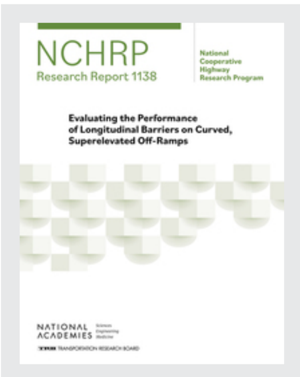

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NCHRP
Research Report 1138

National Cooperative Highway Research Program

Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps

NATIONAL ACADEMIES Sciences Engineering Medicine

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1138

Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps

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in cooperation with the Federal Highway Administration

NATIONAL ACADEMIES *Sciences Engineering Medicine*

TRB TRANSPORTATION RESEARCH BOARD

2025

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state department of transportation (DOT) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation.

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The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors, the FHWA, and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and oversight of research contracts are the responsibilities of NCHRP.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 1138

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FOREWORD

By Roberto Barcena
Staff Officer
Transportation Research Board

NCHRP Research Report 1138: Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps presents insights and guidelines related to the performance of longitudinal barriers placed on varying curved, superelevated ramp sections. The insights and guidelines were developed using vehicle dynamics analyses, finite element crash simulations, and full-scale crash testing.

This report will be of immediate interest to highway designers and safety staff at transportation agencies who seek safer practices in designing, selecting, and deploying longitudinal barriers on curved, superelevated off-ramps.

Longitudinal barriers are roadside safety devices commonly used to prevent errant vehicles from impacting hazards located alongside the traveled way. These barriers have been placed along the roadway, ranging from rigid concrete parapets to semi-rigid beam guardrails to relatively flexible wire rope barriers. Historically, the development and testing of longitudinal barriers have been conducted under the assumption that the barriers are installed in relatively straight sections parallel to the roadway. While the barriers designed under this assumption have performed well, their behavior when installed on curved roadways is largely unknown.

In NCHRP Project 22-29, “Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections” and NCHRP Project 22-29A, “Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections,” vehicle dynamics analyses and crash simulations were applied to determine the effects of typical vehicles leaving the roadway and impacting roadside barriers to evaluate vehicle-to-barrier interfaces and crash impact outcomes for a broad range of conditions (e.g., speed, impact angle, surface profile, vehicle type, barrier designs, and road features).

Under NCHRP Project 22-29B, “Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps,” George Mason University was asked to propose guidelines for selecting and designing traffic barriers for curved, superelevated off-ramps.

In addition to the report published as *NCHRP Research Report 1138*, the following deliverables can be found on the National Academies Press webpage for *NCHRP Research Report 1138: Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps* (https://doi.org/10.17226/28589) under “Resources at a Glance”:

- Appendices A–C
- Appendix D
- Appendices E–J
- A presentation with a summary of the project findings, including embedded simulation animations and crash-testing videos

CONTENTS

CHAPTER 1

Introduction

1.1 Background

The safety performance (i.e., crashworthiness) of longitudinal barriers has traditionally been evaluated under idealized impact conditions (i.e., a straight linear section of the barrier is installed on level terrain and the impacting vehicle is freewheeling with minimum roll and pitch effects). This protocol has evolved to provide a "practical worst-case" impact condition that is reproducible and comparable. In reality, barriers get installed on tangent and curved sections of mainline highways and can be impacted under various conditions. Commonly, similar barriers are installed for safety continuity from mainline highway sections into tighter, curved, superelevated roadway sections for on- and off-ramps. These barriers may have varying radii and superelevation to safely accommodate transitioning traffic. In some situations (e.g., urban areas), tighter radii are more often needed for on- and off-ramps where land space is limited. Vehicles traversing these curved situations are often traveling at speeds higher than posted, raising concerns about leaving the roadway. Thus, similar barriers are continued through these sections. Because the possibility of leaving the travel lane can be increased by higher speeds for the curve, whereby the vehicle traverses the lateral superelevation and shoulder slope before impacting the barrier, the nature of the impact can influence the adequacy of the barrier.

To analyze the safety effectiveness of barriers used on curved, superelevated roadways, NCHRP has undertaken multiple research efforts:

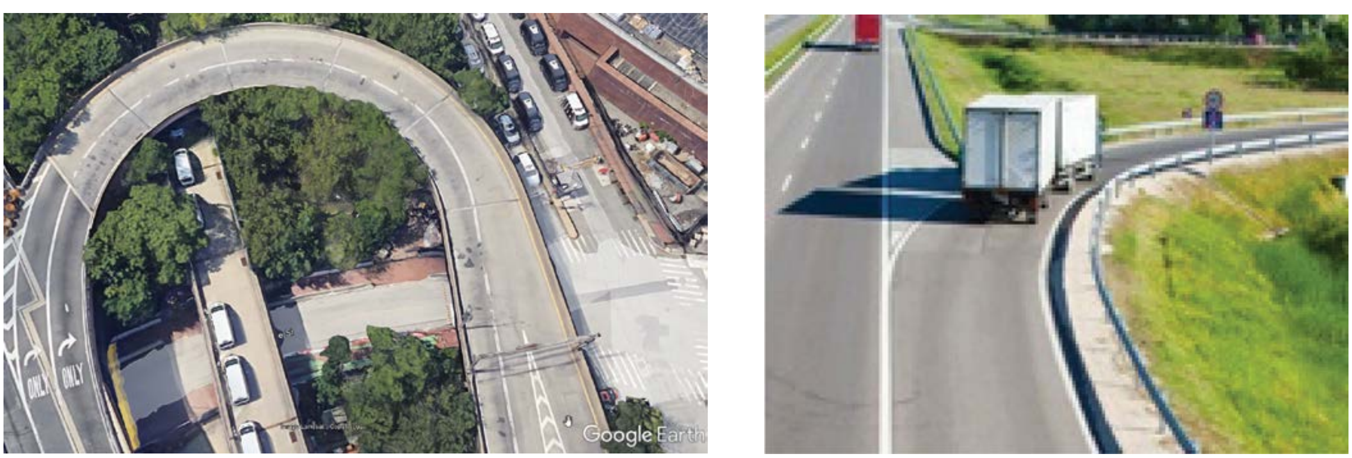
- NCHRP Project 22-29, "Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections"
- NCHRP Project 22-29A, "Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections"
- NCHRP Project 22-29B, "Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps"

These efforts developed a better understanding of the safety performance (i.e., crashworthiness) of barriers used on curved, superelevated roadway sections and recommended options and guidelines for improving barrier selection, design, and deployment in pursuit of enhanced highway safety. The need for these research efforts was predicated by the limits of safety performance evaluation of longitudinal barriers, which, under current and past crashworthiness evaluation criteria, was focused on idealized impact conditions. It was recognized that the barrier can be impacted in a variety of ways, but little effort had been made to understand the nature of impacts under such conditions and to adapt barrier deployments for addressing the variations in impacts on curved, superelevated roadway sections.

Recent research has found that departments of transportation (DOTs) have individually developed practices for the installation of barriers for curved, superelevated roadway sections to offset limited guidelines in both the AASHTO *Policy on Geometric Design* (the Green Book) (*1*) and *Roadside Design Guide* (*2*). NCHRP Project 22-29 research was undertaken to advance the understanding of barrier performance using state-of-the-art analysis approaches and translate the findings into enhanced guidelines for the design, selection, and installation of concrete and steel W-beam longitudinal barriers installed on curved sections of roadways. Curved roadway sections are generally constructed with superelevation to compensate for the centrifugal forces exerted on vehicles and to make it easier for the driver to control the vehicle through the curved section. The analyses provided a means to analyze the combined effects of curvature, superelevation, and shoulder slope on vehicle dynamics for varying vehicle trajectories, orientations, and speeds.

NCHRP Project 22-29B research found that dynamic effects can significantly affect the interface between the vehicle and the barrier during a crash as the vehicle leaves the road. On curved sections, the vehicle is more likely to leave the road at a higher angle and consequently impact the barrier with higher impact severity. The higher impact severity can lead to increased forces on the occupants (and hence occupant risk metrics), more intrusion into the occupant compartment, and ruptured barriers or unusual interactions between contacting components. In addition, a higher impact angle can increase vehicle instability and may lead to vehicle rollover, override, or penetration behind the barrier. The higher impact angle increases the tendency for vehicles to climb rigid barriers and for tire and post snagging to occur for semi-rigid strong-post barriers. Furthermore, the road superelevation will cause the vehicle to approach the barrier at a different orientation (roll and pitch) or height relative to the barrier than would be the case on a flat surface. This is particularly critical when a shoulder has a negative slope relative to the roadway superelevation.

NCHRP Project 22-29 and NCHRP Project 22-29A research could not fully address barrier performance for all curved, superelevated section conditions, so it addressed a range of the most common conditions. The resulting insights provided the basis for proposed new approaches and criteria for barrier design and placement on curved, superelevated off-ramps. This additional research effort, NCHRP Project 22-29B, was initiated to continue the analyses for "tighter" curves typical on highway ramps, where opportunities to achieve the desired design and placement options are typically more limited. This research was initiated with such roadways being called curved, superelevated, off-ramps (CSORs). Examples of longitudinal barrier installations on long- and short-radius CSORs with concrete and steel longitudinal barriers are shown in Figure 1.



(a) (b)

Figure 1. Examples of (a) concrete and (b) steel beam longitudinal barriers on ramps.

1.2 Objective

The objective of this research was to gain additional insights and establish guidelines relative to the crash performance of longitudinal barriers placed on varying curved, superelevated ramp sections. The goal was to apply the analysis approach and models from the completed research in a focus on ramp situations to develop appropriate recommendations for the selection, design, and installation of barriers for such ramp situations. These efforts employed the successful approach used in the previous research to consider the broad set of variables (e.g., road curvature; superelevation; barrier design and type; vehicle size; impact angle and speed; shoulder slope and width; barrier location, height, and orientation) relative to the effectiveness of longitudinal barriers on curved, superelevated highway ramps. The research began with reviews of current practices and designs for barriers on highway ramps. The efficacy of the typical designs for barriers on ramps was critically evaluated using vehicle dynamics analyses, finite element crash simulations, and full-scale crash testing. These efforts are believed to have resulted in new insights on the relative effectiveness of various barrier design, selection, and deployment practices for applications of longitudinal barriers on curved, superelevated off-ramps.

1.3 Research Approach

This research effort followed the successful approach used in NCHRP Research Projects 22-29 and 22-29A. In these efforts, vehicle dynamics analyses and crash simulations were applied to determine the effects of typical vehicles leaving the roadway and impacting a roadside barrier. These analytical tools have been demonstrated to be effective for evaluating vehicle-to-barrier interfaces and crash impact outcomes for a broad range of conditions (e.g., speed, impact angle, surface profile, vehicle type, barrier designs, and road features). This depth of analysis had been shown to provide micro-level indications of barrier effectiveness that would allow agencies to generate recommendations for design guidelines.

Vehicle dynamics analyses and crash simulations were applied to analyze a set of short-radii curved, superelevated ramp sections and a range of vehicle types and impact features. This approach provided a wealth of data for prospective impacts at varying angles over a broad array of typical CSOR design conditions. The research used vehicle dynamics analyses to provide broad insights into variations in barrier effectiveness, supported by deeper analyses using finite element simulation to provide an understanding of impact physics. This was followed by crash testing to validate the findings.

1.4 Organization of Final Report

This final report is intended to provide a synopsis of relevant information and knowledge acquired or developed in the research efforts and to translate the findings into new insights and guidelines for effectively addressing specific needs for barriers used on all varieties of curved, superelevated highway ramps. The report incorporates the methodologies and findings derived from previous efforts under NCHRP Projects 22-29 and 22-29A. The report includes the following:

- Chapter 1: Introduction
- Chapter 2: Background Studies
- Chapter 3: Vehicle Dynamics Analyses
- Chapter 4: Crash Simulation Analyses
- Chapter 5: Full-Scale Crash Testing
- Chapter 6: Research Conclusions and Guidelines for Longitudinal Barriers on CSORs
- Chapter 7: References

This document is intended to (1) provide a concise overview of the relevant findings from related research efforts; (2) document the background studies and analyses completed focusing on issues and considerations for "tight" CSORs; (3) present the conclusions drawn from the various aspects of this research effort; and (4) offer recommendations for improving the design, selection, and deployment of longitudinal barriers on curved, superelevated ramps. The findings provide useful insights into the design, selection, and deployment of common barriers used on curved, superelevated ramps. The findings are also presented in a manner that readily allows agencies to assess their current design guides or inspect specific barrier installations in the field and determine potential effectiveness. The report documents the methods and depth of the research undertaken.

CHAPTER 2

Background Studies

NCHRP Project 22-29A led to the publication of *NCHRP Research Report 894: Performance of Longitudinal Barriers on Curved, Superelevated Roadway Sections* (*3*). In this project, efforts were undertaken to expand the review of the literature to curved, superelevated ramp sections, which generally involve the design of tighter curves to accommodate high-speed movement to, from, and between major highways. As with the previous efforts, the need existed to focus on the design features for CSORs as well as the current practices for deploying barriers on them. Insights were obtained from a literature review as well as contacts with agencies. National sources of data were used to see locations identified by some of the states. These served as real examples of situations for which updated guidelines could be applied. Efforts for NCHRP Project 22-29A provided a background of specific conditions in which agencies sought enhanced guidelines. The findings of both the literature review and the agency contacts are provided in the next sections.

2.1 Literature Review

Earlier efforts (such as NCHRP Project 22-29A) provided the basis for a more detailed literature review, which identified documents related to the analyses of longitudinal barrier crashworthiness. These efforts date back to the previous crashworthiness standards based on *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (*4*) and extend to evaluations under the Manual for Assessing Safety Hardware (MASH) (*5*). It was noted that:

- The bulk of the literature on longitudinal barrier crashworthiness is focused on analyses and testing for straight sections on level terrain. This results from the formulation of crashworthiness criteria based on reproducible "practical, worst-case" scenarios. These documents (not specifically summarized in this report) provide an understanding of the impact performance of these types of barriers.
- Some testing in the early 1990s under the *NCHRP Report 230* criteria showed that various Thrie beam designs would function better than W-beam guardrails on curved sections (*4*). More recent analyses, using simulations, evaluated the performance of concrete barriers behind sloped surfaces (*6*, *7*). These were noted to function adequately. A recent comprehensive evaluation of crashworthiness for barriers on CSORs has not been conducted.
- The Green Book (*1*) and *Roadside Design Guide* (*2*) do not provide special guidelines for longitudinal barriers on CSORs or curved ramps.
- The literature includes numerous examples of the use of simulation tools to analyze barrier performance for various types of impacts, with some recent efforts investigating the effects of sloped conditions.
- Review of the *Roadside Design Guide* (*2*) revealed no specific recommendations for longitudinal barrier installations on curved or superelevated road sections (i.e., barrier installations

on curves follow the same guidelines as for straight roads). These recommendations suggested that:

- Barriers should not be installed on slopes steeper than 6:1 unless the barrier has been tested and found to meet the *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features* (*8*) or MASH (*5*) evaluation criteria.
- Only flexible and semi-rigid barriers should be installed on slopes steeper than 10:1.
- Barriers should be placed as far as possible from the traveled way as is practical without hindering its proper operation and performance. Barrier offset distances (i.e., the shy line) range from 4 ft for a 30-mph design speed to 12 ft for an 80-mph design speed.

These findings were not considered significant enough to alter the identified focus on barriers on CSORs.

The key findings of the literature review undertaken for NCHRP Project 22-29 included the following:

- The AASHTO Green Book (*1*) and *Roadside Design Guide* (*2*) provide the fundamentals for barrier design and deployment on U.S. highways. These documents provide the prevailing rationale, conditions, and parameters for barrier needs; the recommended types; and deployment (placement) details for longitudinal barriers on high-speed, curved, superelevated road sections (CSRSs).
- The AASHTO Green Book (*1*) provides guidelines for curve design that address design speed, maximum superelevation rate, side-friction factor, superelevation distribution methods, selection of curvatures and superelevation, and shoulders. The guidelines establish a safe and comfortable driving environment on curved road sections. These guidelines are used by most states for curve and superelevation design and include the following recommendations:
  - Vehicles traveling on curved roads are subjected to centrifugal force that pushes the vehicle outward from the center as a function of increasing vehicle speed or decreasing radius of curvature. Superelevation is the sloping (banking) of the road to oppose centrifugal force. For high-speed roadways, the Green Book–recommended range for maximum superelevation rate is 6% to 12%. This range is reduced to 6% to 8% in regions where snow or ice is of concern, considering that vehicles traveling at low speeds in snowy or icy conditions tend to slide on roads with high superelevation.
  - The Green Book cites the need for side friction to resist the lateral centrifugal force for a vehicle traveling on a curved road through a combination of superelevation and the friction between tires and the road surface. For a given vehicle speed and curvature radius, an increase in superelevation leads to a lower lateral-friction force (i.e., a larger portion of the centrifugal force is resisted by the superelevation). The side-friction factor is the ratio between this lateral-friction force and the weight of the vehicle (with a small conservative simplification).
  - The Green Book defines design speed as "a selected speed used to determine the various geometric features of the roadway" based on the topography, anticipated operating speed, adjacent land use, and functional classification of the highway. The design speed affects superelevation and curvatures as well as several other design parameters. The Green Book recommendation for minimum design speed on high-speed roadways (highways) is 80 km/h (50 mph). The use of design speeds of 100 km/h (60 mph) or higher is encouraged for urban highways, as the speed can be achieved with minimal additional costs. A 110 km/h (70 mph) design speed is recommended for rural highways and interchange locations consistent with higher design speeds. For mountainous terrain, a design speed of 80 to 100 km/h (50 to 60 mph) is recommended.
  - The Green Book gives an approximation of running speed as a function of design speed. The Green Book recommends that shoulders in heavily traveled high-speed highways be at

least 3 m (10 ft), with a width of 3.66 m (12 ft) preferable. On 4-lane highways, the recommended shoulder width on the left side of the road is 1.22 to 2.44 m (4 to 8 ft) and on the right side is at least 3 m (10 ft). Asphalt and concrete shoulders should be sloped from 2% to 6%. Gravel or crushed rock shoulder slopes should be from 4% to 6% and turf shoulders, 6% to 8% percent.
  - The minimum curvature radius defines the sharpest curvature for a given design speed, maximum superelevation, and maximum side-friction factor.
  - For a given design speed and road curvature, several combinations of superelevation and side friction can be used to resist the lateral centrifugal force. The Green Book lists five methods for the distribution of the superelevation and lateral-friction forces. For high-speed roadways, the Green Book recommends the last method (Method 5). In this method, the superelevation and side friction have a curvilinear relationship with respect to the inverse of the curvature radius.
- Few state-specific road design guidelines were obtained from a state agency survey (see Section 2.2), and a review showed that these guidelines are similar to the Green Book. No specific information was found related to longitudinal barrier installations. A few differences were noted between state DOT and Green Book guidelines, such as maximum superelevation rates, side-friction factors, and superelevation design tables.

The *Roadside Design Guide* revealed no specific recommendations for longitudinal barrier installations on curved and superelevated road sections (*2*). Barrier installations on curves follow the same guidelines as on straight roads. A few recommendations related to the research topic are as follows:

- A barrier should not be installed on a slope steeper than 6H:1V unless it has been tested and found to meet *NCHRP Report 350* (*8*) or MASH (*5*) evaluation criteria.
- Only flexible and semi-rigid barriers should be installed on slopes steeper than 10H:1V.
- A barrier should be placed as far from the traveled way as possible without hindering its proper operation and performance. Barrier offset distances (i.e., the shy line) range from 1.22 m (4 ft) for a 50 km/h (30 mph) design speed to 3.66 m (12 ft) for a 130 km/h (80 mph) design speed.

Previous efforts focused on "roadway sections" and aimed to develop a better understanding of the safety performance (i.e., crashworthiness) of barriers used on CSRSs. The findings led to recommendations for improving barrier selection, design, and deployment in pursuit of enhanced highway safety for CSRSs.

2.1.1 Expanded Literature Review

Highway or highway ramps are typically curved, superelevated roadway sections as well. Chapter 10 of the Green Book addresses grade separation and interchanges. It defines ramps as "all types, arrangements, and sizes of turning roadways that connect two or more legs at an interchange. The components of a ramp are a terminal at each leg and a connecting road" (*1*). It notes that the geometry of the connecting road usually involves some curvature and a grade. Generally, the horizontal and vertical alignment of ramps is based on lower design speeds than the intersecting highways, but in some cases the alignment may be equal.

The Green Book notes that such ramp designs are needed to accommodate high volumes of traffic safely and efficiently through interchanges or special features that include varying degrees of grade separation with varying layouts of ramps to offer effective connections between the intersecting roadways (*1*). These are shown in Figure 2 and Figure 3. Although the literature review findings previously described remain the same and continue to be applicable for the "ramps" associated with interchanges, one thing is readily obvious in the Green Book—these "ramp" roadways take many configurations. These figures include both "off" and "on" ramps (or "exit" and "entrance" ramps) that in some cases reflect similar geometrics.

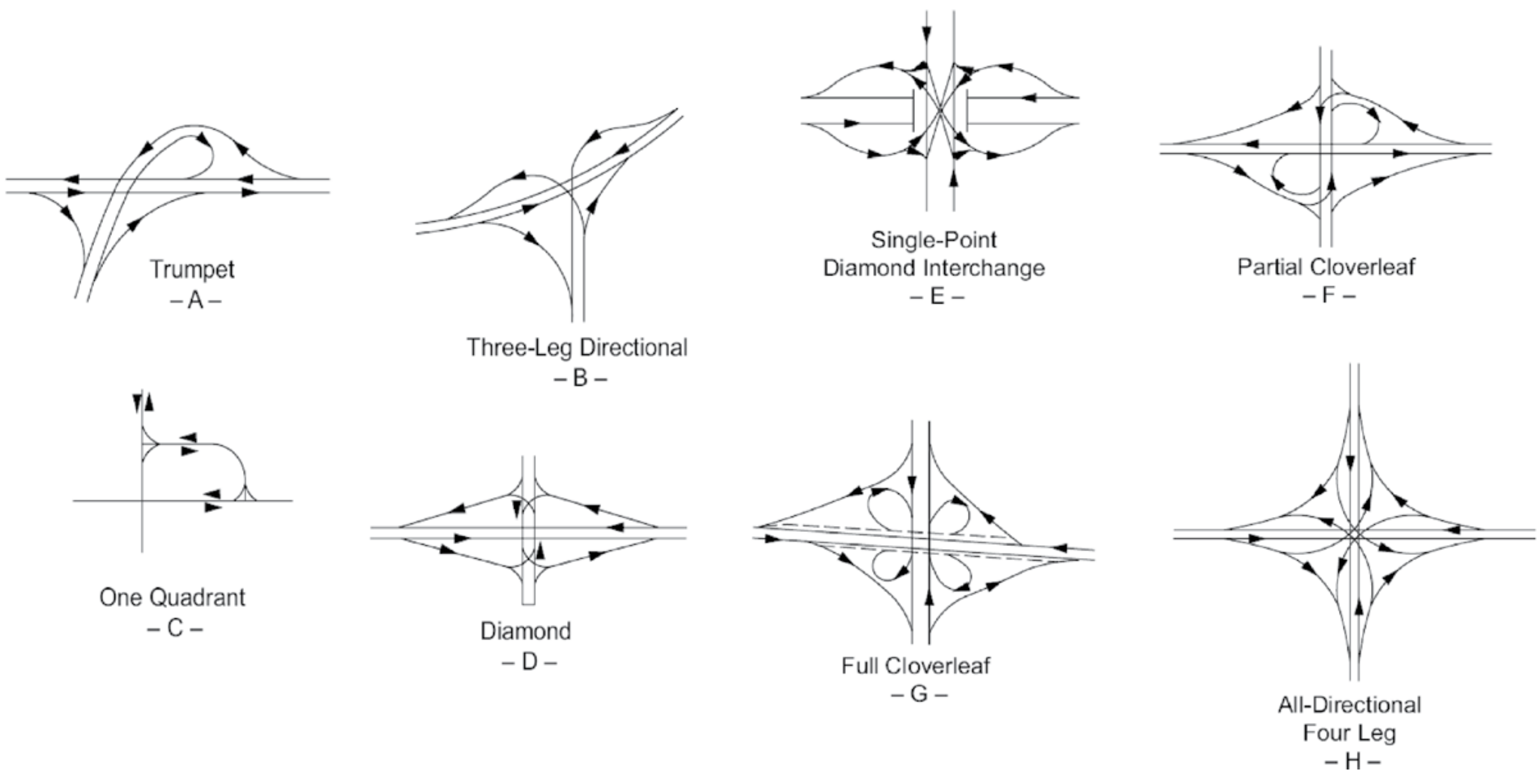


Figure 2. Typical interchange configurations showing various ramp configurations.

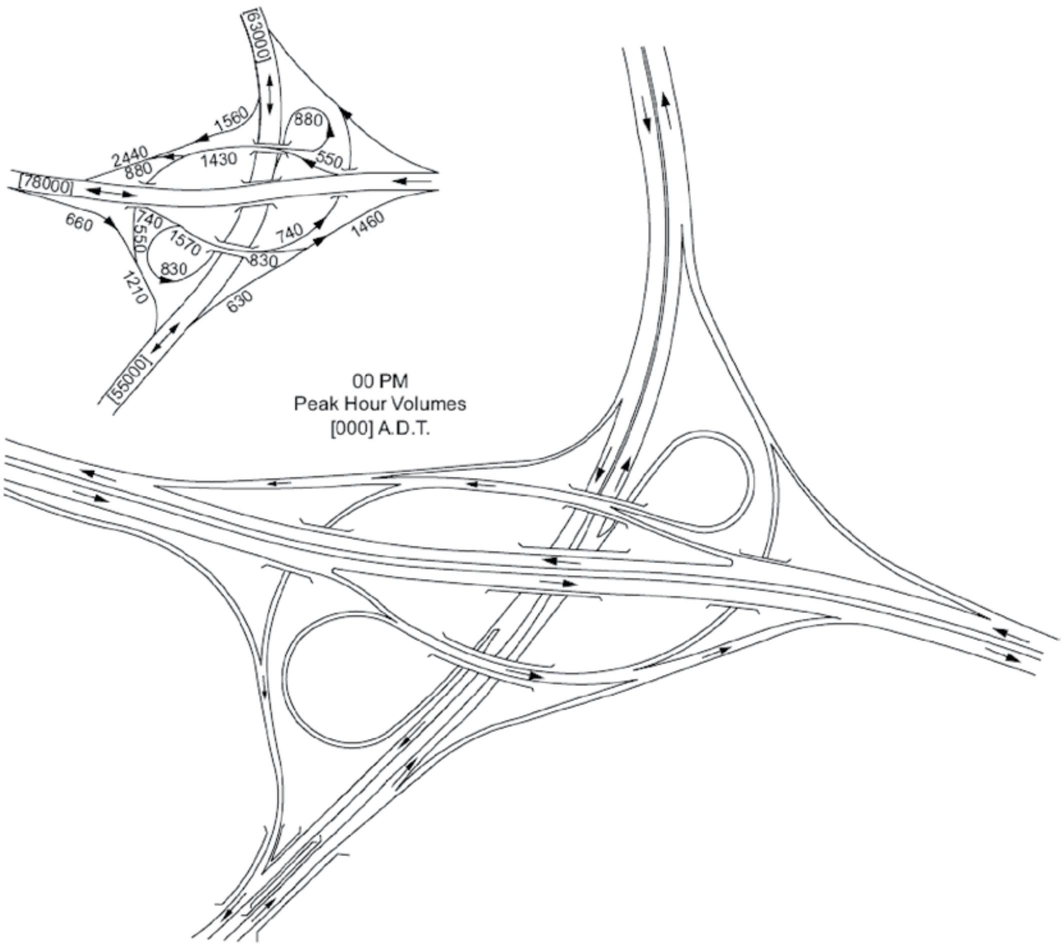


Figure 3. Complex interchange with ramps for varying traffic levels and alignments.

The literature search was expanded to studies about the relative effectiveness of ramps. This was undertaken with the knowledge that past efforts to analyze ramp crashes were limited by multiple issues that prevented effective analysis. Typically, such analyses were limited by issues in getting the pertinent data, such as getting design features for ramps, accurately locating crashes to specific ramps and along them, isolating details about barriers, and finding information on driver behavior, the vehicle, the nature of the impact, and crash outcome. In the previous research, no extensive studies were isolated for crashes on curves, nor were any cited by respondents to the survey undertaken for this project. It was also noted that the Green Book does not cite anything about the relative performance of various types of ramps; however, it does seem to provide general guidelines about the qualitative factors to consider in designing a ramp and its features to address varying aspects of traffic, speeds, and control (*1*).

A Transportation Research International Documentation (TRID) search was undertaken for the key words "ramp safety," and several relevant studies from the last 10–15 years were revealed. These efforts indicated a variety of characteristics that differentiate ramps.

The initial research focused on the viability of curved, superelevated roadway sections of various designs over a range of curvature. Curves with radii of 600–700 ft are typical of many highway ramps, but no specific distinction was made in the safety analyses relative to ramp sections. Previous analyses of curve safety conducted using typical aggregated data found that curvature, barrier types, and barrier safety influence safety individually. Only limited insights were found relative to crash causation and severity or to related factors for ramp sections.

Safety insights for highway ramps have long been limited. Traditionally, crash data analyses provided important insights on street and highway design. Analyses of the frequency and severity of crashes provided a useful metric based on the ability to locate the crash and isolate the factors at the site and the behavior of traffic and drivers. The viability of such analyses has been limited by the accessibility of crash data, its geometric curvature detail, and, critically, the specific crash location. It was also common that the locations of highway features were not properly recorded (i.e., positions of barriers relative to the traveled way). Initial designs failed to provide the needed dimensions after maintenance or modifications led to changes in positions.

The basic data may exist in some agencies, but the details of locating crashes on specific ramps and points on the curve often make such efforts difficult. In this effort, DOTs were specially asked if they had undertaken safety analyses for ramps, but none were cited. It would be useful to undertake a comparative analysis of crash data for ramps to understand the critical elements and the relative performance of barriers deployed on ramps, but this was not considered readily possible nor within the scope of the project.

As an alternative, the survey asked that agencies provide the names of specific ramps in their states that experience more crashes than the norm. Only a few sites were cited, and the pertinent crash data was not provided. These sites were reviewed through digital aerial imagery and are reported under Section 2.3, the review of typical sites.

Efforts to address the general need for a more analytical approach to understanding highway safety, and more importantly, continually maximizing it, helped promote the concept of safety performance functions (SPFs) and crash modification factors (CMFs) (*9*). These evolved from the long-standing interest in having a basis for quantitatively selecting between alternatives. Efforts to create functions and factors to provide an analytic metric started slowly by trying to determine the likely benefit for improvement. Efforts to develop the *Highway Safety Manual* (HSM) (*10*) to share the knowledge gained and enhance the overall safety improvement process led to more efforts in this area. The efforts also tried various methods to account for the contributions of multiple safety improvements. These factors would, in the simplest sense, indicate the degree of safety improvement that might be possible for a given type of change. These efforts also expanded into a broader array of safety improvement needs, including some related to highway ramps. Torbic et al. published *NCHRP Web Document 227: Design of Interchange Loop Ramps and Pavement/Shoulder Cross-Slope Breaks* in 2016 (*11*). They noted that the limited research on the design, safety, and operational characteristics of loop ramps was a major impetus for the effort. The authors differentiated between exit and entrance ramps.

In the efforts to develop improved guidelines for the design of interchange loop ramps and pavement shoulder cross slopes, Torbic et al. examined both entrance and exit ramps because of their differences in vehicle speed and positioning (*11*). These efforts were based on data from 28 ramps that were about equally split between entrance and exit ramps. Vehicle speed data was gathered from driver observations for various points on the ramps and analyzed. Data revealed that speed varied along the lengths of the ramps and was higher in some cases for entrance ramps. Torbic et al. noted differences in the performance between loop and diamond ramps and analyzed multiple lanes and other factors. The document recommended guidelines for ramps with curvatures from 100–300 ft with design speeds from 20–35 mph. These are lower than the design speeds used in the analyses for CSRSs. The Torbic et al. efforts led to guidelines for curvatures and cross slopes, but they did not reflect the needs for barriers and where they should be placed. These efforts developed SPFs intended to support the HSM (*10*), and hence focused more on ramps as an interchange element that can be given an SPF metric. The document noted that these metrics had limits that required further efforts to improve.

Torbic later teamed up with Harwood and Bauer to take a similar approach, examining the differences between loop and diamond ramps (*12*). This effort involved data from 235 loops and 243 diamond ramps in California and Washington, with 5 years of crash data. Torbic, Harwood and Bauer presented data from the study, noting that free-flow loop, partial loop, and diamond ramps, with minimum radii of 78, 137, and 193 ft, respectively, did not show a consistent pattern for whether the entrance or exit ramps had the minimum radii. These efforts led to improved SPFs to support the HSM (*10*). The comparison of the actual data with the predicted numbers found that more specific calibrations were needed.

Torbic and Brewer (*13*) later looked deeper into loop ramps and recommended that they be designed to (1) have radii, design speeds, and lane and shoulder widths that induce speeds lower than the design speeds and (2) have added lane width for outer lanes on multi-lane ramps to better accommodate the speed differences between cars and trucks. These recommendations also included updates to the SPFs developed.

Others have focused more on other speed distribution aspects of ramps, namely, understanding speed profiles of vehicles on ramps and how a vehicle's relationship to the adjacent deceleration lanes influences the driver's propensity to exceed the critical speed when negotiating a ramp. Choi et al. (9) developed SPFs for direct, semi-direct, and loop interchanges. These SPFs were based on the radius of curvature, grade, and lengths of acceleration and deceleration lanes for 201 ramps in Korea in 2007. These analyses of 3 years of data for six interchanges provided the basis for a binomial-based predictive function used to predict the expected number of crashes that would occur for each type of ramp. The initial error rates were high in some cases, but theoretically, as more data is acquired, the reliability of the function will improve. This study is believed to suggest that intrinsic differences exist between ramps. It is unclear from the results whether other factors would be useful for understanding the relative safety of the ramps. These efforts did not consider the width of the road, the shoulders, or the nature of barriers on the ramps. It is possible to isolate other factors, but such efforts were not included in this study.

Van Beinum (*14*) studied turbulence at motorway ramps in the Netherlands. His thesis was that a raised level of turbulence exists around interchanges from the vehicles entering and exiting the highway, and from the behavior of drivers as they anticipate and adjust speeds and position for these maneuvers. Van Beinum's efforts noted that there are two major problems with current roadway design guidelines with respect to turbulence: limited understanding of the effects of turbulence and the lack of quantitative metrics about the relative implications for varying turbulence from design guides. He used the Vissim simulation tool to analyze turbulence effects and found correlations between the intensity and the location of lane changes. The analyses were conducted for on- and off-ramps, and it was noted that on-ramps had lower turbulence. The efforts did not isolate the effects of other aspects of ramp design. The guidelines were examined to determine whether a distinction exists or can be made that might be applied to the designs for ramps, but little empirical data was reported.

Abatan and Savolainen (*15*) used 2010–14 data for more than 400 interchanges in Iowa. This study examined six types of interchanges and noted variations in their safety. SPFs were developed for the various types of interchanges, considering volumes, speed, length, and on- or off-ramp signalization. The SPF models were used to analyze the mainline effects on ramp safety. The models were compared with those developed for Florida interchanges and results from SafetyAnalyst software. This effort indicated that there are differences in interchange safety that can be predicted.

Naturalistic driving studies (NDSs) were initiated some 15 years ago in an attempt to capture more detailed data that would permit deeper analyses into the influences of highway design, traffic conditions, and area features on driver behavior and performance. The efforts began using driver- and road-directed cameras to record actions related to traffic situations. Various technologies were integrated to expand data gathering to include more than 100 variables related to location, vehicle control inputs, road conditions, and driver actions and attention.

Under the Strategic Highway Research Program (SHRP), the owners of several thousand vehicles in 10 states reflecting the various U.S. regions agreed to have their vehicles instrumented for the NDS effort. Each vehicle served as a probe, gathering detailed information on highway travel and the prevailing traffic conditions for wide parts of the national network. The driver's control actions, behavior, and attention for the traffic condition were continually monitored. Traffic conditions were captured from views of the road. Therefore, it was possible to create an extremely detailed driving record for each trip, which could be used to analyze behaviors in varying situations, such as on highway ramps. The massive database that has been created has only been partially tapped by researchers to address specific questions, although several efforts have been made to address questions related to ramp performance.

