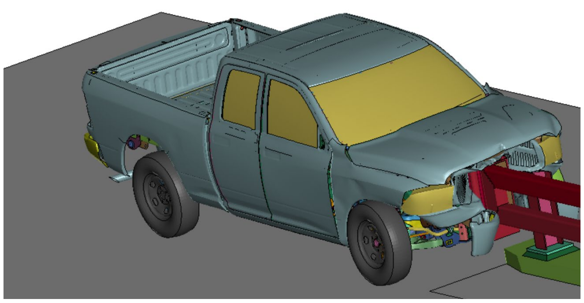

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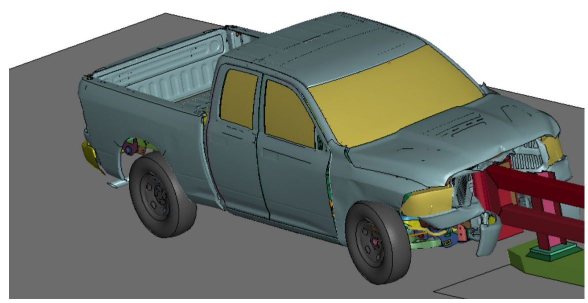

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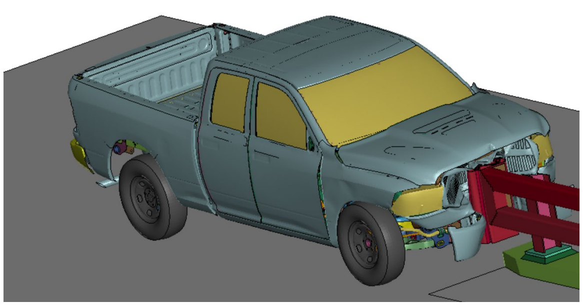

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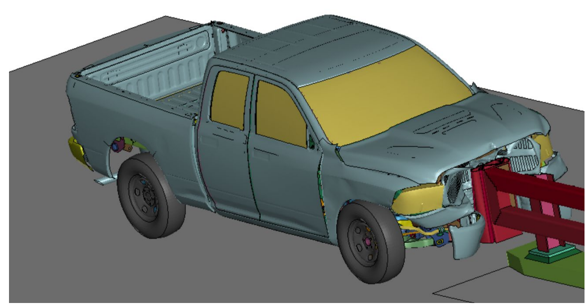

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Figure 5.20. Sequential Images of Pickup Truck Impact with Attenuator Option 4

Table 5.6. Occupant Risk Factors for Option 4

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	38.6	46.8
	Y	1.3	0.9
Ridedown Acceleration(g)	X	8.5	18.2
	Y	5.8	2.2
Max. Angle (degrees)	Roll	1.3	1.8
	Pitch	0.8	2.4
	Yaw	34.1	2.1

5.4.5. Option 5 – Welded six rectangular 3/16-in. and ¼-in. thick HSS tubes

Figure 5.21 illustrates the Option 5 concept. This option used six 12-in. × 6-in. rectangular HSS tubes; three with 3/16-in. thickness and three with 1/4-in. thickness. These rectangular HSS tubes were positioned side-by-side, with HSS of differing thickness arranged sequentially.

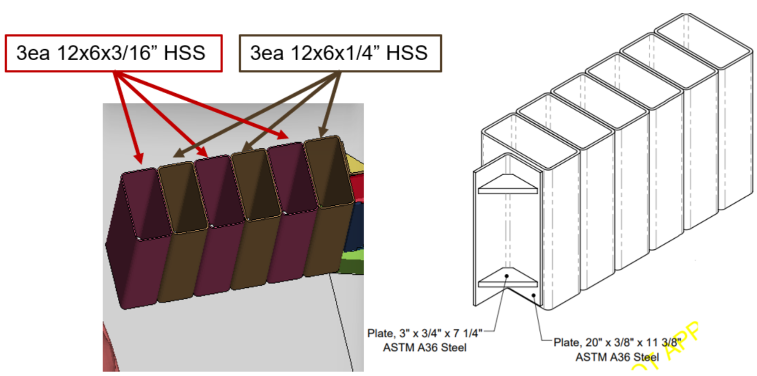


Figure 5.21. Option 5 – Welded Four HSSs with Different Thickness

Figure 5.22 and Figure 5.23 show sequential images for MASH Test 1-30 and Test 1-31 impact simulations. The bridge rail with attenuator Option 5 was successfully able to contain and stop both vehicles. Table 5.7 lists the key occupant risk factors. The OIV for small car and pickup truck impacts decreased to 32.4 ft/sec and 36.4 ft/s, respectively, and the values were under MASH limits. All other occupant risk factors also meet the MASH criteria.

