DRAFT FINAL REPORT FOR:

Crash Test Stone Faced Concrete Bridge Rail

Authors:
Dhafer Marzougui
Cing-Dao (Steve) Kan
Fadi Tahan
The George Mason University
and
Kenneth S. Opiela
Transportation Consultant

Under Contract No. DTFH61-14-D-00012
Task Order: 693JJ319F000387
CCSA Report No. R-22-001
FOIL Test Nos. 21004 and 21005

Sponsored by:
Eastern Federal Lands Highway Division
Federal Highway Administration
U.S. Department of Transportation

July 2022

DISCLAIMER

The contents of this report reflect the views of the authors who are solely responsible for the facts and accuracy of the data, and the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration of the U.S. Department of Transportation, or the George Mason University Center for Collision Safety and Analysis. This report does not constitute a standard, specification, or regulation. In addition, the above listed agencies assume no liability for its contents or use thereof. The names of specific products or manufacturers listed herein do not imply endorsement of those products or manufacturers.

ACKNOWLEDGEMENTS

This study was sponsored by the National Park Service (NPS), Eastern Federal Lands (EFL) Branch of FHWA, in cooperation with Office of Safety Research & Development at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA), of the US Department of Transportation (US DOT).

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2002)

TABLE CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 Problem Statement

A shared objective of the U.S. Department of Transportation, other Federal agencies such as the National Park Service, and the individual state departments of transportation is the promotion of the highest level of safety for highway users on the roads under their jurisdiction. Safety needs are addressed in many ways, including safety-conscious roadway design and the provision of barriers and other devices in areas between and/or adjacent to the roadway to prevent or mitigate adverse consequences of vehicles leaving the roadway or veering into opposite direction traffic. Guidelines for the design of highways has evolved and current standards are found in "A Policy on Geometric Design of Highways and Streets "[1]. Barrier installations are commonly used as Roadway Safety Hardware (RSH) to safely redirect errant vehicles back onto the roadway and away from hazards that may exist beyond the edge of the roadway, or from traffic moving in the opposite direction on the other side of the road. Various types of concrete barrier treatments are used as RSH depending on traffic volumes, speeds, and/or vehicle mix. This dictates the need for medians, roadsides, or bridge rails treatments to serve safety purposes. Recommended RSH treatments are outlined in the "Roadside Design Guide" [2].

The National Park Service (NPS) objectives include providing access in scenic or historic areas in a manner that compliments the environment. Many NPS roads have become important links in growing metropolitan areas and therefore carry greater volumes of traffic at higher speeds than originally conceived. In the interests of meeting safety and aesthetic goals, enhanced designs for RSH on these roads have evolved. The continued agency emphasis on striving for the highest level of highway safety under guidelines such as the Manual for Assessing Safety Hardware (MASH) provided the impetus for this research.[3]

Most concrete barriers used as RSH feature a smooth face, except for the necessary expansion or connection joints. The relatively smooth concrete surface readily allows an impacting vehicle to slide along the barrier as speed and impact energy are dispersed. The rough, natural stone face of the Stone-Faced Concrete Barrier (SFCB) obviously results in greater resistance to sliding along the barrier. This has raised questions about its safety efficacy. It was found that there has been past research and testing to study surface feature effects. These included:

- NCHRP Report 554 by the Texas Transportation Institute [4] which used finite element simulations to analyze the effects various surface asperity features [i.e., a metric relating the frequency, inclination angle, and depth of surface features metrics for varying surface features]. Asperity metrics were examined to develop guidelines for treatments to the surfaces of roadside barriers. They, however, did not address features with "roughness" that would characterize stone-faced barriers like those used by the NPS and EFL. These efforts did, however, provide a basis for analyzing surface coarse roughness of the barrier face on effects of vehicle impacts and offered a nomograph for assessing the criticality of lesser degrees of surface variation.

