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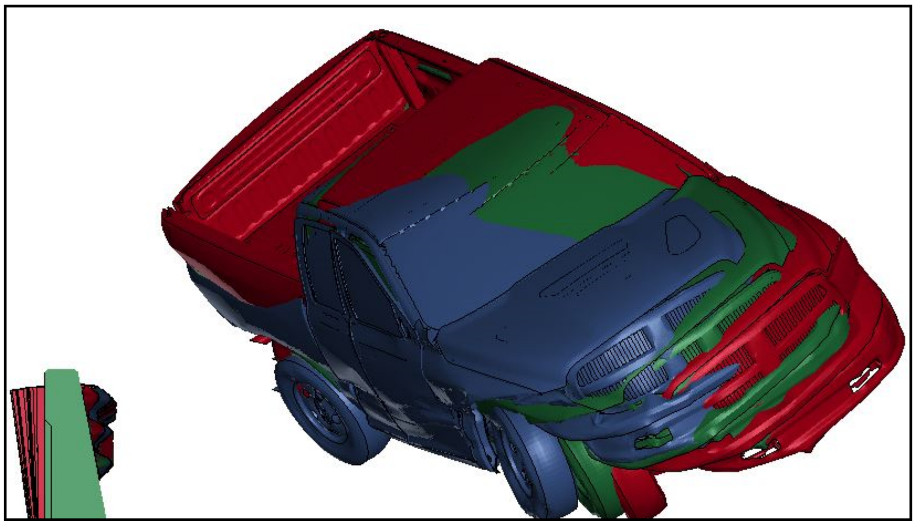

AN EXPLORATION INTO VARIATIONS IN GUARDRAIL APPROACH TRANSITIONS TO RIGID BARRIERS

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Washington State Department of Transportation (WsDOT)

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16. Abstract

This research project aimed to analyze and prioritize installation deficiencies in approach transitions using computer modeling. Approach transitions are considered more challenging than normal beam guardrails in regards to their ability to pass crash tests because they require reduced movement as a vehicle approaches the rigid barrier. However, there has been limited research on retrofitting approach transitions to address this challenge, leading to a need for further understanding of the effects of modifications on their performance. For this study, the researchers conducted an extensive literature review, identified a representative approach guardrail transition, created a computer model of it, and evaluated common field variations using computer simulation. The results of this research will contribute to a better understanding of the behavior of approach transitions and help prioritize field variations for further study.

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AN EXPLORATION INTO VARIATIONS IN GUARDRAIL APPROACH TRANSITIONS TO RIGID BARRIERS

by

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The results reported herein apply only to the article tested. The full-scale crash tests were performed according to TTI Proving Ground quality procedures and American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH), Second Edition, guidelines and standards.

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SI* (MODERN METRIC) CONVERSION FACTORS

Symbol	When You Know	Multiply By	To Find	Symbol
APPROXIMATE CONVERSIONS TO SI UNITS				
		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

Symbol	When You Know	Multiply By	To Find	Symbol
APPROXIMATE CONVERSIONS FROM SI UNITS				
		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

An approach guardrail transition (AGT) is a type of roadside safety feature used to connect two barrier systems with significantly different stiffnesses, such as joining a semirigid W-beam guardrail to a concrete barrier or a bridge rail. AGTs need to be designed to provide a gradual change in stiffness to guarantee a smooth redirection of the vehicle and reduce the possibility of pocketing (Figure 1.1).

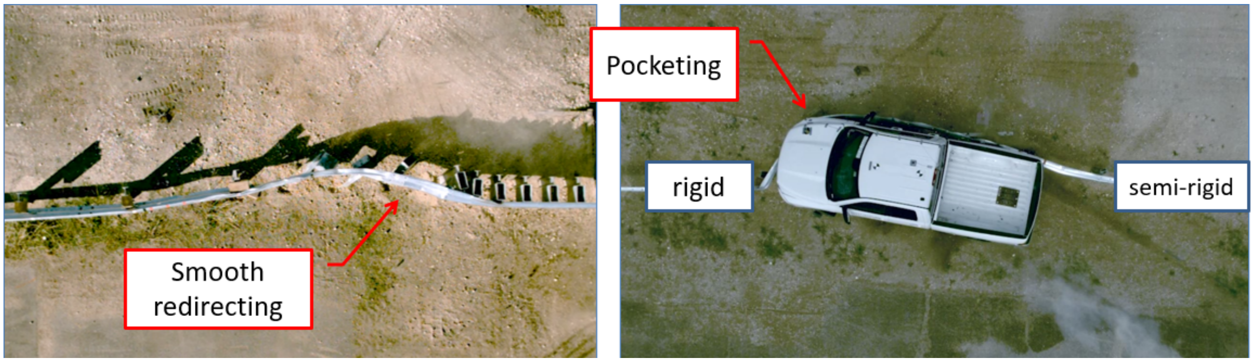


Figure 1.1. Smooth Redirecting in a Properly Designed AGT (Left); Pocketing Effect (Right).

The gradual change in lateral stiffness can be implemented in multiple ways. Changing post spacing, using stronger posts, using thrie-beam instead of W-beam systems, and nesting the rails are a few common methods. Figure 1.2 illustrates some of these methods.

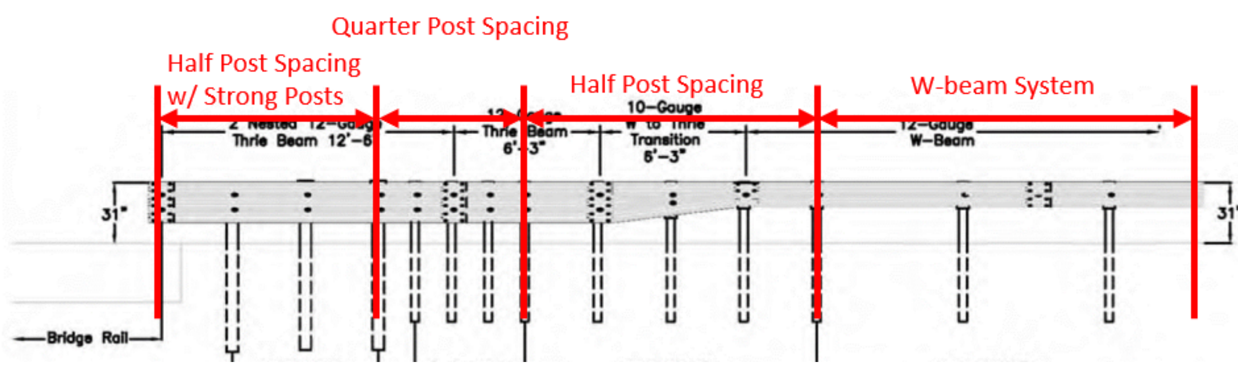


Figure 1.2. Gradual Change in Lateral Stiffness in a Typical AGT.

1.1. PROBLEM STATEMENT

In the field, some approach transitions have deficiencies that should be addressed. However, there are many different transition designs and many different deficiencies in field installation, which makes it difficult to determine how to address the problems. This research project used computer modeling to evaluate installation deficiencies in approach transitions. The simulation-based approach can help reduce costs (as opposed to full-scale crash testing) and provide a more efficient way to evaluate multiple design variations in a shorter amount of time, allowing for more rapid development and implementation of transition systems.

1.2. RESEARCH OBJECTIVE

This research sought to use computer modeling to identify when certain field variations in AGTs may be problematic.

1.3. SCOPE OF RESEARCH

To fulfill the research objective, various tasks were completed. First, the state members of the Roadside Safety Pooled Fund were polled to identify the possible field variations of thrie-beam transitions and prioritize them according to their prevalence. Next, an extensive literature review of previous studies was conducted to identify a representative AGT system. Furthermore, a computer model of the representative system was created and calibrated based on the full-scale physical crash test conducted under American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH) Test Level 3 (TL-3) criteria (*1*). Last, two common field variations were evaluated using computer simulation.

Chapter 2. LITERATURE REVIEW

2.1. BACKGROUND

Historically, AGTs have more difficulty passing crash tests than normal guardrail systems because the transition must reduce deflection (with an increased stiffness) as vehicles approach the rigid barrier. However, limited research has focused on investigating and retrofitting approach transitions (*2*, *3*). The previous studies investigated missing posts, posts installed in loose asphalt millings, and nesting variations (Figure 2.1). Several other modifications have not been reviewed. More research is needed to better understand how approach transitions work and how modifications influence performance. Because large variations exist, computer modeling is needed to explore modifications to determine which ones are problematic.

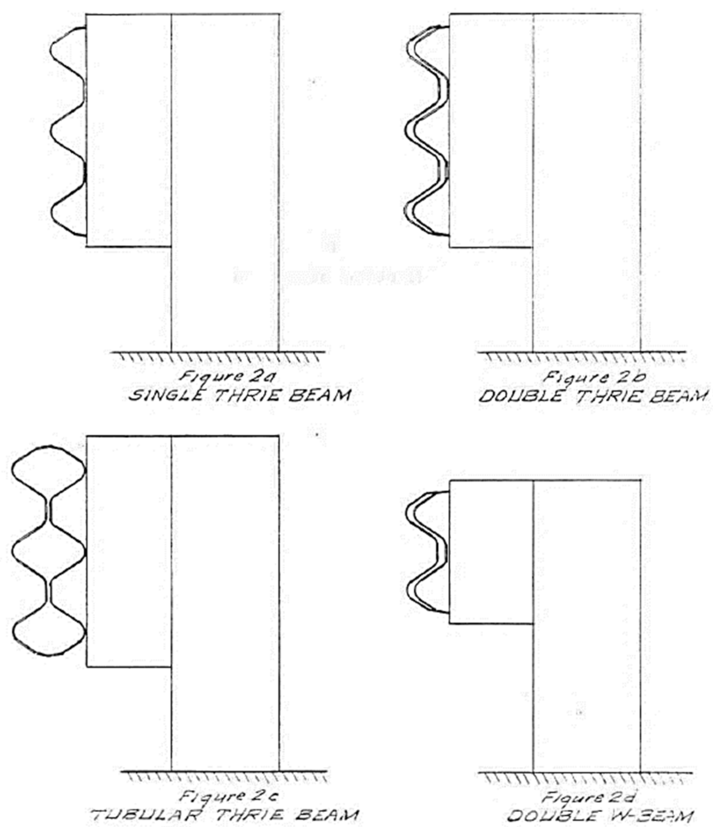


Figure 2.1. Previously Studied Nesting Variations (*3*).