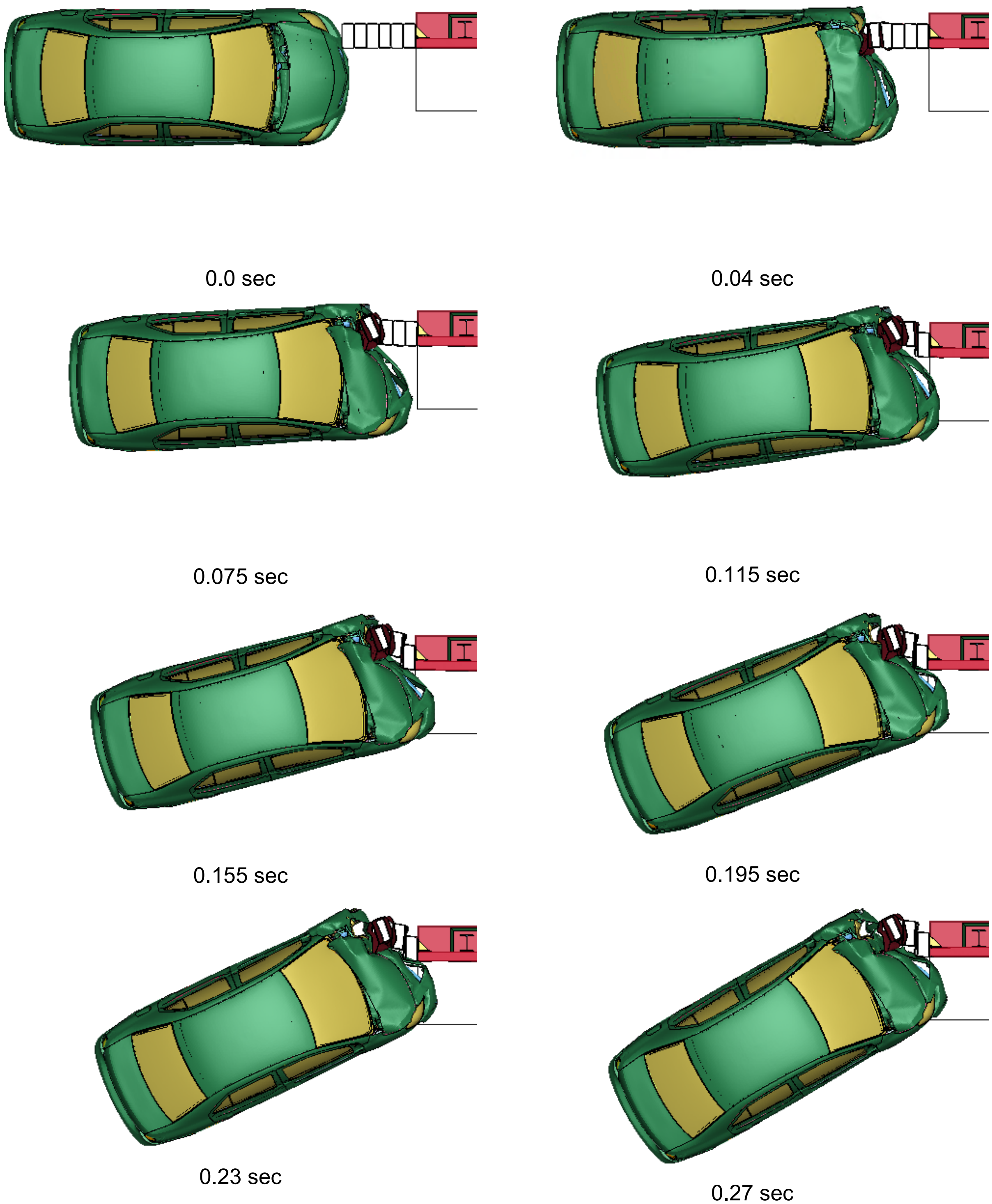


Figure 5.22. Sequential Images of Small Car Impact with Attenuator Option 5

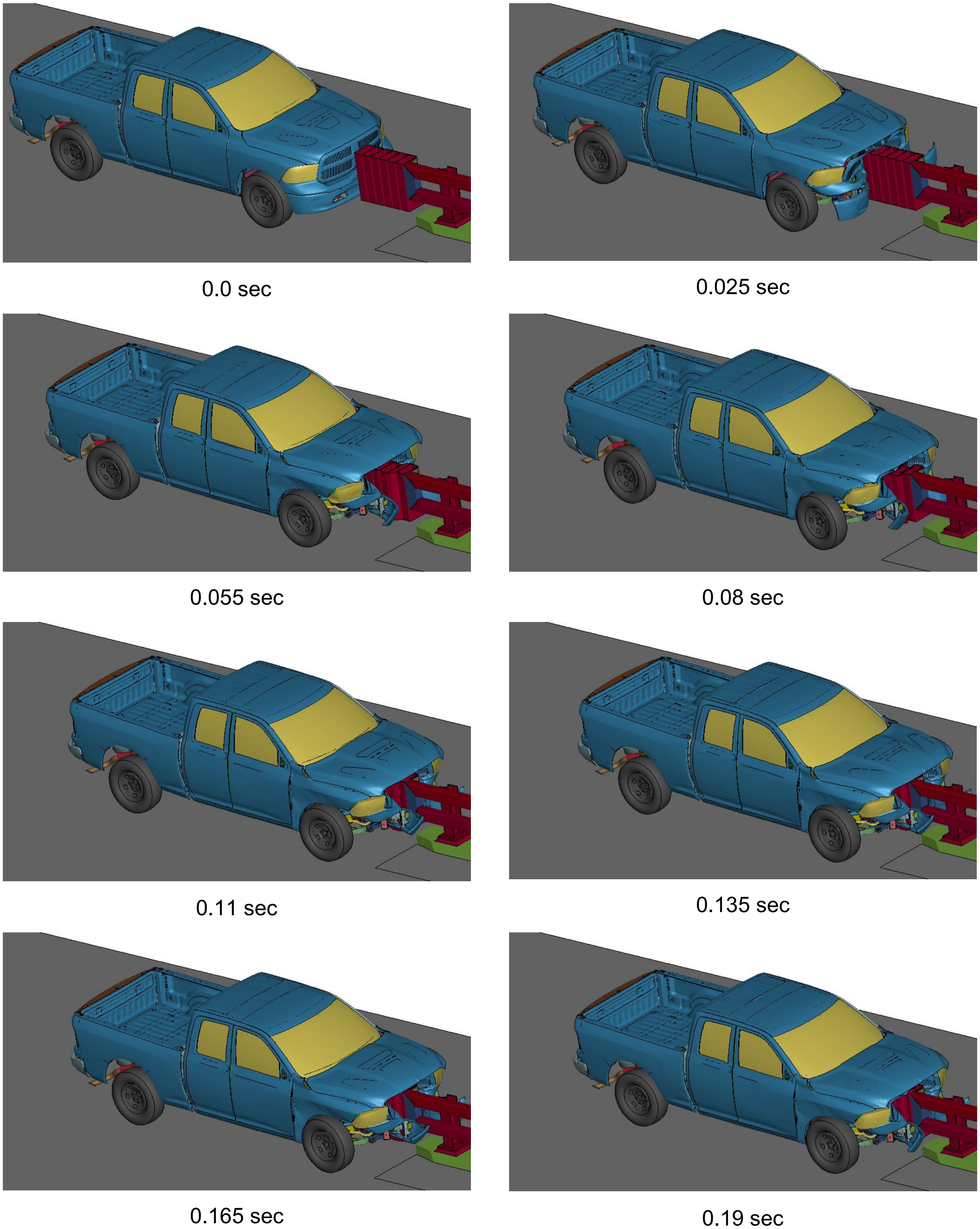


Figure 5.23. Sequential Images of Pickup Truck Impact with Attenuator Option 5

Table 5.7. Occupant Risk Factors for Option 5

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	32.4	36.4
	Y	0.8	1.3
Ridedown Acceleration (g)	X	11.6	18.5
	Y	5.0	2.0
Max. Angle (degrees)	Roll	1.6	14.4
	Pitch	1.1	1.5
	Yaw	32.3	3.1

To evaluate the design Option 5 further, MASH Tests 32 and 33 simulations were performed in accordance with MASH test matrix. Figure 5.24 shows the initial impact