The SHRP 2 Naturalistic Driving Study (SHRP2 NDS) database provides thousands of observations over a large sample of drivers (albeit those who knew that they were being monitored during the study). Repeated observations for the same driver were included to offer a means to track their consistency. Many of the initial efforts to exploit this database have been undertaken by the human factors experts who originally developed the NDS concept. As a result, most of the studies have tended to focus on driver performance aspects and not highway design or safety issues. Those aspects are, however, possible, as the data set does include actual crash events.

Other efforts have been made to understand and control ramp speeds, an important factor in run-off-road crashes. Dadashova, Dixon, and Avelar (*16*) explored the effect of important predictors of ramp speed choice. Their analyses were based on SHRP NDS data on 32 participants for more than 850 trips that provided a rich source of information about driver inputs and reactions when negotiating ramps. The effort examined four interchanges that included diamond, trumpet, and partial cloverleaf designs. The analysis focused on driver characteristics, including age, gender, depth perception, sleeping habits, and Barkley's ADHD screening metrics. Using various statistical techniques, Dadashova, Dixon, and Avelar examined behaviors related to street-to-highway merging and highway-to-street diverging for the various interchanges. It was clear that different speed profile patterns were present at different points along the ramp. These patterns reflected vehicle speeds from about 20 to 70 mph. This data suggests that speed and speed profile clusters from particular ramps could be analyzed to provide insights into speed behavior.

Xu, Zhou, and Xue (*17*) used data from the SHRP2 NDS to analyze the effects of deceleration lane design on deceleration patterns for 10 off-ramp interchanges in Florida. Eight of the sites selected were diamond-style interchanges, and the other two were partial cloverleafs. The locations studied had relatively long single and tandem deceleration lanes before the off-ramps. This research aimed to determine the effectiveness of deceleration lane length, which was considered to provide an opportunity to slow traffic before it reaches the curved ramp. The paper shows data for each location that reflects actual driver behavior related to a specific design feature. The authors note that the speed profiles created for each site show that drivers are not using the deceleration lanes to slow down, but they are driving faster than intended on the ramp curves. Deceleration was taking place 75% to 90% of the time on the ramp sections. This suggests that unfamiliar drivers might encounter hard-braking situations on the ramps and related safety issues. In the case studies, the ramps did not have sharp curvature that might have led to crashes. This study does give credence to the general thinking that speeds are likely to be higher on off-ramps than on-ramps. The authors did develop SPF models that could be used in the design process for determining appropriate deceleration lane lengths.

Similar smaller-scale efforts have been made by others, and projects underway are aimed at establishing a better understanding of the factors that influence ramp safety and performance (*18–20*). These may reinforce the previously described findings.

2.1.2 Conclusions from Literature Review

Based on the literature reviewed, the following conclusions may be appropriate:

- Efforts have been made to determine the relative safety of highway ramps through the development of SPFs or CMFs and NDSs. SPFs are based on establishing a quantitative relationship between design and usage features and the expected number of crashes that will occur.
- Choi et al. (*9*) developed SPFs for direct, semi-direct, and loop interchanges based on curvature radius, grade, and lengths of acceleration and deceleration lanes. However, these efforts did not consider other factors such as the width of the road, shoulders, and the nature of barriers on the ramps.
- NDS data has the potential to provide deeper insights into the relationships between factors that influence ramp performance, but it offers only a snapshot, and its data collection phase has ended. It is unclear whether it will provide sound metrics to differentiate ramps by type.
- It appears that sufficient information to establish the relative safety of all types of highway ramps has yet to be provided. Research is continuing in this area.
- There is no clear evidence that on- versus off-ramps have a specific speed differential that would be a differentiating factor. Studies of deceleration lanes for off-ramps have indicated considerable variation in the speeds selected by drivers. Drivers tend to decelerate harder as they reach the curved section of the ramp, suggesting that impact speed may be higher when, for whatever reason, a vehicle leaves the traveled way on a ramp. This has implications for barrier performance.

References were made to other efforts underway to understand ramp behavior and establish better design and control strategies (*19–22*). It is likely that these efforts will provide additional insights and support for the concepts and metrics measuring variations in ramp performance, but the current status of the literature does not provide a well-established basis for differentiating ramp types.

Based on the literature reviewed, the following conclusions may be appropriate:

- Ramps can be differentiated. Some efforts show that multiple factors do not follow "design" thinking, such as differences in speed for on- and off-ramps.
- Much information reflects the relative safety and performance of highway ramps based on curvature, cross section, traffic, speeds, and shoulder conditions. There are various designs but no "safety" metric that would influence the selection of specific design features.
- Given the focus of this effort on barrier deployment, it is probably prudent to focus on loop ramps in general without providing an operational label (e.g., on- or off-ramps).

Further insights on CSOR issues were of continued importance and sought by agency contacts.

2.2 Agency Survey

State DOTs were contacted at the outset of the project to solicit current information on agency practices and policies relative to the deployment of barriers on highway ramps, as well as the associated design requirements and features of these ramps that may affect the effectiveness of the barriers. To achieve these objectives a survey was initially designed to:

- Reach the persons in the states responsible for ramp design and barrier deployment.
- Determine the extent to which agencies follow the design recommendations in the AASHTO Green Book (*1*) and *Roadside Design Guide* (*2*).

- Assess the latitude agencies have used to establish more specific requirements or define exceptions to the recommendations.
- Solicit suggestions for improved deployment and design practices to identify options to revise the current practices.
- Limit the time state agency personnel are expected to provide identifying and critiquing current practices, considering they have a full set of active responsibilities.
- Request information that taps the unique experience or expertise of DOT staff to ultimately aid in improving practices.
- Request optional data that could be useful in enhancing the credibility of the research effort (e.g., provide crash data for a small subset of ramp locations). The analysis of the aggregate would enhance the depth of understanding derived.
- Focus on short-radius, superelevated curves and their configurations, which are typical of ramps, and the typical practices for selecting and installing barriers.
- Provide an increased direct focus on the grade factors of the curved ramps, as grade factor is a larger consideration for ramps onto grade-separated roadway interchanges.

The initial survey form was designed to capture the following data as effectively as possible:

- Staff perspectives on ramp crash safety issues.
- Information on agency guidelines or practices for the design of ramps, including radius, superelevation, and grade. The nature of the shoulders, including the width, slope relative to the roadway, and offset to the barrier, was shown to influence barrier effectiveness.
- Types of barriers typically used on ramps and their height, offset from the shoulder, and vertical orientation.
- Examples of typical ramp situations in two categories—normal (typical or most common) designed ramps, and tight or difficult ramps (designed to accommodate site limits or under past practices). It was hoped that agencies would provide a few examples in each category by name so the research team could use digital aerial imagery to view them.
- Crash safety perspectives of the persons responsible for the design and deployment roles, to provide the basis for formulating improved guidelines.

The survey was directed to different agency personnel to include, but not be limited to, agency staff from various offices and departments (e.g., Chief Engineer, Safety Director, Construction/Maintenance Staff, Standards Engineer/Director). This was intended to ensure that for any given state, the respondent could be identified to reflect varying perspectives and depth of specific knowledge (e.g., road design, barrier requirements).

A survey instrument developed through iterations of panel review, is shown in Appendix A: State DOT Survey Questionnaire. The instrument is similar to the one used in earlier research but was revised to be shorter, which meant that some of the noted aspects did not get the intended emphasis. The survey also made it easier for respondents to provide links to state documents. However, it was found to require more time from the research team to wade through varying guidelines from online documents to isolate key factors.

The survey was sent to all state DOT representatives in 2019 and again in 2020. After a few follow-ups, a total of 33 states replied. Those states are as follows: Alabama, Alaska, Arizona, Arkansas, Delaware, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Michigan, Mississippi, Montana, Nebraska, New Hampshire, New Jersey, New York, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, South Dakota, Tennessee, Utah, Washington, Wisconsin, and Wyoming. The research team followed up with the remaining states and collected, reviewed, and summarized the received information for inclusion in the project's final report. Pertinent responses for the survey-specific questions are summarized in this section. A summary of the responses relative to ramp design requirements by state is provided in Table 1. A summary of cited CSOR requirements is presented in Table 2.

Table 1. Specific ramp design values cited by survey respondents.

Responding states	Specific design criteria?	Minimum radii	Arterial loop ramp	Maximum superelevation	Downgrade	Maximum grades for vertical alignment
Alabama	Yes	38 ft	38 ft	8%		
Arizona	Yes	230 ft		6%	5%; 6% is acceptable for site restrictions	4%; 6% is also acceptable for site restrictions
Arkansas	Yes	AASHTO GB				
Delaware	No	AASHTO GB				
Hawaii	No					
Idaho	No					
Illinois	Yes	134 ft		8%	–6%	4%
Indiana	Yes	200 ft (180 ft if restricted)	150 ft	8%	6% max.	5% max.
Kansas	No					
Kentucky	No					
Louisiana	Yes	76 ft AASHTO GB		8% rural, 4% urban	5%	5%
Maine	Yes	AASHTO GB	AASHTO	AASHTO 6% highways 4% urban	AASHTO	AASHTO
Michigan	Yes	260 ft	232 ft 222 ft	7%		6%
Mississippi	Yes					
Montana	Yes	255 ft		8%		7%
New Hampshire	Yes	188 ft	100 ft for 30 mph and 8% max	6%		8%
North Dakota	Yes	4-degree curve		6%		
Ohio	Yes	150 ft		5%	8%	7%
Oklahoma	No	AASHTO GB		AASHTO GB	AASHTO GB	
Oregon	Yes	Max. degree of curve should be 30°, 190.99 ft 159.15 for 36°		12%	8% vertical alignment: descending	7% ascending
South Carolina	Yes	134 ft		8%		5% to 7%
South Dakota	Yes	300 ft typical	Lower acceptable	6% for loop		6% and 8% 9% for 55 mph + acceptable
Tennessee	Yes	100 ft		4%	15–25 mph 6%–8% 25–30 mph 5%–7% 40 mph 4%–6% 45 mph + 3%–5%	15–25 mph 6%–8% 25–30 mph 5%–7% 40 mph 4%–6% ≥45 mph 3%–5%
Washington	No	50 ft		10%	9%	7%
Wyoming	No	500 ft		8% in rural, 6% in mountain 4% in urban		Follows AASHTO GB

Table 2. Minimum reported widths for ramp shoulders and traveled way.

Responding states	Right shoulder width		Left shoulder width		Traveled way	
	Typically	Restricted areas	Typically	Restricted areas	Min.	Max.
Alabama	10 ft	8 ft	4 ft	2 ft	9 ft	
Alaska					AASHTO GB	
Arizona	10 ft, Add 2 ft w/ barrier	10 ft, Add 2 ft w/ barrier	6 ft, Add 2 ft w/ barrier	6 ft, Add 2 ft w/ barrier	12 ft	
Arkansas	AASHTO GB	AASHTO GB	AASHTO GB	AASHTO GB	AASHTO GB	
Hawaii	AASHTO GB	AASHTO GB	AASHTO GB	AASHTO GB	AASHTO GB	
Illinois	8 ft, 6 ft if paved	8 ft, 6 ft if paved	6 ft, 4 ft paved	6 ft, 4 ft if paved	12 ft	14 ft, 15 ft ok
Indiana	8 ft	6 ft	4 ft		16 ft	
Iowa		6 ft		4 ft	10 ft (non-interstate)	12 ft (interstate)
Kansas	8 ft AASHTO GB	8 ft AASHTO GB	2 ft AASHTO GB	2 ft AASHTO GB	AASHTO GB	
Louisiana	10 ft	6 ft	4 ft		AASHTO GB	
Maine	8 ft AASHTO GB	8 ft AASHTO GB	4 ft AASHTO GB	4 ft AASHTO GB	14 ft AASHTO GB	
Michigan	8 ft, 7 ft paved		6 ft, 4 ft paved		16 ft	
Mississippi	10 ft	10 ft	8 ft	8 ft		
Montana	6 ft	4 ft			16 ft	
Nebraska		8 ft		0 ft	16 ft	
New Jersey	12 ft	7 ft		7 ft	1 ft (urban) 0 ft (existing)	22 ft paved
North Dakota	8 ft, 6 ft paved					
Ohio	8 ft	8 ft	6 ft	6 ft	18 ft (for radius less than 200 ft)	
Oregon	6 ft	6 ft	4 ft	4 ft	14 ft ok on arterials	16 ft
Pennsylvania		8 ft		4 ft	AASHTO	
South Carolina	10 ft; 6 ft paved (+3.75 ft w/ guardrail)	10 ft; 6 ft paved (+3.75 ft w/ guardrail)	10ft; 4 ft paved (+3.75 ft w/ guardrail)	10 ft; 4 ft paved (+3.75 ft w/ guardrail)		
South Dakota	8 ft	8 ft	2 ft	2 ft	15 ft	19 ft
Tennessee	8 ft; 6 ft paved	8 ft; 6 ft paved	6 ft; 4 ft paved	6 ft; 4 ft paved	16 ft	
Utah		8 ft + 2 ft		4 ft + 2 ft	12 ft	
Washington	8 ft	4 ft	2 ft	2 ft	11 ft	13 ft
Wisconsin	14 ft	6 ft	14 ft	6 ft		
Wyoming	8 ft	4 ft	4 ft	4 ft	12 ft	

Question 1. *Do you have specific design criteria (e.g., minimum radii, maximum superelevation, downgrade) for the geometrics of curved, superelevated ramp sections? If yes, please include information or provide a link to where this information can be accessed.*

Twenty-one states mentioned that they have specific design criteria, whereas 11 states do not have them. The states without design criteria are Alaska, Delaware, Hawaii, Idaho, Kansas, Kentucky, Oklahoma, Pennsylvania, Washington, Wisconsin, and Wyoming. Of these states, Delaware, Oklahoma, and Pennsylvania follow the general guidelines of the AASHTO Green Book (*1*). From the states that have criteria, three states list a radius of 100 ft or less, four states list a radius between 101 ft and 200 ft, and six states list a radius at or above 201 ft. Louisiana has the minimum radius at 76 ft for a 20-mph design speed and an 8% superelevation in rural areas. Eight states did not list their criteria in the survey. Superelevation ranges from 4% to 12% were reported. Oregon is the only state with the maximum value of 12%, and Washington has a 10% superelevation value. Seven states list 8% as the maximum superelevation, mainly in rural areas on highways. Four states have 4% as the maximum superelevation in urban areas. Six states follow AASHTO Green Book guidelines (*1*). Seven states list 6% as the maximum superelevation, mainly for highway roads. Only two states have a maximum superelevation of 7% and 5% each. The maximum grades for vertical alignment for New Jersey are 11% for mountainous roads. South Dakota has a maximum vertical grade of 9%. Vertical grades of 6% and 8% were mentioned by three states each. Seven states have the maximum vertical grade at 7%. Two states have the maximum vertical grade at 5%. Eight states follow AASHTO Green Book guidelines for minimum and maximum vertical grades (*1*). The maximum downgrade for vertical alignment is for Utah and Washington at 9%. For downgrades of 8% and 6%, four and three states, respectively, mentioned them. Louisiana has set the maximum vertical grade at 5%. Seven states follow AASHTO Green Book guidelines for downgrades (*1*). The specific values are summarized in Table 1.

Question 2. *Does your State/Agency specify the design speed for curved, superelevated ramp sections? If yes, please include information, provide a link to where this information can be accessed.*

Twenty-two states mentioned that they have and 10 states mentioned that they do not have a design criterion. Kansas, Maine, and Utah follow the general AASHTO Green Book guidelines (*1*). Six states have a minimum speed of 25 mph, and three other states have a minimum speed of 30 mph. Some states mentioned that they do not specify design speeds for ramps. Instead, they recommend a desirable ramp design speed.

Question 3. *Do you have special criteria to decide if a longitudinal barrier is warranted on a ramp? If yes, please include criteria, provide a link to where this information can be accessed.*

Nine states mentioned that they have a warranted longitudinal barrier on a ramp and 23 states mentioned that they do not. The states with warranted longitudinal barrier criteria are Alabama, Illinois, Indiana, Louisiana, Mississippi, Nebraska, New Jersey, Ohio, and South Dakota. Illinois warrants longitudinal barriers on ramps similarly to other roadways while taking into consideration the clear zone, barrier warrants, and length of need. The clear zones are established using the *Roadside Design Guide* (*2*). The hazard elimination and traversable design treatments are warranted and designed using a stepwise procedure. Louisiana uses a barrier if the clear zone for a design speed cannot be met. The state generally follows guidelines from the *Roadside Design Guide* (*2*). Alabama considers clear zone issues and the need to provide positive separation of ramps. Mississippi typically provides a longitudinal barrier if slopes are steeper than 3:1, if the ramp is located within the clear zone, or if any obstructions are located within the clear zone. New Jersey considers a guide rail warranted if an obstruction's physical characteristics and location are within the clear zone. Barriers are evaluated on an individual basis. Additionally, a final analysis must usually be solved by engineering judgment and cost-effective analysis (i.e., the Roadside Safety Analysis Program).

Question 4. *Please include below how ramp posted speed is determined and/or upload relevant information files.*

New Hampshire and Indiana have advisory speed limits of 18 mph and 20 mph, respectively. Nine states mentioned that they post an advisory speed of 25 mph. These states are Alabama, Illinois (urban roads), Iowa, Montana, Ohio, Oregon, South Carolina, Tennessee, and Washington. Five states, Arkansas, Kentucky, Louisiana, New Jersey, and Wyoming, use ball-bank indicators on the ramps to determine the advisory speed that should be posted. Arkansas, Illinois (rural roads), Michigan, and South Dakota (lower is allowed) have a speed limit of 30 mph.

Question 5. *Please describe how shoulder widths are determined for ramp sections where barriers are installed and/or upload relevant information files.*

Every state has different requirements, and the results are tabulated as shown in Table 2. The states of Alaska, Delaware, Idaho, Kentucky, New Hampshire, and Oklahoma did not reply, so they are not included in the table.

Question 6. *The research team is also very interested in obtaining information about geometry of old sharply curved ramps that are no longer on your State's standard plans and roadside barriers used on these ramps. Please include or upload any relevant information below.*

No state provided any documentation. Many states did not understand the questions, and only four states gave examples. These responding states provided actual highway ramps (highway and exit numbers) that would be examined on available online maps to see actual examples. The states usually reconstruct old ramps, and others use warning devices (chevrons, blinking advance curve signs, blinking delineators, and, most recently, sequential lights on the outside of the curve that are visible in daylight) to prepare drivers before taking the ramp. More details will be analyzed after Question 7.

Question 7. *Please include any additional comments, concerns, or questions that you would like to convey to the research team below. Cite examples of sites where barriers have been used on CSORs.*

Very few states answered this question, while others posted their websites or state manuals as guidelines. Tennessee suggests the need for "a conclusion providing the minimum barrier height and type for curve radius and speed adjusted with max. superelevation (i.e., use concrete rail at 36" for all outside the ramps with a minimum 6' offset)." Iowa reflected that "much of our knowledge regarding longitudinal barriers on curved ramps is a combination of our Design Manual and institutional knowledge, i.e., the knowledge designers have developed over the course of their careers." Hawaii summarizes that "generally, evaluation for barrier installation would be based on the Road Design Guide (e.g., clear zone) and accident history (e.g., existing ramps)." Oregon mentioned that its DOT "uses spirals for horizontal alignment criteria, including interchange ramps." Illinois says agency personnel "do not explicitly consider adjacent superelevation rates in the design of our roadside barriers. The max rollover on the high side is 8 percent, and with the typical Emax of 6 percent we experience a break of 4% to 8% at a point often 6 to 8 ft in front of the face of the barrier. We would be interested to know what issues are pertinent to this type of condition, and what is identified in testing/research." Utah refers to "*TRB Report 894*" that the research team developed (*3*). The respondents would recommend analyzing what types of ramps are effective at what speeds, curve radii, and superelevation conditions.

The survey also asked the agencies to cite specific interchange sites where curved, superelevated ramps had been treated with barriers. Sites offered are described in the following section, an example is provided, and additional details are included in Appendix B: Links to State DOT Documents.

2.3 Review of Typical Sites

The research team received information about the geometry of sharply curved ramps from four states in the survey. The specific ramp sites of "concern" or as "examples" were cited. The research team obtained aerial and driver-level views for most of these sites. This effort was possible using aerial and driver-view images from Google Maps. These interchange sites and the details of these locations served to depict the variety of situations faced by agency staff in their roles to design and maintain their highway system.

Indiana Sites:

- **"Eastbound I-70 to Northbound Keystone Ave. (Exit #85)."**
  This ramp is shown as an example in Figure 4. Measurements (based on the general technique depicted in Figure 5) indicate a radius of curvature of 141 ft.
- **"Northbound I-465 to Westbound I-465 (Exit #106)."**
  The specific location could not be located.
- **"Westbound I-74 to US 52 (Exit #169)."**
  Measurements indicate a radius of curvature of 174 ft. The ramp inside curvature is short and is measured at approximately 460 ft in length (for ~120 degrees), connecting the interstate to the local roadway (US 52).

Oklahoma Sites:

The responder commented, "We have lots of antique ramps with guardrail to share, although 'off your state standard' doesn't really apply to us, since we don't really have state standards, unless I'm not reading that right."

- **"NW Expwy Off-Ramp from I-44:** One of our more notorious ones, we've done chevrons, blinking advance curve signs, chevrons on the guardrail, blinking delineators on the top of the F wall, and most recently some kind of sequential lights on the outside of the curve that are visible in daylight."

Figure 4. Example of imagery obtained for EB I-70 to NB Keystone Ave. (Exit #85 Indiana).

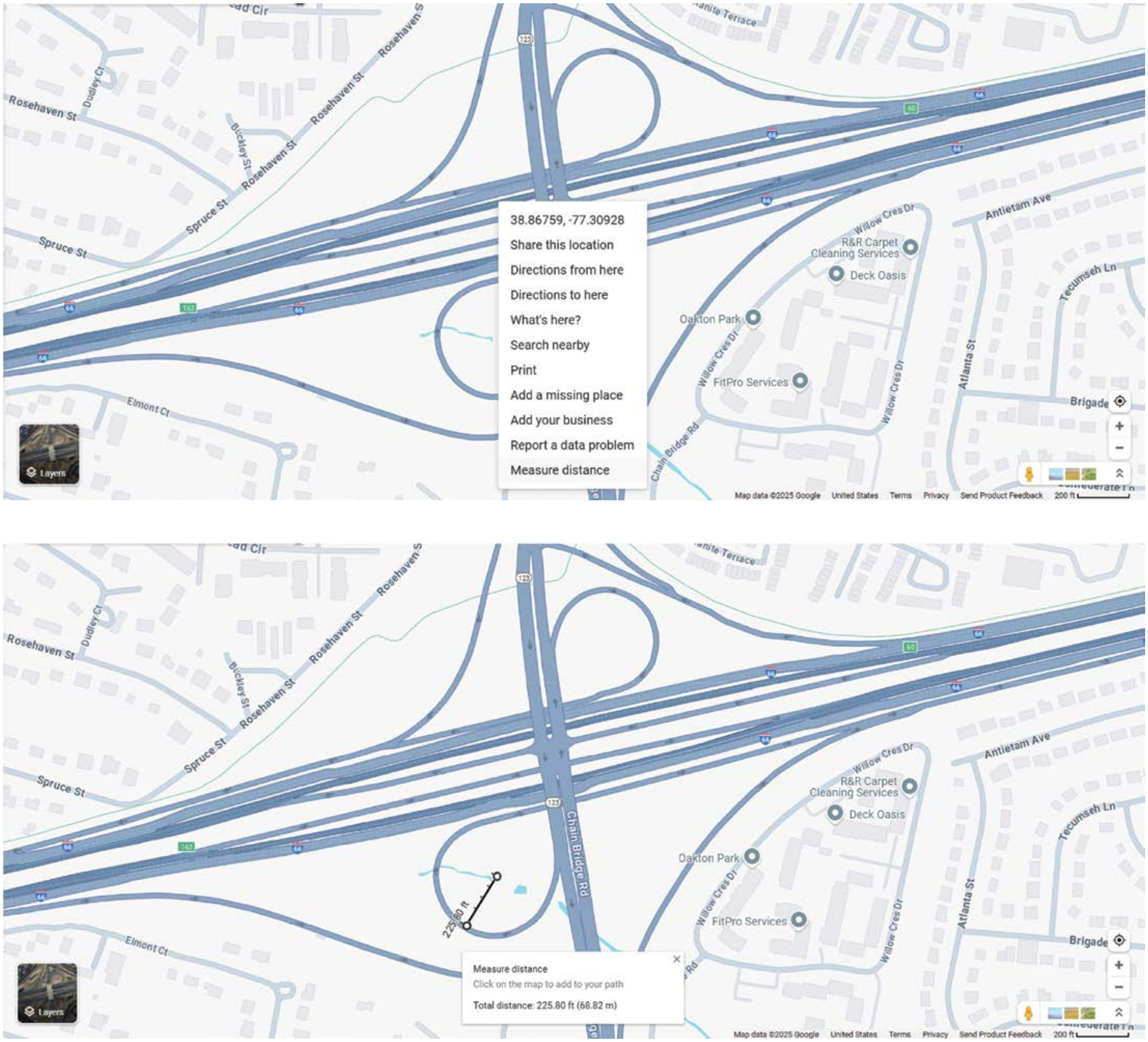


Figure 5. Google Maps feature for determining curve radii from map images.

- **"NW Expwy On-Ramp to I-44 EB."**
- **"I-244 WB to US-169 SB."**
  Measurements indicate a radius of 176 ft.
- **"US-169 SB to I-244 EB."**
  Measurements indicate a radius of 193 ft.
- **"US-75 SB to I-44 EB."**
  Measurements indicate a radius of 170 ft.
- **"I-44 EB to US-75 NB."**
  Measurements indicate a radius of 168 ft.

Utah Sites:

The safety engineer responding to the survey shared with the research team an Excel sheet that summarizes ramps on the state-maintained roadways. Thousands of ramps are listed in the file. Most of the tight radius exits in the Excel sheet were left turn of a diamond-type ramp, not useful to this study. In continued review, a tight loop ramp was identified as follows:

- **"I-15 SB to W-200 N Exit 59"**
  Measurements indicate a radius of 132 ft.

Nebraska Sites:

- **"I-180 SB (US-34) to US-6 EB Cornhusker Hwy"**
  Measurements indicate a radius of 121 ft.
- **"S 84th St. NB to I-80 W"**
  Measurements indicate a radius of 122 ft.
- **"S 13th St. NB to I-80 W"**
  Measurements indicate a radius of 132 ft.

The states have provided many of their state DOT documents and links to download. Additional documents had to be retrieved from state DOT websites to answer the questions of the survey. The links that were shared and the file names that were compiled are documented.

These ramps cited by the states were located on Google Maps and analyzed, and an approximate radius was measured using the tools available. The process to measure radii from Google Maps is straightforward. Once a specific location is opened, the user can right click on a precise feature on the maps and choose "measure distance" from the menu window. Then, the user can select the other side to measure, and Google Maps gives the total distance. The distance is not 100% accurate but it is a useful tool to get approximate values. These steps are shown in Figure 5. For each ramp, several measurements were taken along the ramp diameter, then the curvature radius was estimated and the radius of curvature was measured.

2.4 Overview of Background Study Findings

The background studies indicate, as expected, that limited effort has been made to create a comprehensive understanding of safety on curved, superelevated off-ramps. By extension, highway agencies have not developed uniform practices for the deployment of barriers or criteria (or guidelines) for when they are most often used. The many differences in ramp situations that complicate design efforts, the frequent difficulties in locating crashes on ramps, driver issues, and other factors probably explain the great variations in ramp designs and barrier selections and placement.

Generally, efforts have been made to understand the relationships between ramp design, operation, and maintenance and safety related to the applications of longitudinal barriers. The development of guidelines is complicated by the many factors that must be considered. Agency personnel reflect appropriate concerns in their survey responses, as well as their need for more guidelines. These facets are reflected in the variations of CSOR designs and standard guidelines for barrier selection and placement. The background studies failed to identify sufficiently deep crash analyses across the range of ramps to provide clear indications of critical points and the effectiveness of barrier options and associated placement requirements.

Research into the most common ramp situations is needed, with a focus on the criticality of the tire-to-pavement interface and on the short-radius designs where driver control and the interfaces between the vehicle and the pavement can be issues when speeds are too high (particularly for vehicles that have been traveling at higher speeds). Efforts are needed to identify critical conditions, enhance the knowledge of the vehicle-to-barrier interface for various types of vehicles, and assess the effectiveness of various types of barriers for the most critical locations where short-radius or “tight” curves must exist. A broad analysis is necessary to identify conditions outside the limits and to develop guidelines for individual agencies or the nation.

The efforts of this first part of the research, which included a review of the literature, a survey of the states, and an overview of typical curved, superelevated ramp sites, provided more depth to the research team’s understanding of the problem but revealed few surprises. It is possible that continued digging through the data and information compiled in these efforts, with the help of software improvements, could lead to other locations and possible new insights.

CHAPTER 3

Vehicle Dynamics Analyses

Vehicle dynamics analysis (VDA) was used in previous efforts to analyze barrier effectiveness for CSRSs to assess the trajectories of vehicles leaving the traveled way. This approach proved to be highly effective in understanding the interfaces of errant vehicles with various types of barriers in previous research on CSRSs. Therefore, the same VDA tools were used to develop an improved understanding of the effectiveness of longitudinal barriers used on CSORs. A vehicle departing the driving lanes on a CSOR is influenced by the same factors, including ramp curvatures, superelevation, vertical grade, shoulder and roadside designs, and barrier features. Given that such departures can occur on CSOR ramps of varying configurations, a similar VDA approach was considered appropriate. This VDA needed to reflect the features that would influence the dynamic response of vehicles leaving on-ramps. The roadway, shoulder, and barrier applications for these situations were defined.

Vehicle dynamics simulations were used in the initial phase of the study to yield quick analysis and understanding of the trajectories of errant vehicles on curved, superelevated ramp sections. The insights from these analyses were used to determine the most critical finite element crash simulations needed to investigate in much greater detail. VDA can simulate the trajectory of vehicles in three dimensions, considering the design features of the vehicle (e.g., wheelbase, weight or mass, suspension characteristics), the operating conditions (e.g., speed, driver inputs), and the influence of the surface terrain over which the vehicle is traveling (e.g., slope, grade, friction, softness). VDA uses concepts of free-body physics for the movement of a sprung mass for specific velocity, accelerations and decelerations, and surface conditions to determine vehicle trajectories, including roll, pitch, and yaw factors, for small increments of time.

Two vehicle dynamics software programs were used in this study to predict the vehicle trajectories on curved, superelevated ramps: HVE (Human, Vehicle, and Environment, by the Engineering Dynamics Company) (*23*) and CarSim (by Mechanical Simulation Corporation) (*24*). The programs were developed for use by engineers and safety researchers to study interactions among humans, vehicles, and their environment. HVE and CarSim are high-level simulation tools aimed at creating three-dimensional models of vehicles and environments, allowing the study of their dynamic interaction under selected conditions. The tools provide a detailed description of a motor vehicle's trajectory, considering the influence of weight, suspension system, and other vehicle factors. Available databases include a wide range of high-fidelity vehicle models that can be used in dynamic reconstructions and simulations.

HVE and CarSim provide physical and visual environment models to simulate selected conditions. Weather attributes, road geometry, and pavement-friction properties can be computed and their effects on vehicle dynamics analyzed. Drivers' actions (e.g., throttle, brakes, steering, gear selection) can also be simulated. The models have been thoroughly validated and are capable of accurately predicting a vehicle's trajectory for different terrain profiles. The research team used these programs in previous research studies to assess vehicle-to-barrier interaction when the barrier is placed on non-level terrain (*25–29*).

3.1 Vehicle Dynamics Analyses

Undertaking VDA required physical information about the vehicles and the barriers to be studied, as well as data on ramp configurations (e.g., grade superelevation, side slope), barrier design features, effective interface areas, and the terrain or surface conditions associated with CSORs. The factors considered in the VDA were:

- Vehicle types
  - 1100C small car (Toyota Yaris)
  - 2270P pickup truck (Chevrolet Silverado)
- Barrier types
  - W-beam guardrail (27.75-in. and 31-in. top-of-rail height)
  - Thrie beam guardrail (34-in. top-of-rail height)
  - Concrete barriers (32-in. and 42-in. top height)
- Superelevation and curvature
  - 4%, 6%, and 8% ramp cross slope
  - 150-ft, 300-ft, and 450-ft curvature radius
- Impact conditions
  - Impact angle: 5, 10, 15, 20, and 25 degrees
  - Impact speed: 50, 70, and 100 km/h (31, 43.5, and 62 mph)
- Shoulder width and slope
  - 4-ft, 8-ft, and 12-ft widths
  - 0%, 3%, 6%, and 8% (angle relative to road)
- Other variations
  - Ramp grade: 0%, –4%, and –8% (downward)

The following sections describe the VDA setups, the factors considered, the use of software, and the cases selected for analyses.

3.1.1 Vehicle-to-Barrier Interface Considerations

The study focused primarily on two types of vehicles commonly used for roadside hardware testing: a 1100C small car (1,100 kg) and a 2270P pickup truck (2,270 kg). The specific weight, size, frontal geometry, and suspension systems of these vehicles were incorporated into the VDA model such that they would match typical MASH test vehicles (namely a Toyota Yaris sedan and a Chevrolet Silverado pickup truck).

In these analyses, one point was defined for each type of vehicle and considered to represent its primary interface (engagement) region. These points are labeled 1 and 2 in Figure 6. The primary interfaces are located at positions on the front of the vehicles that are believed to represent the engagement point that differentiates between tendencies to override or underride a barrier. Point 1 for the small vehicle is located at a height of 21 in., while Point 2 for the pickup has a height of 25 in. These point positions were defined by examining the frontal profile of each vehicle and reviewing full-scale crash tests conducted using similar vehicles. The traces of these points are critical in determining the interface with barriers for any vehicle trajectory.

Various barriers were selected for analysis, and an interface region was defined such that if the critical points (Point 1 or Point 2) are inside this region at the start of the impact, the barrier is considered likely to redirect the vehicle. If Point 1 (from the small car) falls below the interface

(a) (b)

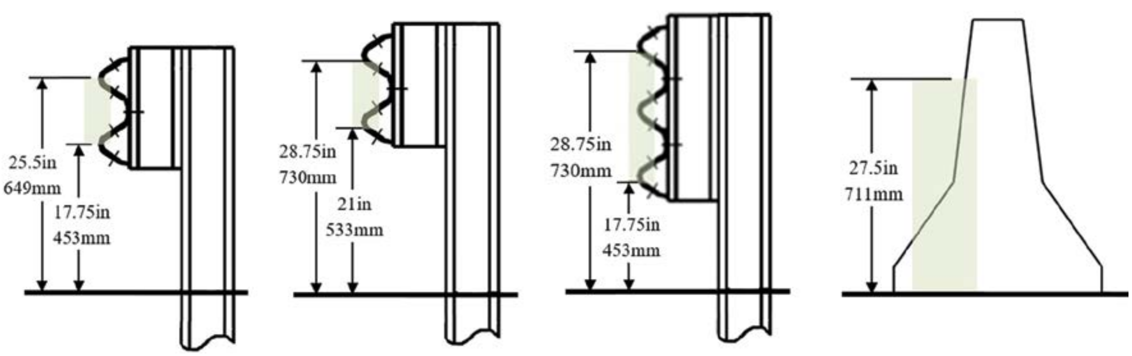
***Figure 6.* (a) 1100C and (b) 2270P vehicle models used in VDA, with interface points indicated.**

region, an underride or significant snagging is likely to occur. Similarly, if Point 2 (from the pickup truck) is above the interface region, vehicle override is likely to occur. The interface regions for some of the barriers analyzed are shown in Figure 7. For each of the barriers, the interface region is represented by a green-shaded box with the corresponding maximum and minimum heights. These regions are based on the geometry of the barrier and a review of full-scale crash tests conducted on these barriers. For concrete barriers, only the override condition is considered; therefore, there is no minimum height.