2.2. IDENTIFYING FIELD VARIATIONS

One of the common field modifications to an AGT is skipping a post (Figure 2.2). Skipping a post in a thrie-beam transition system refers to the practice of leaving extra space between two posts or supports in the guardrail system. This modification can be made for several reasons, such as to accommodate utility lines or other infrastructure that is located near the roadway (Figure 2.3).

Skipping a post in a thrie-beam transition system may affect the performance of the guardrail system, especially in high-speed impact scenarios. Skipping posts may decrease the system's capacity to redirect the vehicle safely and increase the risk of vehicle penetration, pocketing, excessive occupant risk, or rollover. Therefore, the decision to skip a post should be made only after a thorough analysis of the potential impacts on safety, and in accordance with the available guidelines.

Figure 2.2. Practice of Skipping a Post (*4*).

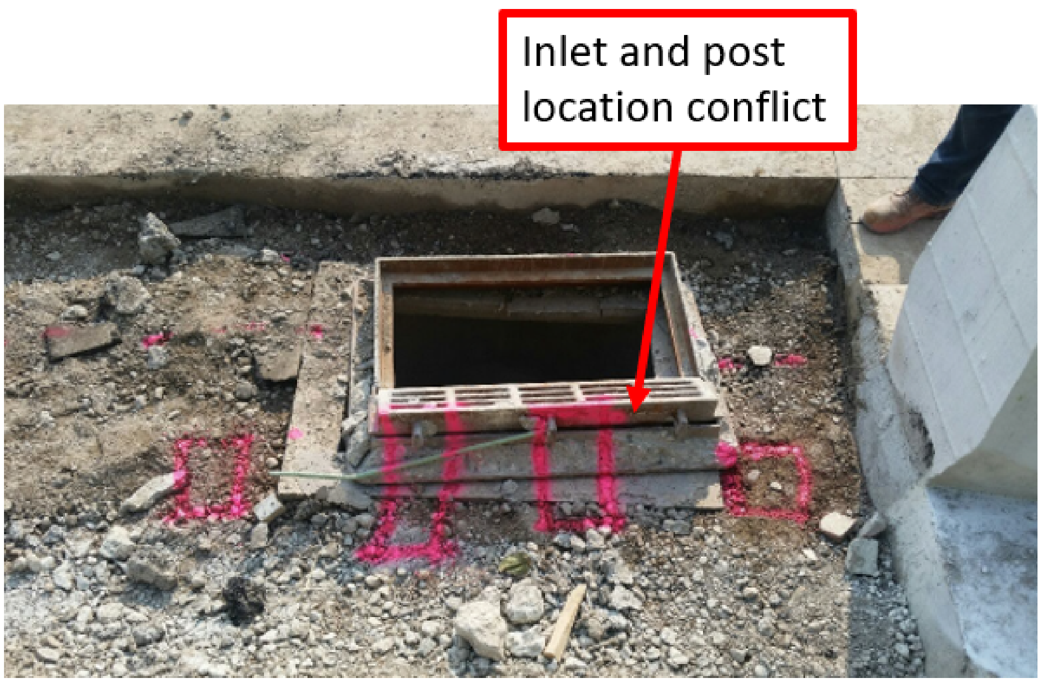


Figure 2.3. Inlet and Post Location Conflict (*4*).

Proper backfill is crucial for ensuring the performance and safety of a thrie-beam transition system. Reduced backfill can be caused by improper grading that resulted in the soil being washed away (Figure 2.4). Inadequate backfill can have a significant impact on the performance of a thrie-beam transition system with a concrete barrier (Figure 2.5). When the posts of the system are not properly backfilled, the effective embedment depth of the posts is reduced. This can cause the rail to deflect more than it would if the posts were properly embedded, which can lead to a number of issues.

One of the main issues that can arise from inadequate backfill is an increased interaction of a vehicle with the blunt end of the concrete barrier. This interaction occurs because the rail deflection causes the vehicle to collide with the concrete barrier instead of the thrie-beam guardrail. Inadequate backfill can also lead to increased rail deflection, which can heighten the risk of vehicle instability.

Figure 2.4. New Thrie-Beam Transition with Drainage Problems (*4*).

Figure 2.5. Inadequate Backfill behind an AGT System (*4*).

Improper height changes in the concrete barrier attached to an AGT can have a negative effect on the stability of a vehicle upon impact. The result can be especially dangerous for high-center-of-gravity vehicles such as pickup trucks. Additionally, an exposed blunt end of a concrete barrier in a thrie-beam transition system can have a significant impact on the performance of the system during a crash event. When the blunt end of the concrete barrier is exposed, a vehicle may severely interact with the concrete barrier rather than be safely redirected by the thrie-beam guardrail. Figure 2.6 shows both the blunt-end case and potential ineffective height change.

Figure 2.6. Example of Blunt End and Potential Ineffective Height Change (*4*).

Some older parapets were built with a notch in the parapet face for attaching the AGT (see Figure 2.7). However, this design feature poses a potential safety concern. The lack of a wooden blockout between the parapet and thrie beam creates a snagging point that increases the likelihood of vehicle instability and higher values of occupant risk factors. More specifically, a vehicle may catch on the snagging point during a crash, causing it to rotate or overturn, which increases the risk of injury to the occupants. Additionally, the snagging point can cause the vehicle to change direction or trajectory and potentially leading to more severe crashes.

Figure 2.7. AGT Attachment to a Concrete Barrier without Wood Blockout That May Cause Vehicle Snagging (*4*).

2.3. SELECTED MASH-TESTED TRANSITIONS

Researchers from the Texas A&M Transportation Institute (TTI) evaluated a guardrail-to-rigid-barrier transition system for use on bridges or culvert structures using a combination of computer simulations and full-scale crash testing (*5*). The system consisted of a 16-ft-long reinforced concrete parapet and moment slab, a 27-ft-long W-beam to thrie-beam to parapet transition section that was anchored to the parapet, 50 ft of W-beam guardrail, and a downstream anchor terminal (DAT). The thrie-beam portion of the installation was anchored to a reinforced concrete wingwall that was embedded in the soil, with the top of the wingwall at grade level. The rest of the posts were embedded directly into the soil. The top edges of the thrie-beam and W-beam rails were at 31 inches above grade. The wingwall was 13 ft long, 12 inches thick, and 5 ft deep. A C6×8.2 rubrail was positioned below the thrie-beam section of the transition.

The target critical impact points (CIPs) were determined using computer simulations. Three crash tests were conducted, two on the upstream of the transition and one on the downstream. The target CIPs for MASH Test 3-20 (Test No. 469549-01-1) and MASH Test 3-21 (Test No. 469549-01-2) were the centerline of post 13 and 14, respectively. The target CIP for MASH Test 3-21 (Test No. 469549-01-4) was 5 inches downstream of the centerline of post 19 at the connection with the rail.

Figure 2.8 shows the transition installation details. Overall, the guardrail-to-rigid-barrier transition attached to a bridge or culvert structure performed acceptably for MASH TL-3 criteria.

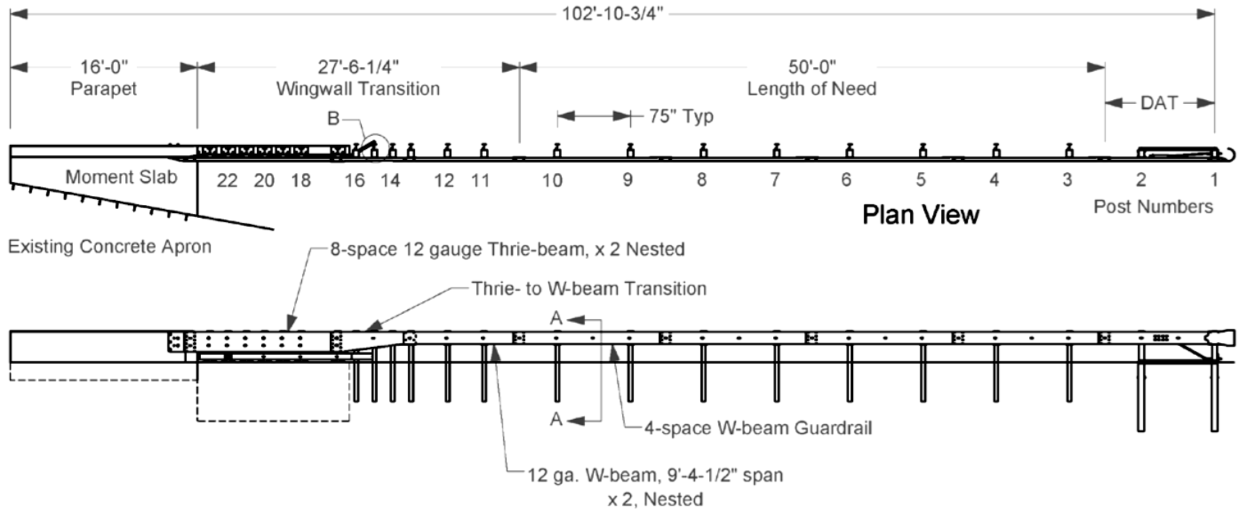


Figure 2.8. Installation Details for Transition on Wingwall or Culvert.

In 2019, TTI researchers examined the feasibility of attaching a thrie-beam AGT directly to the sloped face of a single-slope concrete barrier without using an end-shoe adapter (*6*). This approach involves twisting the nested thrie beam and end shoe and attaching them directly to the inclined face of the concrete barrier instead of using a tapered blockout or adapter. The critical test to evaluate the effectiveness of this approach was MASH Test 3-21 using a pickup truck because the stability of the vehicle was expected to be affected by the twisted thrie-beam rail.