- Testing at the University of Nebraska in 2019 assessed the effects of recessed rectangular areas of the face of vertical concrete bridge rails for MASH 3-10 and 3-11 impacts [5]. These were analyzed by testing the effects of a barrier face design relative to a smooth face. The face designs were rectangular indentations less than two inches deep with a beveled edge for each depressed pattern. The recessed rectangular patterns were 60 inches wide by

15 inches high on a 34-inch wall, so an errant vehicle sliding across the face would encounter several indentations (both vertical and horizontal). Crash testing was considered necessary as this surface treatment was not considered “covered” by NCHRP Report 554. MASH Tests 3-10 and 3-11, however, showed acceptable crashworthiness for impacts with barriers having this feature by small and large vehicles at a speed of 62 mph and a 25-degree impact angle (MASH Tests 3-10 & 3-11).

- California department of transportation performed several crash tests on longitudinal barriers with different surface textures [6]. The textures included: 1- a deep cobblestone, 2- a 19-mm deep fluted rib angled to 45°, 3- a “Mission Arch”, 4- a “Cobble Reveal”, 5- a “Drystack stone”, 6- a “Stone Ground Fractured Granite”, and 7- a “shallow cobblestone”. The tested barriers had profile similar to the Type 60 concrete barrier. The barriers varied in height from 1220 mm to 1422 mm. The testing was performed in accordance with NCHRP Report 350 recommended procedure and evaluations. The barriers were tested at test level 3 (100 km/hr) with the small car (820C) and pickup truck (2000P). The test results showed that the “Mission Arch”, “Cobble Reveal”, “Drystack stone”, and “Stone Ground Fractured Granite” textured barriers met the criteria and were recommended for approval on California highways requiring TL-3 longitudinal barriers. The “deep cobblestone”, “shallow cobblestone”, and “fluted ribs at a 45°” Textured barriers were not recommended.

These limited insights on the effects of barrier surface treatments on barriers like the SFCB, motivated the National Park Service and the Eastern Federal Land Division to fund research that included crash tests to confirm that the desired MASH requirements including post-impact effects are achieved.

1.2 Objective

This effort was initiated to further analyze and test the efficacy of the Stone-Faced Concrete Barriers (SFCBs) used as bridge rails, median barriers, or roadside treatment on highways under the jurisdiction of the Federal Lands management agencies and National Park Service. Aesthetic barriers such as the rough stone-faced walls and steel-backed timber (SBT) guardrail have been developed and tested for use in parks and other historic or scenic areas. The growth of urban areas has some roads, where these barriers are being used, carrying greater amounts of traffic at higher speeds than originally anticipated. This effort is aimed at determining whether the typical stone-faced concrete barriers that are widely used on roads under the jurisdiction of the National Park Service (NPS) meet the latest safety requirements (MASH 2016)

1.3 Scope of Study

The research effort included the following five tasks:

- Task 1: Develop a Conceptual Model of the Stone-Faced Concrete Median Barrier
- Task 2: Perform Crash Simulation Analysis
- Task 3: Perform the Design and Detailing
- Task 4: Perform Crash Tests for Validation
- Task 5: Prepare Final Report

The research team undertook these tasks following methods that proved to be effective in over twenty-five years of efforts to pioneer the development of the crash simulation methods and models, applying simulation to a broad range of crashes, and the integration of evaluation of analyses, testing, and documentation of results for many types of barriers. Crash simulation has been used extensively for the development or improvement of all kinds of RSH as in the formulation of safety standards.

The efforts under this project focused on the modeling, analysis, and testing of SFCB in accordance with MASH guidelines at the TL3 impact conditions. Both median and roadside versions of the SFCB were investigated and assessed in this project. Transition devices to connect these barriers to SBT guardrails were also investigated. Full-scale crash testing was performed on the median versions of the SFCB. Summary of these efforts are summarized in the following sections.