Interface analyses accounted for the effects of vehicle orientation (changes in roll, pitch, and yaw angles) in computations to determine the positions of Points 1 and 2 relative to the vehicle's center of gravity. Further, variations in the designs of the barriers, such as the inclusion of rub rails, increased heights, or different shapes for the concrete barrier, were not considered. The evaluations based on these interface regions were used in the VDA only as preliminary criteria to identify cases to be simulated in the finite element analysis. The actual impact is simulated in the finite element evaluations and the barrier performance is assessed on the basis of these results.

3.1.2 Ramp Curvature and Grading Conditions

Using information collected from the state agency survey, this study considered various degrees of ramp curvature to reflect the range of applications commonly found on highways.



(a) (b) (c) (d)

***Figure 7.* Sample interface regions for selected (a) 27¾″ W-beam, (b) 31″ W-beam, (c) 34″ Thrie beam, and (d) 32″ concrete barrier.**

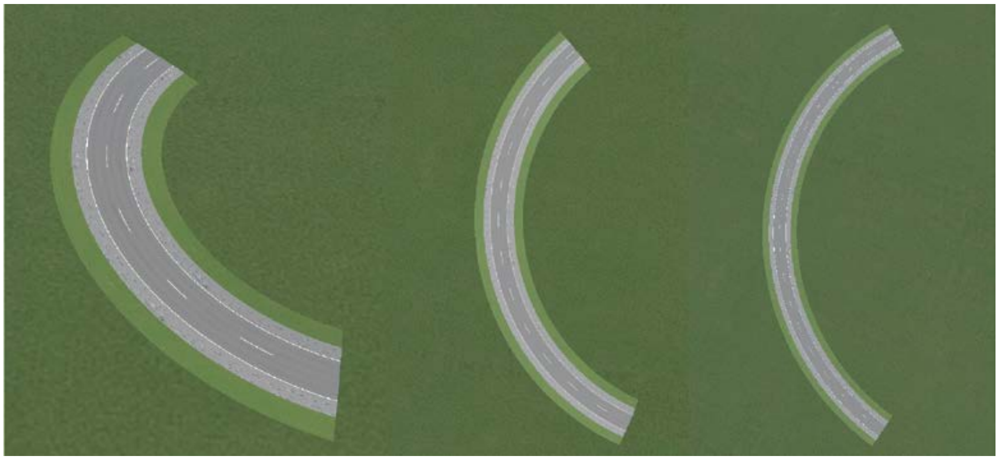


Figure 8. Roadway curvatures used in VDA.

A total of nine roadway curve conditions with different superelevations (4%, 6%, and 8%) and curvatures (150, 300, and 450 ft) were analyzed in the VDA to investigate crash simulations. Figure 8 describes the types of ramp curvature considered in the VDA and crash simulations.

3.1.3 Analysis of CSOR Vehicle Trajectories

Figure 9 illustrates the typical path or trajectory (via sequential vehicle images) of a vehicle negotiating a curve before departing the ramp, as marked by the red line. The cross section of a superelevated curve perpendicular to the centerline (indicated by the black line) is depicted. The banking of the roadway surface is exaggerated in this case. The shoulders can be designed to have the same slope relative to the roadway cross section or to have negative slopes for drainage. The red line shows the typical path or horizontal trajectory of an errant vehicle leaving the road on a CSOR. The figure shows a rising surface, reflecting a diagonal crossing of the superelevation followed by a diagonal traversing of the negative shoulder and side slope.

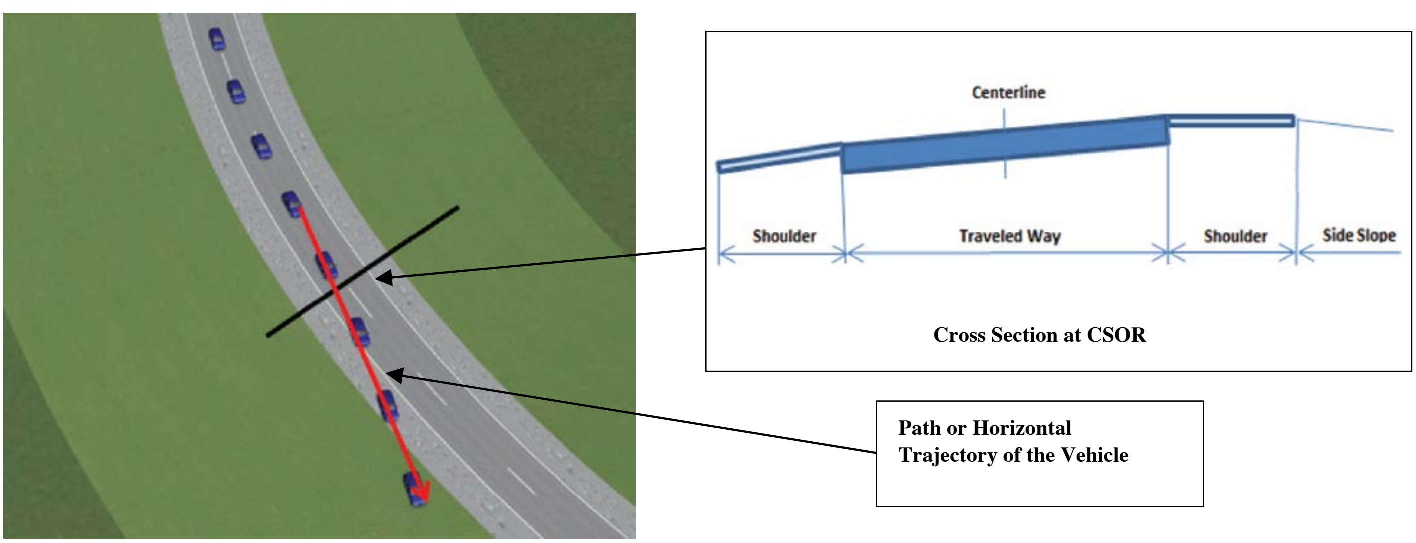


Figure 9. Sample VDA perspective of vehicle leaving the road.

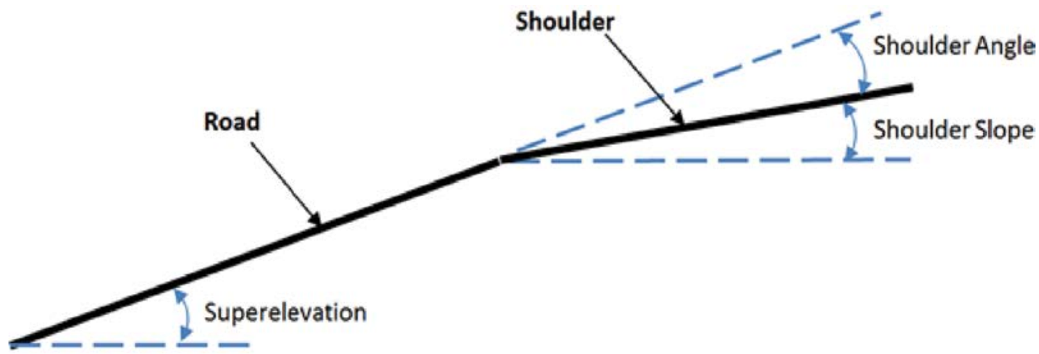


Figure 10. Sample surface cross sections analyzed for superelevated ramps.

Table 3. Shoulder slopes used in VDA.

Shoulder Angles Analyzed	4% Superelevation	6% Superelevation	8 % Superelevation
	Corresponding Shoulder Slope		
0%	4%	6%	8%
3%	1%	3%	5%
6%	-2%	0%	2%
8%	-4%	-2%	0%

In the VDA, the vehicle was run a distance of about 330 ft (100 m) on this surface to be in a "curve operation" equilibrium state before it was directed off the road. Several defined departure paths were input into the software to represent various departure angles. Repeated simulations of vehicles traversing such paths were conducted, varied to reflect exit angles of 5, 10, 15, 20, and 25 degrees for vehicles traveling at 31, 43.5, and 62 mph (50, 70, and 100 km/h). The roadway-to-shoulder angles analyzed are depicted in Figure 10 with a 12H:1V roadside slope. Table 3 lists the shoulder angles (defined as the angle relative to the road and different from the common shoulder slope definition) relative to the road that were used and the corresponding shoulder slopes.

3.2 Vehicle Dynamics Analyses Results

The VDA software was used to generate trajectories for each vehicle at the selected exit angles and speeds for each road departure condition. Figure 11 shows the vertical trajectories or trace paths of Point 1 for the 1100C vehicle (brown) and Point 2 for the 2270P vehicle (blue) negotiating a curve and departing onto the roadside at different speeds and angles. Multiple curves reflect variations in departure speed and angle for each vehicle, speed, and angle. The differences in basic vehicle heights are reflected by the relative positions of the two sets of curves. Consistency is present in the heights with the road profile shown by the black line at the base of the graph. Dynamic effects of the sprung mass cause the curves to vary for the changes in cross-section conditions. A similar graph was generated for each set of conditions in the analysis matrix.

Figure 12 provides an example of the normalized representation of the vertical trajectory for the same conditions. In the normalized view, the variations in trajectory are indicated relative to a horizontal plane as opposed to the actual cross-section surface. The curve on the bottom shows

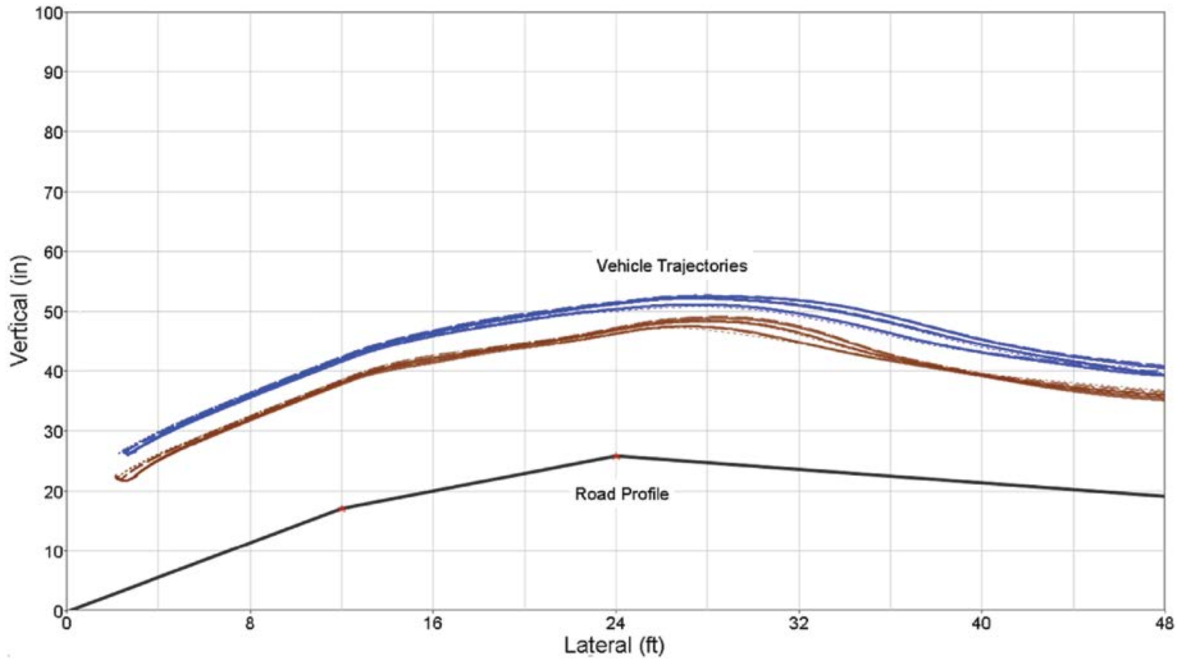


Figure 11. Sample plot of non-normalized vehicle point trajectories.

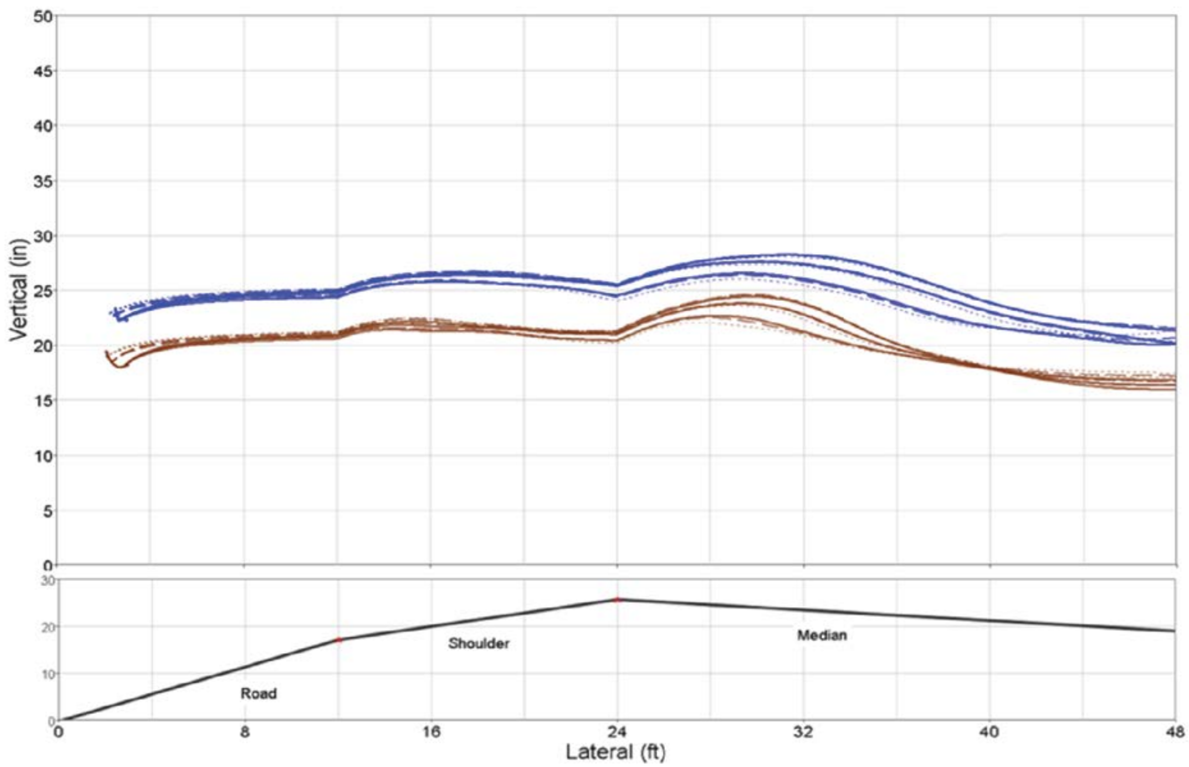


Figure 12. Sample plot of normalized vehicle trajectories on CSORs.

the road profile or cross section as a reference for the vehicle dynamics traces. The normalized view provides a convenient means to analyze and compare vehicle dynamics effects for different conditions simultaneously. The normalized version is also useful for translating the vertical trajectories to a common plane to allow the aggregation of groups of results to define limits.

Figure 13 illustrates a primary use of the normalized graphs of the trajectory data. All trajectory traces for a given set of CSOR conditions were plotted to derive maximum and minimum limit curves. The bold red line represents the maximum trajectory height limit across the entire path, while the bold green line indicates the minimum trajectory height. These limits indicate the requirements for any barrier system in that roadside configuration for all lateral positions beyond the shoulder. This approach can be used to determine the potential effectiveness of varying barrier systems across all possible lateral positions for a given roadside configuration.

Figure 14 shows more specific examples of how the plot of maximums and minimums can be applied. For a given superelevated curve and roadside configuration (e.g., 150-ft radius curvature, 6% superelevation, 8-ft shoulder width, 6% shoulder angle, and –6% vertical grade), the limits can be plotted along with the interface area provided by a specific barrier. These interface areas are represented by the blue and green lines that reflect the maximum and minimum vertical positions of the vehicle's critical points as it leaves the roadway and moves onto the roadside. For the barrier to be effective, it must have a good interface for both large and small vehicles at any given lateral position. The graph shows the limits for the 31-in. W-beam MGS (or Midwest Guardrail System) barrier as yellow lines across the graph for various positions where the barrier can be placed. If the maximum and minimum limits fall within the yellow lines, then the barrier will have a good interface for both types of vehicles. Where the blue line goes above the top yellow line, the possibility of an override exists. Where the green line falls below the lowest yellow line, the possibility of an underride exists.

The lower portion of Figure 14 shows the profile or cross section of the road related to the upper graph. Effective placement areas are shown in this pane. The red-shaded area defines the lateral

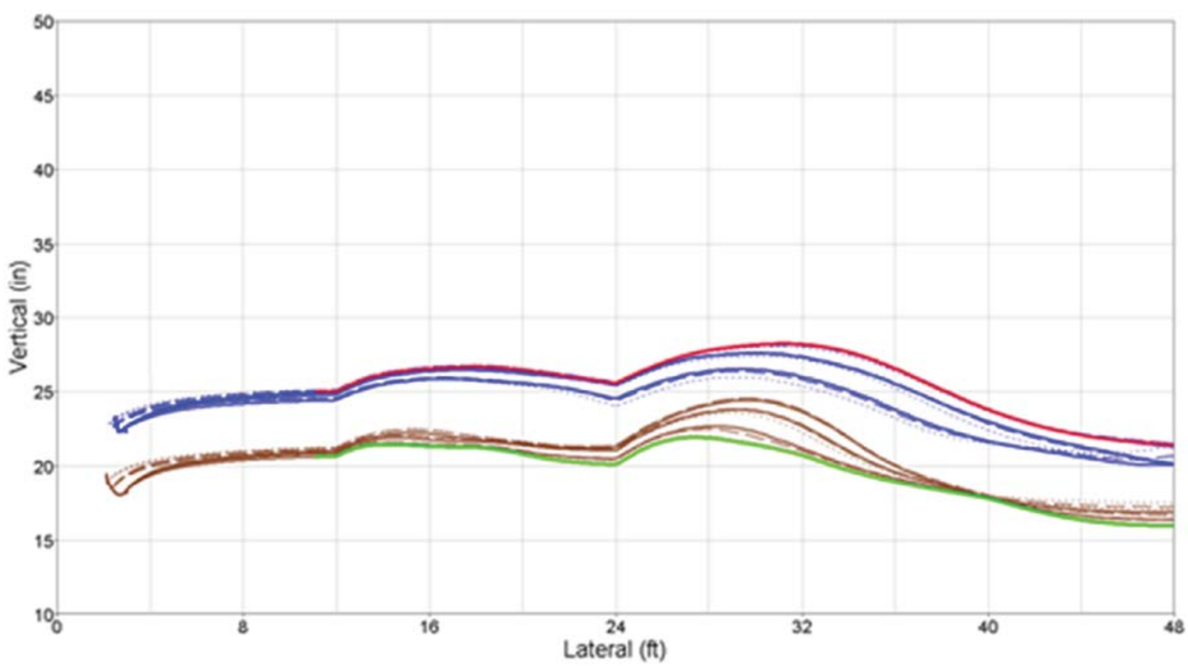


Figure 13. Sample plot of normalized view to show limiting (maximum and minimum) conditions.

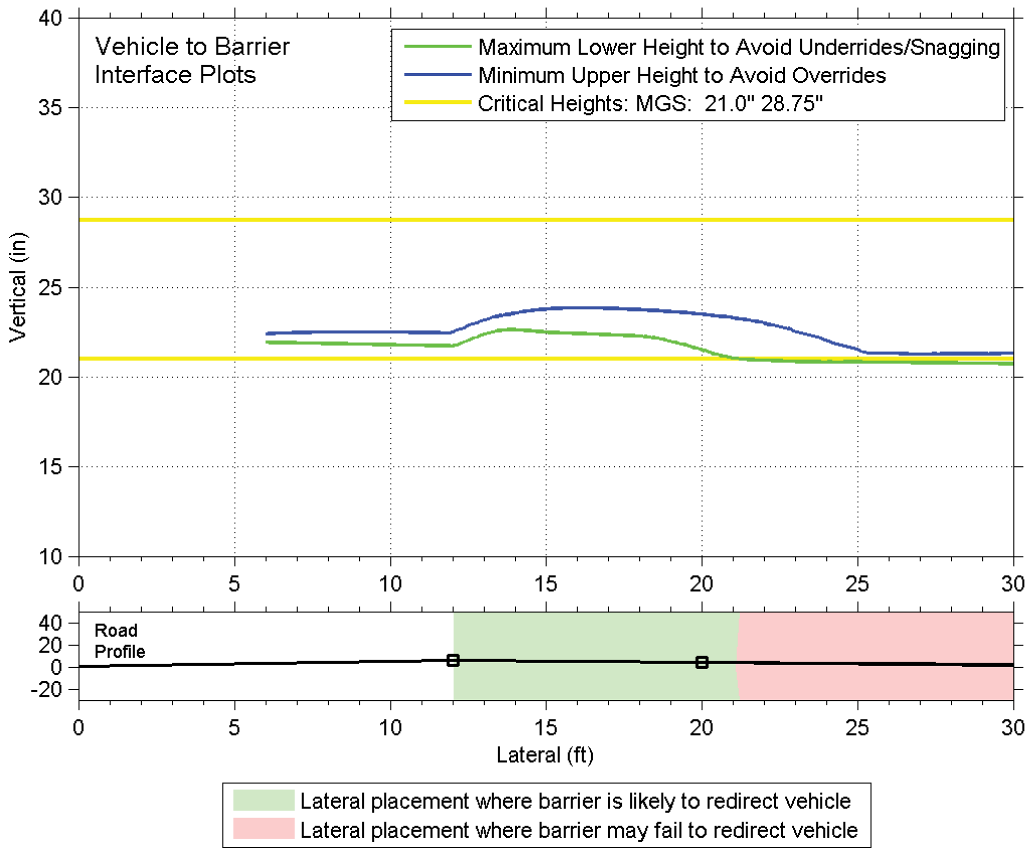


Figure 14. Typical barrier interface and effectiveness for a given profile.

positions where the specific barrier has an interface area above the maximum lower height limit (green curve), below the minimum height limit (blue curve), or both. Effective lateral placement occurs where both criteria are met, and this is shown shaded green. Plots of this type for all selected curve and roadside configurations were generated and are presented in Appendix C. Because of the large number of configurations considered in the study, plots from only one of the barriers analyzed (the 31-in. top-of-rail height W-beam barrier) are included in Appendix D and Appendix E. Similar plots were generated for the other barriers and can be supplied upon request.

3.3 Aggregated VDA Metrics for CSORs

The VDA simulations were used to determine the maximum and minimum heights of the critical points on the bumper (Points 1 and 2) as the vehicle first comes in contact with the barrier. Barrier lateral placement in these evaluations was 1 ft off the shoulder for each of the three barrier systems selected. All combinations of curvature, superelevation, and shoulder width and slope for the different speeds and impact angles were used in the evaluations. The maximum and minimum heights are shown in Table 4 to Table 9. These tables show the critical heights for the four analyzed barriers with all speeds (31, 43.5, and 62 mph) and angles (5, 10, 15, 20, 25 degrees) considered. Table 8 and Table 9 show the results for the 27.55-in. and 31-in. top-of-rail height W-beam barriers with only the lower speed (31 mph) considered. Each cell represents the barrier height for the specific conditions. If the value is shaded red, it implies that the height is outside the limits (i.e., too high or too low) and hence indicates that there is not a "good" interface. These tables, as well as the other interface plots, are used to provide the basis for determining those cases or types of cases that need to be analyzed with crash finite element simulation.

Table 4. Vehicle interfaces for 27.75-in. W-beam [G4(1S)] system for all speeds and angles.

Road Curvature Radius			150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
Road Superelevation			4 %		6 %		8 %		4 %		6 %		8 %		4 %		6 %		8 %	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0 %	4 ft	0 %	19.46	23.69	19.39	23.88	19.57	23.96	20.24	24.19	20.85	24.23	21.44	24.27	22.94	24.64	23.01	24.69	23.09	24.74
		3 %	20.11	24.41	19.95	24.66	19.84	24.81	20.22	25.07	20.66	25.10	21.25	25.13	23.34	25.49	23.39	25.52	23.45	25.59
		6 %	20.91	25.19	20.62	25.49	20.45	25.68	20.24	25.97	20.49	26.00	21.17	26.01	23.75	26.38	23.79	26.40	23.84	26.45
		8 %	21.53	25.80	21.17	26.08	20.97	26.28	20.27	26.60	20.44	26.62	21.09	26.62	24.06	26.99	24.08	27.01	24.12	27.06
	8 ft	0 %	19.70	24.02	19.74	24.23	19.67	24.26	21.04	24.33	21.15	24.37	22.51	24.43	22.83	24.85	22.90	24.92	22.99	24.99
		3 %	20.13	24.69	19.98	25.09	19.84	25.18	21.29	25.25	21.38	25.29	22.70	25.32	22.83	25.80	22.87	25.85	22.93	25.91
		6 %	20.73	25.44	20.48	25.90	20.33	26.01	21.69	26.10	21.66	26.10	22.77	26.14	22.92	26.63	22.93	26.65	22.96	26.70
		8 %	21.21	25.96	20.91	26.42	20.73	26.55	21.99	26.65	21.88	26.63	22.47	26.64	23.02	27.15	23.00	27.15	23.01	27.17
	12 ft	0 %	19.93	24.22	19.83	24.35	19.99	24.15	21.15	24.35	22.43	24.41	22.46	24.82	22.70	25.01	22.78	25.08	22.86	25.18
		3 %	20.30	24.58	20.11	24.81	20.04	24.58	21.21	24.79	21.47	24.81	22.34	24.90	22.58	25.49	22.63	25.52	22.70	25.58
		6 %	20.91	25.03	20.63	25.27	20.50	24.97	21.26	25.22	21.50	25.20	22.18	25.26	22.42	25.97	22.46	25.94	22.53	25.94
		8 %	21.42	25.35	21.17	25.59	20.98	25.26	21.25	25.43	21.43	25.46	22.11	25.44	22.31	26.21	22.34	26.19	22.38	26.14
-3 %	4 ft	0 %	19.32	23.21	19.30	23.28	19.26	23.30	19.96	23.59	21.19	23.65	22.21	23.72	22.65	24.08	22.73	24.10	22.81	24.13
		3 %	20.00	23.94	19.91	24.11	19.84	24.16	20.02	24.46	21.21	24.51	22.54	24.56	23.05	24.92	23.11	24.93	23.18	24.95
		6 %	20.83	24.74	20.66	24.96	20.49	25.05	20.12	25.35	21.23	25.39	22.93	25.42	23.47	25.80	23.51	25.81	23.57	25.83
		8 %	21.46	25.29	21.26	25.54	21.05	25.65	20.21	25.96	21.25	25.99	23.22	26.04	23.78	26.43	23.81	26.43	23.86	26.44
	8 ft	0 %	19.55	23.25	19.48	23.35	19.49	23.23	21.17	23.60	21.67	23.68	22.29	23.78	22.49	24.25	22.58	24.28	22.66	24.33
		3 %	20.08	24.04	19.95	24.23	19.86	24.11	21.45	24.50	21.81	24.56	22.39	24.63	22.47	25.16	22.52	25.18	22.58	25.21
		6 %	20.74	24.80	20.53	25.01	20.38	24.93	21.37	25.32	21.99	25.36	22.42	25.40	22.55	25.98	22.57	25.97	22.60	25.99
		8 %	21.27	25.29	21.00	25.51	20.83	25.47	21.31	25.81	22.13	25.86	22.54	25.90	22.63	26.51	22.68	26.49	22.69	26.49
	12 ft	0 %	19.92	23.14	19.80	23.11	19.84	22.97	21.07	23.54	21.97	23.62	22.16	24.04	22.35	24.39	22.43	24.43	22.52	24.48
		3 %	20.31	23.50	20.15	23.49	20.11	23.31	21.16	23.90	21.96	23.94	22.00	24.20	22.20	24.93	22.26	24.94	22.34	25.00
		6 %	20.91	23.86	20.69	23.84	20.55	23.62	21.25	24.24	21.80	24.24	21.83	24.43	22.02	25.36	22.07	25.39	22.13	25.39
		8 %	21.11	24.13	21.03	24.10	20.96	23.86	21.39	24.47	21.72	24.45	21.75	24.59	21.89	25.61	21.93	25.58	21.98	25.54
-6 %	4 ft	0 %	19.25	22.67	19.14	22.68	19.09	22.64	19.65	23.08	20.96	23.12	21.92	23.17	22.29	23.60	22.35	23.62	22.42	23.64
		3 %	19.95	23.44	19.80	23.51	19.70	23.49	19.84	23.89	21.03	23.93	22.22	23.98	22.70	24.43	22.76	24.44	22.83	24.46
		6 %	20.81	24.25	20.61	24.36	20.44	24.37	20.05	24.77	21.13	24.81	22.58	24.85	23.12	25.34	23.16	25.32	23.21	25.33
		8 %	21.46	24.80	21.24	24.94	21.04	24.98	20.21	25.39	21.20	25.41	22.84	25.44	23.43	25.97	23.46	25.94	23.50	25.94
	8 ft	0 %	19.52	22.51	19.42	22.50	19.38	22.39	20.48	22.96	21.39	23.01	21.97	23.06	22.10	23.65	22.18	23.67	22.26	23.69
		3 %	20.07	23.33	19.92	23.36	19.84	23.25	20.31	23.83	21.46	23.87	22.00	23.93	22.07	24.57	22.12	24.57	22.18	24.58
		6 %	20.77	24.06	20.57	24.14	20.43	24.04	20.26	24.62	21.58	24.67	22.03	24.71	22.14	25.39	22.16	25.37	22.19	25.37
		8 %	21.31	24.53	21.08	24.65	20.91	24.57	20.31	25.14	21.69	25.18	22.09	25.20	22.22	25.89	22.27	25.89	22.28	25.87
	12 ft	0 %	19.89	22.23	19.82	22.20	19.76	22.15	20.93	22.78	21.72	22.84	21.79	23.02	21.94	23.66	22.02	23.68	22.11	23.71
		3 %	20.25	22.54	20.13	22.54	20.05	22.43	20.95	23.14	21.58	23.17	21.62	23.25	21.78	24.23	21.85	24.22	21.92	24.23
		6 %	20.69	22.83	20.62	22.84	20.52	22.69	20.88	23.48	21.42	23.47	21.44	23.55	21.56	24.67	21.59	24.63	21.62	24.60
		8 %	20.75	23.05	20.70	23.08	20.62	22.90	20.88	23.71	21.29	23.68	21.30	23.68	21.42	24.86	21.42	24.86	21.43	24.81

Table 5. Vehicle interfaces for 31-in. W-beam (MGS) system for all speeds and angles.

Road Curvature Radius			150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
Road Superelevation			4%		6%		8%		4%		6%		8%		4%		6%		8%	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0%	4 ft	0%	19.46	23.69	19.39	23.88	19.57	23.96	20.24	24.19	20.85	24.23	21.44	24.27	22.94	24.64	23.01	24.69	23.09	24.74
		3%	20.11	24.41	19.95	24.66	19.84	24.81	20.22	25.07	20.66	25.10	21.25	25.13	23.34	25.49	23.39	25.52	23.45	25.59
		6%	20.91	25.19	20.62	25.49	20.45	25.68	20.24	25.97	20.49	26.00	21.17	26.01	23.75	26.38	23.79	26.40	23.84	26.45
		8%	21.53	25.80	21.17	26.08	20.97	26.28	20.27	26.60	20.44	26.62	21.09	26.62	24.06	26.99	24.08	27.01	24.12	27.06
	8 ft	0%	19.70	24.02	19.74	24.23	19.67	24.26	21.04	24.33	21.15	24.37	22.51	24.43	22.83	24.85	22.90	24.92	22.99	24.99
		3%	20.13	24.69	19.98	25.09	19.84	25.18	21.29	25.25	21.38	25.29	22.70	25.32	22.83	25.80	22.87	25.85	22.93	25.91
		6%	20.73	25.44	20.48	25.90	20.33	26.01	21.69	26.10	21.66	26.10	22.77	26.14	22.92	26.63	22.93	26.65	22.96	26.70
		8%	21.21	25.96	20.91	26.42	20.73	26.55	21.99	26.65	21.88	26.63	22.47	26.64	23.02	27.15	23.00	27.15	23.01	27.17
	12 ft	0%	19.93	24.22	19.83	24.35	19.99	24.15	21.15	24.35	22.43	24.41	22.46	24.82	22.70	25.01	22.78	25.08	22.86	25.18
		3%	20.30	24.58	20.11	24.81	20.04	24.58	21.21	24.79	21.47	24.81	22.34	24.90	22.58	25.49	22.63	25.52	22.70	25.58
		6%	20.91	25.03	20.63	25.27	20.50	24.97	21.26	25.22	21.50	25.20	22.18	25.26	22.42	25.97	22.46	25.94	22.53	25.94
		8%	21.42	25.35	21.17	25.59	20.98	25.26	21.25	25.43	21.43	25.46	22.11	25.44	22.31	26.21	22.34	26.19	22.38	26.14
-3%	4 ft	0%	19.32	23.21	19.30	23.28	19.26	23.30	19.96	23.59	21.19	23.65	22.21	23.72	22.65	24.08	22.73	24.10	22.81	24.13
		3%	20.00	23.94	19.91	24.11	19.84	24.16	20.02	24.46	21.21	24.51	22.54	24.56	23.05	24.92	23.11	24.93	23.18	24.95
		6%	20.83	24.74	20.66	24.96	20.49	25.05	20.12	25.35	21.23	25.39	22.93	25.42	23.47	25.80	23.51	25.81	23.57	25.83
		8%	21.46	25.29	21.26	25.54	21.05	25.65	20.21	25.96	21.25	25.99	23.22	26.04	23.78	26.43	23.81	26.43	23.86	26.44
	8 ft	0%	19.55	23.25	19.48	23.35	19.49	23.23	21.17	23.60	21.67	23.68	22.29	23.78	22.49	24.25	22.58	24.28	22.66	24.33
		3%	20.08	24.04	19.95	24.23	19.86	24.11	21.45	24.50	21.81	24.56	22.39	24.63	22.47	25.16	22.52	25.18	22.58	25.21
		6%	20.74	24.80	20.53	25.01	20.38	24.93	21.37	25.32	21.99	25.36	22.42	25.40	22.55	25.98	22.57	25.97	22.60	25.99
		8%	21.27	25.29	21.00	25.51	20.83	25.47	21.31	25.81	22.13	25.86	22.54	25.90	22.63	26.51	22.68	26.49	22.69	26.49
	12 ft	0%	19.92	23.14	19.80	23.11	19.84	22.97	21.07	23.54	21.97	23.62	22.16	24.04	22.35	24.39	22.43	24.43	22.52	24.48
		3%	20.31	23.50	20.15	23.49	20.11	23.31	21.16	23.90	21.96	23.94	22.00	24.20	22.20	24.93	22.26	24.94	22.34	25.00
		6%	20.91	23.86	20.69	23.84	20.55	23.62	21.25	24.24	21.80	24.24	21.83	24.43	22.02	25.36	22.07	25.39	22.13	25.39
		8%	21.11	24.13	21.03	24.10	20.96	23.86	21.39	24.47	21.72	24.45	21.75	24.59	21.89	25.61	21.93	25.58	21.98	25.54
-6%	4 ft	0%	19.25	22.67	19.14	22.68	19.09	22.64	19.65	23.08	20.96	23.12	21.92	23.17	22.29	23.60	22.35	23.62	22.42	23.64
		3%	19.95	23.44	19.80	23.51	19.70	23.49	19.84	23.89	21.03	23.93	22.22	23.98	22.70	24.43	22.76	24.44	22.83	24.46
		6%	20.81	24.25	20.61	24.36	20.44	24.37	20.05	24.77	21.13	24.81	22.58	24.85	23.12	25.34	23.16	25.32	23.21	25.33
		8%	21.46	24.80	21.24	24.94	21.04	24.98	20.21	25.39	21.20	25.41	22.84	25.44	23.43	25.97	23.46	25.94	23.50	25.94
	8 ft	0%	19.52	22.51	19.42	22.50	19.38	22.39	20.48	22.96	21.39	23.01	21.97	23.06	22.10	23.65	22.18	23.67	22.26	23.69
		3%	20.07	23.33	19.92	23.36	19.84	23.25	20.31	23.83	21.46	23.87	22.00	23.93	22.07	24.57	22.12	24.57	22.18	24.58
		6%	20.77	24.06	20.57	24.14	20.43	24.04	20.26	24.62	21.58	24.67	22.03	24.71	22.14	25.39	22.16	25.37	22.19	25.37
		8%	21.31	24.53	21.08	24.65	20.91	24.57	20.31	25.14	21.69	25.18	22.09	25.20	22.22	25.89	22.27	25.89	22.28	25.87
	12 ft	0%	19.89	22.23	19.82	22.20	19.76	22.15	20.93	22.78	21.72	22.84	21.79	23.02	21.94	23.66	22.02	23.68	22.11	23.71
		3%	20.25	22.54	20.13	22.54	20.05	22.43	20.95	23.14	21.58	23.17	21.62	23.25	21.78	24.23	21.85	24.22	21.92	24.23
		6%	20.69	22.83	20.62	22.84	20.52	22.69	20.88	23.48	21.42	23.47	21.44	23.55	21.56	24.67	21.59	24.63	21.62	24.60
		8%	20.75	23.05	20.70	23.08	20.62	22.90	20.88	23.71	21.29	23.68	21.30	23.68	21.42	24.86	21.42	24.86	21.43	24.81

Table 6. Vehicle interfaces for Thrie beam (SGR09b) system for all speeds and angles.