Texas Department of Transportation (TxDOT) bridge-rail standards include two configurations for approach transitions: a 32-inch F-shape parapet (Type T551) and a 36-inch single-slope traffic rail (SSTR). The SSTR has an 11-degree slope on the traffic face, compared to a 6.5-degree slope on the upper face of the F-shape parapet. The greater slope of the SSTR made it the more critical profile for evaluating the thrie-beam transition without an end-shoe block. Therefore, a successful result with the more critical SSTR would also apply to the T551 F-shape bridge rail. MASH Test 3-21 was conducted on the thrie-beam system attached to a 36-inch-tall SSTR, as shown in Figure 2.9, and the system performed satisfactorily according to the evaluation criteria of MASH Test 3-21.

Figure 2.9. Thrie-Beam Transition without End-Shoe Block.

In 2019, the performance of a two-tube bridge-rail thrie-beam transition was evaluated by TTI researchers according to safety performance guidelines in MASH (*7*). The test installation consisted of a 154-ft-long section of reinforced concrete bridge deck with two steel rails, a 12½-ft-long section of nested thrie beams, a thrie-beam terminal connector, a standard symmetrical 75-inch-long thrie-beam to W-beam transition rail section, 25 ft of W-beam guardrail, and a standard 9-ft 4½-inch long TxDOT DAT terminal (Figure 2.10).

The target CIP for each test was determined in accordance with the guidance provided in MASH. For MASH Test 3-20, the target CIP was 5.1 ft upstream of the end of the concrete parapet. The target CIP for MASH Test 3-21 on the thrie-beam to bridge-rail transition was 7.0 ft upstream of the concrete parapet. The target CIP for MASH Test 3-21 on the W-beam to thrie-beam transition was 7.3 ft upstream of the centerline of post 7. TTI researchers determined that MASH Test 3-20 on the W-beam to thrie-beam transition was not necessary and was therefore not performed. The two-tube bridge-rail thrie-beam transition performed acceptably for a MASH TL-3 transition.

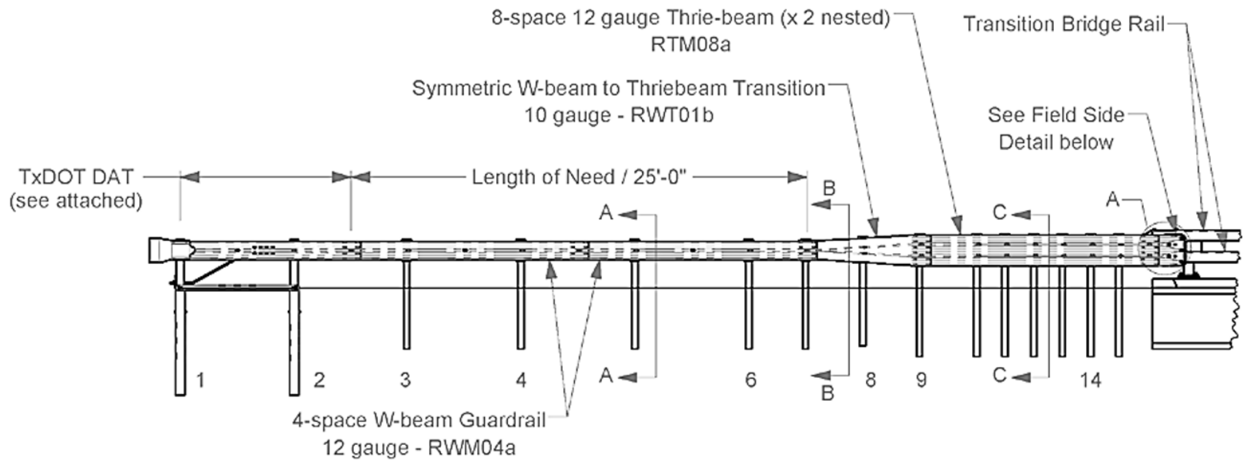


Figure 2.10. Details of 2019 MASH Two-Tube Bridge-Rail Thrie-Beam Transition.

In 2013, TTI researchers evaluated the performance of a simplified approach transition design without a curb or a rubrail (Figure 2.11) (*8*) according to the MASH criteria under Test 3-21. The single-slope bridge rail was built to TxDOT standards at a height of 36 inches. Posts 1 and 2 were part of the standard 31-inch ET-2000 terminal, while posts 3–11 were part of a standard 12-gauge W-beam guardrail using 72-inch-long W6×8.5 posts attached to the 12-gauge rail element with 8-inch wood blockouts. The posts were placed at the mid-span of each rail. Between posts 11 and 13, a 10-gauge W-to-thrie asymmetric transition piece was used, supported by 72-inch-tall posts. A nested 12-gauge thrie-beam rail was used between post 13 and the end of the single-slope barrier, with 84-inch-long W6×8.5 posts with 6×8×18-inch wood blockouts. A 10-gauge thrie-beam end shoe was used to attach the nested thrie beam to the ¼-inch-thick adapter plate. The TxDOT TL-3 transition did not perform acceptably for MASH Test 3-21 due to a pickup truck rollover. Figure 2.12 shows signs of wheel snagging at the blunt end of the single-slope concrete barrier that possibly contributed to the vehicle instability and consequent rollover. The TTI researchers suggested that the presence of a curb could have mitigated the snagging and prevented the vehicle instability.

Figure 2.11. Thrie-Beam Transition without Curb and Rubrail.

Figure 2.12. Tire Snagging to the Single-Slope Concrete Barrier Toe.

In 2021, researchers at TTI examined the development of a shorter thrie-beam transition from a W-beam guardrail to a parapet (*9*). The goal was to create a simplified TL-3 transition without any rubrail or curb using two nested 75-inch-long sections of thrie-beam guardrail that were transitioned to a W-beam system using a W-to-thrie asymmetric segment. To prevent tire snagging on the parapet's blunt end, a deflector plate was added to the parapet's toe, as shown in Figure 2.13. The system was tested under MASH Test 3-21 criteria, but due to high occupant ridedown acceleration during the crash test, it did not meet the performance criteria for MASH Test 3-21 for transitions (Figure 2.14).

Figure 2.13. Short, Simplified TL-3 Transition.

Figure 2.14. Excessive Interaction of the Pickup Truck with the Parapet Blunt End.

2.4. STATE DOT SURVEY AND STANDARD DRAWINGS REVIEW

To understand the prevalent practices among state departments of transportation (DOTs) regarding the variation of transition systems to concrete barriers, TTI researchers conducted a survey of state members and analyzed the collected standard drawings. The goal of this research was to identify the different treatments and recommendations for attaching thrie-beam transitions to concrete parapets in DOT standards.

The survey included questions about the types of AGTs used, the methods for attaching AGTs to concrete barriers, and any variations or modifications that were made in the field. The researchers collected standard drawings from each state to identify the specific details and designs used in the AGTs.

Based on the survey results and standard drawing analysis, the researchers identified a range of treatments and recommendations for attaching thrie-beam transitions to concrete parapets. These included different configurations of AGTs such as different lengths, post spacing, post size, etc.

In order to further understand the field variations that DOTs experience, a second survey was conducted. The second survey focused on identifying and prioritizing the most common field variations that DOTs encounter with regards to the attachment of thrie-beam transitions to concrete barriers. The results of this survey were used to select the representative transition system for the computer simulation task.

Among the field variations identified in the DOT survey, reducing the embedment of posts and skipping a post were prioritized the highest. Including a curb was also high on the list.

However, according to previous studies of various AGTs, in crash testing of transitions designed with or without a curb, curb presence completely changes the containment mechanism and consequently the impact performance of the system. Thus, in this study, the presence of a curb was not investigated.

2.5. REPRESENTATIVE TRANSITION SYSTEM

The researchers selected the TxDOT thrie-beam AGT with a curb as the representative system to be modeled and used for implementing the field variations. This system, which has been successfully crash tested (*6*), features a nested thrie-beam design. Additionally, the system has the more commonly used asymmetrically tapered transition segment, which helps to gradually transition from the thrie-beam section to the standard W-beam system and reduce the likelihood of tire snagging.

The nested thrie-beam rail is attached to a 36-inch-tall single-slope barrier directly without using any end-shoe adapter. The system consists of six 7-ft-tall W6×8.5 posts with quarter-post spacing followed by four 6-ft-tall posts with half-post spacing at the upstream of the nested thrie-beam rail. Figure 2.15 presents the system's overall details, and Figure 2.16 shows images of the transition system.

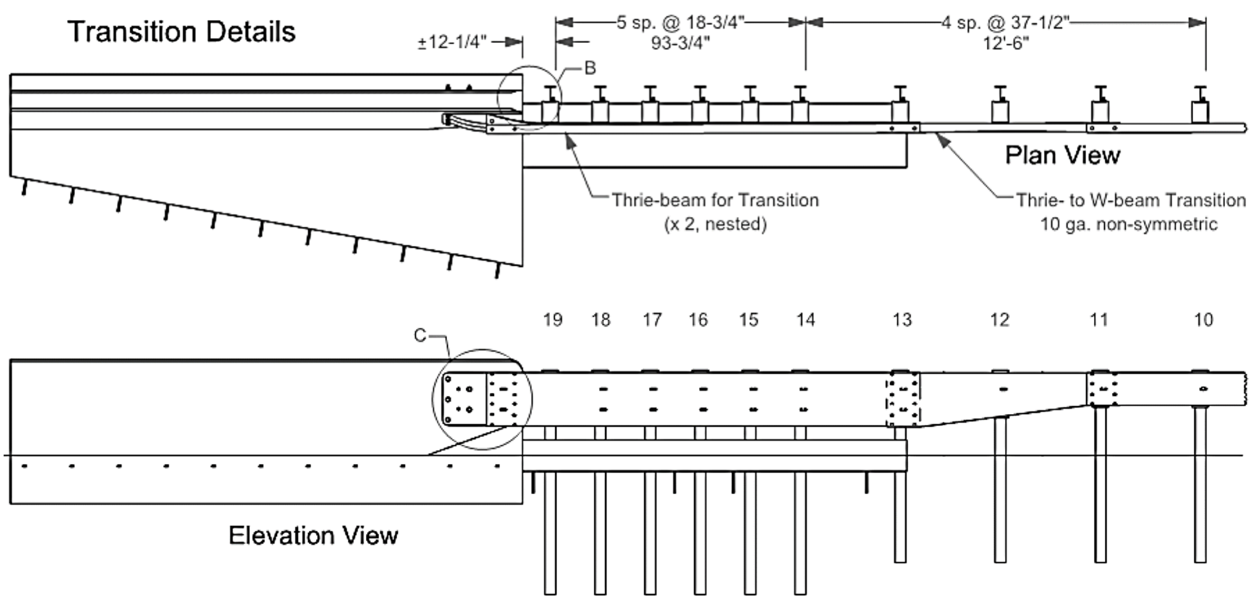


Figure 2.15. Overall Details of the Thrie-Beam Transition without End-Shoe Block (*6*).