setups for Tests 1-32 and 1-33. The small car and pickup truck were set at an impact angle of 15 degrees with an impact speed of 31 mph to impact at the center of the attenuator end.

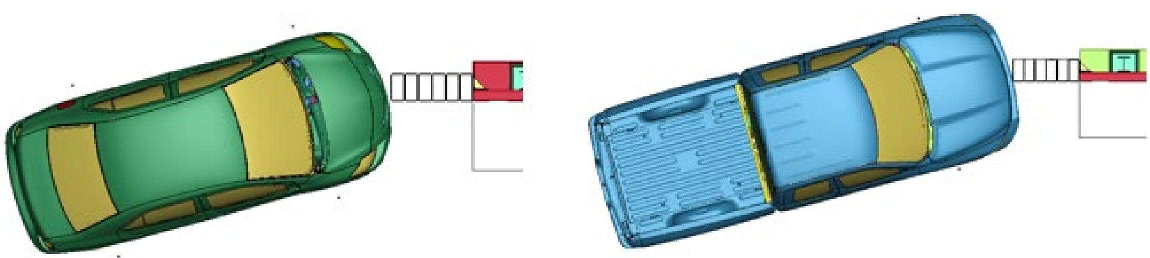


Figure 5.24. Initial Setups for Tests 1-32 and 1-33 Impact Simulations

Figure 5.25 and Figure 5.26 show sequential images for MASH Test 1-32 and Test 1-33 impact simulations with attenuator Option 5, respectively. With an impact angle of 15 degrees, the attenuator Option 5 was able to stop and contain both vehicles. The occupant risk factors for both tests are listed in Table 5.8. All values were under MASH limits.