2 Development of Conceptual SFCB Designs

2.1 Overview

A primary mission of the FHWA and other agencies is to provide the safest possible highway system. Safety is the cumulative result of efforts in many different sectors with the highway infrastructure (i.e., RSH) representing a major aspect. FHWA has, and continues to, promote standards for the design, deployment, operation, and maintenance of the many RSH elements that are part of the highway infrastructure. Roadside barriers play a key role in keeping vehicles from wandering into opposing lanes of traffic or encroaching into hazards on the roadside. Over more than a century of major highway building efforts, agencies incrementally learned of effective alternatives to limit hazards, and developed both safety standards and protocols for assessing them, many types of roadside barriers and bridge rails have evolved. Additionally, and means to evaluate them physically and analytically have evolved significantly. Government agencies have required the states to use barriers that meet “safety standards,” but federal agencies often also promoted other factors (e.g., esthetics, natural effects, etc.) for highways under their jurisdictions. Recently, federal agencies issued enhanced requirements for roadside safety features also meet the prevailing safety standards. This implies that continuing efforts are necessary to “analyze” and/or “test” typical barriers used on all Federal roads (e.g., stone faced bridge rails, timber guardrails) to demonstrate that they offer the same current levels of safety for the highway users.

Generally, crash simulation has played an increasing role in the analysis of highway crashes and RSH effectiveness. Crash simulation and modeling has evolved and has repeatedly demonstrated to offer a tremendously powerful means to analyze safety issues and develop new and improved highway barriers and appurtenances. The FHWA’s initiatives to develop the fundamental tools, make detailed finite elements (FE) of vehicles and barriers readily available, and fund efforts to use the FE tools to address safety issues emerging from changes in the vehicle fleet, highway designs, traffic mix, and other factors has led to safer roads. Considerable knowledge is gained from crash simulation faster and at a lower cost, providing a sound basis for enhanced crashworthiness for both vehicles and highways.

The National Park Service (NPS) has aimed, as appropriate, to try to preserve the natural or scenic character of the areas where its roads are needed. To meet the objectives, it does not routinely use the same types of traffic barriers commonly used on most public roads throughout the country. Rather than the standard galvanized steel W-beam or the concrete safety shape barrier, aesthetic barriers such as the rough stone-faced walls (Figure 1) and steel-backed timber (STB) guardrail (Figure 2) have been developed and tested for use in the Parks and other scenic areas. These barriers, however, have not all been tested to the latest safety standards. This effort is aimed at determining whether the SFCB designs that are widely used on roads under the jurisdiction of the National Park Service (NPS) meets the latest safety requirements.