Figure 2.16. Photo of Thrie-Beam Transition without End-Shoe Block (*6*).

2.6. SUMMARY

The aim of this chapter was to survey the available literature and data on potential field variations in transition systems and to choose a representative system for further analysis. The TxDOT thrie-beam AGT with a curb was selected for computer simulation in the subsequent chapters.

Chapter 3. BASELINE MODEL DEVELOPMENT

3.1. INTRODUCTION

Recent technological advancements have enabled researchers in the field of roadside safety to use finite element analysis (FEA) to study the dynamic response of vehicle impacts into barrier systems. FEA is a powerful tool that allows for the detailed evaluation of both vehicle components and safety barrier and hardware crashworthiness. The FEA simulations performed in this study were conducted using the LS-DYNA software (*10*). LS-DYNA is a well-known and widely used general purpose, explicit finite element code that can accurately simulate the nonlinear and dynamic response of three-dimensional problems. Its ability to capture complex interactions and dynamic load-time history responses makes it particularly well-suited for simulating vehicle-barrier impact scenarios. In this chapter a representative transition system was chosen as the baseline model, considering its widespread use and availability of full-scale crash test data. The baseline model was developed and calibrated based on the full-scale crash test data and was then used for the evaluation of different field variations.

3.2. MODEL CREATION

3.2.1. Representative Transition Model

An explicit finite element model of the representative transition system was created to develop a baseline system. Figure 3.1 and Figure 3.2 show the front and rear views of the modeled system, respectively, including the parapet, transition posts, nested thrie section, and approaching W-beam guardrail. The front view shows the use of a twisted nested thrie beam to attach to the face of the single-slope barrier. The single-slope parapet and the curb were modeled as rigid.

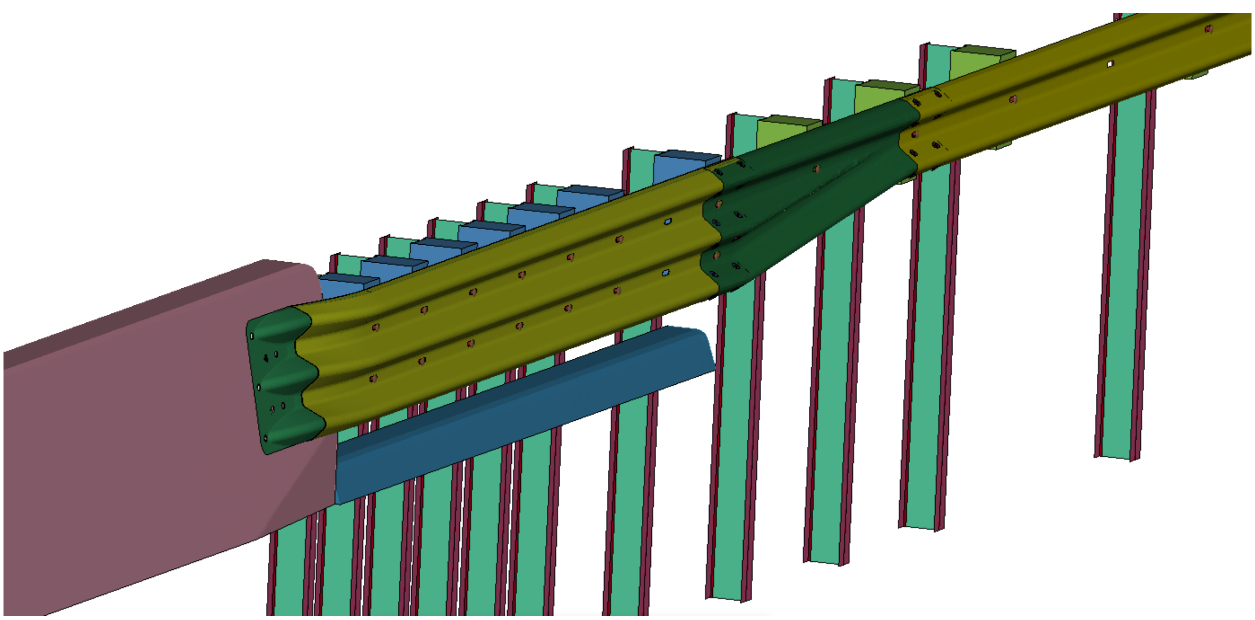


Figure 3.1. Computer Model of the System—Front View.

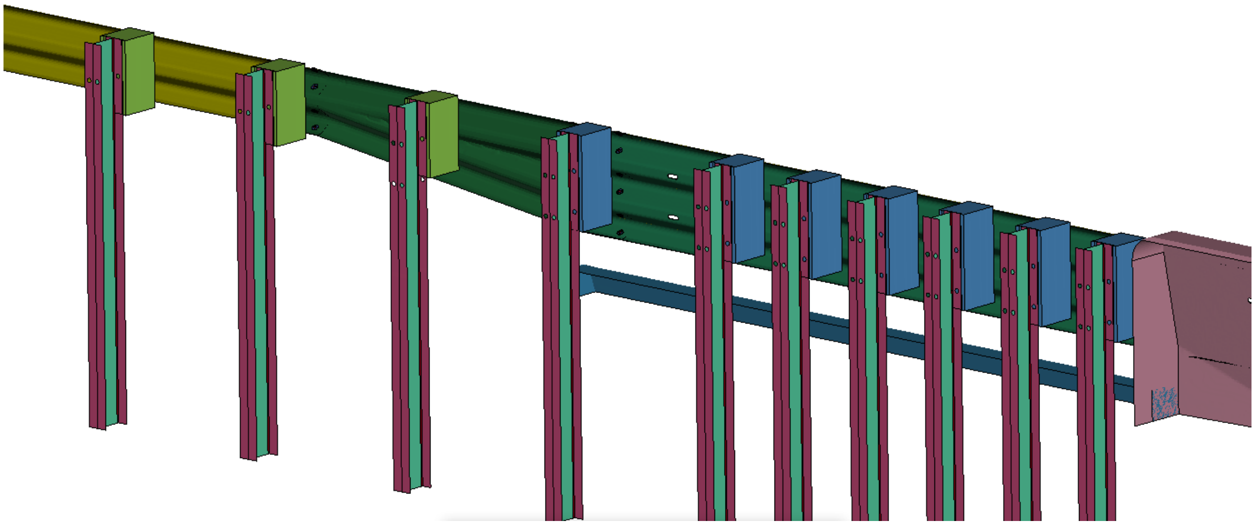


Figure 3.2. Computer Model of the System—Rear View.

3.2.2. Pickup Truck Impact Simulation

MASH Test 3-21 involves a pickup truck with a weight of 5000 lb ± 110 lb impacting the CIP on a transition system at a speed of 62 mi/h ± 2.5 mi/h and at an angle of 25 degrees ± 1.5 degrees. The CIP for MASH Test 3-21 on the thrie-beam transition without an end-shoe block was 93 inches upstream of the end of the concrete barrier. The test used a 2013 RAM 1500 vehicle with a weight of 5038 lb and an actual impact speed and angle of 62.3 mi/h and 25.1 degrees, respectively. The actual point of impact was 97.7 inches upstream of the end of the concrete barrier. The actual impact speed and angle as well as the actual crash test CIP were used in the computer simulation. Figure 3.3 illustrates the full-scale crash test simulation assembly and the impact point.

TTI researchers used the Center for Collision Safety and Analysis (CCSA) finite element model of a 2018 Dodge Ram pickup truck for the simulations (*11*). Certain components of the vehicle model required mesh refinement to prevent issues with contact during the impact event against the finer meshed components of the test article.

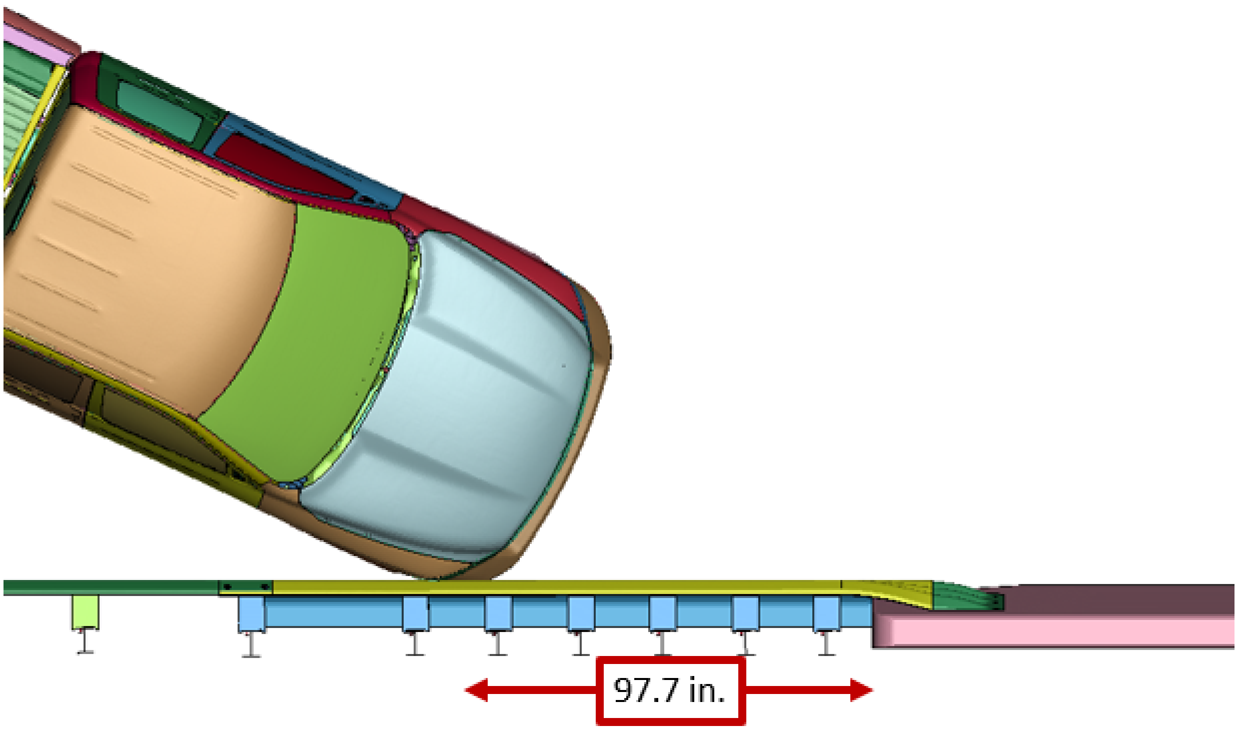


Figure 3.3. Full-Scale Crash Test Simulation Assembly and Impact Point.