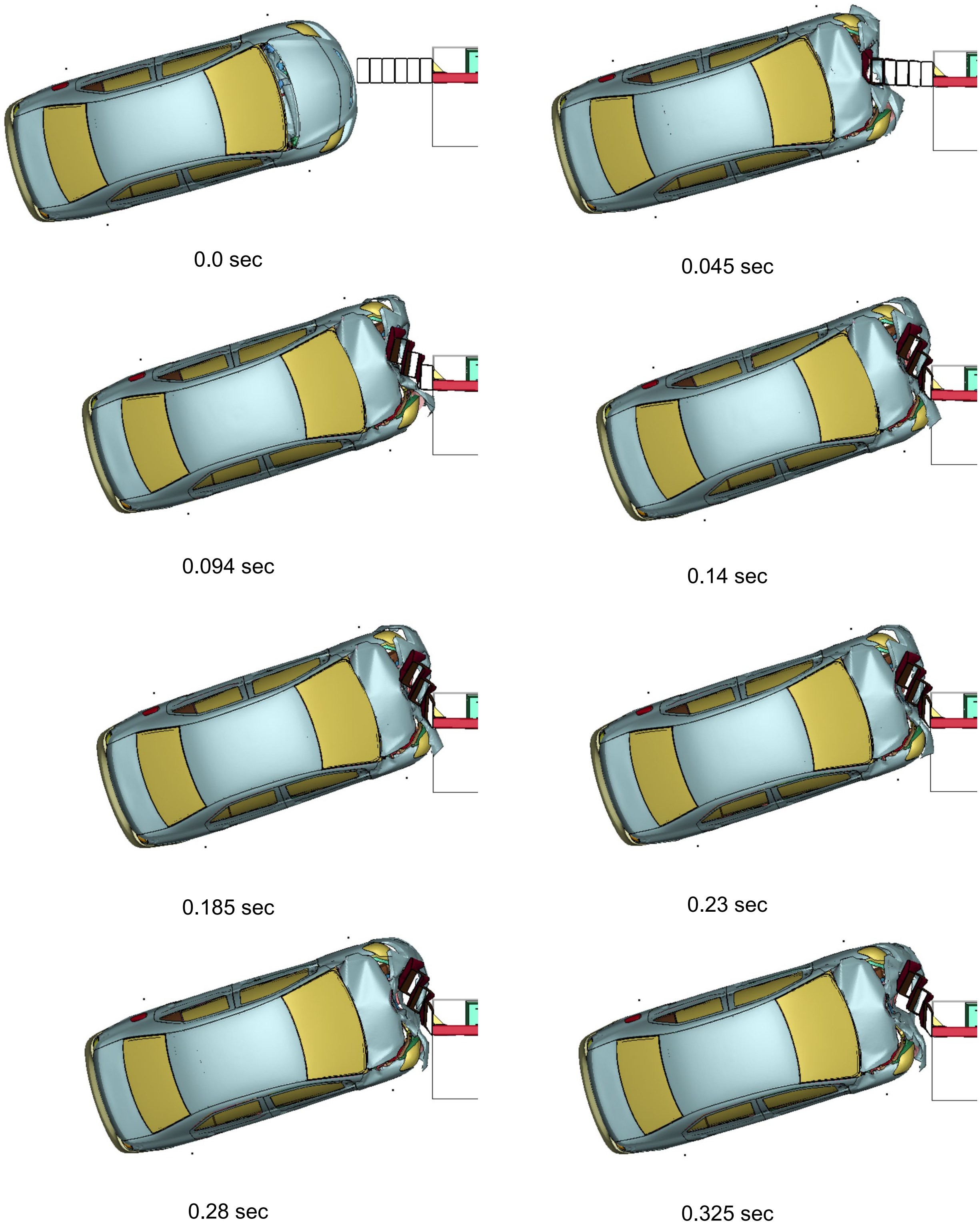
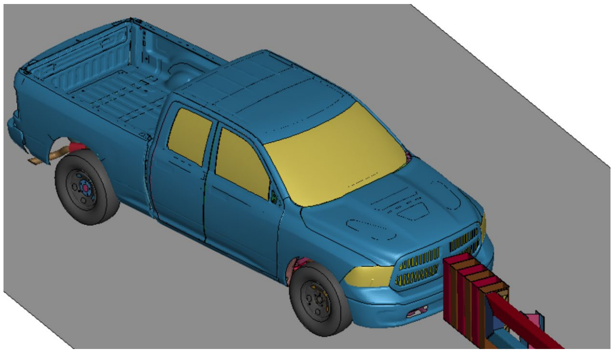