Road Curvature Radius			150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
Road Superelevation			4 %		6 %		8 %		4 %		6 %		8 %		4 %		6 %		8 %	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0 %	4 ft	0 %	22.23	23.46	22.27	23.49	22.33	23.53	22.78	24.13	22.83	24.20	22.89	24.27	22.94	24.51	23.01	24.59	23.09	24.67
		3 %	22.66	24.31	22.68	24.33	22.73	24.37	23.19	24.98	23.22	25.03	23.27	25.10	23.34	25.36	23.39	25.42	23.45	25.49
		6 %	23.12	25.19	23.13	25.20	23.16	25.22	23.61	25.84	23.63	25.88	23.67	25.94	23.75	26.22	23.79	26.26	23.84	26.32
		8 %	23.46	25.80	23.46	25.80	23.48	25.81	23.92	26.43	23.94	26.47	23.96	26.51	24.06	26.80	24.08	26.84	24.12	26.89
	8 ft	0 %	22.08	23.50	22.15	23.55	22.23	23.60	22.64	24.18	22.70	24.25	22.77	24.33	22.83	24.64	22.90	24.72	22.99	24.83
		3 %	22.13	24.31	22.16	24.32	22.20	24.36	22.65	25.02	22.68	25.07	22.72	25.14	22.83	25.52	22.87	25.59	22.93	25.68
		6 %	22.27	25.03	22.27	25.02	22.28	25.04	22.75	25.77	22.76	25.80	22.77	25.85	22.92	26.30	22.93	26.35	22.96	26.42
		8 %	22.41	25.51	22.43	25.49	22.42	25.51	22.86	26.22	22.89	26.27	22.89	26.30	23.02	26.79	23.00	26.83	23.01	26.89
	12 ft	0 %	21.96	23.52	22.03	23.56	22.10	23.61	22.52	24.13	22.59	24.21	22.69	24.30	22.70	24.68	22.78	24.78	22.89	24.90
		3 %	21.85	23.65	21.91	23.69	21.97	23.71	22.38	24.38	22.44	24.40	22.51	24.47	22.58	24.99	22.63	25.06	22.70	25.15
		6 %	21.70	23.78	21.75	23.75	21.80	23.75	22.23	24.58	22.27	24.58	22.32	24.62	22.42	25.29	22.46	25.32	22.53	25.39
		8 %	21.62	23.88	21.64	23.83	21.68	23.80	22.11	24.73	22.14	24.71	22.18	24.73	22.31	25.43	22.34	25.51	22.38	25.56
-3 %	4 ft	0 %	21.90	22.82	21.94	22.86	22.00	22.91	22.47	23.38	22.53	23.44	22.61	23.51	22.65	23.65	22.73	23.72	22.81	23.80
		3 %	22.33	23.65	22.36	23.68	22.41	23.71	22.88	24.19	22.93	24.24	22.99	24.30	23.05	24.46	23.11	24.52	23.18	24.60
		6 %	22.79	24.51	22.81	24.52	22.83	24.54	23.31	25.01	23.34	25.05	23.39	25.10	23.47	25.28	23.51	25.33	23.57	25.39
		8 %	23.13	25.09	23.14	25.09	23.15	25.10	23.62	25.58	23.65	25.60	23.68	25.64	23.78	25.83	23.81	25.88	23.86	25.93
	8 ft	0 %	21.70	22.79	21.76	22.83	21.82	22.88	22.29	23.31	22.37	23.38	22.44	23.45	22.49	23.58	22.58	23.67	22.66	23.75
		3 %	21.73	23.56	21.77	23.58	21.80	23.60	22.28	24.07	22.34	24.12	22.39	24.17	22.47	24.36	22.52	24.43	22.58	24.50
		6 %	21.85	24.23	21.88	24.25	21.88	24.26	22.35	24.74	22.41	24.77	22.42	24.80	22.55	25.04	22.57	25.10	22.60	25.15
		8 %	22.03	24.70	22.04	24.68	22.02	24.68	22.50	25.18	22.48	25.19	22.54	25.21	22.63	25.48	22.68	25.53	22.69	25.57
	12 ft	0 %	21.53	22.75	21.59	22.79	21.66	22.84	22.15	23.23	22.23	23.29	22.31	23.36	22.35	23.47	22.43	23.54	22.52	23.63
		3 %	21.42	22.82	21.46	22.83	21.51	22.86	22.00	23.34	22.06	23.40	22.14	23.43	22.20	23.62	22.26	23.68	22.34	23.74
		6 %	21.27	22.89	21.29	22.87	21.33	22.87	21.82	23.46	21.87	23.45	21.93	23.46	22.02	23.74	22.07	23.80	22.13	23.83
		8 %	21.18	22.94	21.18	22.90	21.21	22.88	21.70	23.55	21.74	23.51	21.78	23.50	21.89	23.84	21.93	23.89	21.98	23.90
-6 %	4 ft	0 %	21.52	22.26	21.57	22.31	21.63	22.36	22.11	22.78	22.17	22.84	22.24	22.92	22.29	22.97	22.35	23.04	22.42	23.12
		3 %	21.95	22.99	21.99	23.03	22.03	23.07	22.52	23.48	22.57	23.53	22.63	23.60	22.70	23.67	22.76	23.73	22.83	23.81
		6 %	22.41	23.83	22.43	23.86	22.46	23.89	22.95	24.28	22.99	24.33	23.03	24.38	23.12	24.46	23.16	24.51	23.21	24.57
		8 %	22.75	24.41	22.77	24.43	22.79	24.45	23.26	24.83	23.30	24.87	23.33	24.91	23.43	25.00	23.46	25.04	23.50	25.09
	8 ft	0 %	21.30	22.06	21.35	22.12	21.41	22.18	21.90	22.58	21.97	22.65	22.05	22.73	22.10	22.76	22.18	22.84	22.26	22.93
		3 %	21.33	22.80	21.35	22.84	21.38	22.88	21.88	23.26	21.92	23.31	22.00	23.37	22.07	23.44	22.12	23.50	22.18	23.58
		6 %	21.47	23.48	21.45	23.49	21.45	23.52	21.96	23.89	21.97	23.92	22.03	23.98	22.14	24.06	22.16	24.10	22.19	24.17
		8 %	21.60	23.91	21.61	23.91	21.59	23.93	22.10	24.30	22.09	24.32	22.09	24.37	22.22	24.47	22.27	24.49	22.28	24.56
	12 ft	0 %	21.11	21.95	21.17	22.00	21.24	22.07	21.73	22.41	21.81	22.48	21.89	22.56	21.94	22.58	22.02	22.65	22.11	22.74
		3 %	20.99	22.00	21.03	22.05	21.08	22.08	21.58	22.47	21.64	22.50	21.71	22.58	21.78	22.67	21.85	22.70	21.92	22.76
		6 %	20.84	22.05	20.86	22.02	20.90	22.07	21.40	22.47	21.44	22.53	21.46	22.55	21.56	22.69	21.59	22.70	21.62	22.73
		8 %	20.75	22.08	20.75	22.03	20.77	22.08	21.27	22.58	21.29	22.56	21.30	22.56	21.42	22.75	21.42	22.74	21.43	22.83

Table 7. Vehicle interfaces for 32-in. concrete barrier for all speeds and angles.

Road Curvature Radius			150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
Road Superelevation			4 %		6 %		8 %		4 %		6 %		8 %		4 %		6 %		8 %	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0 %	4 ft	0 %	19.46	23.69	19.39	23.88	19.57	23.96	20.24	24.19	20.85	24.23	21.44	24.27	22.94	24.64	23.01	24.69	23.09	24.74
		3 %	20.11	24.41	19.95	24.66	19.84	24.81	20.22	25.07	20.66	25.10	21.25	25.13	23.34	25.49	23.39	25.52	23.45	25.59
		6 %	20.91	25.19	20.62	25.49	20.45	25.68	20.24	25.97	20.49	26.00	21.17	26.01	23.75	26.38	23.79	26.40	23.84	26.45
		8 %	21.53	25.80	21.17	26.08	20.97	26.28	20.27	26.60	20.44	26.62	21.09	26.62	24.06	26.99	24.08	27.01	24.12	27.06
	8 ft	0 %	19.70	24.02	19.74	24.23	19.67	24.26	21.04	24.33	21.15	24.37	22.51	24.43	22.83	24.85	22.90	24.92	22.99	24.99
		3 %	20.13	24.69	19.98	25.09	19.84	25.18	21.29	25.25	21.38	25.29	22.70	25.32	22.83	25.80	22.87	25.85	22.93	25.91
		6 %	20.73	25.44	20.48	25.90	20.33	26.01	21.69	26.10	21.66	26.10	22.77	26.14	22.92	26.63	22.93	26.65	22.96	26.70
		8 %	21.21	25.96	20.91	26.42	20.73	26.55	21.99	26.65	21.88	26.63	22.47	26.64	23.02	27.15	23.00	27.15	23.01	27.17
	12 ft	0 %	19.93	24.22	19.83	24.35	19.99	24.15	21.15	24.35	22.43	24.41	22.46	24.82	22.70	25.01	22.78	25.08	22.86	25.18
		3 %	20.30	24.58	20.11	24.81	20.04	24.58	21.21	24.79	21.47	24.81	22.34	24.90	22.58	25.49	22.63	25.52	22.70	25.58
		6 %	20.91	25.03	20.63	25.27	20.50	24.97	21.26	25.22	21.50	25.20	22.18	25.26	22.42	25.97	22.46	25.94	22.53	25.94
		8 %	21.42	25.35	21.17	25.59	20.98	25.26	21.25	25.43	21.43	25.46	22.11	25.44	22.31	26.21	22.34	26.19	22.38	26.14
-3 %	4 ft	0 %	19.32	23.21	19.30	23.28	19.26	23.30	19.96	23.59	21.19	23.65	22.21	23.72	22.65	24.08	22.73	24.10	22.81	24.13
		3 %	20.00	23.94	19.91	24.11	19.84	24.16	20.02	24.46	21.21	24.51	22.54	24.56	23.05	24.92	23.11	24.93	23.18	24.95
		6 %	20.83	24.74	20.66	24.96	20.49	25.05	20.12	25.35	21.23	25.39	22.93	25.42	23.47	25.80	23.51	25.81	23.57	25.83
		8 %	21.46	25.29	21.26	25.54	21.05	25.65	20.21	25.96	21.25	25.99	23.22	26.04	23.78	26.43	23.81	26.43	23.86	26.44
	8 ft	0 %	19.55	23.25	19.48	23.35	19.49	23.23	21.17	23.60	21.67	23.68	22.29	23.78	22.49	24.25	22.58	24.28	22.66	24.33
		3 %	20.08	24.04	19.95	24.23	19.86	24.11	21.45	24.50	21.81	24.56	22.39	24.63	22.47	25.16	22.52	25.18	22.58	25.21
		6 %	20.74	24.80	20.53	25.01	20.38	24.93	21.37	25.32	21.99	25.36	22.42	25.40	22.55	25.98	22.57	25.97	22.60	25.99
		8 %	21.27	25.29	21.00	25.51	20.83	25.47	21.31	25.81	22.13	25.86	22.54	25.90	22.63	26.51	22.68	26.49	22.69	26.49
	12 ft	0 %	19.92	23.14	19.80	23.11	19.84	22.97	21.07	23.54	21.97	23.62	22.16	24.04	22.35	24.39	22.43	24.43	22.52	24.48
		3 %	20.31	23.50	20.15	23.49	20.11	23.31	21.16	23.90	21.96	23.94	22.00	24.20	22.20	24.93	22.26	24.94	22.34	25.00
		6 %	20.91	23.86	20.69	23.84	20.55	23.62	21.25	24.24	21.80	24.24	21.83	24.43	22.02	25.36	22.07	25.39	22.13	25.39
		8 %	21.11	24.13	21.03	24.10	20.96	23.86	21.39	24.47	21.72	24.45	21.75	24.59	21.89	25.61	21.93	25.58	21.98	25.54
-6 %	4 ft	0 %	19.25	22.67	19.14	22.68	19.09	22.64	19.65	23.08	20.96	23.12	21.92	23.17	22.29	23.60	22.35	23.62	22.42	23.64
		3 %	19.95	23.44	19.80	23.51	19.70	23.49	19.84	23.89	21.03	23.93	22.22	23.98	22.70	24.43	22.76	24.44	22.83	24.46
		6 %	20.81	24.25	20.61	24.36	20.44	24.37	20.05	24.77	21.13	24.81	22.58	24.85	23.12	25.34	23.16	25.32	23.21	25.33
		8 %	21.46	24.80	21.24	24.94	21.04	24.98	20.21	25.39	21.20	25.41	22.84	25.44	23.43	25.97	23.46	25.94	23.50	25.94
	8 ft	0 %	19.52	22.51	19.42	22.50	19.38	22.39	20.48	22.96	21.39	23.01	21.97	23.06	22.10	23.65	22.18	23.67	22.26	23.69
		3 %	20.07	23.33	19.92	23.36	19.84	23.25	20.31	23.83	21.46	23.87	22.00	23.93	22.07	24.57	22.12	24.57	22.18	24.58
		6 %	20.77	24.06	20.57	24.14	20.43	24.04	20.26	24.62	21.58	24.67	22.03	24.71	22.14	25.39	22.16	25.37	22.19	25.37
		8 %	21.31	24.53	21.08	24.65	20.91	24.57	20.31	25.14	21.69	25.18	22.09	25.20	22.22	25.89	22.27	25.89	22.28	25.87
	12 ft	0 %	19.89	22.23	19.82	22.20	19.76	22.15	20.93	22.78	21.72	22.84	21.79	23.02	21.94	23.66	22.02	23.68	22.11	23.71
		3 %	20.25	22.54	20.13	22.54	20.05	22.43	20.95	23.14	21.58	23.17	21.62	23.25	21.78	24.23	21.85	24.22	21.92	24.23
		6 %	20.69	22.83	20.62	22.84	20.52	22.69	20.88	23.48	21.42	23.47	21.44	23.55	21.56	24.67	21.59	24.63	21.62	24.60
		8 %	20.75	23.05	20.70	23.08	20.62	22.90	20.88	23.71	21.29	23.68	21.30	23.68	21.42	24.86	21.42	24.86	21.43	24.81

Table 8. Vehicle interfaces for 27.75-in. W-beam [G4(1S)] system for low speeds (31 mph).

		Road Curvature Radius	150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
		Road Superelevation	4%		6%		8%		4%		6%		8%		4%		6%		8%	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0%	4 ft	0%	22.23	23.46	22.27	23.49	22.33	23.53	22.78	24.13	22.83	24.20	22.89	24.27	22.94	24.51	23.01	24.59	23.09	24.67
		3%	22.66	24.31	22.68	24.33	22.73	24.37	23.19	24.98	23.22	25.03	23.27	25.10	23.34	25.36	23.39	25.42	23.45	25.49
		6%	23.12	25.19	23.13	25.20	23.16	25.22	23.61	25.84	23.63	25.88	23.67	25.94	23.75	26.22	23.79	26.26	23.84	26.32
		8%	23.46	25.80	23.46	25.80	23.48	25.81	23.92	26.43	23.94	26.47	23.96	26.51	24.06	26.80	24.08	26.84	24.12	26.89
	8 ft	0%	22.08	23.50	22.15	23.55	22.23	23.60	22.64	24.18	22.70	24.25	22.77	24.33	22.83	24.64	22.90	24.72	22.99	24.83
		3%	22.13	24.31	22.16	24.32	22.20	24.36	22.65	25.02	22.68	25.07	22.72	25.14	22.83	25.52	22.87	25.59	22.93	25.68
		6%	22.27	25.03	22.27	25.02	22.28	25.04	22.75	25.77	22.76	25.80	22.77	25.85	22.92	26.30	22.93	26.35	22.96	26.42
		8%	22.41	25.51	22.43	25.49	22.42	25.51	22.86	26.22	22.89	26.27	22.89	26.30	23.02	26.79	23.00	26.83	23.01	26.89
	12 ft	0%	21.96	23.52	22.03	23.56	22.10	23.61	22.52	24.13	22.59	24.21	22.69	24.30	22.70	24.68	22.78	24.78	22.89	24.90
		3%	21.85	23.65	21.91	23.69	21.97	23.71	22.38	24.38	22.44	24.40	22.51	24.47	22.58	24.99	22.63	25.06	22.70	25.15
		6%	21.70	23.78	21.75	23.75	21.80	23.75	22.23	24.58	22.27	24.58	22.32	24.62	22.42	25.29	22.46	25.32	22.53	25.39
		8%	21.62	23.88	21.64	23.83	21.68	23.80	22.11	24.73	22.14	24.71	22.18	24.73	22.31	25.43	22.34	25.51	22.38	25.56
-3%	4 ft	0%	21.90	22.82	21.94	22.86	22.00	22.91	22.47	23.38	22.53	23.44	22.61	23.51	22.65	23.65	22.73	23.72	22.81	23.80
		3%	22.33	23.65	22.36	23.68	22.41	23.71	22.88	24.19	22.93	24.24	22.99	24.30	23.05	24.46	23.11	24.52	23.18	24.60
		6%	22.79	24.51	22.81	24.52	22.83	24.54	23.31	25.01	23.34	25.05	23.39	25.10	23.47	25.28	23.51	25.33	23.57	25.39
		8%	23.13	25.09	23.14	25.09	23.15	25.10	23.62	25.58	23.65	25.60	23.68	25.64	23.78	25.83	23.81	25.88	23.86	25.93
	8 ft	0%	21.70	22.79	21.76	22.83	21.82	22.88	22.29	23.31	22.37	23.38	22.44	23.45	22.49	23.58	22.58	23.67	22.66	23.75
		3%	21.73	23.56	21.77	23.58	21.80	23.60	22.28	24.07	22.34	24.12	22.39	24.17	22.47	24.36	22.52	24.43	22.58	24.50
		6%	21.85	24.23	21.88	24.25	21.88	24.26	22.35	24.74	22.41	24.77	22.42	24.80	22.55	25.04	22.57	25.10	22.60	25.15
		8%	22.03	24.70	22.04	24.68	22.02	24.68	22.50	25.18	22.48	25.19	22.54	25.21	22.63	25.48	22.68	25.53	22.69	25.57
	12 ft	0%	21.53	22.75	21.59	22.79	21.66	22.84	22.15	23.23	22.23	23.29	22.31	23.36	22.35	23.47	22.43	23.54	22.52	23.63
		3%	21.42	22.82	21.46	22.83	21.51	22.86	22.00	23.34	22.06	23.40	22.14	23.43	22.20	23.62	22.26	23.68	22.34	23.74
		6%	21.27	22.89	21.29	22.87	21.33	22.87	21.82	23.46	21.87	23.45	21.93	23.46	22.02	23.74	22.07	23.80	22.13	23.83
		8%	21.18	22.94	21.18	22.90	21.21	22.88	21.70	23.55	21.74	23.51	21.78	23.50	21.89	23.84	21.93	23.89	21.98	23.90
-6%	4 ft	0%	21.52	22.26	21.57	22.31	21.63	22.36	22.11	22.78	22.17	22.84	22.24	22.92	22.29	22.97	22.35	23.04	22.42	23.12
		3%	21.95	22.99	21.99	23.03	22.03	23.07	22.52	23.48	22.57	23.53	22.63	23.60	22.70	23.67	22.76	23.73	22.83	23.81
		6%	22.41	23.83	22.43	23.86	22.46	23.89	22.95	24.28	22.99	24.33	23.03	24.38	23.12	24.46	23.16	24.51	23.21	24.57
		8%	22.75	24.41	22.77	24.43	22.79	24.45	23.26	24.83	23.30	24.87	23.33	24.91	23.43	25.00	23.46	25.04	23.50	25.09
	8 ft	0%	21.30	22.06	21.35	22.12	21.41	22.18	21.90	22.58	21.97	22.65	22.05	22.73	22.10	22.76	22.18	22.84	22.26	22.93
		3%	21.33	22.80	21.35	22.84	21.38	22.88	21.88	23.26	21.92	23.31	22.00	23.37	22.07	23.44	22.12	23.50	22.18	23.58
		6%	21.47	23.48	21.45	23.49	21.45	23.52	21.96	23.89	21.97	23.92	22.03	23.98	22.14	24.06	22.16	24.10	22.19	24.17
		8%	21.60	23.91	21.61	23.91	21.59	23.93	22.10	24.30	22.09	24.32	22.09	24.37	22.22	24.47	22.27	24.49	22.28	24.56
	12 ft	0%	21.11	21.95	21.17	22.00	21.24	22.07	21.73	22.41	21.81	22.48	21.89	22.56	21.94	22.58	22.02	22.65	22.11	22.74
		3%	20.99	22.00	21.03	22.05	21.08	22.08	21.58	22.47	21.64	22.50	21.71	22.58	21.78	22.67	21.85	22.70	21.92	22.76
		6%	20.84	22.05	20.86	22.02	20.90	22.07	21.40	22.47	21.44	22.53	21.46	22.55	21.56	22.69	21.59	22.70	21.62	22.73
		8%	20.75	22.08	20.75	22.03	20.77	22.08	21.27	22.58	21.29	22.56	21.30	22.56	21.42	22.75	21.42	22.74	21.43	22.83

Table 9. Vehicle interfaces for 31-in. W-beam (MGS) system for low speeds (31 mph).

Road Curvature Radius			150 ft (45 m)						300 ft (90 m)						450 ft (135 m)					
Road Superelevation			4 %		6 %		8 %		4 %		6 %		8 %		4 %		6 %		8 %	
Vertical Grade	Shoulder Width	Shoulder Angle	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)	Min (in)	Max (in)
0 %	4 ft	0 %	22.23	23.46	22.27	23.49	22.33	23.53	22.78	24.13	22.83	24.20	22.89	24.27	22.94	24.51	23.01	24.59	23.09	24.67
		3 %	22.66	24.31	22.68	24.33	22.73	24.37	23.19	24.98	23.22	25.03	23.27	25.10	23.34	25.36	23.39	25.42	23.45	25.49
		6 %	23.12	25.19	23.13	25.20	23.16	25.22	23.61	25.84	23.63	25.88	23.67	25.94	23.75	26.22	23.79	26.26	23.84	26.32
		8 %	23.46	25.80	23.46	25.80	23.48	25.81	23.92	26.43	23.94	26.47	23.96	26.51	24.06	26.80	24.08	26.84	24.12	26.89
	8 ft	0 %	22.08	23.50	22.15	23.55	22.23	23.60	22.64	24.18	22.70	24.25	22.77	24.33	22.83	24.64	22.90	24.72	22.99	24.83
		3 %	22.13	24.31	22.16	24.32	22.20	24.36	22.65	25.02	22.68	25.07	22.72	25.14	22.83	25.52	22.87	25.59	22.93	25.68
		6 %	22.27	25.03	22.27	25.02	22.28	25.04	22.75	25.77	22.76	25.80	22.77	25.85	22.92	26.30	22.93	26.35	22.96	26.42
		8 %	22.41	25.51	22.43	25.49	22.42	25.51	22.86	26.22	22.89	26.27	22.89	26.30	23.02	26.79	23.00	26.83	23.01	26.89
	12 ft	0 %	21.96	23.52	22.03	23.56	22.10	23.61	22.52	24.13	22.59	24.21	22.69	24.30	22.70	24.68	22.78	24.78	22.89	24.90
		3 %	21.85	23.65	21.91	23.69	21.97	23.71	22.38	24.38	22.44	24.40	22.51	24.47	22.58	24.99	22.63	25.06	22.70	25.15
		6 %	21.70	23.78	21.75	23.75	21.80	23.75	22.23	24.58	22.27	24.58	22.32	24.62	22.42	25.29	22.46	25.32	22.53	25.39
		8 %	21.62	23.88	21.64	23.83	21.68	23.80	22.11	24.73	22.14	24.71	22.18	24.73	22.31	25.43	22.34	25.51	22.38	25.56
-3 %	4 ft	0 %	21.90	22.82	21.94	22.86	22.00	22.91	22.47	23.38	22.53	23.44	22.61	23.51	22.65	23.65	22.73	23.72	22.81	23.80
		3 %	22.33	23.65	22.36	23.68	22.41	23.71	22.88	24.19	22.93	24.24	22.99	24.30	23.05	24.46	23.11	24.52	23.18	24.60
		6 %	22.79	24.51	22.81	24.52	22.83	24.54	23.31	25.01	23.34	25.05	23.39	25.10	23.47	25.28	23.51	25.33	23.57	25.39
		8 %	23.13	25.09	23.14	25.09	23.15	25.10	23.62	25.58	23.65	25.60	23.68	25.64	23.78	25.83	23.81	25.88	23.86	25.93
	8 ft	0 %	21.70	22.79	21.76	22.83	21.82	22.88	22.29	23.31	22.37	23.38	22.44	23.45	22.49	23.58	22.58	23.67	22.66	23.75
		3 %	21.73	23.56	21.77	23.58	21.80	23.60	22.28	24.07	22.34	24.12	22.39	24.17	22.47	24.36	22.52	24.43	22.58	24.50
		6 %	21.85	24.23	21.88	24.25	21.88	24.26	22.35	24.74	22.41	24.77	22.42	24.80	22.55	25.04	22.57	25.10	22.60	25.15
		8 %	22.03	24.70	22.04	24.68	22.02	24.68	22.50	25.18	22.48	25.19	22.54	25.21	22.63	25.48	22.68	25.53	22.69	25.57
	12 ft	0 %	21.53	22.75	21.59	22.79	21.66	22.84	22.15	23.23	22.23	23.29	22.31	23.36	22.35	23.47	22.43	23.54	22.52	23.63
		3 %	21.42	22.82	21.46	22.83	21.51	22.86	22.00	23.34	22.06	23.40	22.14	23.43	22.20	23.62	22.26	23.68	22.34	23.74
		6 %	21.27	22.89	21.29	22.87	21.33	22.87	21.82	23.46	21.87	23.45	21.93	23.46	22.02	23.74	22.07	23.80	22.13	23.83
		8 %	21.18	22.94	21.18	22.90	21.21	22.88	21.70	23.55	21.74	23.51	21.78	23.50	21.89	23.84	21.93	23.89	21.98	23.90
-6 %	4 ft	0 %	21.52	22.26	21.57	22.31	21.63	22.36	22.11	22.78	22.17	22.84	22.24	22.92	22.29	22.97	22.35	23.04	22.42	23.12
		3 %	21.95	22.99	21.99	23.03	22.03	23.07	22.52	23.48	22.57	23.53	22.63	23.60	22.70	23.67	22.76	23.73	22.83	23.81
		6 %	22.41	23.83	22.43	23.86	22.46	23.89	22.95	24.28	22.99	24.33	23.03	24.38	23.12	24.46	23.16	24.51	23.21	24.57
		8 %	22.75	24.41	22.77	24.43	22.79	24.45	23.26	24.83	23.30	24.87	23.33	24.91	23.43	25.00	23.46	25.04	23.50	25.09
	8 ft	0 %	21.30	22.06	21.35	22.12	21.41	22.18	21.90	22.58	21.97	22.65	22.05	22.73	22.10	22.76	22.18	22.84	22.26	22.93
		3 %	21.33	22.80	21.35	22.84	21.38	22.88	21.88	23.26	21.92	23.31	22.00	23.37	22.07	23.44	22.12	23.50	22.18	23.58
		6 %	21.47	23.48	21.45	23.49	21.45	23.52	21.96	23.89	21.97	23.92	22.03	23.98	22.14	24.06	22.16	24.10	22.19	24.17
		8 %	21.60	23.91	21.61	23.91	21.59	23.93	22.10	24.30	22.09	24.32	22.09	24.37	22.22	24.47	22.27	24.49	22.28	24.56
	12 ft	0 %	21.11	21.95	21.17	22.00	21.24	22.07	21.73	22.41	21.81	22.48	21.89	22.56	21.94	22.58	22.02	22.65	22.11	22.74
		3 %	20.99	22.00	21.03	22.05	21.08	22.08	21.58	22.47	21.64	22.50	21.71	22.58	21.78	22.67	21.85	22.70	21.92	22.76
		6 %	20.84	22.05	20.86	22.02	20.90	22.07	21.40	22.47	21.44	22.53	21.46	22.55	21.56	22.69	21.59	22.70	21.62	22.73
		8 %	20.75	22.08	20.75	22.03	20.77	22.08	21.27	22.58	21.29	22.56	21.30	22.56	21.42	22.75	21.42	22.74	21.43	22.83

Looking across all the values in the table, it can be seen that the critical heights range from just under 21 in. to almost 28 in. When examining the results in each of the tables, some of the following insights can be noted:

- For the 32-in. height concrete barriers:
  - Because the concrete barrier has a 0-in. minimum interface height (i.e., no potential for underrides), this barrier works for all minimum cases for all the curvature, superelevation, shoulder, and vertical grade conditions. It can be observed from Table 7 that no red values are in any of the minimum rows.
  - Similarly, this barrier provides a good interface for all offsets by noting no red values.
  - Because the VDA showed good vehicle-to-barrier interface for the 32-in. height concrete barriers, it can be concluded that the 42-in. height barriers would also have adequate interface. (Finite element analyses would be needed to assess the effects of impact severity.)
- For the Thrie beam barrier (SGR09b):
  - VDA indicates that the Thrie beam barrier meets the minimum interface requirements for all cases (Table 6), indicating less susceptibility to underride for the CSOR road profiles and impact conditions considered.
  - Similarly, the greater height of the Thrie beam barrier led to all "good" maximum interface indications across the range of conditions considered, indicating less susceptibility to override for the CSOR road profile.
- For the W-beam barrier with 27.75-in. top-of-rail height (G4(1S)):
  - The G4(1S) barrier appears to meet the minimum interface requirements for all cases, as Table 4 shows no red-shaded cells for any of the minimum columns, indicating less susceptibility to underride for the CSOR road profiles and impact configurations considered.
  - Table 4, however, shows cases in which the maximum requirement is not met, as indicated by the red-shaded cells. Hence, there is an increased chance of override from the CSOR road profile. Red values are more noticeable with the higher shoulder slope angle (8%), lower vertical grade (0%), and higher curvature (450 ft).
  - In Table 8, only the lower speed (31 mph) is considered, as fewer cases of override were observed.
- For the W-beam barrier with 31-in. top-of-rail height (MGS):
  - The greater height of the MGS barrier provides more adequate maximum interface indications across a range of conditions, indicating less susceptibility to override with the CSOR road profile compared with the G4(1S) system (Table 5).
  - However, there is no corresponding meeting of the minimum requirements. Several cells in Table 5 do not meet this criterion, indicating susceptibility to a vehicle going under the barrier and its potential for snagging posts. Cases are more noticeable for sharper CSORs (150 ft).
  - Much fewer cases of underride were observed when considering only the lower-speed (31 mph) cases, as seen in Table 9.

These and other insights demonstrate the value of the VDA results. VDA provides an indication of how well or poorly the barrier would perform based on the vehicle dynamics and geometry of the barrier. It does not account for the increased or decreased severity of the impact attributable to changes in vehicle orientation and speed. This aspect of performance is analyzed using finite element simulations and crash testing in the next chapter.

CHAPTER 4

Crash Simulation Analyses

The second type of computer simulation used in this research involves finite element crash simulation techniques. In these efforts, specific barriers and vehicles are represented by "finite element" models that represent the basic parts of a barrier and an impacting vehicle. The models can be considered representations of every part in a vehicle or barrier as small three-dimensional cubes that reflect the shape, material, and position or connections to adjacent elements of each part. The geometry, size, shape, and material (and its properties), as well as the connection to the adjacent elements, are defined in building the model. The size of the elements is dictated by the level of detail desired and the available computational capabilities.

Finite element simulation involves tracking the effects of imposing forces on the "elements." Repeating the process for small units of time allows each force and its effects to reflect the "state of the system" for each unit of time. The properties of the element's material dictate whether that element moves, deforms, or fractures as a result of the force or forces. For each time increment in the simulation, tracking the movement and conditions of each element leads to a representation of a series of micro-changes that over multiple iterations reflect the crash outcome condition.

The accuracy of the representation of the crash outcomes is determined by the size (and number) of elements and the rigor in defining the object and characterizing its properties and how they react to the effects imposed. It requires "effective representation" (or "computation") of these transitions over many small increments of time to reflect a representative crash outcome. Several decades of developing this process have achieved high degrees of correlation between an observed crash outcome and the "computer-generated" outcome.

The technologies used in finite element simulations follow the laws of physics, materials science, structural engineering, and the like, such that a post-impact assessment can reveal the efficacy of an item under a given "loading" condition. In the safety realm, this implies the condition of the barrier, the vehicle, and all occupants. Comparisons of simulated and actual crashes of vehicles into barriers have become accurate, and hence the tool has become widely used to analyze various safety performance aspects. It requires that "models" of objects be developed accurately, that users be knowledgeable about effective use of the software functions, and that a powerful computing capability be available. The effort to create models is significant, but the base models can be reused for many studies. Variations in features can be implemented by changing element properties (e.g., different steel or concrete properties). Although computing times for finite element simulations can take much longer than VDA simulations, transfer of models or alterations of properties can be readily used to consider design improvements. The computational intensity in finite element simulations does not, however, make it the best tool for incremental analyses of effects on vehicle paths, as with VDA.

4.1 Crash Simulation Analysis Requirements

Finite element crash computer simulation has advanced in the past 25 years and has proven effective in determining the outcome of vehicle-to-barrier impacts under various deployment scenarios. The aim of crash simulation analysis is to create performance envelopes for longitudinal barriers installed on CSORs. The first part of the project involved adapting, developing, and validating models for roadside hardware devices and vehicles, allowing for the evaluation of different highway safety treatments for specific CSOR conditions. The following section summarizes the efforts made to determine the relative effectiveness of various types of barriers for CSOR situations, given that the geometry and conditions of these situations can significantly affect the treatment's effectiveness. The focus of this effort was to determine whether safety requirements would be met in these situations.

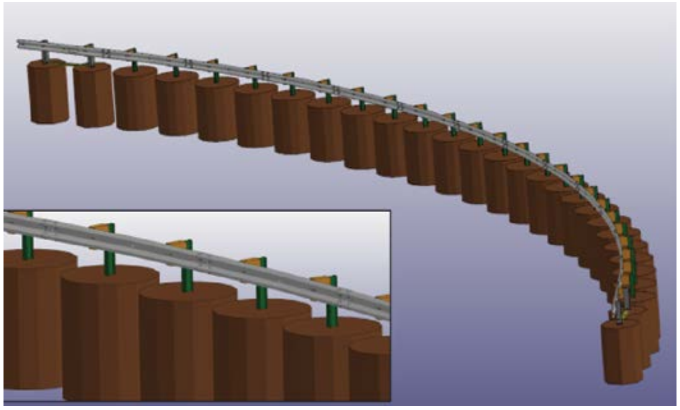
4.1.1 Roadside Barrier Models

The first step involved adapting the computer models of the roadside hardware devices from NCHRP Project 22-29A to address this project's objectives. Several longitudinal barrier models have been developed over the years and validated through full-scale crash tests (e.g., modified G4(1S) guardrail, Thrie beam guardrail, MGS guardrail, portable and median concrete barriers with different shapes). Models developed and validated under the previous part of the project and the tools created to generate the barriers with various curvatures and slopes were updated in this part of the project for generating the CSOR models and conducting simulations. Figure 15 illustrates variations of one barrier model, the New Jersey concrete barrier, with different radii. Figure 16 shows W-beam, Thrie beam, and concrete longitudinal barrier models adapted to reflect the ramp curvature and evaluate the barriers' performances under different impact conditions on CSORs.