To ensure the numerical validity of the LS-DYNA model, various energies of the system were inspected (Figure 3.4). The kinetic energy imparted by the vehicle on the barrier during impact is transformed into other forms of energy. Internal energy refers to the energy stored in a component through plastic and elastic deformation temperature change. Sliding energy refers to the energy dissipated due to friction between different components. Since this is a closed system, the energy is conserved, and the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equal the initial kinetic energy of the vehicle.

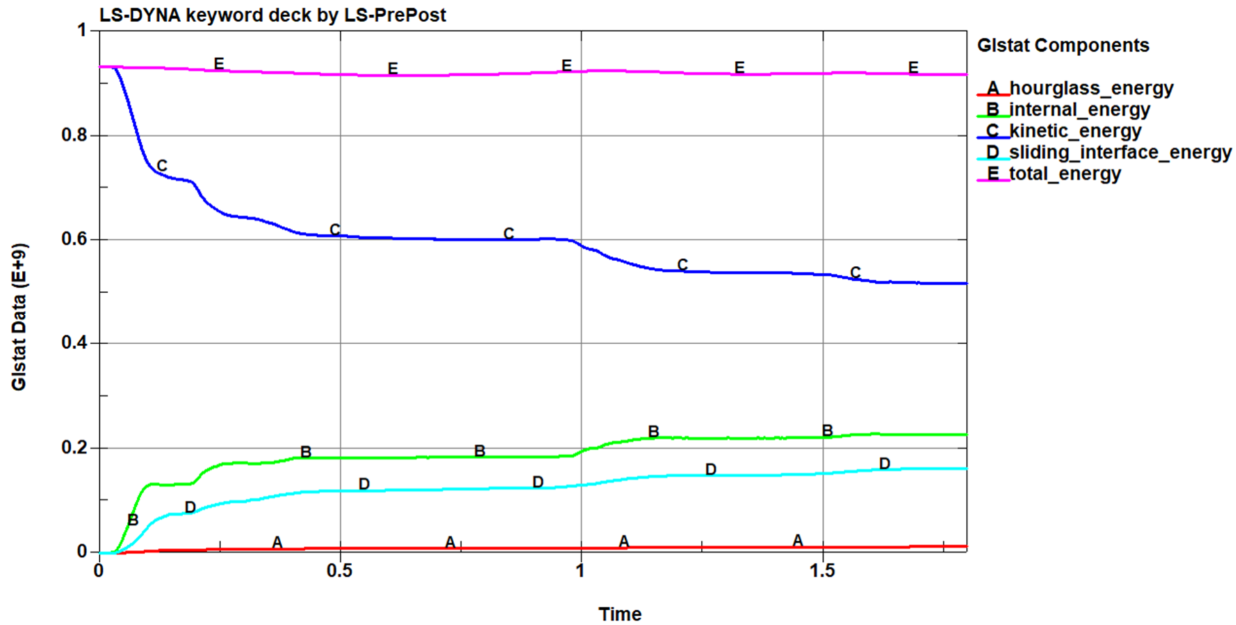


Figure 3.4. Energy Distribution Time History.

3.3. MODEL CALIBRATION WITH THE CRASH TEST

The transition baseline model was calibrated using data from Test No. 469469-5 (*6*), which involved a 2270P pickup truck impacting the TxDOT transition system. The impact conditions were in line with MASH TL-3 criteria. The simulated impact conditions were based on the actual impact speed and angle obtained from the test results.

Occupant risk factors, vehicle stability, and dynamic deflection of the system were investigated as part of the model calibration process. The results of these evaluations were compared to the data obtained from the full-scale crash test to ensure the accuracy and validity of the computer simulation model. By thoroughly evaluating these factors, the researchers were able to fine-tune the model to better predict the behavior of the vehicle and occupants during a collision.

The Test Risk Assessment Program (TRAP) was utilized to assess the risk factors for occupant safety (*12*). The simulation showed that the vehicle remained upright throughout the collision event. The velocity of the occupants during the impact was 17 ft/s and 30.1 ft/s for the longitudinal and lateral directions, respectively. The acceleration of the vehicle during the impact was measured at 6.6 g and 14.4 g for the longitudinal and lateral directions, respectively. The vehicular displacements (e.g., roll, pitch, and yaw) of the vehicle were also recorded. The maximum roll, pitch, and yaw angles of the computer simulation were 32.7, 5.4, and 46.3 degrees, respectively. Table 3.1 shows the comparison of the data recorded from the computer simulation, with Test No. 469469-5 as the representative transition system.

While there is no uniform standard for the level of agreement that is considered acceptable between computer simulation and crash test results, it is generally expected that the simulation accurately captures the behavior of the system being studied. This allows the simulation model to be used for investigating different variations of the system under study. The sequential image comparison presented in Table 3.2 and Table 3.3 demonstrates a high level of agreement between the predictions of the computer model and the results of the full-scale crash test. This finding indicates that the baseline model is able to accurately simulate the behavior of the vehicle in a crash scenario and can be used to investigate different field variations of the transition system. This is particularly useful for understanding how different factors can affect the vehicle's stability and the system's crashworthiness.

Chapter 4 describes the use of the model to simulate a range of scenarios and variations of the transition system, allowing researchers to evaluate the impact of different design choices on vehicle performance in a crash. This type of evaluation can help identify potential issues and areas for improvement and inform the development of safer and more efficient transition systems for vehicles.

Table 3.1. Occupant Risk Value Comparisons.

Risk Factor		Crash Test No. 469469-5	Results from Simulation	Relative Difference
Occupant Impact Velocity (OIV) (ft/s)	**Longitudinal**	20.3	17.0	3.3
	Lateral	26.2	30.1	3.9
Occupant Ridedown Acceleration (ORA) (g)	**Longitudinal**	6.6	5.2	1.4
	Lateral	14.4	12	2.4
Max. Angular Displacement (deg.)	**Roll**	24	32.7	8.7
	Pitch	7	5.4	1.6
	Yaw	47	46.3	0.7
Max. Dynamic Deflection (in.)		4	4.6	0.6

Table 3.2. Sequential Image Comparison between Crash Test and Computer Simulation—Front View.

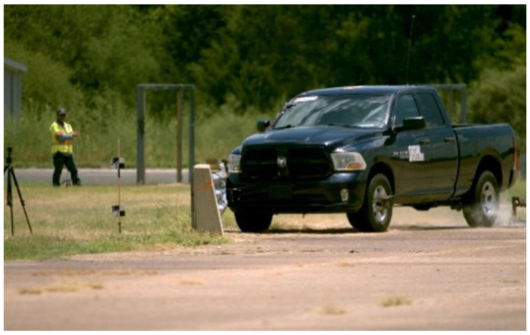
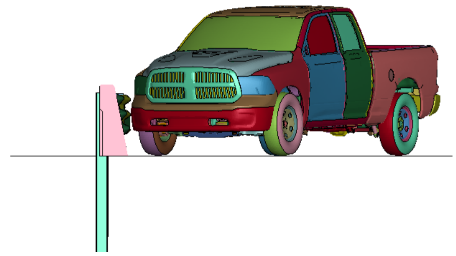
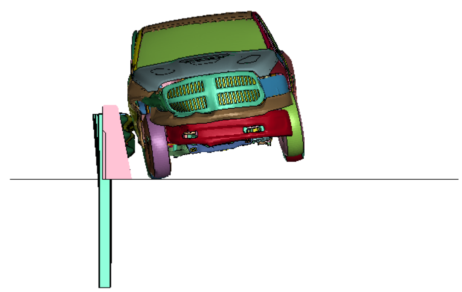
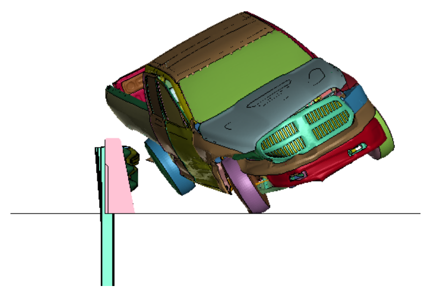
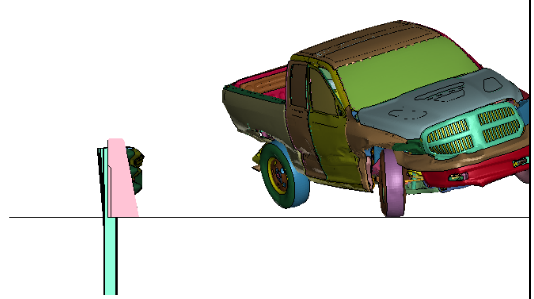
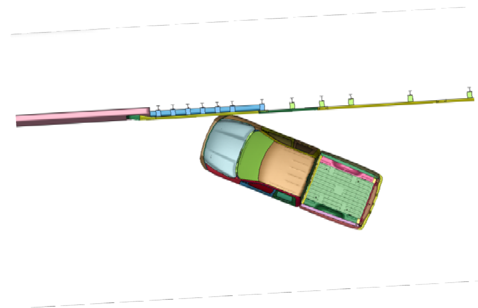
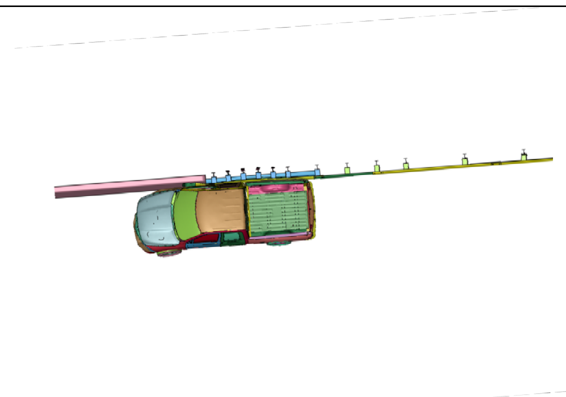
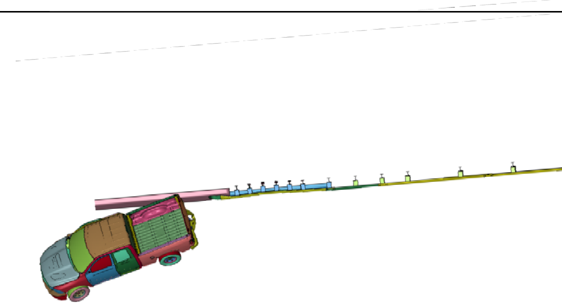
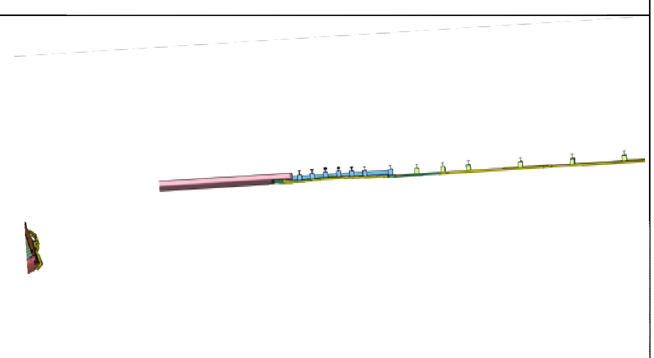
Time (s)	Test 469469-5	FEA Simulation
0.000		
0.200		
0.400		
0.700		