Figure 5.25. Sequential Images of Small Car Impact Option 5 at 15 Degrees



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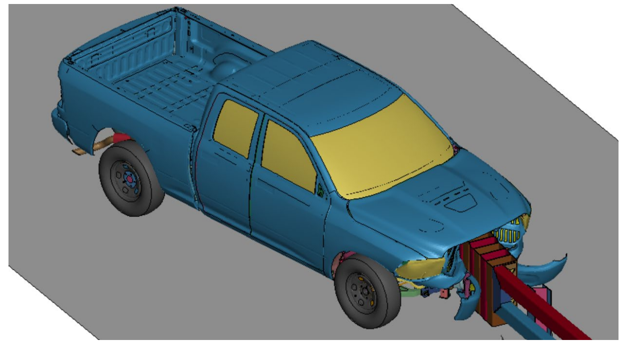

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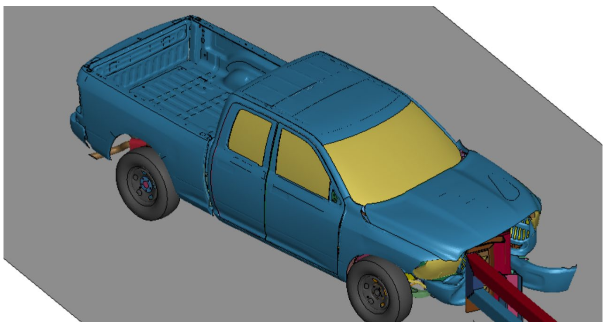

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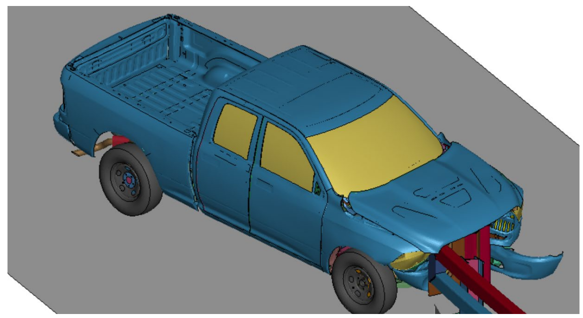

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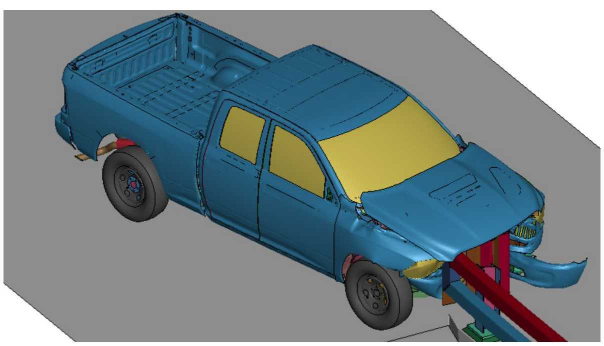

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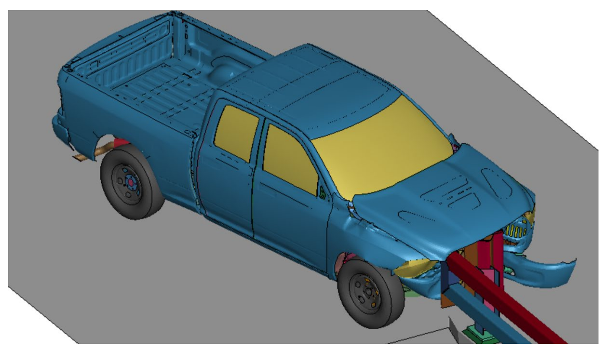

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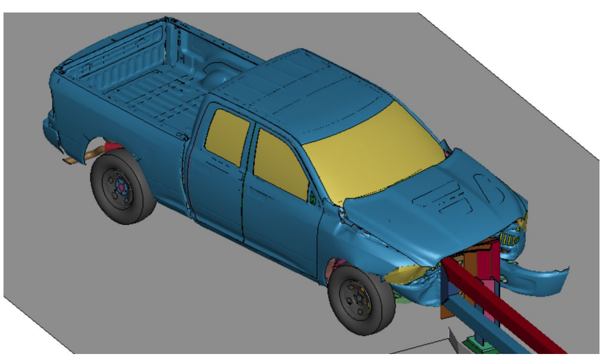

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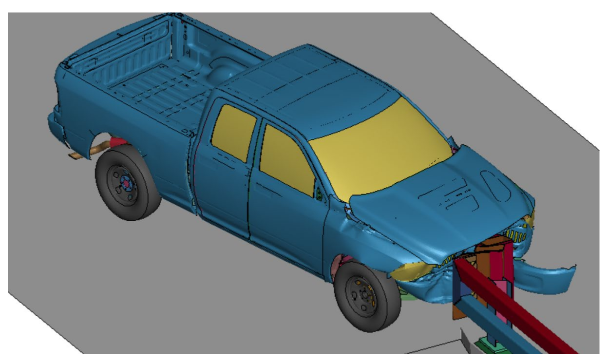