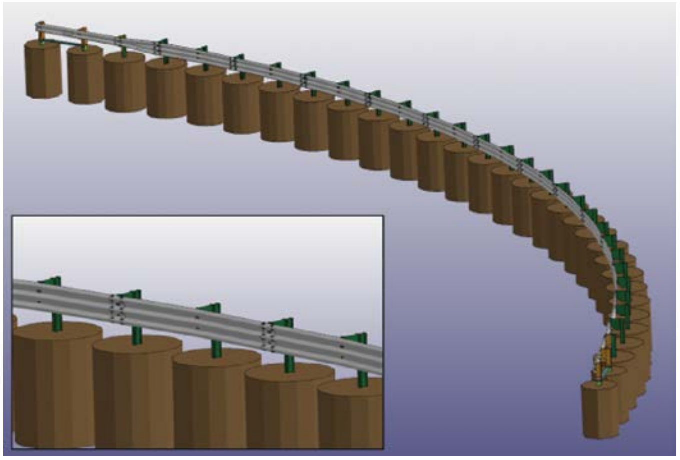
4.1.2 Vehicle Models

To simulate the longitudinal barriers' performance when placed on CSORs, digital models of the impacting objects (i.e., vehicles) are required to simulate impacts with models of the barriers. Although an array of vehicle models is available, the ones representing MASH test vehicles were the primary focus in this study. For the MASH Test Level 3 and 4 (TL3/TL4) impact conditions, the three test vehicles recommended are the 1100C passenger car, the 2270P pickup, and the 10000S single-unit truck (SUT). These models have been widely used for finite element analyses to evaluate the safety performance of roadside barriers (*30–35*). The simulations considered three typical vehicles for crash analyses, as shown in Table 10, representing TL3/TL4 standard vehicles.

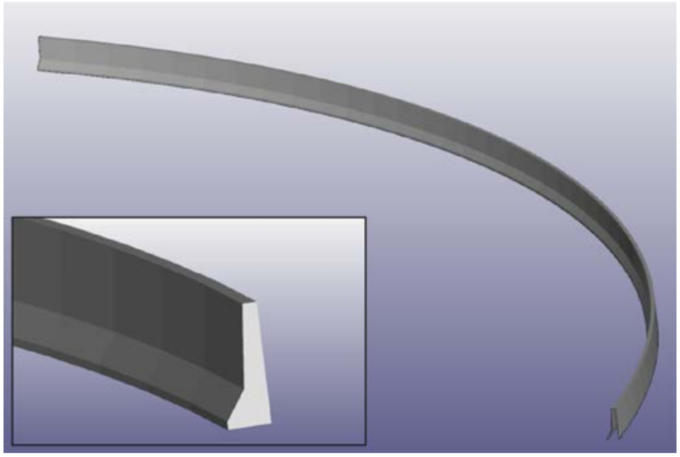
Figure 15. Barrier models with different curvatures.



(a)



(b)



(c)

Figure 16. Models of different curved longitudinal barriers analyzed in the study (a) W-beam guardrail (MGS), (b) Thrie beam guardrail (SGR09b), and (c) concrete barrier (New Jersey, F-, and single-slope shapes).

Table 10. Models representing MASH test vehicles.

Description	Vehicle Image
2010 Toyota Yaris • Weight: 1,100 kg CG (1,004 mm rear, 569 mm high) • Model Parameters o Parts: 919 o Elements/Nodes: 393,165/378,395 o Shells/Beams/Solids: 358,457/4,685/15,234	
2007 Chevrolet Silverado Pickup Truck • Weight: 2,270 kg, CG (1,545 mm rear, 710mm high) • Model Parameters o Parts: 605 o Elements/Nodes: 261,647/250,932 o Shells/Beams/Solids: 235,921/2,463/12,525	
10000S SUT Ford F800 • Weight: 8,000 kg and 10,000 kg • Model Parameters o Parts: 138 o Elements/Nodes: 57,437/61,675 o Shells/Beams/Solids: 55,303/552/1,886	

Note: CG = center of gravity.

4.1.3 Computer Model Validations

Model validation involves simulating a known crash test and comparing the results. A solid validation effort provides confidence that reasonable variations of the model to reflect other situations will yield representative results. For this effort, multiple validations for each barrier were selected for analysis. These validations made use of the best available crash test data that existed at the time of the analysis. Table 11 lists the crash tests used for the model validations.

A rigorous verification and validation (V&V) effort was undertaken to provide confidence that the models for each of the three barriers are viable in replicating crashes into barriers on CSRSs. The results from the eight comparisons are summarized to provide an opportunity to review the viability or strengths of the validations based on the V&V results. A summary of the validation efforts is provided in Table 12, which includes the graphic of vehicle roll, pitch, and yaw angular rotations and the change in vehicle velocity along the *x*-, *y*-, and *z*-directions.

V&V analytic comparisons for all seven validation cases were also undertaken based on *NCHRP Report 179: Evaluating Options in Statewide Transportation Planning/Programming*

Table 11. Full-scale crash tests used for validations.

Barrier	Vehicle	Test	Date	Place	Evaluation	Ref.
NJ Shaped Concrete	2002 Kia Rio	2214NJ-1	5/28/04	MwRSF	MASH	(*36*)
	2007 Silverado	476460-1-4	1/10/09	TTI	MASH	(*37*)
G4(1S)	1989 C2500	405421-1	11/16/95	TTI	350	(*38*)
	2002 Dodge Ram	2214WB-2	4/08/05	MwRSF	MASH	(*39*)
MGS	2002 Kia Rio	2214MG-3	11/08/04	MwRSF	MASH	(*40*)
	1994 Geo Metro	NPG-1	6/29/01	MwRSF	350	(*41*)
	2002 Dodge Ram	2214MG-2	8/20/01	MwRSF	MASH	(*42*)
Florida Jersey Concrete	1995 Ford F800	421323-1	2/18/03	TTI	350	(*43*)
Texas DOT 36-in. Concrete	1995 Ford F800	469467-1-1	8/15/17	TTI	MASH	(*44*)

Note: MwRSF = Midwest Roadside Safety Facility; TTI = Texas A&M Transportation Institute.

Table 12. Summary of validation results for change in vehicle velocities and rotations.

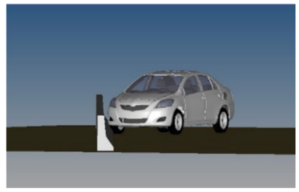
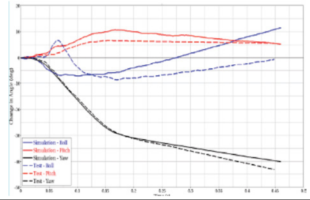
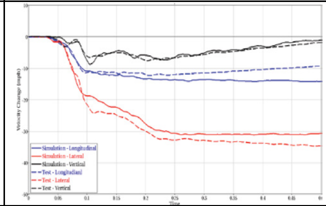
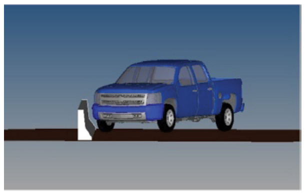
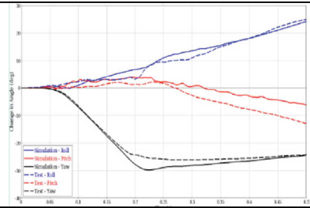
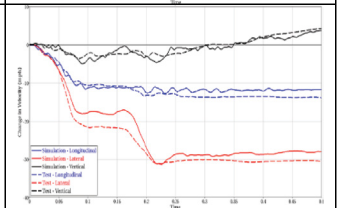
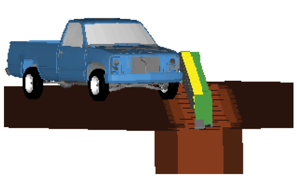
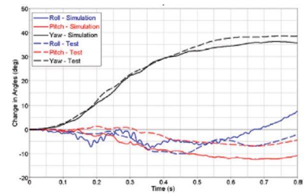
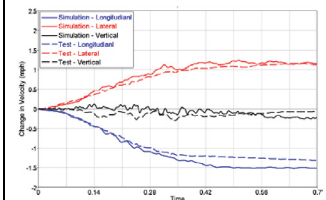
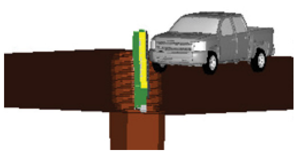
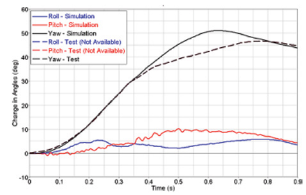
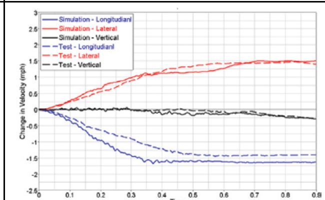
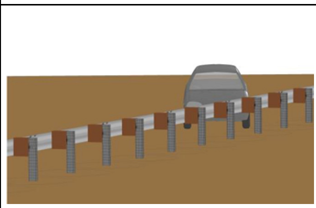
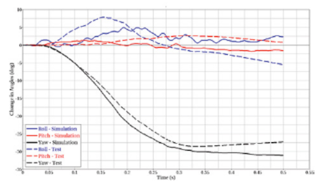
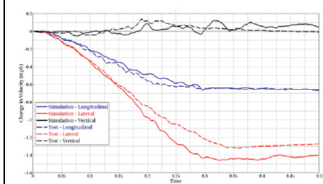
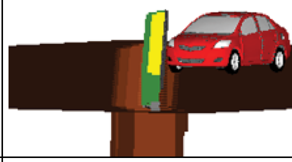
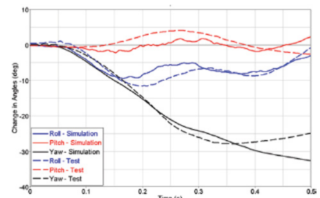
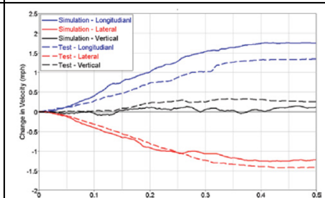
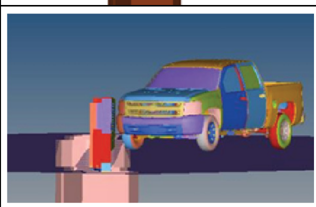
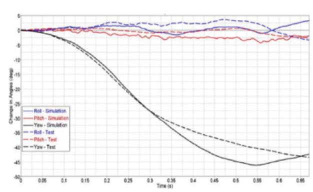
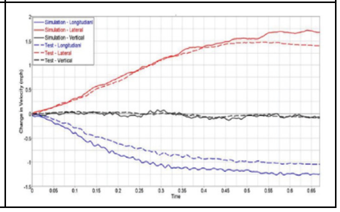
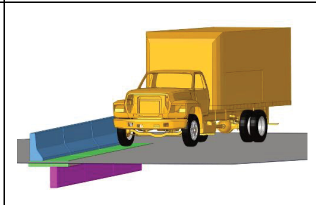
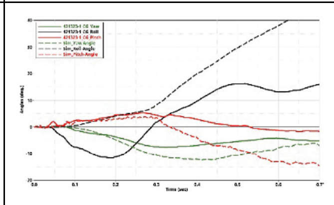
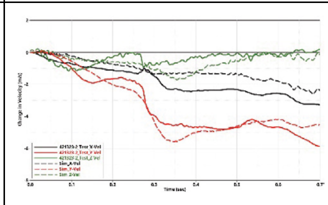
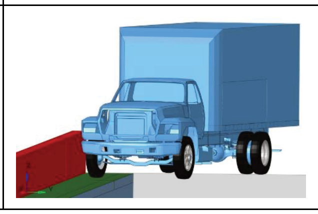
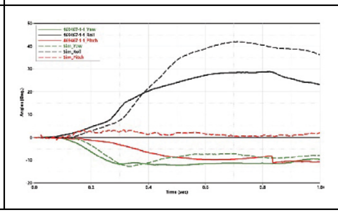
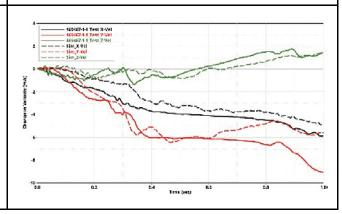
Test	Model Set-Up	Angular Rotations	Change in Velocity
NJ Concrete Barrier w/ Kia Rio 1100C			
NJ Concrete Barrier w/ Silverado 2270P			
G4(1S) w/ C2500 2000P			
G4(1S) w/ Dodge Ram 2270P			
MGS w/ Geo Metro 820C			
MGS w/ Kia Rio 1100C			
MGS w/ Dodge Ram 2270P			

Table 12. (Continued).

Test	Model Setup	Angular Rotations	Change in Velocity
Florida Jersey Bridge Rail Barrier w/F800 (8000S)			
Texas DOT 36-in. Vertical Wall Concrete Barrier w/ F800 (10000S)			

Issues, Techniques, and Their Relationships (*45*), and Roadside Safety Verification and Validation Program (RSVVP) tables and phenomena importance ranking tables (PIRTs) were generated. Sample V&V results are included in the next sections. Full V&V reports for each of the seven cases selected are provided in Appendix C of *NCHRP Research Report 894* (*3*).

The validity of the models was assessed by analyzing the distribution of energy associated with the crash event. The laws of physics dictate that the total energy is balanced. Typically, an energy balance graph is generated to assess changes in kinetic, internal, sliding, hourglass, and total energy. All of the comparisons were characterized in the following manner:

- Relatively constant energy balances were noted, suggesting that there are no unusual characterizations in the structure of the model that would be an unrealistic sink (point of dissipation) of the energy.
- The kinetic energy associated with the motion of the vehicle dropped off as the velocity was decreased during the crash.
- Internal energy increased as components of the vehicle absorbed energy through deformation.
- Sliding energy, which is associated with the friction between the vehicle and barrier, increased as expected during the simulations.

All V&V criteria for energy balance were met. These aspects led to the conclusion that the model met the fundamental requirements for crash simulation.

The RSVVP procedure consists of applying statistical tests to determine how well the simulation curves compare with data collected from the test. Various means of comparing the data are shown in each comparison, including:

- Time history plot: The red line indicates the simulated data, and the blue line indicates the test data for the crash event. Each data point is a measure of the acceleration recorded.
- Plot of integrated time histories: Integrating the change of acceleration data allows the changes in velocity to be plotted. A general decrease in velocity is noted, as expected, although some deviation exists between the test and the simulation after the impact.
- MPC metrics: This statistical metric provides a measure of "goodness of fit" between the two curves. Three parameters are used for the evaluation: the magnitude (M), phase (P), and comprehensive (C, combined magnitude and phase). A value of less than 40 for M, P, and C is considered passing the criteria.

- ANOVA metrics: Analysis of variance is also used to compare the test and simulation curves' "goodness of fit." Two parameters are used for the comparison: the average residual between the curves and the standard deviation of the residuals. Values of less than 5% for the average residual and 35% for the standard deviation are considered to pass the criteria. In the *NCHRP Research Report 894* example, the metric meets the criteria, and hence the boxes are labeled "pass" (*3*).
- Residual plots (time history, histogram, and cumulative): These plots show the residual (i.e., the difference between the two curves in different forms). In the first plot, time history, the residual is shown versus time. In the second, the residual is shown in a histogram format in which the percentage of the residual is plotted against the percentage of its occurrence. In the third plot, the cumulative sum of residuals is plotted.

The program allows various types of single-channel data to be analyzed. The common crash test and simulation metrics compared are:

- *x*-acceleration: change in acceleration in the original direction of travel of the vehicle.
- *y*-acceleration: change in acceleration in the lateral direction of travel of the vehicle.
- *z*-acceleration: change in acceleration in the vertical direction of travel of the vehicle.
- Yaw rate: rate of change in the original direction of travel of the vehicle.
- Roll rate: rate of change in the lateral direction of travel of the vehicle.
- Pitch rate: rate of change in the vertical direction of travel of the vehicle.

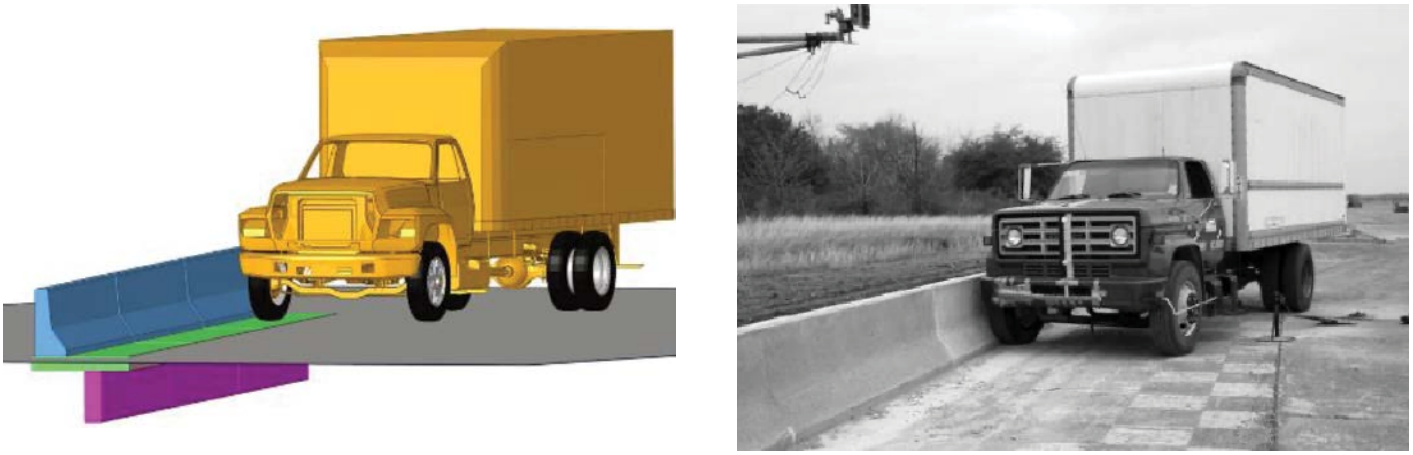
Because not all measurements have the same importance in the tests (e.g., in some tests, little roll, pitch, *x*-acceleration, etc., are observed), these low-magnitude channels could fail the evaluation metrics even if the simulation were valid. A multi-channel comparison, in which each channel is given a weighting factor based on magnitude, is incorporated into the validation process to address the issue. These weights are used to determine the importance of each channel in the overall comparison of the two sets of data (test and simulations).

In addition to the RSVVP evaluations, PIRTs based on *NCHRP Report 179* V&V procedures (*45*) were created to compare other aspects of the impact, such as occupant risk numbers, barrier maximum deflections, and rotations. Full V&V reports in accordance with *NCHRP Report 179* were generated for each validation case. These validation reports are included in Appendix C. Summaries from two of these validation cases, which were used for calibrating the SUT, are included in the following sections.

4.1.3.1 Validation for Florida Jersey Bridge Barrier Using NCHRP Report 350 TL 4-12

The first test used for SUT model validation is from *NCHRP Report 350* (*8*), Test Level 4-12, conducted by the Texas A&M Transportation Institute (TTI). The barrier used is the FL-J-BR system. In this test (Test 421323-1), a GMC Sierra 7000 SUT (8000S) impacted the barrier at a 14.3-degree angle and a speed of 50.6 mph (*43*). The setup details for this test are noted in Figure 17. This test was simulated using the finite element model of the FL-J-BR barrier and a Ford F800 SUT (representing the 8000S single-unit truck test vehicle).

The sequential side-by-side views in Figure 18, Figure 19, and Figure 20 show that the SUT impacted the barrier and maintained contact as its velocity decreased and it was redirected. In the front view (Figure 18), it can be noted that vehicles behave similarly between the simulation and the crash test impact. Vehicle pitch and yaw are similar in the test and simulation, but the vehicle roll angles are slightly off in the simulation because the front axle in the model did not fail, as happened in the test. In the overhead view (Figure 20), the vehicle yaw is similar in both the test and the simulation. These are considered to reflect a good correlation between the test and the simulation of it.



(a) (b)

Figure 17. (a) Simulation and (b) test crash setups for Test 421323-1.

Figure 21 provides the energy balance diagram for the simulation. It depicts a balance of internal and sliding interface (contact) energy to offset the kinetic energy. The figure indicates no unusual effects, suggesting that the model functioned as expected in the simulation. A graphical comparison of the change in velocity of the SUT ballast center of gravity, as derived from the accelerometers installed on the truck, is provided in Figure 22. On the graph, the solid lines indicate the changes in velocity for the *x*-, *y*-, and *z*-axes from the crash tests. The corresponding velocities for the simulation are shown by the dashed lines. Little difference exists in the velocities for the *x*-, *y*- and *z*-axes, as noted by the similar tracks for each metric. These are considered to indicate good correlation between the test and simulation results because the movement of the vehicle at the center of gravity was effectively replicated by the computer model.

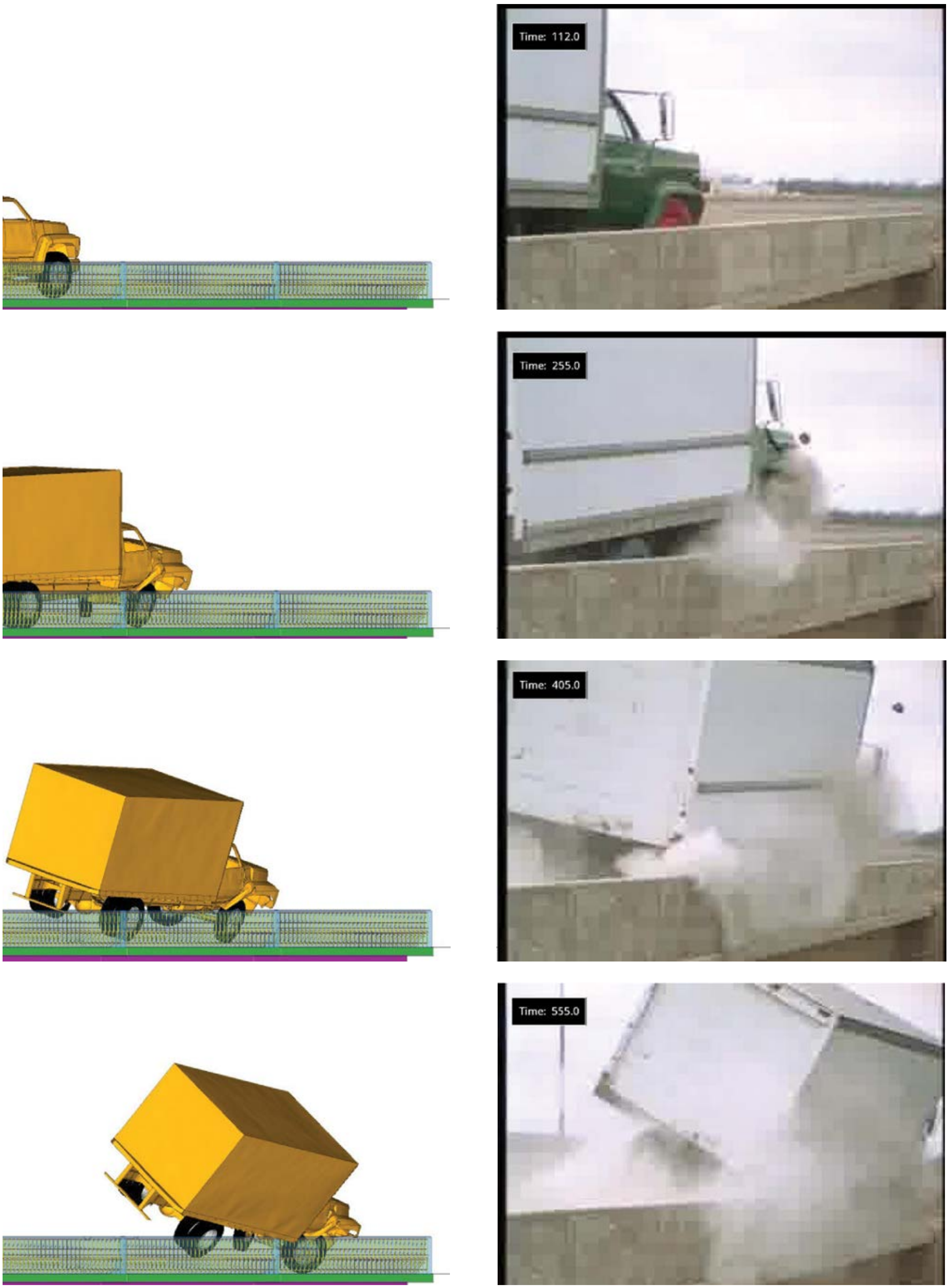
Figure 23 shows the changes in the roll, pitch, and yaw of the SUT between the test and the simulation. The plot indicates a close correlation of the pitch (red solid and dashed lines) and yaw (green solid and dashed lines). The roll (black solid and dashed lines) angles show some differences because the SUT front axle failed in the test. These results are considered to indicate good correlations between the test and the simulations using the finite element models.

V&V analytical comparisons of these results were undertaken based on *NCHRP Report 179* (*45*). RSVVP tables and PIRTs were generated. The metrics derived from the RSVVP procedure are summarized in Figure 24 for multi-channel analyses. V&V comparisons and the full V&V report are provided in Appendix C. The overall results confirm that the simulation is considered validated based on the multiple listed comparison steps and the justifications included in the tables.

4.1.3.2 Validation for Texas DOT 36-in. Vertical Wall Barrier MASH TL 4-12

A MASH TL 4-12 was conducted by TTI to show that the Texas DOT 36-in. vertical wall barrier meets MASH requirements. In TTI Test 469467-1-1, an International 4200 SUT 10000S impacted the barrier at a 15-degree angle and a speed of 56 mph (*44*). The setup details for this test are noted in Figure 25. This test was simulated using the finite element model of the FL-J-BR barrier and a Ford F800 SUT (representing the 10000S test vehicle).

Figure 18. Front views for (a) simulation and (b) Test 421323-1.



0 s

0.240 s

0.440 s

0.640 s

(a) (b)

Figure 19. Isometric rear views for (a) simulation and (b) Test 421323-1.

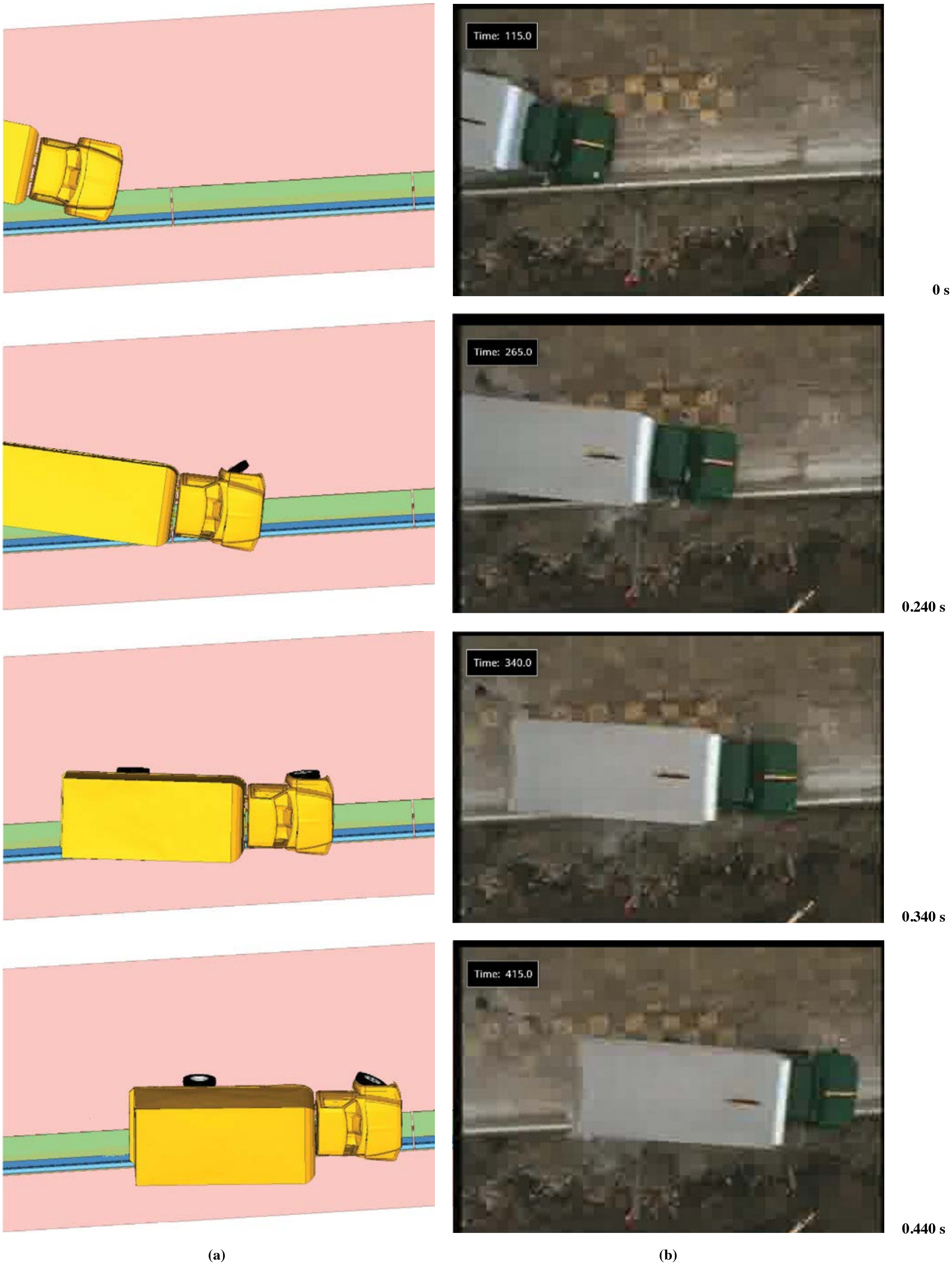


Figure 20. Overhead views for (a) simulation and (b) Test 421323-1.

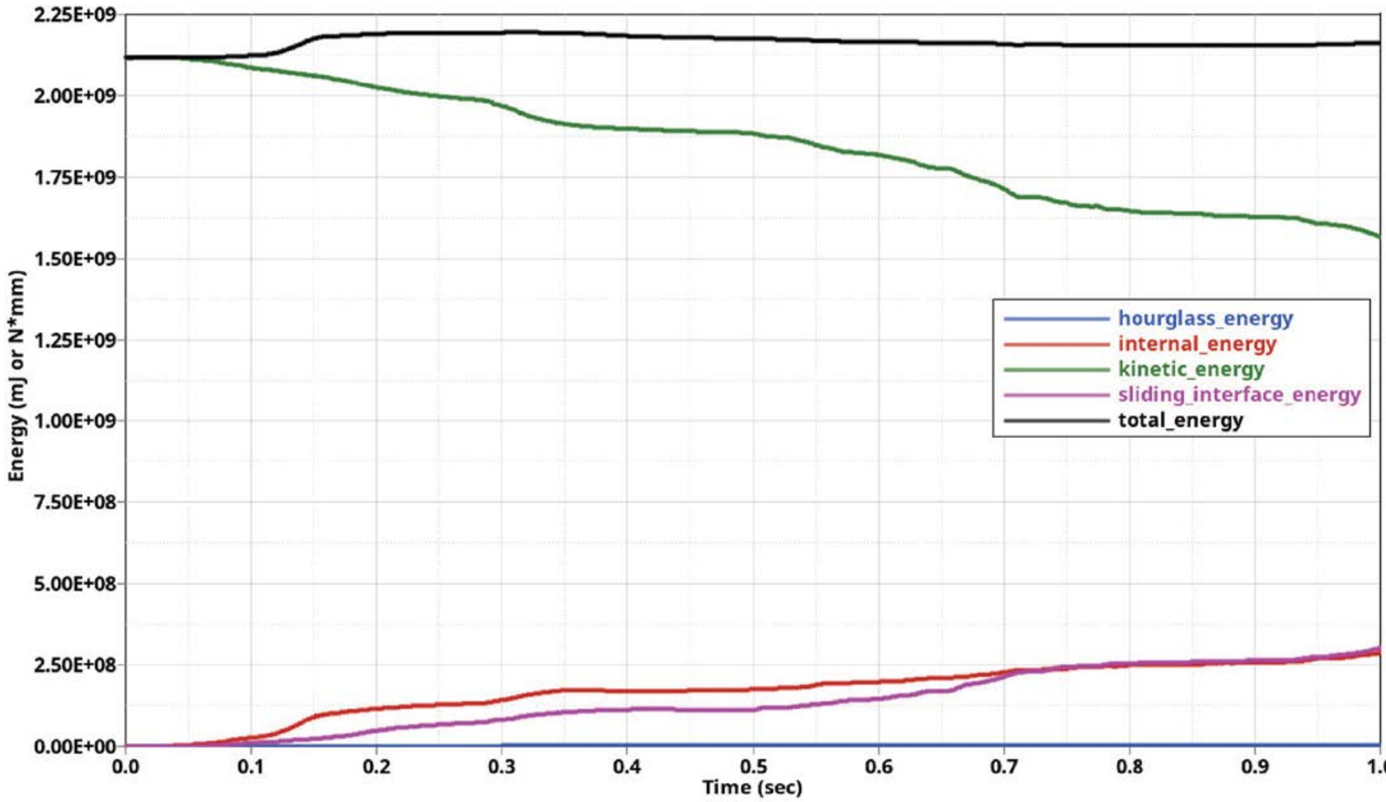


Figure 21. Energy balance diagram from simulation for Test 421323-1.

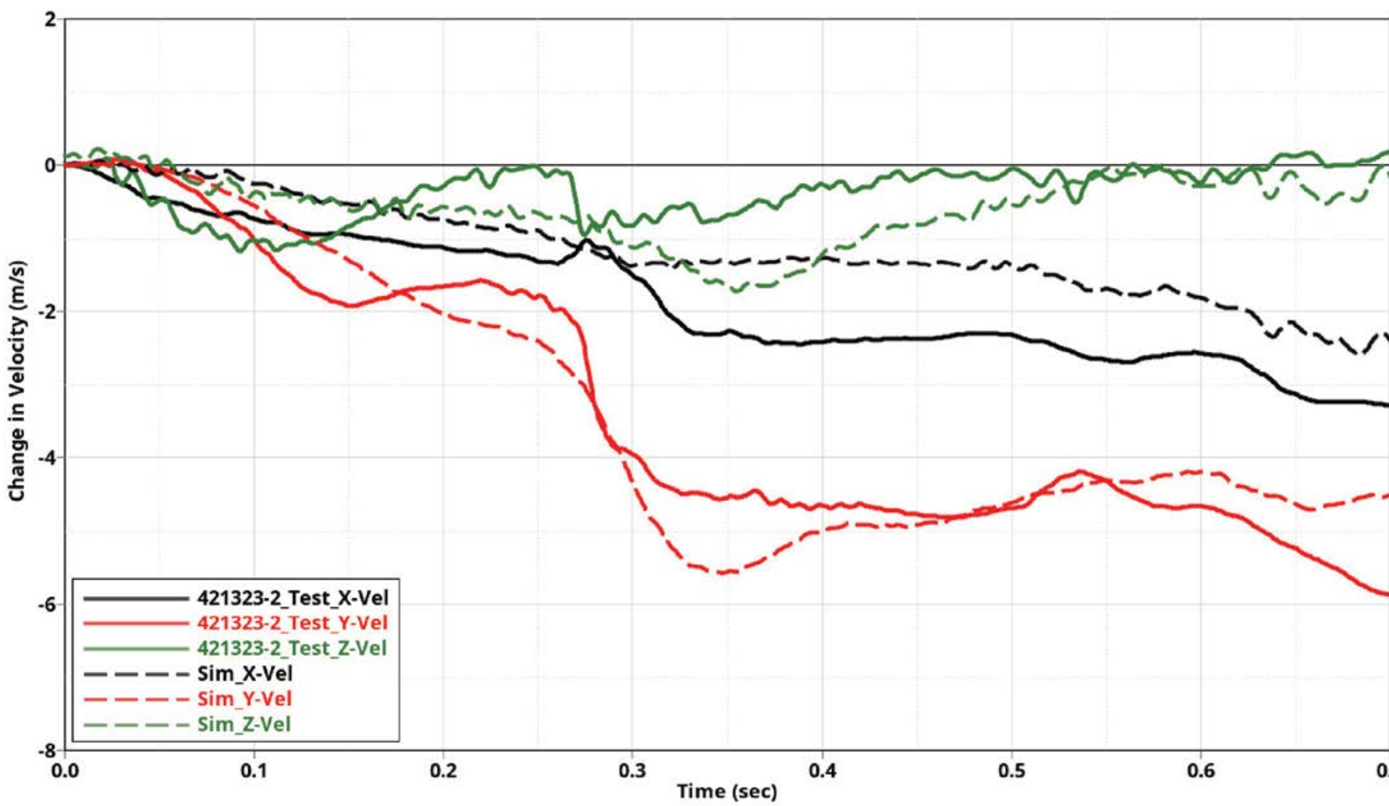


Figure 22. x, y, and z change in velocity test-to-simulation comparisons for Test 421323-1.