Table 3.3. Sequential Image Comparison between Crash Test and Computer Simulation—Top View.

Time (s)	Test 469469-5	FEA Simulation
0.000		
0.200		
0.400		
0.700		

3.4. SUMMARY

The goal of the task described in this chapter was to ensure that the developed model accurately reflected the behavior of a vehicle during a real-world impact. The chapter discussed various aspects of the simulation, such as the vehicle's stability and position relative to the test article, as well as the dynamic deflection of the system. Overall, the computer model of the TxDOT transition system realistically replicated the results observed through the full-scale crash test and could be used for incorporating field variations for further investigation, as described in the following chapter.

Chapter 4. PREDICTIVE EVALUATION OF FIELD VARIATIONS

4.1. INTRODUCTION

This chapter is divided into two sections: evaluation criteria and field variation investigation. The evaluation criteria section outlines the key parameters that need to be considered when evaluating the performance of a transition system during an impact. The field variation investigation section focuses on the investigation of the various field variations in approach transitions that were selected based on a comprehensive survey of state DOT standards and the associated safety risks.

4.2. EVALUATION CRITERIA

4.2.1. Ridedown Acceleration

Vehicle pocketing and possible snag were investigated by recording maximum lateral ridedown acceleration. Maximum ridedown acceleration represents the highest level of deceleration experienced by a vehicle during a crash. It is a commonly used metric in crash analysis because it provides insight into the severity of the impact experienced by the vehicle and its occupants. The greater the maximum ridedown acceleration, the higher the forces involved in the crash and the more likely an injury to the occupants will occur. High values of maximum ridedown acceleration can indicate that a vehicle is experiencing excessive penetration into the guardrail system, which can lead to vehicle pocketing. In other words, high values of maximum ridedown acceleration are often associated with vehicle pocketing.

4.2.2. Dynamic Deflection

The dynamic deflection of a transition system is directly related to its performance. If the dynamic deflection within a system is too high, excessive barrier movement may occur, which can result in vehicle pocketing, high exit angles, and instability. On the other hand, if the dynamic deflection is within an acceptable range, the system is more likely to perform as desired during a crash event. The results of full-scale vehicle crash tests showed that transition systems were considered inadequate when the dynamic deflection within the thrie-beam section reached or exceeded 10 inches. Conversely, transition systems were deemed successful when the dynamic deflection was less than or equal to 7.6 inches (*2*).

Excessive dynamic deflection results in a higher interaction of the vehicle with the blunt end of the parapet, which in turn results in vehicular instability (*9*). In similar transition configurations, the presence of a curb or rubrail reduced the amount of dynamic deflection, and consequently, the system passed under MASH criteria (*5*, *6*).

Table 4.1 presents the impact of the presence of a curb or rubrail on the dynamic deflection of similar transition systems. The absence of a curb or rubrail in the shorter transition system resulted in a failure due to high values of ridedown acceleration caused by the excessive interaction between the vehicle and the blunt end of the parapet. On the other hand, the TxDOT transition system with a bolted wingwall and a rubrail was able to limit the dynamic deflection to

6.3 inches, which was a significant factor in passing the system under MASH TL-3 criteria. The TxDOT transition system without an end-shoe block but with a curb was able to further limit the dynamic deflection, resulting in passing MASH criteria.

Table 4.1. Comparison of the Effect of the Presence of a Curb or Rubrail on Dynamic Deflection of a Transition System.

	Shorter Transition without Curb or Rubrail (*9*)	TxDOT Transition Bolted on Wingwall with Rubrail (*5*)	TxDOT Transition with No End-Shoe Block with Curb (*6*)
Dynamic Deflection (in.)	10.4	6.3	4

4.2.3. Vehicle Roll Angle

The vehicle roll angle is an important parameter in evaluating the performance of a transition system during an impact. It is a measure of the lateral rotation of the vehicle about its longitudinal axis. According to MASH, the maximum allowable roll angle is limited to 75 degrees (*1*). An excessive roll angle can result in a loss of vehicle stability and a higher likelihood of a rollover event, which can be catastrophic for the occupants of the vehicle. It is therefore critical that the transition system be designed and installed in such a way that the vehicle's roll angle falls within the specified limits. This can be achieved through a combination of factors, including properly designing the transition system, providing adequate backfill, and ensuring appropriate maintenance and upkeep of the transition system. To ensure that a transition system meets the MASH requirements, it is important to conduct regular inspections and maintenance activities.

4.3. FIELD VARIATIONS

4.3.1. Skipping/Missing a Transition Post

This section discusses the researchers' efforts to investigate the potential consequences of skipping a post in transition systems—a practice commonly found in roadways. Computer models representing each excluded post position within the transition system were created to analyze the consequences associated with field variation. The research in this study was limited to analyzing the effects of a single missing post in the transition system simulation. Results were compared against the evaluation criteria, as noted previously.

The calibrated baseline model presented in Chapter 3 was modified to represent the systems with a missing post in various locations through the nested thrie-beam region. Six missing post locations were examined. Because altering the system may affect the location of the CIPs, the first objective was to determine if the critical point of impact changed as a result of skipping any post. Therefore, a parametric analysis was conducted, and vehicle maximum roll angle and lateral ridedown acceleration were investigated. For clarity, the posts were numbered from upstream to downstream of the nested thrie-beam part of the transition system, as depicted in Figure 4.1.

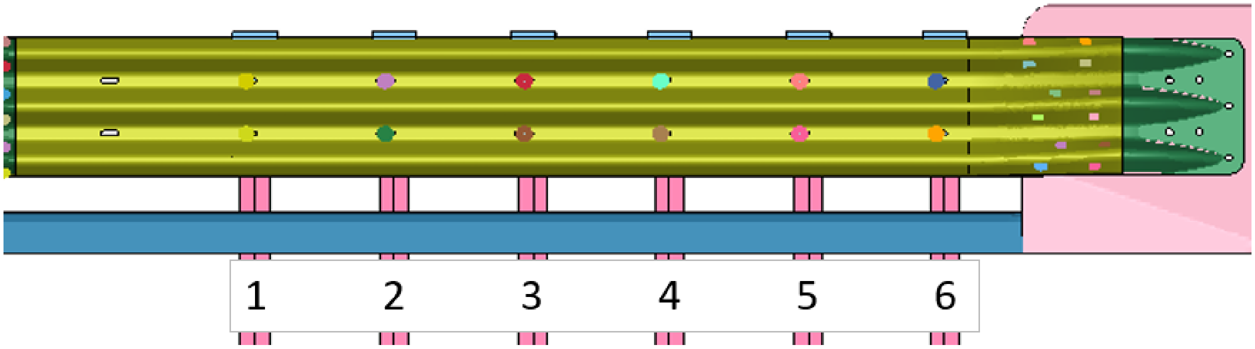


Figure 4.1. Missing Post Numbering.

For simplicity, each model was impacted at post locations along the transition system. As presented in Figure 4.2, regardless of the location of the missing post, the maximum roll angle was consistently highest when the vehicle impacted posts 1 and 2. This finding aligns with the results of the crash testing of the representative transition system, where the CIP was determined to be between posts 1 and 2 (*6*). Thus, it can be concluded that the CIP of the system remains unchanged even if there is a missing post through the nested thrie-beam section of the transition system.