0.33 sec

Figure 5.26. Sequential Images of Small Car Impact Option 5 at 15 Degrees

Table 5.8. Occupant Risk Factors for Tests 1-32 and 1-33 with Option 5

Vehicle Model		Small Car	Pickup Truck
Occupant Impact Velocity (ft/s)	X	33.6	34.6
	Y	1.2	1.2
Ridedown Acceleration (g)	X	12.2	16.2
	Y	4.1	2.2
Max. Angle (degrees)	Roll	1.6	1.9
	Pitch	2.2	1.5
	Yaw	3.8	2.1

5.5. SUMMARY AND DISCUSSION

The research team used LS-DYNA to simulate vehicle impacts under MASH TL-1 conditions. The simulations involved impacting the Alaska 2-tube steel bridge rail system with small car and pickup truck model. MASH Tests 30 and 31 were simulated first to determine an attenuator option that is likely to meet MASH test matrix for a crash cushion or non-gating terminal. Test simulations on blunt rail end showed OIVs of 44.6 ft/s and 51.5 ft/s for the small car and pickup truck impact simulations, respectively. Both exceeded the MASH limit of 40 ft/s, indicating high injury risk. To mitigate high occupant risks, five attenuator design options were evaluated. These designs featured various configurations of rectangular HSS tubes, some incorporating mixed wall thicknesses to optimize energy absorption. Among the options, Option 5 shown in Figure 5.27 performed best with a reduced OIVs of 32.4 ft/s and 36.4 ft/s for the small car and pickup truck impacts, respectively. Results of Test 1-30 and Test 1-31 impact simulations with Option 5 design met the MASH evaluation criteria. This attenuator option was also simulated using MASH Tests 1-32 and 1-33 impact conditions. Simulation results showed that Option 5 design met the MASH evaluation criteria for Tests 1-32 and 1-33 as well. Details of the Option 5 are shown in Figure 5.27.

Based on the simulation analyses, a minimum attenuator length of 36 in. was considered sufficient for TL-1 conditions, and the attenuator can be directly attached to the bridge rail end without requiring additional ground support. Simulation results support the feasibility of Option 5 attenuator design as an effective safety solution for constrained bridge sites. For broader application, the addition of a cover or cap over the attenuator — not considered in this study — could be further investigated to prevent snow or slush intrusion and to mitigate the impact of plowing operations, which may reduce its intended energy absorption capacity.