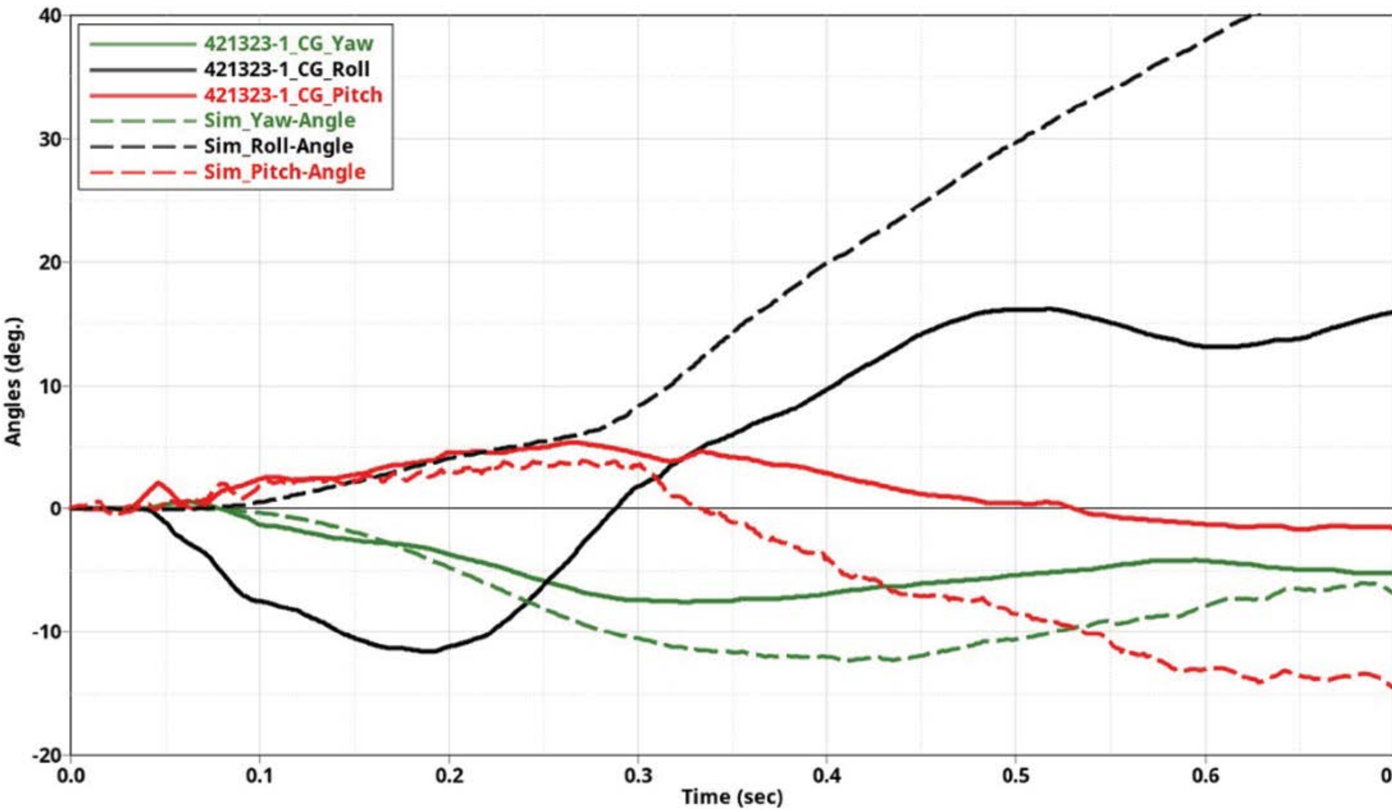


Figure 23. Roll, pitch, and yaw test-to-simulation comparisons for Test 421323-1.

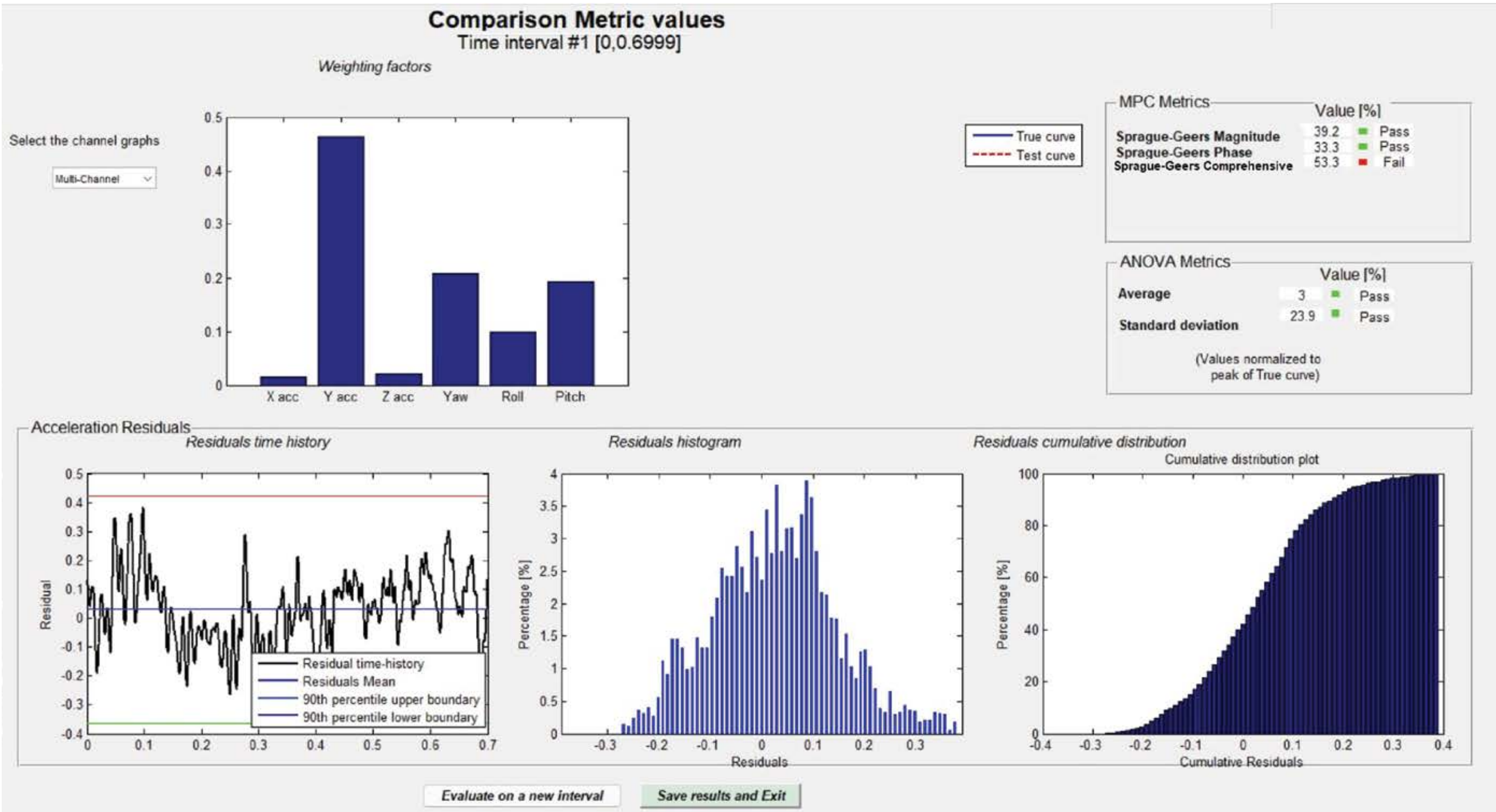


Figure 24. RSVVP multi-channel evaluation for Test 421323-1.

(a) (b)

Figure 25. (a) Simulation and (b) test crash setups for Test 469467-1-1.

The sequential side-by-side views in Figure 26, Figure 27, and Figure 28 show that the SUT impacted the barrier and maintained contact as its velocity decreased and it was redirected. In the front view (Figure 26), the vehicles behave similarly between the simulation and the crash test impact. Similar vehicle pitch and yaw exists in the test and simulation, but the vehicle roll angles are slightly off because the vehicle in the model is older and from a different manufacturer than the one in the test. These views are considered to reflect a good correlation between the test and a simulation of it.

Figure 29 provides the energy balance diagram for the simulation. It depicts a balance of internal and sliding interface (contact) energy to offset the kinetic energy. There are no unusual effects, suggesting that the model functioned as expected in the simulation.

A graphical comparison of the change in velocity of the SUT ballast center of gravity, as derived from the accelerometers installed on the truck, is provided in Figure 30. On the graph, the solid lines indicate the changes in velocity for the *x*-, *y*-, and *z*-axes from the crash tests. The corresponding velocities for the simulation are shown by the dashed lines. Little difference exists in the velocities for the *x*-, *y*- and *z*-axes, as noted by the similar tracks for each metric. These tracks are considered to indicate good correlation between the test and the simulation results because the movement of the vehicle at the center of gravity was effectively replicated by the computer model.

Figure 31 shows the changes in the roll, pitch, and yaw of the SUT between the test and the simulation. The plot indicates a close correlation of the pitch (red solid and dashed lines) and yaw (green solid and dashed lines). The roll (black solid and dashed lines) angles show some differences because SUTs in the test and the simulation are from different manufacturers. These results are considered to indicate good correlations between the test and the simulations using the finite element models.

V&V analytical comparisons of these results were undertaken based on *NCHRP Report 179* (*45*). RSVVP tables and PIRTs were generated. The metrics derived from the RSVVP procedure are summarized in Figure 32 for multi-channel analyses. V&V comparisons and the full V&V report are provided in Appendix C. The overall results confirm that the simulation is considered validated based on the multiple listed comparison steps and the justifications included in the tables.

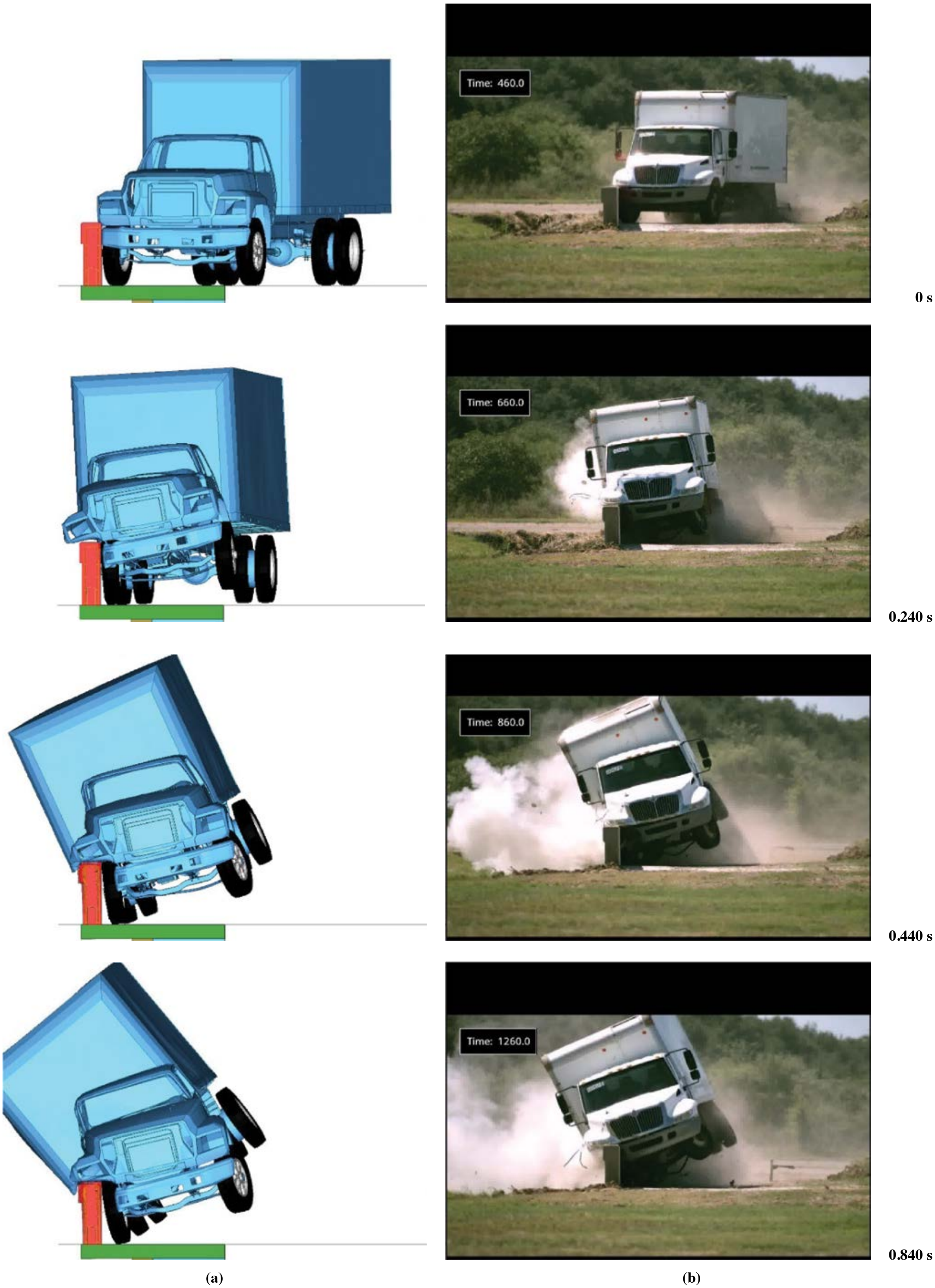
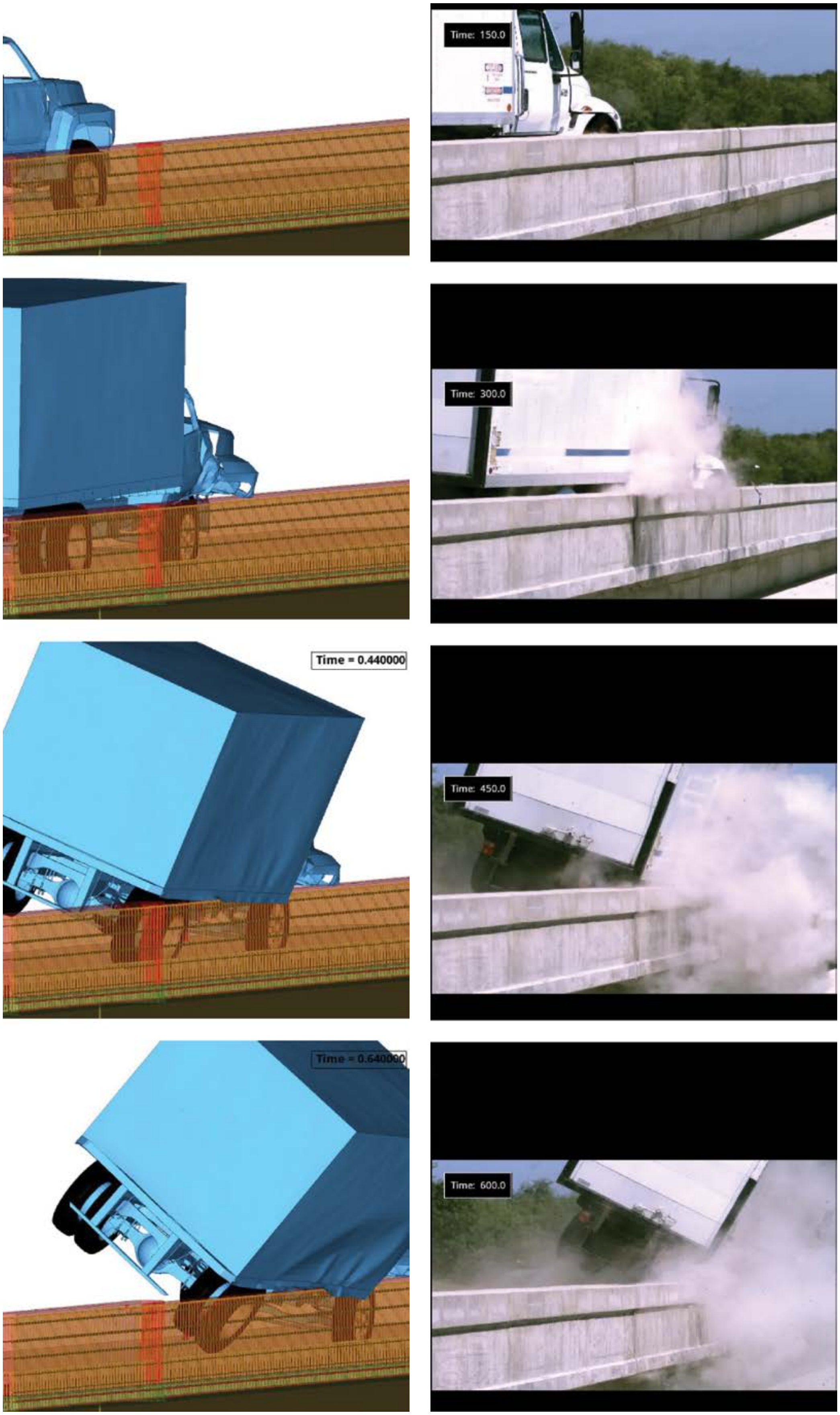


Figure 26. Front views for (a) simulation and (b) Test 469467-1-1.



0 s

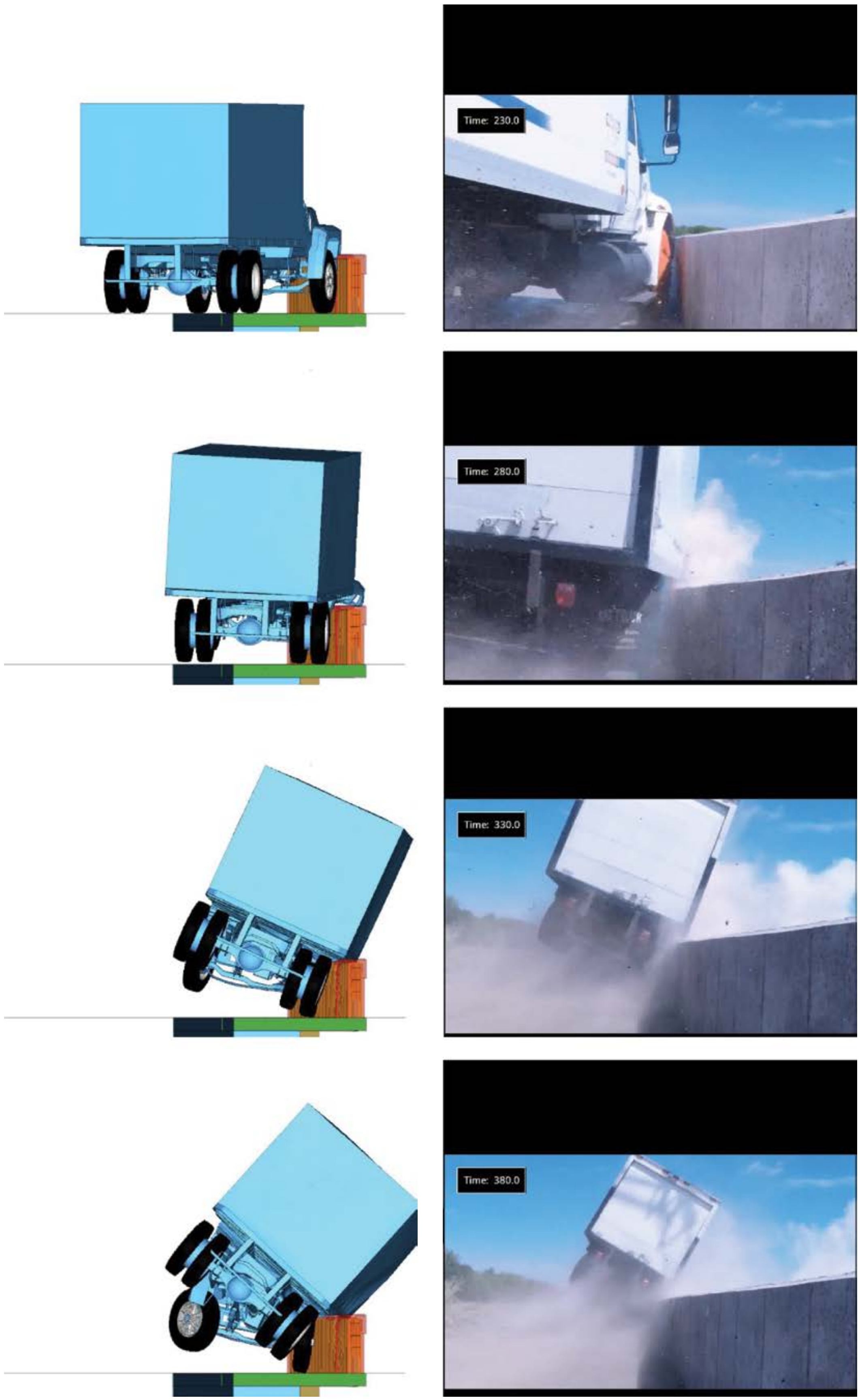
0.240 s

0.440 s

0.640 s

(a) (b)

Figure 27. Isometric real views for (a) simulation and (b) Test 469467-1-1.



0 s

0.240 s

0.440 s

0.640 s

(a) (b)

Figure 28. Back views for (a) simulation and (b) Test 469467-1-1.

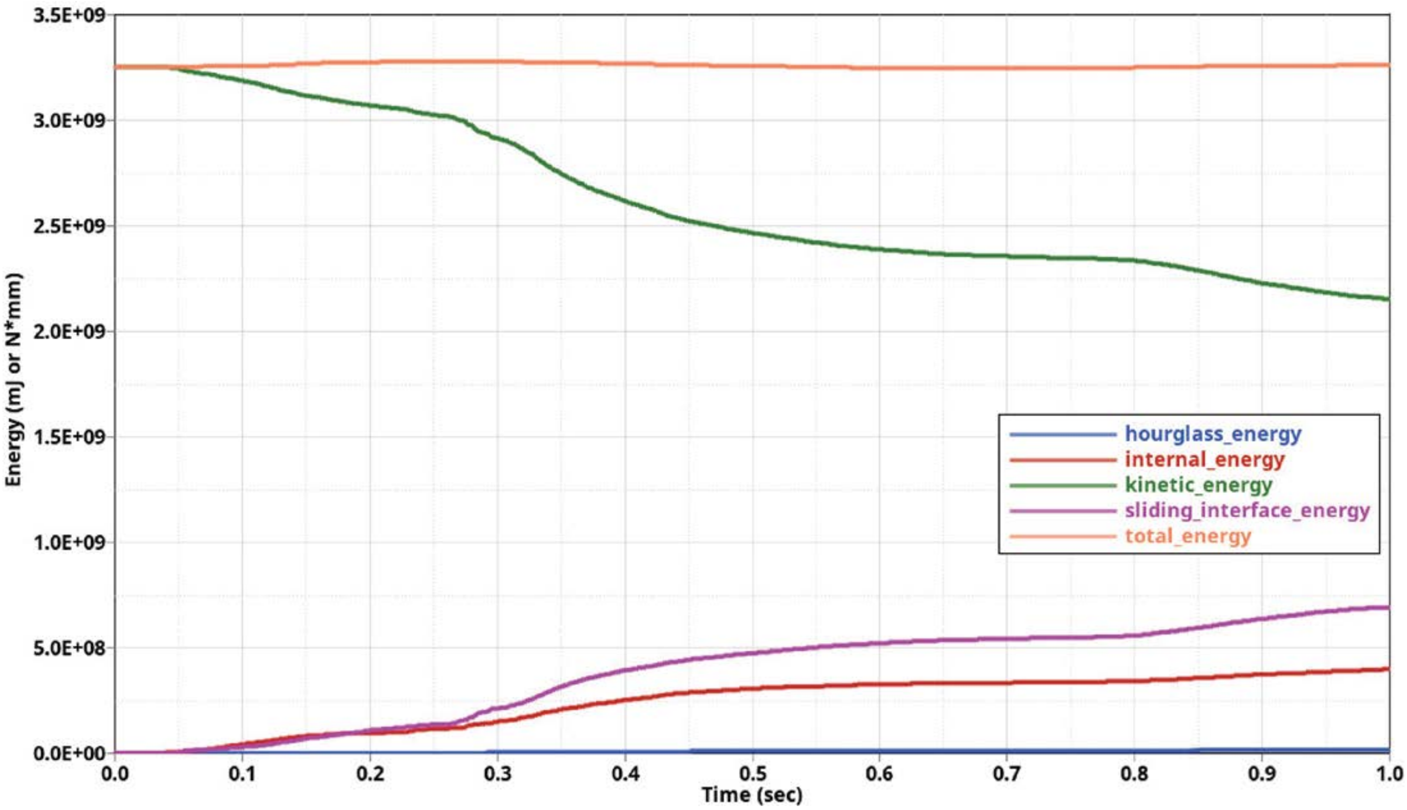


Figure 29. Energy balance diagram from simulation for Test 469467-1-1.

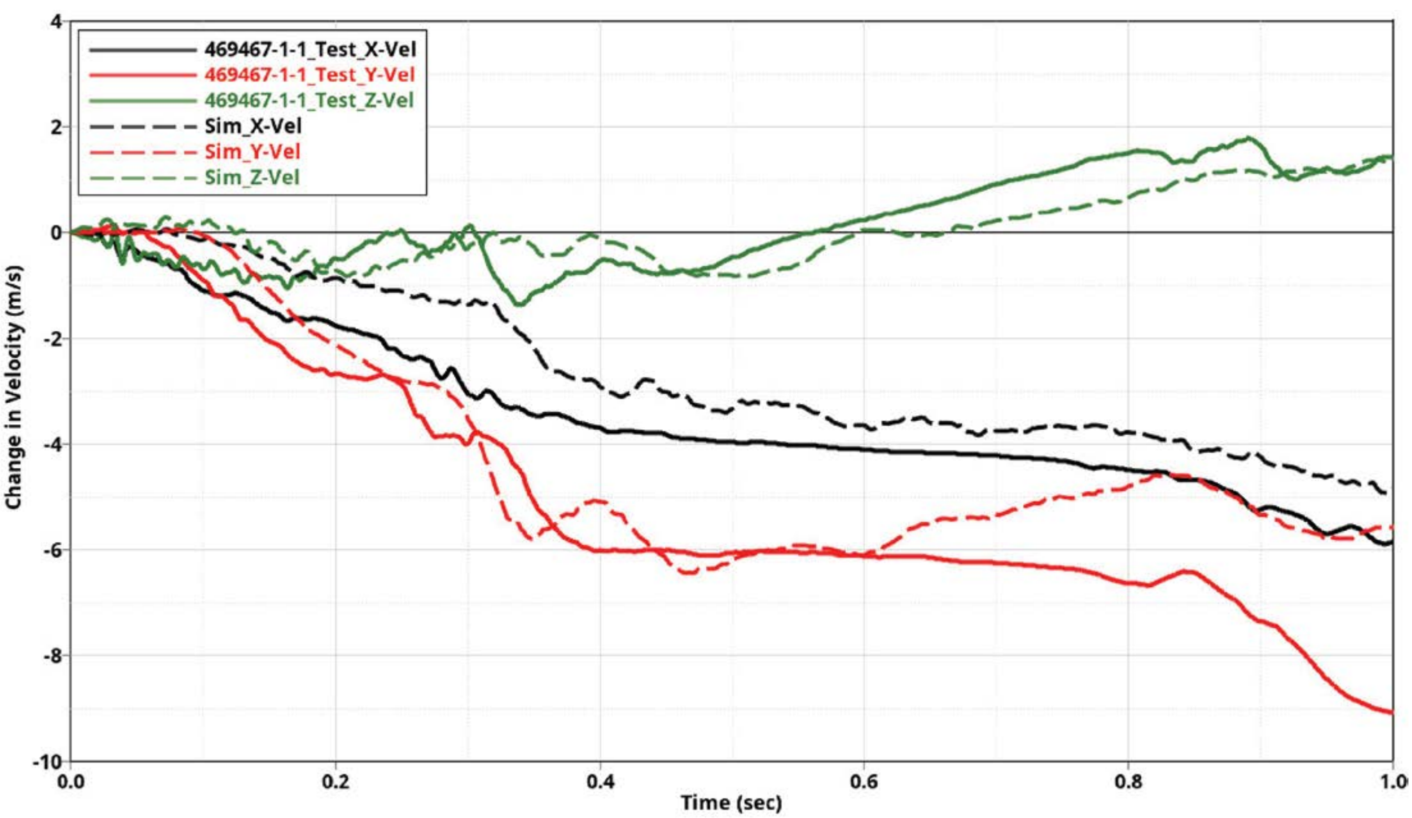


Figure 30. x, y, and z change of velocity test-to-simulation comparisons for Test 469467-1-1.

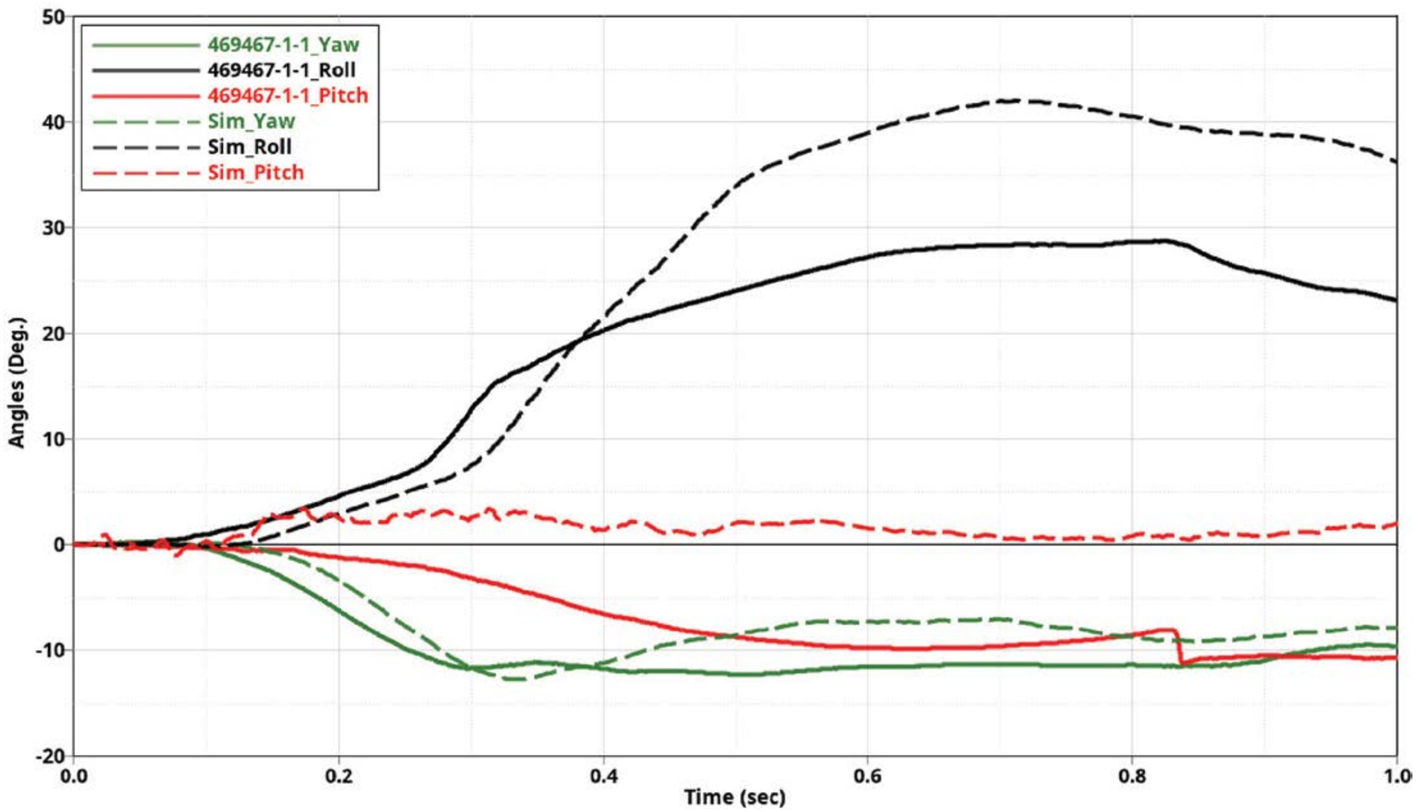


Figure 31. Roll, pitch, and yaw test-to-simulation comparisons for Test 469467-1-1.

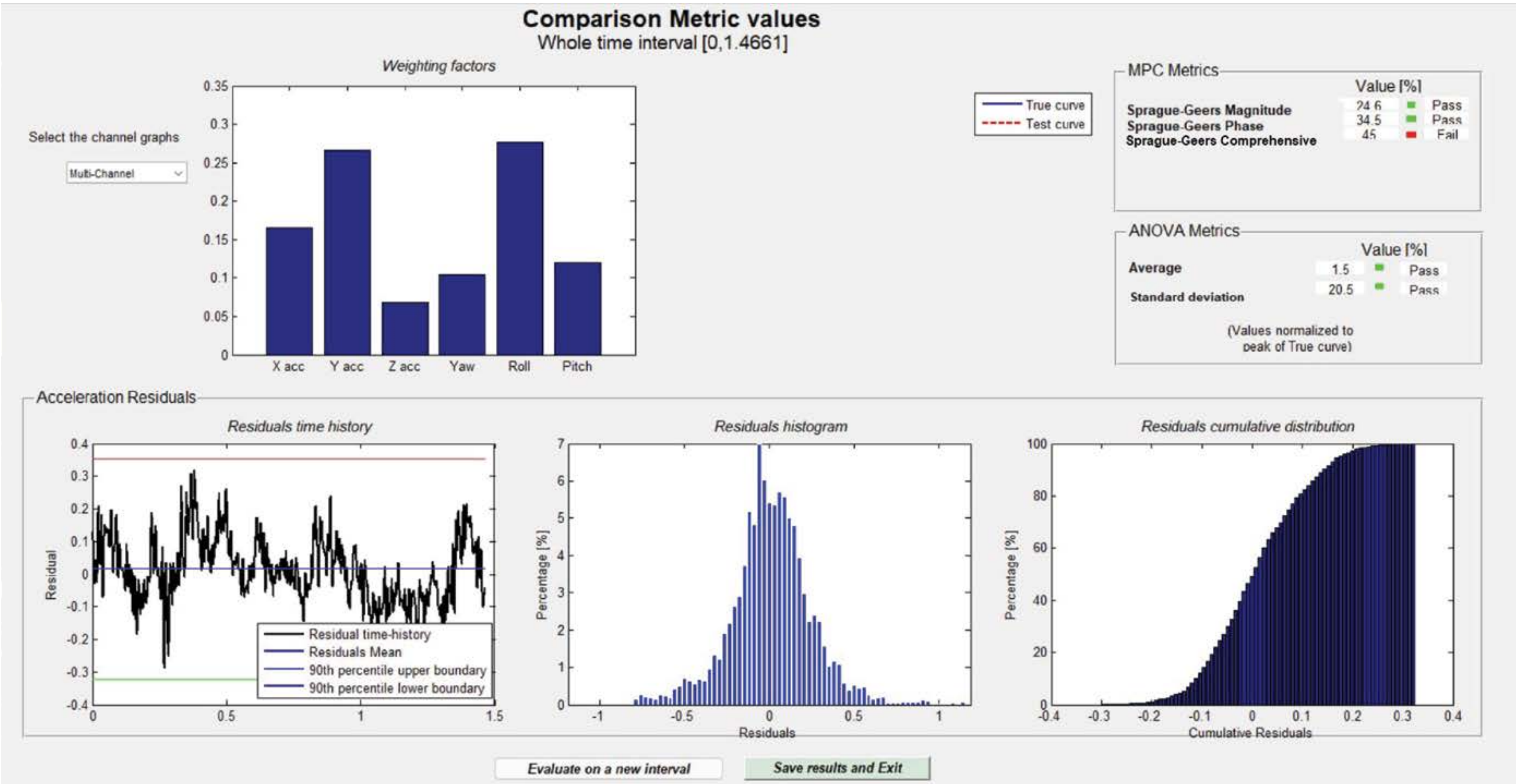


Figure 32. RSVVP multi-channel evaluation for Test 469467-1-1.