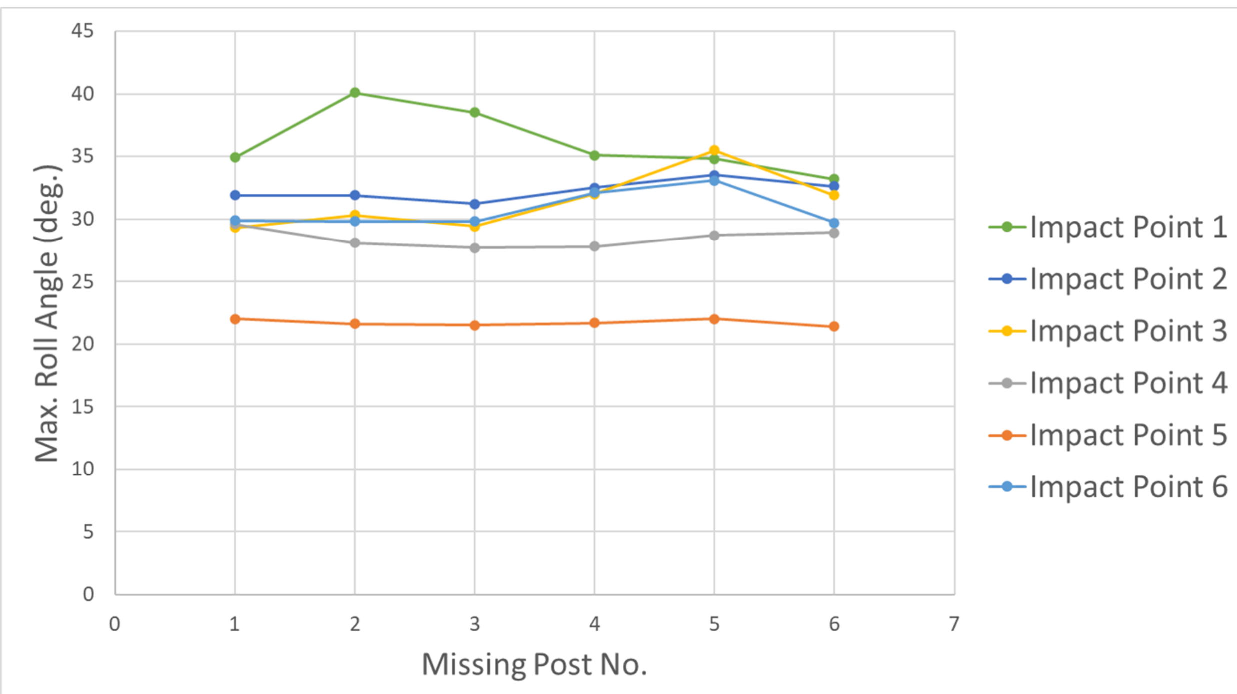


Figure 4.2. Parametric Analysis of the Systems with Missing Posts.

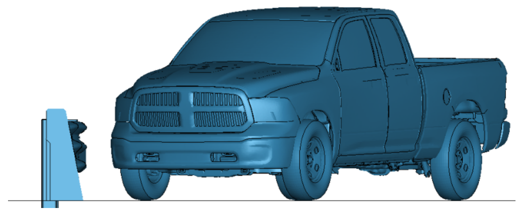
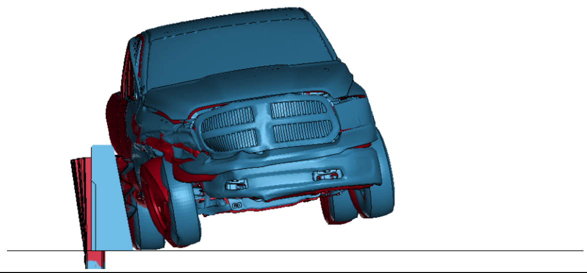
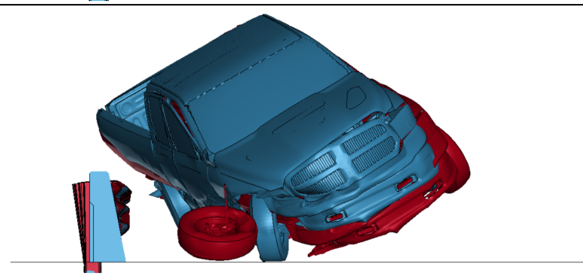
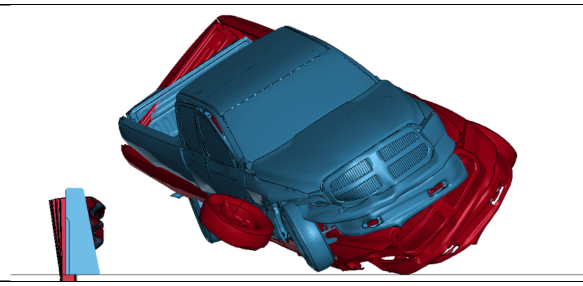
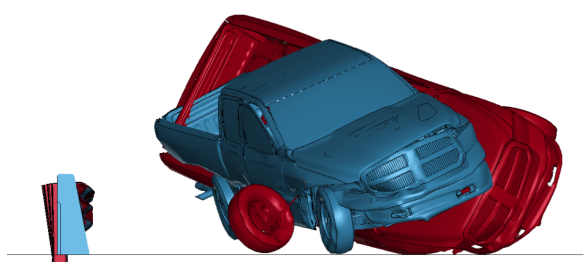
Table 4.2 presents the maximum values corresponding to each of the evaluation parameters for each transition with a missing post impacted at post 1. As shown, compared to the baseline system, the values of the evaluation parameters are higher for each variation of the transition system, which indicates an increased likelihood of failure upon impact. The roll angle values in particular are higher when the missing post is located upstream of the thrie-beam section, farther away from the parapet.

Table 4.2. Simulation Summary of Various Parameter Comparisons for Missing Post Cases.

Evaluation Parameter	Baseline System	Missing Post Location (Impacting at Post 1)					
		1	2	3	4	5	6
Max. Roll Angle (deg.)	32.7	34.9	40.1	38.5	35.1	34.8	33.2
Max. Lateral Ridedown (g)	12	13.5	12	14	14.1	13.3	13.2
Max. Dynamic Deflection (in.)	4	5.8	6.7	6.7	5.7	5.1	4.9

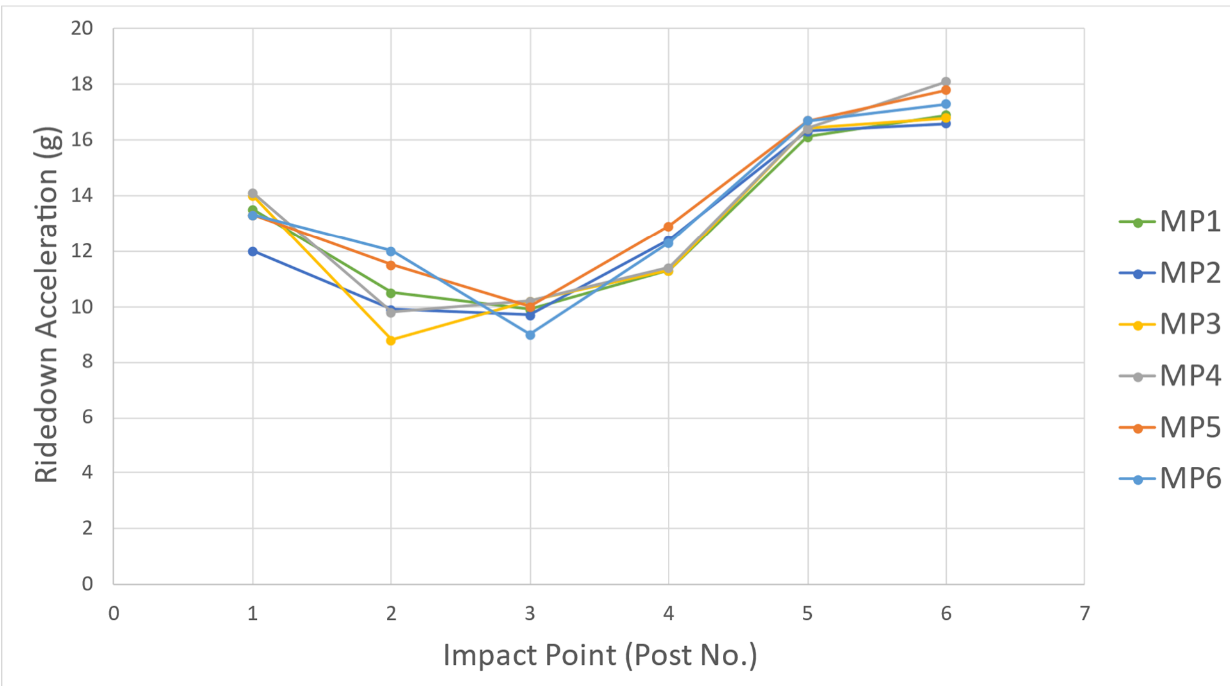
The study also investigated the effect of tire detachment on the performance of the transition system in the event of an impact. For this purpose, the appropriate level of failure was incorporated into the pickup truck suspension system to ensure a complete detachment of the tire from the suspension. The transition system model that showed the highest roll angle and deflection (missing post 2) was simulated under the scenario of tire disengagement. The results of the simulation showed that in the event of tire detachment, the roll angle increased significantly and there was a high possibility of the vehicle rolling over (Table 4.3).

Table 4.3. Sequential Image Comparison between the Baseline Model and the Model with Missing Post 2 When Tire Disengagement Is Activated.

Time (s)	Baseline Model (blue) vs. Missing Post 2 Model (red)
0.000	
0.200	
0.400	
0.600	
0.800	

The results of the simulation showed that skipping a post near the parapet of a transition system led to a higher ridedown acceleration, as shown in Figure 4.3. This finding was due to vehicle pocketing and excessive interaction with the blunt end of the parapet. The higher ridedown acceleration was a result of the vehicle impacting the parapet with more force and velocity. This could have potentially resulted in a more severe crash outcome and a higher risk of injury to the vehicle occupants. Since these results were based on simulations and may not necessarily reflect real-world outcomes, further testing and analysis may be required to fully understand the consequences of skipping a post in the vicinity of the parapet.

In the absence of a curb or rubrail in the transition system, the impact to the blunt end can be severe and result in a high value of ridedown acceleration or possibly rollover (*8*, *9*), which may ultimately result in the failure of the crash test. However, in this study, the presence of a curb in the transition system helped to mitigate this impact and reduce the severity of the crash by absorbing some of the energy from the collision.



Note: MP = Missing Post.

Figure 4.3. Effect of a Missing Post on the Lateral Ridedown Acceleration (Occupant Risk).