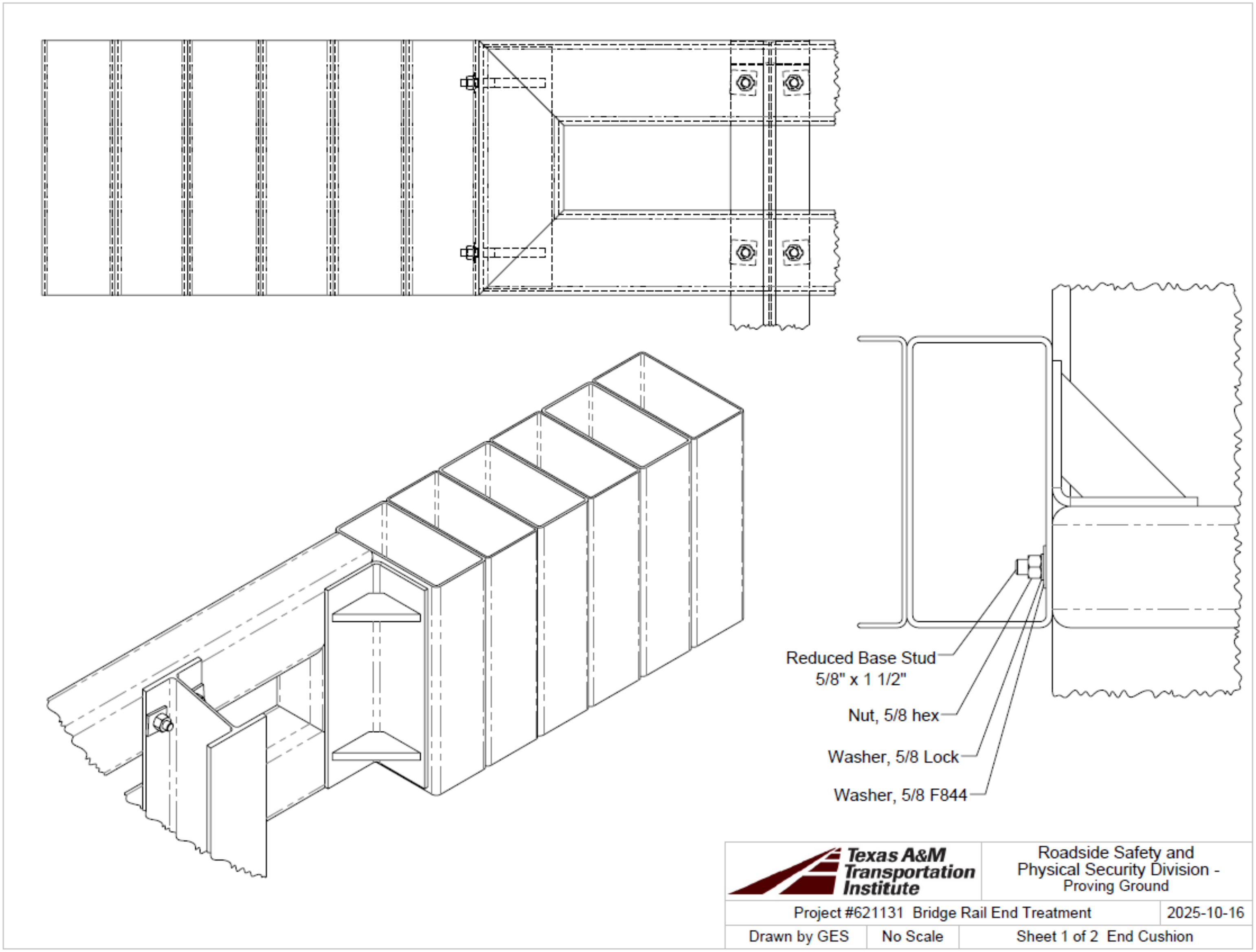

Figure 5.27. Details of Attenuator Option 5

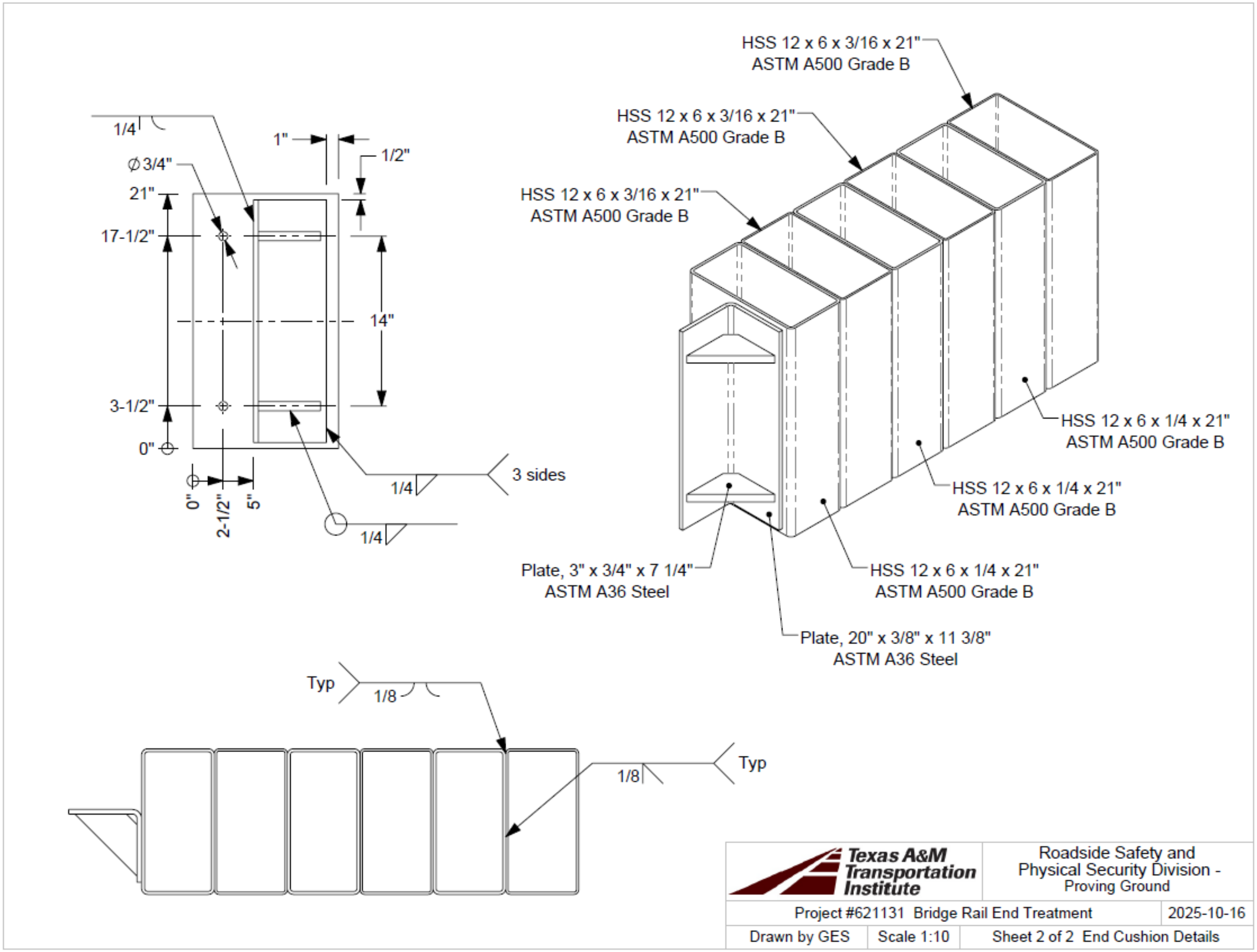

Figure 5.27. Details of Attenuator Option 5 (Continue)