4.2 Crash Simulation Analyses

As part of the research efforts, finite element computer simulations were used to assess the various aspects of safety performance for barriers installed on ramps under different impact conditions and various road curvatures and superelevations. A set of impacting vehicle types was selected for the analyses (e.g., the basic TL3 MASH vehicles with the addition of the TL4 SUT). Similarly, off-ramp geometries, barrier types, and other factors were defined for the matrix of the simulations. The LS-DYNA program (*46*, *47*) was used to carry out the finite element simulations. The simulations generated various metrics that established performance envelopes to assess barrier effectiveness under different conditions and develop understanding of the vehicle response to off-the-road impacts. Critical cases were identified for full-scale crash testing to verify and validate these simulation results. The resulting performance envelopes provided a basis for the development of enhanced guidelines for barrier treatments on CSORs.

4.2.1 Factors Considered

Based on the findings from the literature review and the state DOT survey, parameters believed to affect the safety performance of longitudinal barriers when placed on ramps have been identified. The parameters and their associated ranges were finalized with the review panel. Some parameters included in the analyses and their variations and ranges were:

- Barrier type
  - Concrete barriers
    - New Jersey 32-in. and 42-in. height
  - Steel guardrails
    - MGS design with 31-in. top-of-rail height
    - Thrie beam with 34-in. top-of-rail height
- Vehicle type
  - 1100C small car (Toyota Yaris)
  - 2270P pickup truck (Chevrolet Silverado)
  - 10000S SUT (Ford F800)
- Superelevation/curvature
  - 4% and 8% ramp cross slope
  - 150-ft and 200-ft curve (ramp) radius
- Shoulder width and slope
  - 4-ft and 12-ft widths
  - 0% and 8% (angle relative to road)
- Impact conditions
  - Impact angle: 5, 10, 15, 20, and 25 degrees
  - Impact speed: 80, 100, and 120 km/h
- Other variations
  - Ramp grade: 0 and –6% (downward)
  - Vertical orientation (parallel to true vertical)

4.2.2 Performance Metrics

The simulated crashworthiness performance of the longitudinal barriers was evaluated in accordance with the criteria presented in MASH (*5*). The MASH acceptance criteria focus on the effectiveness of the barrier to "safely" redirect the vehicle, as well as the rate of ride-down accelerations that affect the occupants. For evaluations of TL3 impacts on longitudinal barriers with the 1100C small car and the 2270P pickup truck, the evaluations are based on the following three factors and MASH acceptance criteria (*5*):

Structural adequacy

A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation, although controlled lateral deflection of the test article is acceptable.

Occupant risk

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
H. Occupant impact velocities should satisfy the following: longitudinal and lateral occupant impact velocity of 30 ft/s (preferred), 40 ft/s (maximum).
I. Occupant ride-down accelerations should satisfy the following: longitudinal and lateral occupant ride-down accelerations should be less than 15.0 G (the preferred gravitational constant) to 20.49 G (maximum).

Vehicle trajectory

The vehicle shall exit the barrier within the exit box.

For the TL4 impact with the 10000S vehicle, the evaluations are based on the following MASH criteria (*5*):

Structural adequacy

A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation, although controlled lateral deflection of the test article is acceptable.

Occupant risk

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.
G. It is preferable, although not essential, that the vehicle remain upright during and after collision.

To assess the barrier performance, the results from each simulation were carefully evaluated using the aforementioned criteria. The evaluations were then summarized in a concise and easy-to-read tabular format. These tables were used to establish the performance of the selected barriers under various impact conditions. This information is important for developing guidelines and making informed decisions regarding barrier selection and placement.

4.3 Computer Simulation Analysis for CSORs

The approach used in the finite element simulation analyses was similar to one used in NCHRP Project 22-29A. Simulation runs were made to assess the effectiveness of three common barriers in different roadway situations. The simulation analyses considered MASH impacts with the small car (1100C) and the large pickup truck (2270P). Each simulation reflected a specific CSOR design. The features of the CSOR included the radius of the curved ramp, its superelevation and grade, the width of the shoulder, and its angle relative to the highway lanes. These factors defined the surface a vehicle would traverse before impacting a barrier. The vehicle speed and angle were also varied in the analyses.

For each simulation, a comprehensive summary of results in tabular form was generated. A sample of the summary results is shown in Table 13, which depicts the behavior of the vehicle and all pertinent MASH metrics and evaluations. The upper portion of the table indicates the basic barrier features and impact conditions, while the image provides a visual representation of the vehicle's position at various points in the 2-s crash event. The lower portion of the table summarizes the MASH crashworthiness evaluation metrics for the simulated conditions. The yaw, pitch, and roll of the vehicle were computed and compared with the acceptable levels specified in national standards to determine whether the impact met the pass or fail criteria for maximum effects (*5*).

The position of the vehicle relative to the barrier is a critical aspect, as it influences the manner in which the vehicle will be restrained and the rates of deceleration that impose forces on the driver or occupant. The simulation tools generate metrics to determine the safe levels of these forces resulting from an impact. Criteria that reflect a consensus on what "safe" is are computed based on the physics of the simulated crash. The sequential views reflect tendencies to roll or pitch excessively, or to override or penetrate the barrier. These are determined computationally but generally with a high degree of realism.

The simulation tool was set to undertake the analysis incrementally across a set range of factors. Analysis summaries were generated for more than 500 cases to consider the effectiveness of the various barrier types, including:

- 32-in. and 42-in. New Jersey shaped-concrete barrier (Appendix D—405 cases)
- 31-in. W-beam barrier (MGS) (Appendix E—50 cases)
- 34-in. Thrie beam barrier (Appendix F—50 cases)

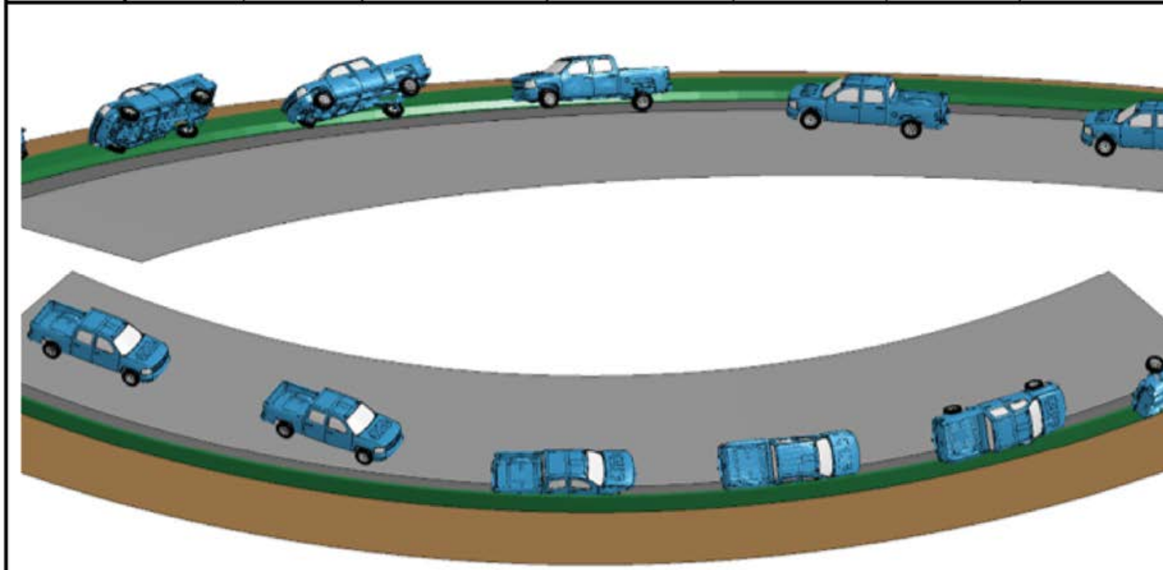
These summary tables are included in Appendices D through F as listed. These cases were further summarized in one table: Table 15 includes summary of results for the concrete barrier, considering all MASH criteria in the barrier performance evaluation. Table 16 includes the same cases for the concrete barrier but considers only rollover in the barrier performance evaluations. Based on the overall simulation results, a tabular summary was compiled of vehicle-to-barrier interfaces (and redirection) where effectiveness was unlikely.

The guidelines are reflected in Table 15 and Table 16. The shortest radii curves are the most problematic, so for radii of 150 and 200 ft for varying superelevations (4% and 8%) and impact angles (5, 10, 15, 20, and 25 degrees), a column was provided in each matrix. A row was provided in each table for 1100C and 2270P vehicles. Rows were added for vehicle grades of 0% and –6%. Rows were also added for shoulder angles of 0% and 8%. Finally, rows were added for impact speeds of 80, 100, and 120 km/h. This formed a matrix of cells that reflect common variations of conditions. In Table 15, cells indicated by simulation to pass were shaded green and marked with a "P" for "pass." The cells where the MASH criteria were not met were shaded red, indicating that they would not meet the full set of MASH criteria. Similarly, in Table 16, the same stratifications was created to consider only cases in which the MASH rollover criteria would not likely be met.

Similar analyses were performed to assess the barrier performance at the TL4 impacts with the MASH SUT model. A sample of the summary results is shown in Table 14. Similar to the cases for the TL3 impacts, the upper portion of the table indicates the basic barrier features and impact conditions, while the image provides a visual representation of the vehicle's position at various points in the 2-s crash event. The lower portion of the table summarizes the MASH

Table 13. Sample summary of simulation results with pickup truck.

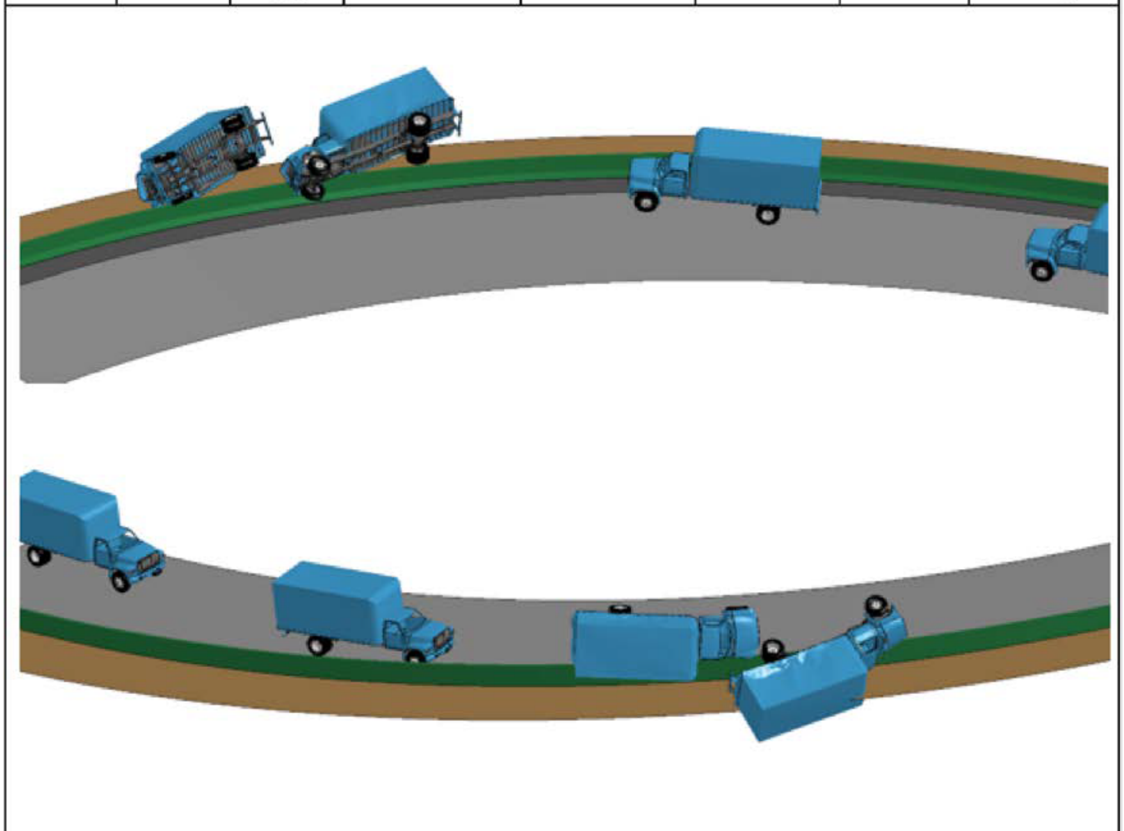
2270P Vehicle – 32" NJ-Shape Concrete Barrier							
Radius	Super	Grade	Shoulder Width	Shoulder Angle	Barrier Orient.	Speed	Angle
150 ft	4%	0%	4 ft	0%	⊥ to Road	120 km/hr	25 deg



Evaluation Criteria				
A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.			Fail
D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone.			Pass
	All Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	Windshield ≤ 76 mm	31	Pass
		Roof ≤ 102 mm	33	
		Floor ≤ 229 mm	174	
F	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	Roll ≤ 75° deg	164	Fail
		Pitch ≤ 75° deg	96	
H	Longitudinal & lateral OIV should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Vx ≤ 12.2 m/s	4.7	Pass
		Vy ≤ 12.2 m/s	9.3	
I	Longitudinal & lateral ORA should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g	Ax ≤ 20.49 g	5.7	Fail
		Ay ≤ 20.49 g	25.1	

Table 14. Sample summary of simulation results with SUT.

10000S Vehicle – 42" NJ-Shape Concrete Barrier							
Radius	**Super**	**Grade**	**Shoulder Width**	**Shoulder Angle**	**Barrier Orient.**	**Speed**	**Angle**
200 ft	**4%**	**0%**	**4 ft**	**0%**	**⊥ to Road**	**90 km/hr**	**25 deg**



Evaluation Criteria		
A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Fail
D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone	Pass
G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Fail*

*Note: * = This evaluation criterion is preferable and not required to pass to meet MASH.*

Table 15. Summary of results for concrete barrier considering all MASH criteria.

Road Curvature				150 ft (45 m)										200 ft (61 m)									
Road Superelevation				4%					8%					4%					8%				
Impact Angle (degrees)				5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
Vehicle	Vertical Grade	Shoulder Angle	Impact Speed																				
1100C	0%	0%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			120 km/h	F	F	F	F	P	F	F	P	P	P	F	F	F	F	P	F	F	P	F	F
		8%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			120 km/h	F	F	P	P	P	F	F	P	P	P	F	F	F	P	P	F	F	P	P	P
	−6%	0%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			120 km/h	F	F	F	F	P	F	F	P	P	P	F	F	F	P	P	F	F	P	P	P
		8%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			120 km/h	F	F	P	P	P	F	F	P	P	P	F	F	F	P	P	F	F	F	P	P
2270P	0%	0%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	F	F	F	F	F	F	F	F	F	P	F	F	F	F	P	F	F	F	F
			120 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	P	F	F	F	P	P	F	F	F	P	F	F	F	F	F	F	F	F	F
			120 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	−6%	0%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	F	F	F	F	P	F	F	F	F	P	F	F	F	F	P	F	F	F	F
			120 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	80 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			100 km/h	P	P	F	F	F	P	P	F	F	F	P	F	F	F	F	P	P	F	F	F
			120 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

F Not Meeting MASH   P Meeting MASH

Table 16. Summary of results for concrete barrier considering only rollover.

Road Curvature				150 ft (45 m)										200 ft (61 m)									
Road Super Elevation				4%					8%					4%					8%				
Impact Angle (degrees)				5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
Vehicle	Vertical Grade	Shoulder Angle	Impact Speed																				
1100C	0%	0%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		8%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	–6%	0%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		8%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
2270P	0%	0%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	R	R	R	R	R	R	R	R	R	R	R	R	N	N	N	R	R	R	R	R
		8%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	R	R	R	N	N	N	N	N	N	N	R	F	F	F	F
	–6%	0%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	N	N	N
		8%	80 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			100 km/h	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
			120 km/h	N	N	N	N	N	R	R	R	R	N	N	N	N	N	N	R	N	N	N	N

R Override/Rollover N No Override/Rollover crashworthiness evaluation metrics for the simulated conditions. MASH criteria A, D, and G are the only applicable criteria and the ones used for the evaluation to determine whether the barrier is classified as pass or fail (*5*).

The analyses of the SUT impact evaluations initially focused on a 32-in. height New Jersey concrete system, and later a 42-in. height system was analyzed. Table 17 shows the summary of the results from simulations with these two systems. Summary tables from the individual cases are included in Appendix D. As expected, the simulations show that the 32-in. height system does not meet the MASH criteria at the recommended 90 km/h impact speed and 15-degree impact angle. The simulations also revealed that, at that speed, the system would not meet the evaluation criteria even at the lowest 5-degree impact angle analyzed. Simulations at lower speeds, 50 and 70 km/h, showed that the 32-in. height system would meet criteria for cases at only 50 km/h and impact angles of only 5 and 10 degrees.

Because the simulations indicated poor performance of the 32-in. height system, additional simulations were carried out with a 42-in. height system. The 42-in. height system was found to have better performance, meeting the MASH criteria for the 50 km/h cases at all simulated angles (5 to 25 degrees). However, the simulations still showed that the 42-in. height system did not meet MASH criteria at the 70 and 90 km/h speeds. Notably, the simulations highlighted that the impact speed and angle significantly influenced the system's performance, whereas other parameters such as road profile and shoulder configuration had negligible effects, as evident in Table 17.

Several observations can be deduced from the 1100C and 2270P simulation results:

- The simulations show that impacts of the 2270P vehicle (pickup truck) are more critical than those of the 1100C (small car). The lower halves of Table 15 and Table 16 (which include the pickup truck cases) have more red cells (not passing) than the upper half.
- It can be observed from the individual summary tables (included in Appendix D) that nearly all the 1100C cases that did not meet MASH were attributable to excess in occupant impact velocity (OIV). None of these cases led to vehicle rollover.
- Similarly, the majority of the 2270P cases that did not meet MASH were attributable to high occupant ride-down accelerations (ORA). Several of these cases, specifically at the 120 km/h speed, led to rollover.
- Comparing the different impact angle results, Table 15 shows that some cases with the 1100C vehicle fail the MASH criteria at lower impact angles, while similar cases with higher impact angles meet the MASH criteria. This indicates that lower angles are more critical for the 1100C vehicle. When examining the individual cases, the simulations predict higher OIV (the critical metric for the small car cases) with lower impact angles. The simulations, however, did not show a significant increase of the vehicle climbing over the barrier at lower impact angles.
- The opposite observation can be made for the 2270C vehicle: higher impact angles are more critical. The table shows cases failing the MASH criteria at higher impact angles, while similar cases at lower impact angles meet MASH. The individual simulations show that the ORA (the critical metric for the pickup truck cases) is higher for higher impact angles.
- At different speeds, the simulations show, the barrier would meet the MASH criteria at 80 km/h, would have marginal performance with several cases not meeting the MASH criteria at 100 km/h, and would in almost all cases not meet MASH at 120 km/h. The 120 km/h is especially critical for the 2270P vehicle, with most of the cases not meeting MASH.
- Regarding the effects of shoulder angle, the simulations show that cases with an 8% shoulder angle are less critical than 0% shoulder angle cases (where the shoulder is parallel to the road).
- For cases with different road superelevations, the results show some increase in severity at lower superelevations. Fewer cases fail with an 8% superelevation than with a 4% superelevation.
- The simulation results indicate that impacts with sharper curvature (with the 150-ft radius) are more critical for rollover than the 200-ft radius cases. More cases fail with the 150-ft radius barrier than with the 200-ft radius barrier.

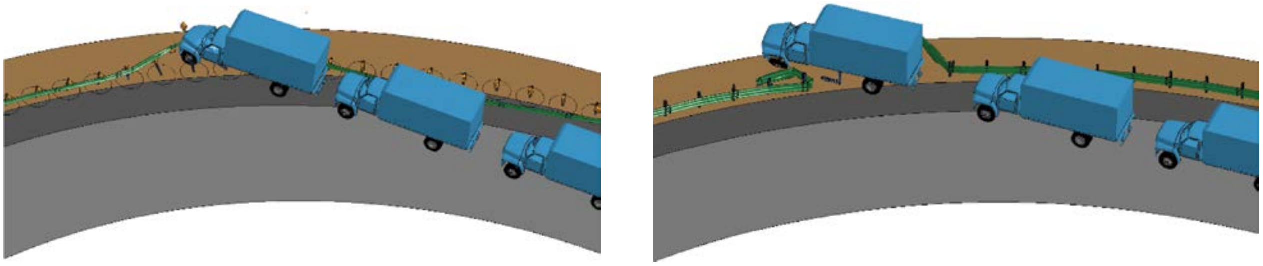
Table 17. Summary of results for concrete barrier with SUT.

Road Curvature				150 ft (45 m)										200 ft (61 m)									
Road Super Elevation				4%					8%					4%					8%				
Impact Angle (degrees)				5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
Barrier Height	Vertical Grade	Shoulder Angle	Impact Speed																				
35 in.	0%	0%	50 km/h	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	50 km/h	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	−6%	0%	50 km/h	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	50 km/h	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F	P	P	F	F	F
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
42 in.	0%	0%	50 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	50 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	−6%	0%	50 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
		8%	50 km/h	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
			70 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
			90 km/h	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

F Not Meeting MASH

P Meeting MASH

68 Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps



(a) (b)

Figure 33. Sample results from SUT to (a) W-beam and (b) Thrie beam impacts.

- When examining the effects of grade, simulations show almost no difference between the 0% grade cases and the –6% (down) grade cases. This was noted for all road and shoulder profiles and for all speeds and angles. Lack of difference could be attributed to the speed when the vehicle comes into contact with the barrier being similar for the 0% and –6% grade cases. The downgrade does not increase the speed from the vehicles' initial position to the initial impact with the barrier.

The research team conducted simulation analyses on two semi-flexible barriers: the 31-in. W-beam and the 34-in. Thrie beam guardrails. The simulations were performed for TL3 impacts using the 1100C and 2207P vehicles. The results demonstrated that both semi-flexible barriers successfully met the MASH criteria for the majority of the analyzed cases. If summary tables, akin to Table 15 and Table 16, were generated for these barriers, they would predominantly show green cells, with only a few red cells. Individual summary tables for the 31-in. W-beam and 34-in. Thrie beam guardrails are included in Appendix E and Appendix F, respectively. These summaries indicate that the majority of cases meet the MASH requirements. However, it is essential to acknowledge the complexities involved in simulating and predicting rail rupture in these simulations. To validate these results, further investigations and testing should be conducted.

Simulations using the SUT vehicle impacting the 31-in. W-beam and 34-in. Thrie beam semi-flexible barriers at the TL4 impacts, on the other hand, show that almost all cases failed to meet the MASH criteria. Even at lower impact speeds (50 and 70 km/h) and lower angles (5 and 10 degrees), the simulation showed potential for the vehicle overriding the barrier. Sample results are included in Figure 33. If summary tables analogous to Table 15 and Table 16 were generated for the SUT impacts for the W-beam and Thrie beam barriers, they would have all red cells.

4.4 Applicability of Results to Practice

The results from this project provide useful insights to state DOTs and roadside hardware safety researchers about the performance of barriers used in conditions other than those for which they are typically tested. The results lessen the gap of knowledge about the safety performance of longitudinal barriers placed on curved, superelevated ramp sections. Specific recommendations for the design, selection, and installation of longitudinal barriers on CSORs are offered. This will allow individual agencies to update their standards and practices. This can also be expected to motivate the development of innovative barriers if needs are identified. Furthermore, the results are useful in determining whether new crashworthiness evaluation criteria need to be formulated to test barriers installed on ramps.

The primary intended audience for the results of this project is DOTs, as the recommendations will be useful to individuals and agencies responsible for designing, installing, and maintaining safety hardware. The nature of the recommendations may motivate them to implement changes to guidelines and practices related to roadside barriers, particularly, but not limited to, road design and safety management practices. Other groups will be affected, including state and consultant personnel responsible for roadway design and the provision or maintenance of safety features.

The information in Tables 4–9 is useful in understanding the position of the front edge of a vehicle crossing roadside terrain. For the "best" conditions, it provides an index of the "window" or "capture zone" for an errant vehicle, considering that many difficult-to-control factors are present. The firmness of the soil, the surface vegetation (cut or uncut), and the moisture content of the soil may become important relative to having either a firm (or even slippery) surface or mud. The tables, however, define the window for catching the vehicle's front bumper. The data recognizes the vertical influences that project a vehicle upward when a curb is hit, for example.

Similarly, Table 15 to Table 17 summarize the results from the simulation analyses in a way that allows information to be readily used by agencies in making highway and barrier design decisions. These cases were simulated across ranges of situational factors in an attempt to determine whether the barriers were effective across a range of conditions. The cases generated were selected to provide a wide cross section of scenarios while focusing on the factors influencing the pass/fail metrics.

CHAPTER 5

Full-Scale Crash Testing

To validate that crash simulation efforts are valid representations of crashes, it is a common practice to conduct full-scale crash tests for selected configurations of a barrier for critical impact conditions. Four crash tests were undertaken in the project to validate the simulation results. Effective redirection of the vehicle, acceptable degrees of damage, and similar measured deformations and forces from these tests provided a strong indication of the validity of the crash simulation analyses. These crash tests involved vehicles impacting the barrier placed on a representative section of a curved, superelevated off-ramp. The tests involved impacts at 100 km/h with the 1100C and 2270P MASH test vehicles and at 80 km/h with mid-size and large sedans. The four tests conducted under this project for analyzing impacts with a typical CSOR are as follows:

- Test 22010: Small (1100C) passenger vehicle at 100 km/h with a 10-degree angle
- Test 22011: Pickup (2270P) truck at 100 km/h with a 10-degree angle
- Test 22013: Mid-size (1500A) passenger vehicle at 70 km/h with a 10-degree angle
- Test 22014: Crossover SUV vehicle at 70 km/h with a 10-degree angle

The research team selected the 32-in. concrete barrier installed on a 200-ft radius ramp, 8% superelevation, 0-ft shoulder width, and 8% shoulder angle, on a 0% grade for testing (Figure 34). Based on the computer simulations, this was judged one of the most critical barrier profiles. The same barrier was used for all four tests because of cost limitations. The impact angle was also the same: 10 degrees, for all four tests. The barrier was impacted at 100 km/h by the two TL3 MASH vehicles, 1100C and 2270P. The barrier underwent no damage during these impacts and was used in two additional tests to see the performance at lower speeds (70 km/h). The vehicles used in the last two tests were a mid-size sedan and a larger crossover SUV (Figure 35). Summaries of these tests are included in the next sections.

5.1 Test Article and Installation Details

The test installation consisted of a Jersey concrete barrier, approximately 100-ft long with a 200-ft radius curvature. Figure 36 shows the installation setup with the barrier cross section and the curved, superelevated ramp profile and details. The Jersey safety barrier was 32-in. (813 mm) tall, with an 8-in. (203 mm) top and a 17-in. (432 mm) base barrier. It was oriented such that its back face was parallel to true vertical. The barrier had a 3-in. vertical section at its base, a 10-in. lower sloped surface angled at 55 degrees from the road, and a 19-in. upper sloped surface angled at 84 degrees from the road. The break point of the two sloped surfaces was 13 in. above the pavement.

Figure 36 also depicts the system along the 200-ft radius curvature. The road was superelevated at 8%. This system was fabricated using standard roadside safety hardware elements and fabrication methods. The horizontal longitudinal reinforcement in the barrier was #4 rebars at

(a)

(b)

Figure 34. Pre-impact views of the CSOR installation.

(a)

(b)

(c)

(d)

Figure 35. Vehicles used in (a) Test 22010, (b) Test 22011, (c) Test 22013, and (d) Test 22014.

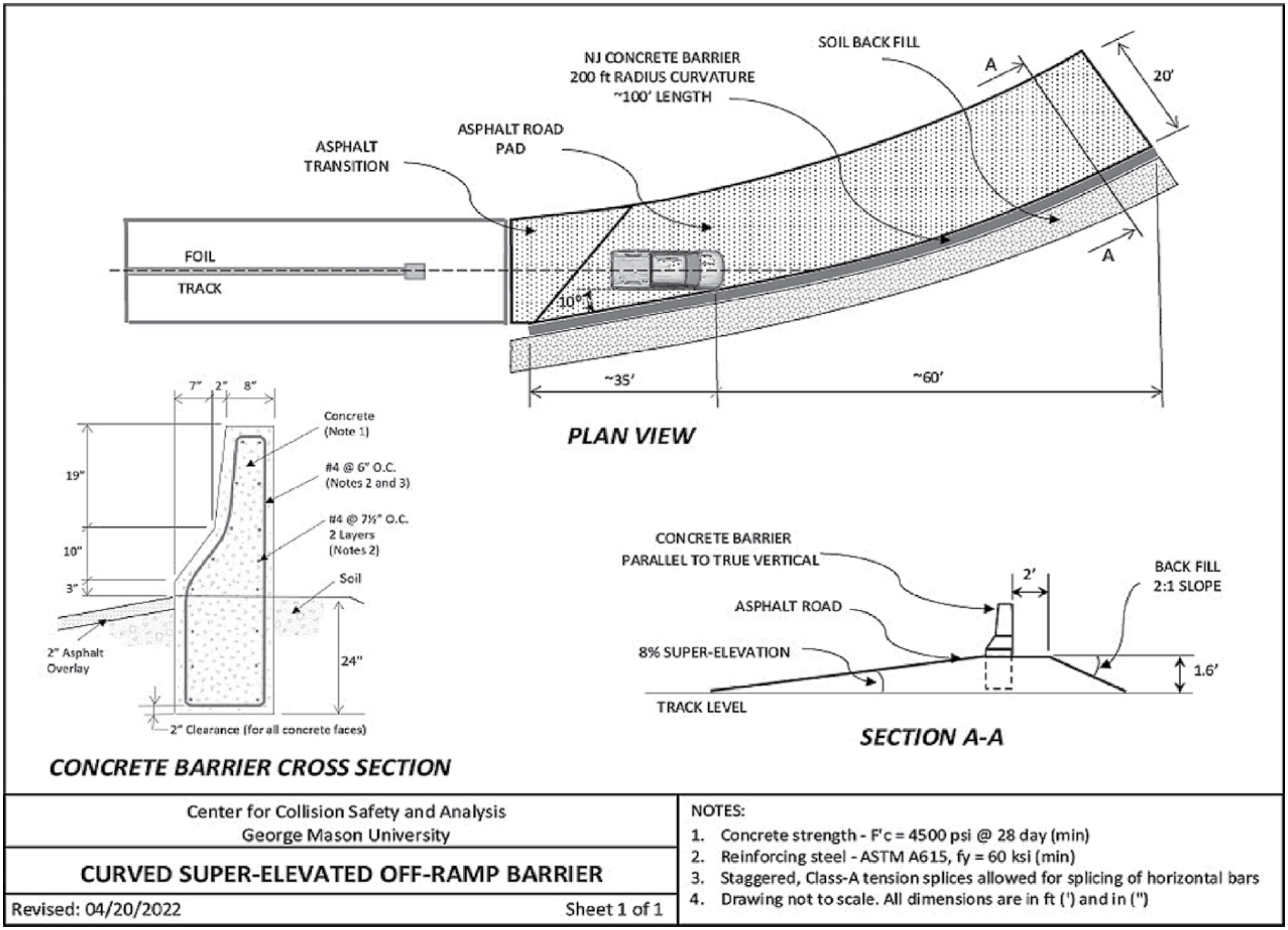


Figure 36. CSOR barrier test installation details.

7½ in. on center and the vertical loop shape reinforcement was #4 rebars at 6 in. on center. All reinforcement steel bars were made of ASTM A615 with a 60 ksi minimum strength. A concrete mix with a 28-day minimum strength of 4,500 psi was used for the barrier. The materials and hardware elements delivered met the basic standards in accordance with suppliers or certifications on file at the FHWA Federal Outdoor Impact Lab (FOIL).

5.2 Test Vehicles

Figure 35 shows photos of the four vehicles used in the four tests. A 2017 Nissan Versa passenger car weighing 2,555.2 lbs was used for Test 22010, a 2014 Ram 1500 quad-cab pickup truck weighing 4,925.1 lbs for Test 22011, a 2012 Hyundai Sonata weighing 3,251.8 lbs for Test 22013, and a 2010 Toyota Venza weighing 3,714.8 lbs for Test 22014. Standard procedures were completed to prepare the vehicle for the test: drain fluids then take accurate measurements of the vehicle, weight, tires, and related features. Vehicles were painted blue to maximize the viewability of the impact outcomes in the multiple video cameras.

5.3 Test Summaries

Four full-scale crash tests were undertaken at FOIL to show that the actual crashes reflected in the simulation analyses represent such events. The conditions tested and rationale are summarized in Table 18. The FOIL team generated a detailed test report for each crash test conducted. These reports document all the pertinent data, descriptions, imagery, and associated evaluations. These four reports are provided in Appendices G through J. Additional details about test setup and the detailed digital and visual results of the tests are available from FOIL and George Mason University's Center for Collision Safety and Analysis (CCSA). The data derived from the tests and comparisons with the simulation outputs provided a high level of confidence in the accuracy of the simulation analyses.

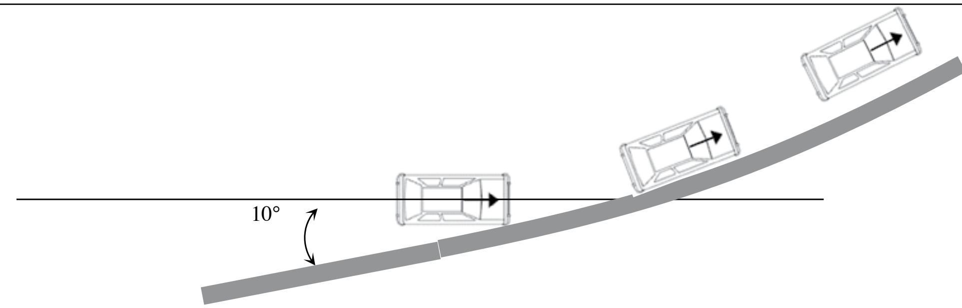
The tests were set up and performed in accordance with the recommended MASH procedures. High-speed cameras, accelerometers, rate transducers, and speed measuring devices were used to capture the vehicle and barrier responses during the impact. Eight high-speed cameras are typically used for full-scale crash tests. One camera is placed over the impact region to capture an overhead view. Seven additional cameras are placed at locations surrounding the impact region to capture left, right, front, rear, and isometric views of the crash event. Two tri-axial accelerometers were mounted at the vehicle center of gravity to measure the x-, y-, and z-accelerations of the vehicle. This data was used to compute the occupant ride-down acceleration and OIV. Additionally, two tri-axial rate transducers were used to measure the vehicle roll, pitch, and yaw. Contact switches were installed on the vehicle and the test article to synchronize time zero during the impact for the sensor data and high-speed movies.

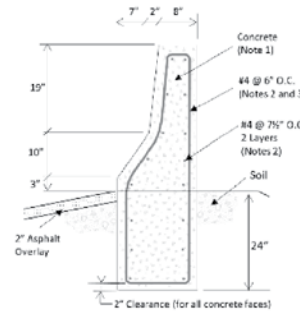
Further details regarding each test and their respective outcomes are provided in the standard test summary pages presented in Figure 37 to Figure 40. The profile sheets present all the relevant setup and measured values from the tests that closely matched the simulation results. In all cases, the validation crash tests produced the expected outcomes, providing greater credibility to the various simulation efforts described in this chapter. Therefore, the research team was confident that these tests provided credibility to the simulations.

Table 18. Summary of full-scale crash tests.