4.3.2. Reduced Post Embedment

Inadequate backfill leads to higher rail deflection, which consequently negatively impacts the performance of the transition system. In the results, the curb helped to limit excess deflections of the approach transition. However, the curb likely increased the probability of rollover due to a more severe tire-curb interaction. In some cases, this can even lead to vehicle rollover and ultimately cause the system to fail. It is important to ensure that proper backfill and drainage are in place to maintain the effectiveness of the transition system.

The exit box is a specific term within MASH (*1*). It is the area defined by the end of the barrier, the ground, and the lateral sides of the barrier that extends to a certain distance from the end of the barrier. The exit box is an important factor in determining vehicular stability because a high exit angle can result in the loss of control and stability of the vehicle. When a vehicle exits the transition system at a high angle, the vehicle may tip over, leading to a more severe crash scenario, or it may veer into oncoming traffic, causing a secondary crash. Moreover, the high exit angle can be caused by excessive dynamic deflection within the transition system, leading to pocketing or snagging of the vehicle. To maintain vehicular stability and reduce the risk of a high exit angle, it is important to design and implement transition systems that minimize dynamic deflection and vehicle pocketing.

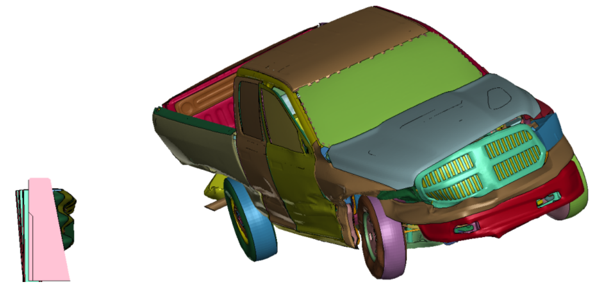
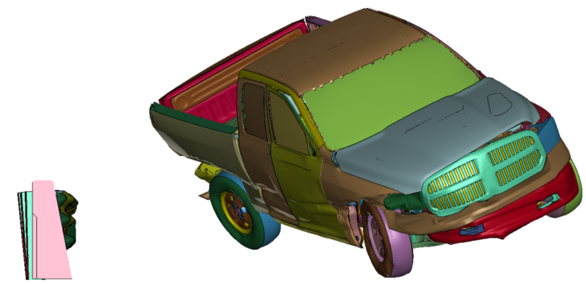
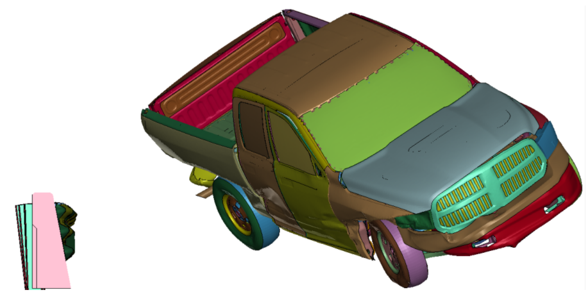
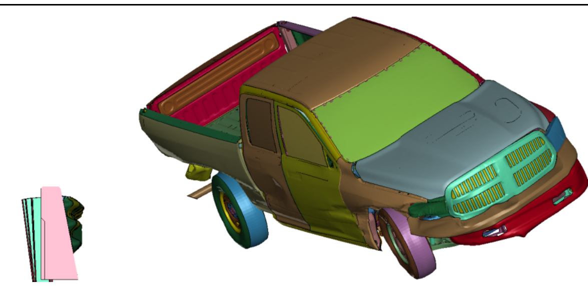
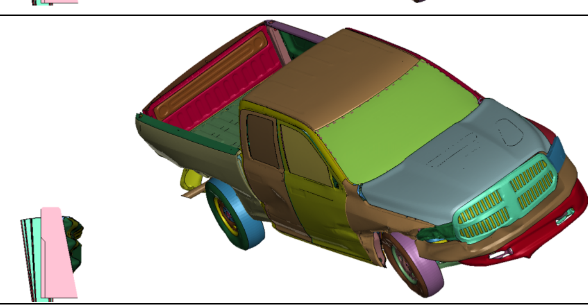
The purpose of the computer model modification was to study the impact of different backfill scenarios on the performance of the transition system. Table 4.4 shows a comparison of the baseline model with different cases where the backfill was reduced from 3 inches to 12 inches in increments of 3 inches. The comparison shows that as the backfill decreases, the yaw angle of the vehicle increases, leading to a higher probability of the vehicle encroaching into the opposite lane on roads without any median barriers.

Table 4.5 illustrates a qualitative comparison of the front view of the vehicle in different scenarios used to examine the roll angle of the vehicle. While this evaluation was subjective in nature, previous studies that were conducted using BARRIER VII computer simulation (*13*) suggested that up to 3 inches of lower backfill can be considered acceptable (*2*). However, beyond this level, lower backfill can result in higher roll angles, which can increase the risk of vehicle instability and pose a potential hazard to road users. Thus, it is crucial to consider the impact of backfill on vehicle stability in the design and evaluation of transition systems.

Table 4.4. Effect of Insufficient Backfill on Vehicular Stability—Top View.

	Pickup Position against the Transition at Time 0.8 s
Baseline	
3-in. Lower Backfill	
6-in. Lower Backfill	
9-in. Lower Backfill	
12-in. Lower Backfill	

Table 4.5. Effect of Insufficient Backfill on Vehicular Stability—Front View.

	Pickup Position against the Transition at Time 0.8 s
Baseline	
3-in. Lower Backfill	
6-in. Lower Backfill	
9-in. Lower Backfill	
12-in. Lower Backfill	

In addition, Table 4.6 demonstrates a clear correlation between the reduction in post embedment and the increase in the maximum dynamic deflection of the thrie-beam transition system. Maximum dynamic deflection is an important parameter that reflects the overall energy dissipation capacity of the transition system during an impact. A higher maximum dynamic deflection indicates that the system has a higher energy dissipation capacity, which is desirable in mitigating the risk of injury to vehicle occupants.

However, the increased maximum dynamic deflection also increases the possibility of vehicular instability since a more flexible transition system may not be able to control the vehicle's motion as effectively as its stiffer counterpart. This could lead to a higher likelihood of the vehicle encroaching into the opposing lane due to a larger exit angle (i.e., higher yaw angle) or even rolling over (i.e., higher roll angle), both of which are hazardous scenarios.

The results shown in Table 4.6 highlight the importance of ensuring proper post embedment depth in the installation of transition systems. A proper post embedment depth ensures that the transition system has sufficient stiffness to control the vehicle's motion during an impact and to prevent vehicular instability.

Table 4.6. Complete Evaluation Criteria of Reduced Post Embedment Cases from Computer Simulation.

Case	Backfill Level	Max. Dynamic Deflection (in.)	OIV (ft/s)		ORA (g)		Vehicular Displacement (deg.)		
			Long.	Lat.	Long.	Lat.	Roll	Pitch	Yaw
Baseline	**Ground Level**	4.6	17	30.1	5.2	12	32.7	5.4	46.3
Run 01	**3-in. Lower**	5.24	16.3	29.7	5.6	11.5	33.5	7.3	53.2
Run 02	**6-in. Lower**	5.86	16.3	29.7	5.6	11.9	37.7	9.8	59.2
Run 03	**9-in. Lower**	6.5	16	29.5	4.8	12.4	37	9.8	68.1
Run 04	**12-in. Lower**	7.04	16.1	29.4	4.8	11	39.2	10.6	86.2

Note: Long. = Longitudinal; Lat. = Lateral.

4.4. SUMMARY

The objective of this chapter was to assess the field variations of the representative transition system. To do this, two common field variations, namely skipping a post and reduced post embedment, were analyzed using computer simulations. The results showed that both variations led to an increase in vehicular instability, as there was a rise in the dynamic deflection of the transition system.

Chapter 5. SUMMARY AND CONCLUSIONS

Field variations of transition systems refer to differences in the design or installation of transition systems from the standard or recommended specifications. These variations can include differences such as skipping of a post to accommodate utility lines and reduction in post embedment depth due to inadequate soil backfill level. The presence of field variations in approach transition systems can alter the performance of the system during a vehicle impact event. As such, it is important to understand and investigate the effects of these variations or deficiencies on the safety performance of transition systems. This task can be done through physical crash testing or computer simulation.

The two field variations that were investigated through computer simulation in this study were missing post and lower embedment cases. In the missing post variation, the simulation analyzed the effect of a missing post in the transition system and evaluated the performance of the system under crash conditions. The results of the simulation showed that a missing post could significantly affect the performance of the transition system, increasing the risk of vehicular instability and rollover.

The computer simulation showed that skipping a post in the upstream region of the nested thrie-beam length results in a relatively higher deflection and higher roll angle. On the other hand, when any post in the vicinity of the parapet is missing, the outcome is an increase in ridedown acceleration resulting from vehicle pocketing and consequently the excessive interaction of the vehicle with the parapet blunt end.

In the lower embedment case, the simulation aimed to determine the impact of reduced soil backfill level on the overall performance of the transition system. A reduction in soil backfill level can result in reduced stiffness of the system, which in turn can lead to an increase in the maximum dynamic deflection. The results of the simulation showed that the increased flexibility of the transition system could result in higher exit angles and roll angles of the vehicle, which can negatively affect the stability of the vehicle and increase the risk of rollover events.

The transition system under study featured a concrete curb that played an important role in absorbing a significant amount of the impact energy during a crash. If a similar transition without the curb were to be studied, it is possible that different types of failures may occur. For instance, excessive deflection could cause the vehicle to vault or penetrate the approach transition. In addition, the lack of a curb could increase the interaction between the vehicle and the rigid barrier, potentially leading to more severe damage.

These findings emphasize the importance of considering proper treatment in cases where a post needs to be skipped or the backfill level is inadequate due to improper drainage systems. Proper attention to the backfill level can help ensure that the transition system retains its designed level of stiffness and performs as intended, providing a safer vehicle containment upon impact.

To improve the safety of approach transitions, transportation agencies may consider several measures, including reviewing their existing designs with crash-tested models, evaluating their approach transition design and construction procedures, providing training to their staff, and researching ways to improve existing transitions. While some modifications have not been thoroughly evaluated, additional research is recommended to identify potential issues and ensure the highest level of safety.

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