Chapter 6. SUMMARY AND RECOMMENDATIONS

This research performed a literature review of existing federal guidelines and crash data, highlighting that for bridges with posted speed limits of 30 mph or less, vehicle safety systems are generally sufficient to protect occupants. However, for bridges with speed limits between 31 and 45 mph, installation of crashworthy terminals and transitions are shown to be risk-beneficial

Standard MASH or NCHRP Report 350 TL-2 compliant terminals and crash cushions typically require a minimum installation length of 37.5 feet, which is impractical for constrained sites due to limited space and geometric restrictions. In contrast, the attenuator designs proposed in this study can be as short as 36 inches under MASH TL-1 impact conditions. These compact designs can be directly attached to the bridge rail end, eliminating the need for additional ground support and making them suitable for constrained environments.

Finite element simulations comparing blunt-end impacts versus attenuated-end impacts showed significant safety improvements. For example, simulations of blunt-end impacts resulted in OIV of 44.6 ft/s for the small car and 51.5 ft/s for the pickup truck, both exceeding the MASH limit of 40 ft/s. However, simulations of the proposed attenuator design (Option 5) reduced OIV to 32.4 ft/s for the small car and 36.4 ft/s for the pickup truck, both within acceptable safety thresholds.

To support implementation, this research also provides an example of guideline for LSLV bridge rail end treatments for constrained site conditions. Figure 6.1 shows the flow chart to guide how to select LSLV bridge rail end treatment method. Designers or engineers first assess site conditions such as posted speed and the volume of traffic, then identify the limitations, whether the site can accommodate a crashworthy crash cushion or terminal. Using RSAP and the analysis results, the designers and engineers can select whether existing crashworthy devices can be used or not. If it is determined that a crashworthy rail end treatment device is not beneficial, an attenuator similar to the one proposed in this study may be considered.

It should be noted that the guidance proposed herein is based primarily on the computer simulation results. The models of the proposed attenuator designs were not directly validated against full-scale crash testing or experimental data. Confidence in the model relied on expertise with impact phenomena and responses observed in common vehicle-barrier impacts. Full-scale crash testing would improve confidence in the proposed attenuator design function and performance. However, designers may desire to utilize these solutions rather than leave the site conditions as is.

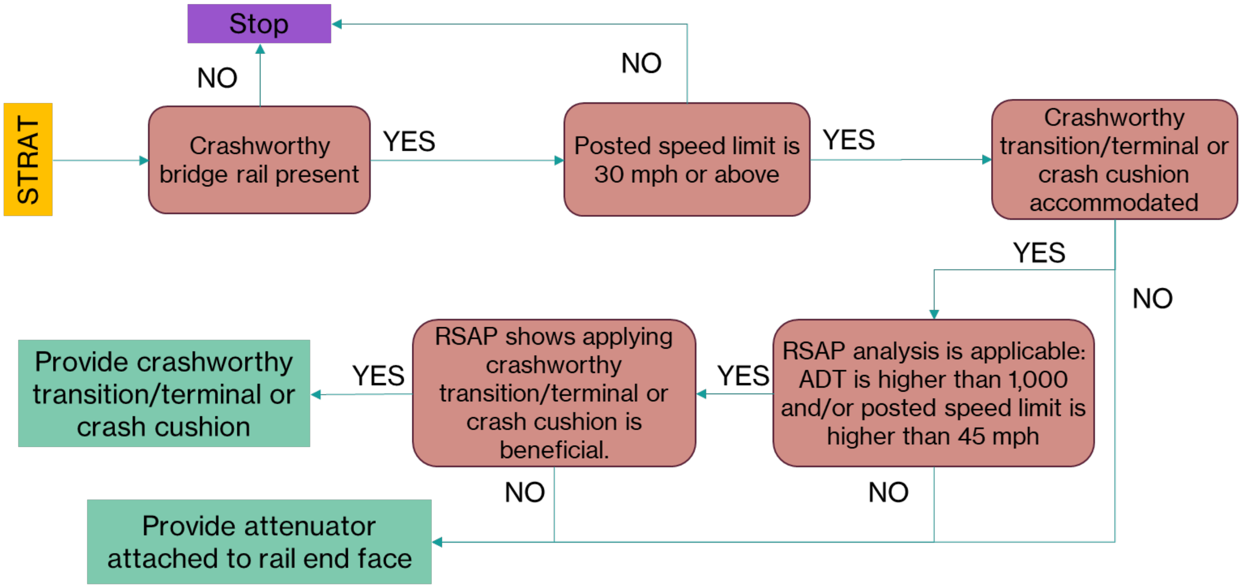

Figure 6.1. Low-Speed and Low-Volume Bridge Rail End Treatment Guidance for Constrained Site Condition

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