Test	Date	Test Purpose	MASH
22010	08/09/22	Hit CSOR w/small car @ 100 km/h, 10 degrees	Pass
22011	08/16/22	Hit CSOR w/pickup truck @ 100 km/h, 10 degrees	Pass
22013	09/01/22	Hit CSOR w/mid-size car @ 70 km/h, 10 degrees	Pass
22014	09/13/22	Hit CSOR w/crossover SUV@ 70 km/h, 10 degrees	Pass

0.000 s 0.460 s 1.140 s 1.600 s





General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 22010
- Date 08/09/2022

Test Article:
- Type .... Concrete Barrier on Curved Ramp
  - Name or Mfg .... Generic
- Installation Length ...... 100 ft (30.5 m) length
- Key Elements .... Concrete 200 ft (61 m) curvature
  - Size/dimension .... 32-in. height NJ shaped-concrete barrier
  - Material .... Concrete, rebar, asphalt, 21a soil
  - Other .... 8% superelevation

Test Vehicle:
- Type/Designation 1100C
- Make and Model .... Nissan Versa
  - VIN 3N1CN7AP9HL840745
  - Curb .... 2,418.5 lb (1,097.0 kg)
- Test Inertial .... 2,398.6 lb (1,088.0 kg)
- Gross Static .... 2,555.2 lb (1,159.0. kg)

Soil Conditions:
- Type of Soil .... Well-graded gravel with silt and sand
- Soil Strength .... MASH Standard Soil

Impact Conditions:
- Speed .... 62.0 mph (100.0 km/h)
- Angle .... 10 degrees
- Location/Orientation....... Vehicle right front corner aligned with the front face of the barrier 37.0 ft (11.3 m) downstream from start of barrier

Exit Conditions:
- Speed .... 51.0 mph (82.0 km/h)
- Angle .... 5 degrees
- Exit Box Criterion ...... Vehicle exited within box

Post-Impact Trajectory:
- Stopping Distance .... NA (emergency brakes applied)
- Vehicle Snagging .... None
- Vehicle Pocketing .... None

Occupant Risk:
- Longitudinal OIV .... 11.5 ft/s (3.5 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 22.3 ft/s (6.8m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal RA .... 4.2 G ≤ 20.49 G
- Lateral RA .... 7.2 G ≤ 20.49 G
- THIV .... 25.3 ft/s (17.2 mph) 7.7 m/s (27.7 km/h)
- PHD .... 7.3 G

Test Article Damage:
No significant damage to test article.

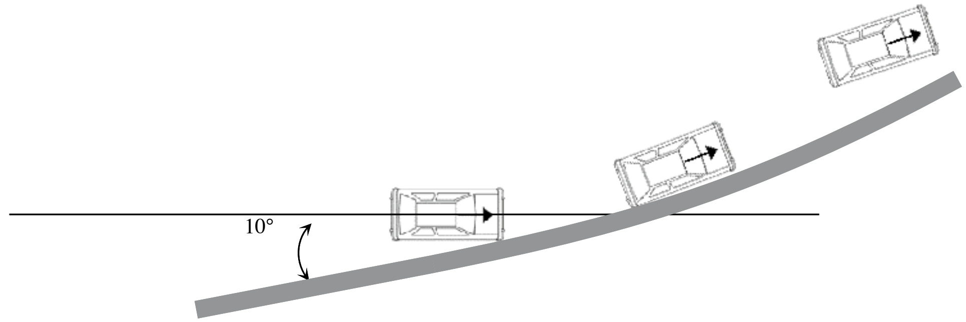
Test Article Deflections:
- Permanent Set .... 0.0 ft (0 m)
- Dynamic .... 0.5 in. (1.2 cm)
- Working Width .... 0.5 in. (1.2 cm)

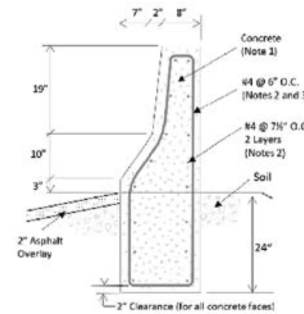
Vehicle Damage:
- VDS............................ 1RFQ3
- CDC............................ 01FZEW3
- Max. Deformation
  - Exterior .... 2.2 in. (5.5 cm)
  - Windshield .... 0.8 in. (2.0 cm)
  - Occupant Comp. ..... 2.0 in. (5.2 cm)

Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle .... 39.4 deg ≤ 75 deg
- Max. Pitch Angle .... –10.6 deg ≤ 75 deg
- Max. Yaw Angle .... –26.5 deg

Overall Performance: Pass

Figure 37. ***Crash Test 22010 summary page.***





General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 22011
- Date 08/16/2022

Test Article:
- Type .... Concrete barrier on curved ramp
  - Name or Mfg .... Generic
- Installation Length ...... 100 ft (30.5m) length
- Key Elements .... Concrete 200 ft (61 m) curvature
  - Size/dimension .... 32 in. height NJ shaped-concrete barrier
  - Material .... Concrete, rebar, asphalt, 21A soil
  - Other .... 8% superelevation

Test Vehicle:
- Type/Designation 2270P
- Make and Model.......... Ram 1500 quad-cab pickup
  - VIN........................... 1C6RR6FTXES154591
  - Curb .... 5,015.5 lb (2,275.0 kg)
- Test Inertial .... 4,925.1 lb (2,234.0 kg)
- Gross Static .... 4,925.1 lb (2,234.0. kg)

Soil Conditions:
- Type of Soil .... Well-graded gravel with silt and sand
- Soil Strength .... MASH Standard Soil

Impact Conditions:
- Speed .... 62.0 mph (100.0 km/h)
- Angle .... 10 degrees
- Location/Orientation ...... Vehicle right front corner aligned with the front face of the barrier 37.0 ft. (11.3 m) downstream from start of barrier

Exit Conditions:
- Speed ....54.0 mph (87.0 km/h)
- Angle .... 7 degrees
- Exit Box Criterion .... Vehicle exited within box

Post-Impact Trajectory:
- Stopping Distance .... NA (Emergency brakes applied)
- Vehicle Snagging .... None
- Vehicle Pocketing .... None

Occupant Risk:
- Longitudinal OIV .... 10.8 ft/s (3.3 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 17.3 ft/s (5.3 m/s) ≤ 40 ft/s (12 m/s))
- Longitudinal RA .... 5.8 G ≤ 20.49 G
- Lateral RA .... 8.8 G ≤ 20.49 G
- THIV .... 21.3 ft/s (14.5 mph) 6.5 m/s (23.2 km/h)
- PHD ....8.9. G

Test Article Damage:
No significant damage to test article.

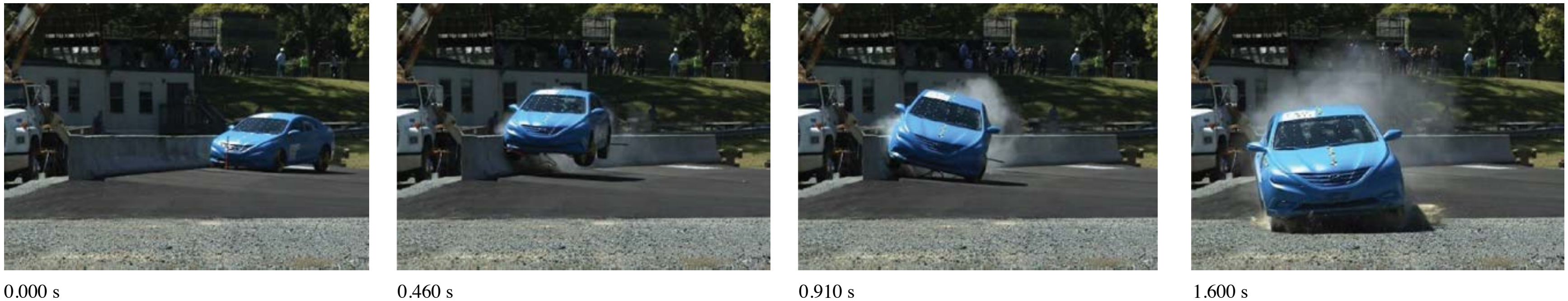
Test Article Deflections:
- Permanent Set .... 0.0 ft (0 m)
- Dynamic .... 1.0 in. (2.54 cm)
- Working Width .... 1.0 in. (2.54 cm)

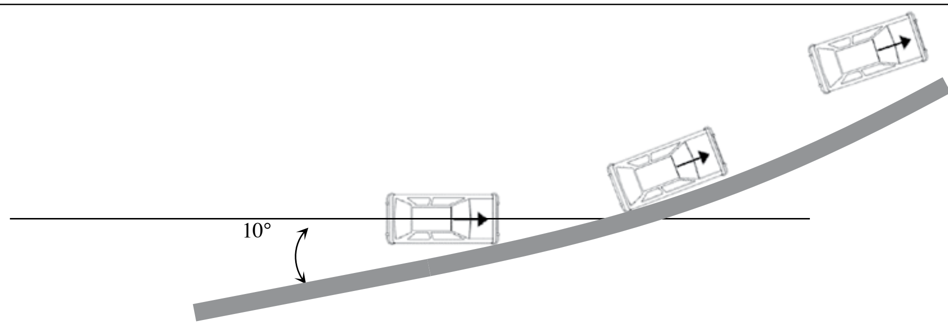
Vehicle Damage:
- VDS 1RFQ1
- CDC 01FZEW1
- Max. Deformation
  - Exterior .... 0.9 in (2.2 cm)
  - Windshield .... 0.3 in (0.8 cm)
  - Occupant Comp. ..... 1.4 in (3.6 cm)

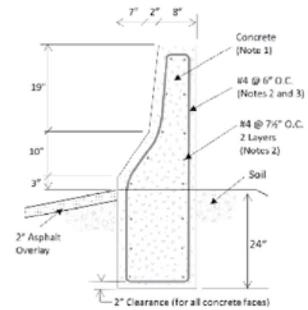
Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle .... 31.1 deg ≤ 75 deg
- Max. Pitch Angle .... 46.5 deg ≤ 75 deg
- Max. Yaw Angle .... 20.5 deg

Overall Performance: Pass

Figure 38. Crash Test 22011 summary page.







General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 22013
- Date 09/01/2022

Test Article:
- Type .... Concrete barrier on curved ramp
  Name or Mfg .... Generic
- Installation Length ...... 100 ft (30.5m) length
- Key Elements .... Concrete 200 ft (61 m) curvature
  Size/dimension .... 32 in. height NJ shaped-concrete barrier
  Material .... Concrete, rebar, asphalt, 21A soil
  Other .... 8% superelevation

Test Vehicle:
- Type/Designation 1500A
- Make and Model.......... Hyundai Sonata
  VIN 5NPEC4AC2CH376171
  Curb .... 3,244.1 lb (1,471.5 kg)
- Test Inertial .... 3,151.8 lb (1,475.0 kg)
- Gross Static .... 3,251.8 lb (1,475.0. kg)

Soil Conditions:
- Type of Soil .... Well-graded gravel with silt and sand
- Soil Strength .... MASH Standard Soil

Impact Conditions:
- Speed........................... 43.5 mph (70.0 km/h)
- Angle........................... 10 degrees
- Location/Orientation....... Vehicle right front corner aligned with the front face of the barrier 37.0 ft. (11.3 m) downstream from start of barrier

Exit Conditions:
- Speed ....34.0 mph (55.0 km/h)
- Angle .... 8 degrees
- Exit Box Criterion .... Vehicle exited within box

Post-Impact Trajectory:
- Stopping Distance .... NA (Emergency brakes applied)
- Vehicle Snagging .... None
- Vehicle Pocketing .... None

Occupant Risk:
- Longitudinal OIV .... 1.6 ft/s (0.5 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 13.1 ft/s (4.0 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal RA .... 1.9 G ≤ 20.49 G
- Lateral RA .... 3.3 G ≤ 20.49 G
- THIV ....13.5 ft/s (9.2 mph) 4.1 m/s (14.8 km/h)
- PHD .... 3.3 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0.0 ft (0 m)
- Dynamic .... 0.5 in. (1.2 cm)
- Working Width .... 0.5 in. (1.2 cm)

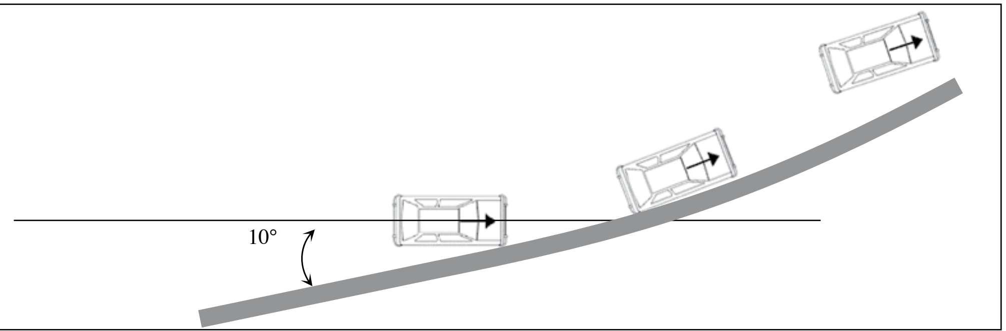
Vehicle Damage:
- VDS............................ 1RFQ1
- CDC 01FZEW1
- Max. Deformation
  Exterior .... 0.2 in (0.5 cm)
  Windshield .... 0.2 in (0.4 cm)
  Occupant Comp. ..... 0.2 in (0.6 cm)

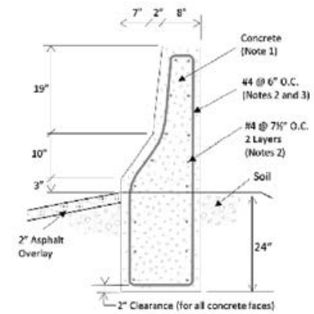
Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle .... 14.2 deg ≤ 75 deg
- Max. Pitch Angle .... 9.8 deg ≤ 75 deg
- Max. Yaw Angle .... 33.6 deg

Overall Performance: Pass

Figure 39. Crash Test 22013 summary page.

0.000 s　0.290 s　0.570 s　0.860 s





General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 22014
- Date 09/13/2022

Test Article:
- Type .... Concrete barrier on curved ramp
  - Name or Mfg .... Generic
- Installation Length ...... 100 ft (30.5m) length
- Key Elements .... Concrete 200 ft (61 m) curvature
  - Size/dimension .... 32 in. height NJ shaped-concrete barrier
  - Material .... Concrete, rebar, asphalt, 21A soil
  - Other .... 8% superelevation

Test Vehicle:
- Type/Designation .... Crossover SUV
- Make and Model.......... Toyota Venza
  - VIN 4T3BABB4AU018246
  - Curb .... 3,858.1 lb (1,750.5 kg)
- Test Inertial .... 3,714.8 lb (1,685.0 kg)
- Gross Static .... 3,714.8 lb (1,685.0. kg)

Soil Conditions:
- Type of Soil .... Well-graded gravel with silt and sand
- Soil Strength .... MASH Standard Soil

Impact Conditions:
- Speed .... 43.5 mph (70.0 km/h)
- Angle .... 10 degrees
- Location/Orientation .... Vehicle right front corner aligned with the front face of the barrier 37.0 ft (11.3 m) downstream from start of barrier

Exit Conditions:
- Speed ....32.0 mph (52.0 km/h)
- Angle .... 8 degrees
- Exit Box Criterion .... Vehicle exited within box

Post-Impact Trajectory:
- Stopping Distance .... NA (Emergency brakes applied)
- Vehicle Snagging .... None
- Vehicle Pocketing .... None

Occupant Risk:
- Longitudinal OIV .... 16.7 ft/s (5.1 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 9.8 ft/s (3.0 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal RA .... 4.0 G ≤ 20.49 G
- Lateral RA .... 3.9 G ≤ 20.49 G
- THIV .... 18.3 ft/s (12.5 mph) 5.6 m/s (20.1 km/h)
- PHD .... 5.1 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0.0 ft (0 m)
- Dynamic .... 0.5 in. (1.2 cm)
- Working Width .... 0.5 in. (1.2 cm)

Vehicle Damage:
- VDS............................. 1RFQ1
- CDC 01FZEW1
- Max. Deformation
  - Exterior .... 0.3 in (0.7 cm)
  - Windshield .... 0.2 in (0.6 cm)
  - Occupant Comp. ..... 0.3 in (0.7 cm)

Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle .... 9.7 deg ≤ 75 deg
- Max. Pitch Angle .... 16.4 deg ≤ 75 deg
- Max. Yaw Angle .... 20.9 deg

Overall Performance: Pass

Figure 40. Crash Test 22014 summary page.

5.4 Conclusions

Four tests were conducted to ensure that the results of the simulated crashes were consistent with actual field performance. These tests were carefully selected to represent critical conditions and thereby enhance confidence in the simulation results. Results from these tests matched the simulation results, which reconfirmed the results of the numerical analyses and the matrix of simulations.

CHAPTER 6

Research Conclusions and Guidelines for Longitudinal Barriers on CSORs

A significant amount of information was derived in this project from the vehicle dynamics analyses, crash simulation analyses, and crash testing relative to vehicle-to-barrier interfaces and crashworthiness of longitudinal barriers used on CSORs. This effort extended insights on the effectiveness of barriers when deployed on typical highway curves to those on the shorter radius curves that characterize major highway interchange ramps. In these situations, space is often inadequate to construct ramps with longer radii to facilitate driving and enhance safety. Drivers exiting high-speed highways often do not appropriately lower their speeds from mainline levels as they negotiate off-ramps, and they find themselves at risk of running off the road.

Longitudinal barriers are often placed on ramps, but doing so requires consideration of varying shoulder and roadside conditions and the implications of these on barrier selection and placement. The effects of these conditions were identified in earlier research on barrier placement for highway horizontal curves (*3*). This report documents the research efforts undertaken and the insights derived for the selection, design, and placement of longitudinal barriers for use on CSORs. A summary of the findings of this research and thoughts on applying them are noted in this chapter. These set the stage for groups such as AASHTO to consider the safety implications for CSORs and promote efforts to reflect these findings into current guidelines for appropriate design, selection, and installation of longitudinal barriers on CSORs.

6.1 Analyses of Vehicle Dynamics Effects of Barrier Interface on CSOR Ramps

Various CSOR scenarios were evaluated using VDA and crash simulation to assess the effects of various CSOR features on barrier effectiveness. These efforts considered the effects of impacts by small cars, large pickup trucks, and SUTs negotiating CSOR ramps. VDA and crash simulations were conducted to reflect various parameters, including the following conditions that characterize CSOR ramps:

- CSOR ramp radii: 150 to 450 ft
- Ramp superelevation: 4% to 8%
- Ramp grade: 0% to –8%
- Shoulder width: 4 to 12 ft
- Shoulder angle: 0% to 8%
- Impact speed: 50 to 120 km/h
- Impact angles: 5 to 25 degrees
- Vehicle weights: 1,100 kg, 2,270 kg, and 10,000 kg

In this effort, VDA was first used to focus on interface variations for vehicles running off the road for four common types of barriers used on CSORs, namely W-beam guardrails (G4(1S)) and W-beam (MGS), Thrie beam (SGR09b), and concrete barriers. Interface envelopes were determined and tabulated to provide the basic minimum and maximum barrier heights for effectiveness on different CSORs. Effectiveness was shown to be a function of the grade and superelevation of the CSORs, as well as shoulder features and barrier type and position. Errant vehicles on CSORs take paths that can lead to sharper impact angles over varying surface slopes, and roadside slope can influence barrier installation. Project efforts included comprehensive analyses of the dynamics of vehicles leaving the ramp roadway and traversing the shoulder before encountering the roadside barrier. An understanding of these factors was needed to address the simple question: Will the barrier provide an effective interface with an errant vehicle?

The degree of slope change between the ramp superelevation and the shoulder was found to change the effective vehicle-to-barrier interface area on CSOR ramps. An immediately useful product of this effort is the interface tables that reflect a broad range of curvature, shoulder widths and angles, grades and superelevation, and barrier placement guidelines. The minimum and maximum measures for vehicle-to-barrier impacts allow an agency to analytically evaluate CSOR location and determine whether the variations in the effects of CSOR design parameters can lead to inadequate interfaces for the type of barrier deployed or considered. The indicated "effective" vertical coverage of the barriers for an errant vehicle on a given CSOR ramp can be evaluated by comparing measurements of the top and the bottom of the barrier with the maximum and minimum effective heights. Where the potential exists for a poor vehicle-to-barrier interface, actions can be initiated to make changes. In the tables, those situations shaded in red flag conditions that need attention to promote safety for typical vehicles. This information provides useful guidelines to practitioners for the selection, design, and installation of the barriers for the features of a CSOR location. The tables cover a broad range of conditions to provide usefulness in design, installation, and maintenance efforts. This information can also support safety investigations. The results can be extended to other barriers that have similar dimensions and placement guidelines.

Crash simulation analyses were used to determine whether the barrier would provide adequate strength to capture or redirect an errant vehicle across various combinations of CSOR geometrics and barrier impact conditions. The simulation software generated detailed metrics for each crash scenario over the duration of the crash event. The numerical results were stored in separate computer files to allow various types of analyses, but the critical end-state metrics were captured to generate a basic visual performance summary for each case. These summaries show the effects of the impact on the vehicles' position as well as provide the metrics associated with crash physics. The computed metrics were also compared with acceptance requirements to indicate whether safety requirements were met.

Performance summaries were generated to provide a diagram showing the crash and its aftermath as well as the comparison of critical metrics with acceptability. These visualized results are a summary of multiple simulations that reflect the vehicle dynamics and crash physics of the impact with the barrier during the 2- to 3-s crash event. On each summary, the graphic shows views of the vehicle's trajectory for a given ramp curve and surface, as well as the barrier installation. Each summary also shows the conditions from different views. Although the details are limited for these page-size views, these impacts can be viewed as a video to provide more clarity. These views were generated to show the variations in the impact effects and barrier deformations for the various conditions.

6.2 CSOR Simulations

Using a basic simulation model for a vehicle impacting a barrier on a superelevated curve, the research team executed more than 500 simulations reflecting the impact of a vehicle with a particular type of barrier for various ramp configurations. The conditions reflected the various combinations of barriers, CSOR designs, and barrier placement guidelines for typical MASH analyses with small and large vehicles. The simulation software undertook the computations of the movement of the vehicle into contact with the barrier and then interactions of the crushing or deformations of the vehicle and barrier for every second for a crash event period of about 2 s. These runs each took about 5 h to complete, but the many micro-level outputs provided the basis to visualize the details of the crash event, follow the trajectory of the vehicle, and monitor the impact effects on the barrier. For most combinations of the factors, a finite element simulation was performed. The conditions that occurred as a result of the impact of the vehicle as influenced by the road and shoulder features, the barrier type, and placement were computed.

The simulation runs generated detailed data reflecting changes in elements, the overall forces acting on the barrier and the vehicle, the effects of the crash, material strengths, the trace of the vehicle during the crash event, and many other factors. Ancillary software allowed the crash event to be visualized. The vehicle's position heading into impact with the barrier was noted, as was the point of contact with the barrier. The visualization function allowed the roll, pitch, and yaw effects to be observed for each crash simulation. The visualization display also allowed the crash event to be viewed from different sides, as shown. This helps observers to understand the effects on the vehicle as well as the barrier. The visualization tools allowed these views to be expanded to evaluate detailed aspects, such as the bumper snagging on a post or wheels climbing the face of a concrete barrier. The full set of these results is available from the research team.

The performance summary charts included in Appendices D through F report the analysis results from each simulation reflecting a particular barrier, CSOR design, and vehicle type. Across the top of the chart, the vehicle type and barrier setup are noted. In the second line, the features of the curve and barrier installation are noted. The lower parts of these individual crash simulation summaries show the results of a standard MASH evaluation of the efficacy of the specific barrier. A large number of conditions were considered, and based on the cumulative results, various barriers were determined to be effective for most CSOR ramp situations. The following sections offer recommendations for adopting the findings of these efforts, their application to the highway design process, and the needs for future research.

6.3 Proposed CSOR Guidelines

The derived findings of the various aspects of the project provide useful insights and examples for performance envelopes that may be evaluated and considered for an update to the AASHTO *Roadside Design Guide* (*2*). The intent of this effort was to analyze concerns and problems related to highway safety for a given aspect of the highway system. The efforts considered various questions for installations of longitudinal barriers on CSORs. The results cover a wide range of CSOR situations. The research team addressed a representative cross section of conditions, undertook a rigorous set of analyses, presented detailed results, and formulated recommendations to improve standards and practices for further discussion and debate. The research team made every effort to ensure that the recommendations are comprehensive, concise, and well supported.

AASHTO and others may carefully review the findings in the context of their considerable direct experience to consider the results of these efforts, tempered by experiences, and the reality of agency resources and priorities. The results of this effort may provide some agencies insights and support for addressing lingering needs by applying the results to problem locations. Over time, if evaluated and considered appropriate, the results may be generalized and considered for inclusion as an update to the highway safety guidelines for states—as well as for the nation—provided by the *Roadside Design Guide* (*2*).

Table 19 summarizes the significant implications and guidelines derived for the barriers and CSOR conditions analyzed. The guidelines imply an understanding of the implications of

Table 19. CSOR implications and guidelines derived from NCHRP Project 22-29B efforts and results.

Aspect	Elements of Implications and Guidelines
	Barrier Design
General	• Poor vehicle-to-barrier interface limits barrier functions in a crash. • Good interface is a necessary, but not a sufficient, condition for selection of a barrier type. The degree of impact severity needs to be assessed. • **Consider using interface analyses (i.e., VDA) to evaluate special cases or other types of barriers to increase confidence in the design.** • **Consider higher barriers to better accommodate larger vehicles for CSOR applications.**
Concrete Barriers	• Concrete safety shapes do not have underride problems, but face slopes can induce rollovers. • **Use higher concrete barriers when concern is expressed about overrides associated with CSOR features.** • Concrete barriers with an appropriate face slope may be considered the most universally effective design for CSOR conditions. • **Design concrete barriers with a vertical or near-vertical face slope to limit vehicle ride-up and maintain a viable interface area overlap.**
W-Beam Barrier	• The need for a higher barrier may be apparent but increasing the rail height necessitates review of underride potentials. • **Increases in barrier height are most important for tight curves where excessive speeds are likely to occur (e.g., off-ramps, downhill).** • **Follow the FHWA Tech Memo of May 17, 2010, recommending that nominal heights for new installations of G4(1S) barriers be at 29 in. for CSORs (*6*).** • **Consider 31-in. high W-beam barrier designs for CSOR situations.**
	Selection
Curvature and Superelevation	• **Limit the use of tight curves with high superelevation.** **Consider using higher barriers on CSORs with appropriate underride protection.**
	Barrier Design
General	• Poor vehicle-to-barrier interface limits barrier functions in a crash. • Good interface is a necessary, but not a sufficient, condition for selection of a barrier type. The degree of impact severity needs to be assessed. • **Consider using interface analyses (i.e., VDA) to evaluate special cases or other types of barriers to increase confidence in the design.** • **Consider higher barriers to better accommodate larger vehicles for CSOR applications.**
Concrete Barriers	• Concrete safety shapes do not have underride problems, but face slopes can induce rollovers. • **Use higher concrete barriers when concern is expressed about overrides associated with CSOR features.** • Concrete barriers with an appropriate face slope may be considered the most universally effective design for CSOR conditions. • **Design concrete barriers with a vertical or near-vertical face slope to limit vehicle ride-up and maintain a viable interface area overlap.**
W-Beam Barrier	• The need for a higher barrier may be apparent but increasing the rail height necessitates review of underride potentials. • **Increases in barrier height are most important for tight curves where excessive speeds are likely to occur (e.g., off-ramps, downhill).** • **Follow the FHWA Tech Memo of May 17, 2010, recommending that nominal heights for new installations of G4(1S) barriers be at 29 in. for CSORs (*6*).** • **Consider 31-in. high W-beam barrier designs for CSOR situations.**

Table 19. (Continued).

Aspect	Elements of Implications and Guidelines
Barrier Design	
Shoulder Width and Angle	• **Minimize changes in slope between road and shoulder to minimize the effects of vehicle suspension and maximize the potential for good vehicle-to-barrier impact interface.** • **Use wider shoulders where slope changes must be large to allow the suspension to stabilize the vehicle before impact.**
Roadside Slope	• **Limit the variation of slope change on the roadside for situations where the barrier is not placed adjacent to the shoulder to provide an acceptable interface.**
Barrier Type	• **Consider higher (e.g., 31 in.) W-beam barrier designs for CSOR situations.** • **Select barriers with increased height for tight curves where high speeds are likely to occur.** • **Consider using concrete barriers with vertical or near-vertical face slope (e.g., single slope or F-shape) to reduce the risk of rollover.**
Installation	
Orientation	• **Promote use of barrier orientation perpendicular to the roadway for concrete barriers.**
Barrier Design	
General	• Poor vehicle-to-barrier interface limits barrier functions in a crash. • Good interface is a necessary, but not a sufficient, condition for selection of a barrier type. The degree of impact severity needs to be assessed. • **Consider using interface analyses (i.e., VDA) to evaluate special cases or other types of barriers to increase confidence in the design.** • **Consider higher barriers to better accommodate larger vehicles for CSOR applications.**
Concrete Barriers	• Concrete safety shapes do not have underride problems, but face slopes can induce rollovers. • **Use higher concrete barriers when concern is expressed about overrides associated with CSOR features.** • Concrete barriers with an appropriate face slope may be considered the most universally effective design for CSOR conditions. • **Design concrete barriers with a vertical or near-vertical face slope to limit vehicle ride-up and maintain a viable interface area overlap.**
W-Beam Barrier	• The need for a higher barrier may be apparent but increasing the rail height necessitates review of underride potentials. • **Increases in barrier height are most important for tight curves where excessive speeds are likely to occur (e.g., off-ramps, downhill).** • **Follow the FHWA Tech Memo of May 17, 2010, recommending that nominal heights for new installations of G4(1S) barriers be at 29 in. for CSORs (*6*).** • **Consider 31-in. high W-beam barrier designs for CSOR situations.**
Placement	• **Limit the placement of barriers to the edge of the shoulder on CSORs, particularly when a non-trivial (more than 6%) slope change is going to the roadside slope.** • **Use wider shoulders with lower shoulder angles relative to the road on CSORs with short radii and high superelevation.**
Maintenance	• **Analysis on the effectiveness of damaged barriers on CSORs is needed.** • **Further analysis of relative priorities for barrier maintenance on CSORs may be needed.**

vehicle-to-barrier impacts on CSORs. These implications are included, along with the critical elements of guidelines (in bold) that evolved from this research. It is hoped that this construct offers a useful means to summarize the findings of the multi-faceted analyses and those related findings that support the recommended guidelines for barrier design, selection, and installation.

6.4 Conclusions

In continuing research to enhance efforts to ensure that highways are designed and maintained to provide a high level of safety, the research team recognized that understanding of the influences of CSOR features on safety was limited. The research team found that physics-based criteria had been created to determine appropriate curvature and banking parameters to allow vehicles to safely negotiate curves under varying surface conditions. Criteria for basic curve design are found in the AASHTO Green Book (*1*). It was noted, however, that limited guidelines were available for addressing concerns about vehicles leaving the roadway under CSOR conditions.

While it is basic understanding that crashes occur more often on curves than tangent sections, the influences of CSOR features on crash propensity were unclear. It was noted that a fundamental issue exists with the level of details associated with crash reporting that limit analysis options. The usual data captured for crashes falls short on details about the features of the road at or upstream of the crash location. In some cases, basic features are provided on crash reports (e.g., pavement condition), but rarely are details on grade, curvature, or basic features captured. The limited capability to analyze CSOR crashes is understandable, as needed data items are not routinely captured. The problem occurs even if an agency has data on road features but cannot link it to specific crash sites.

Understanding has been growing about the dynamics of vehicles as they traverse specific surfaces, but such analyses have not typically been undertaken in crash analysis efforts, despite the availability of software tools for the purpose. It is also understandable that the sophisticated simulation tools that allow the physics of vehicle dynamics and vehicle-to-barrier impacts to be analyzed are not applied because funds and in-house capabilities may be limited. The interest in understanding the safety performance of barriers on CSORs provides an impetus for using advanced tools when ordinary research approaches are limited.

This effort was undertaken in three phases to rigorously generate the insights needed to enhance the understanding of the safety performance of barriers on CSORs and develop guidelines for their effective design, selection, and installation. The following insights resulted from this research:

- Previously, little effort had been made specifically to determine whether longitudinal barriers adjacent to CSORs perform the same as on tangent sections.
- Current guidelines for barrier design, selection, and maintenance are unclear but are assumed to be the same as for tangent sections.
- VDA using commercially available tools provides a means to study the effects of speed, surface features, and vehicle type on the trajectory and orientations of a vehicle departing the traveled way on a CSOR.
- Vehicle trajectories for two types of vehicles on roads at different speeds were studied to relate them to the nature of the interface with barriers at varying positions along the road, as well as on interchange ramps.
- VDA provided useful information on vehicle-to-barrier interfaces for a range of CSOR conditions. These analyses can serve many useful functions for DOTs looking to improve safety on CSORs.

- VDA results were used to determine situations that warranted deeper analyses using simulation.
- Finite element simulations were undertaken to investigate the impact performance (i.e., physics) of selected vehicles actually impacting one of three types of barriers placed on a CSOR. This effort generated many simulations that may be a useful resource for studying problem locations.
- The simulation analyses focused on varied impact conditions to evaluate the performance of New Jersey concrete, G4(1S) W-beam, and MGS barriers using MASH criteria.
- The results indicated some potential for failures, but options for addressing the problems exist.
- Full-scale crash tests were conducted, which were deemed to validate the simulation analyses. These also demonstrated approaches for conducting future tests of barriers that may be used on CSORs.

The findings from all three aspects of the research were summarized and translated into proposed actions that could increase barrier safety on CSORs. Needs for future research were also defined. This final report documents the analyses and results from the project. These provide the necessary understanding of barrier effectiveness that can be applied to generate or update agency recommendations for effective design, selection, and installation of longitudinal barriers on CSORs.

6.5 Needs for Future Research

The findings presented in this report provide a solid basis for agencies to assess and improve their guidelines and practices for deploying longitudinal barriers on CSORs. The results suggest that these findings can enhance safety, but as things change, the guidelines will need to be updated. The following list of topics may warrant future efforts to expand the guidelines, address changing conditions, and consider new barrier treatments and vehicle capabilities:

- Assess other conditions at CSOR sites to expand guidelines and understanding of impact likelihood and consequences:
  - Formulate tables structured to reflect other conditions or related aspects, such as transitions.
  - Assess varied hardware.
  - Consider new or emerging vehicle types.
  - Consider other factors (e.g., vehicle loading, driver input, braking, slippery roads) and a combination of these factors (e.g., yawing and braking).
- Aid agencies in addressing the adequacy of their design guidelines.
- Consider the implications of new and alternative barriers in testing and approval routines for their applicability on CSORs.
- Address crash testing needs:
  - Consider testing conditions that improve representation of ramp conditions.
  - Consider needs for additional imagery, data items, and impact conditions.
  - Define testing requirements specific to barriers on CSORs to include in MASH.
- Incorporate new research findings:
  - VDA and crash simulation tools provide important perspectives and data on CSOR crashes and a means to assess and compare specific conditions or agency standards.
  - Tabular summaries of effective interface areas provide fundamental guidelines for barrier selection and deployment. Shaded areas highlight critical conditions.
  - Establish a basis for developing standards for barriers on ramps that consider ramp features.
  - Demonstrate viability of testing protocols for basic conditions.
  - Identify the importance of and needs for improved barrier installation guidelines for CSORs.

Overall, the findings provide valuable insights for improving the design, selection, and installation of longitudinal barriers on CSORs. However, additional research and updates to guidelines may be needed as conditions change, new barrier treatments are developed, and vehicle capabilities evolve.

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Appendices

The following appendices can be found on the National Academies Press webpage for *NCHRP Research Report 1138: Evaluating the Performance of Longitudinal Barriers on Curved, Superelevated Off-Ramps* (https://doi.org/10.17226/28589) under "Resources at a Glance":

1. Appendix A: State DOT Survey Questionnaire
2. Appendix B: Links to State DOT Documents
3. Appendix C: Finite Element Model Validations
4. Appendix D: FE Simulation Results – New Jersey Shape Concrete Barrier
5. Appendix E: FE Simulation Results – 31" W-Beam Barrier (MGS)
6. Appendix F: FE Simulation Results – 34" Thrie Beam Barrier (SGR-09b)
7. Appendix G: Summary Report for Test 22010
8. Appendix H: Summary Report for Test 22011
9. Appendix I: Summary Report for Test 22013
10. Appendix J: Summary Report for Test 22014

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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