Figure 1 – Examples of Installed Stone-Faced Barriers

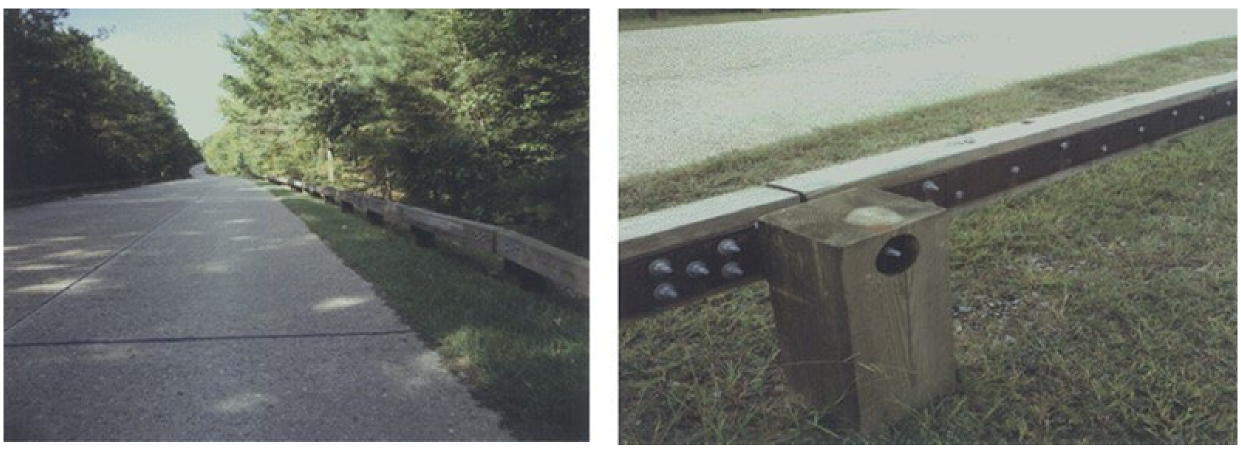


Figure 2 – Examples of Steel Backed Timber Guardrail Installation

In this project, research was undertaken that follows current practices to develop, upgrade, or modify barrier systems. The process involves the use of finite-element models of vehicles and barriers to "simulate" impacts of a vehicle with the barrier. The simulations analyze the response (i.e., physics) of both the vehicle and barrier when an impact occurs. The computer tracks the stresses, deformations, translations, fractures, and other effects on each element of the vehicle and barrier resulting from the impact. These analyses take place at the "element-level", which might best be thought of as many small cubes characterizing the item. The impact forces are distributed across all the cubes and the forces distributed by the properties of each cube and those adjacent to it. These simulations have been shown to be capable of extremely accurate representations of the effects of the collision.

These results have been compared at high levels of detail with the results of full-scale crash testing demonstrating the capability to replicate crashes across the spectrum of speeds and angles. The accuracy of the models used in the simulations to trace the sequential effects of basic physics of impacts influences the viability of the result, hence the need to detailed representations of the vehicle and barrier (for example, the stone face). The effects are considered in terms of the transmission of forces, deformation of elements, the failure of materials, and related effects at sub-second increments of time. The crash simulation technology has been developed over the last 40+ years and have often become the first aspect in efforts to design and analyze barrier safety. Validations of the process over the years have shown very high degrees of reliability in tracing crash effects as well as replicating the overall end result by parallel full-scale crash testing. Simulation rapidly allows designs to be varied, a range of impact angles and speeds to be considered, and various barrier designs and vehicles to be considered.

2.2 Development of Conceptual Models for SFCB

The project began with the development of conceptual models for representing stone-faced, concrete barriers (SFCB). While there exists a broad set of models of roadside safety hardware, these do not include models of the various stoned-faced concrete median barrier versions. These models are necessary to allow the use of crash simulation analyses to evaluate various SFCB barrier designs. The effects of the rough stone face under varying crash scenarios needs to be considered in evaluating barrier crashworthiness. The conceptual models that were expected to evolve from this project were expected to meet the following objectives:

- SFCB conceptual designs needed to address three things:
  - The designs must support efforts to assess MASH 2016 test and evaluation criteria, particularly for Test Level 3 (TL-3), with Tests 3-10 and 3-11 deemed to be the most critical.
  - Stone faced surfaces needed have similar appearance and features of current deployments to permit evaluation of current applications.
  - Hardware elements related to SFCB systems, including terminals, and transitions, also needed to be considered within the limits of contract resources.
- The literature review revealed limited testing of similar designs, especially for the effects of stones (extrusion and mortar strength) on stability. The relevant findings of these efforts were to be reflected in the SFCB models.
- The SFCB design, specifically the median version, needed to be crash tested to confirm the simulation modeling results for MASH Tests 3-10 and 3-11. Future efforts may be needed to consider the other systems evaluated.
- Efforts to analyze and confirm the crashworthiness of transitions between the SFCBs (both median and roadside versions) and the SBT guardrail systems.

Project efforts that addressed these objectives are described in the following sections.

2.3 Developing Models for Impact Simulation with SFCB Barriers

A major consideration of “stone-faced barriers” is the uneven surface of the barrier resulting from the natural stone bonded to the reinforced concrete structure of the barrier as shown in Figure 3. Detailed measurements were taken as shown in Figure 4 to characterize the random stone face. This project focused on developing conceptual designs for two types of stone-faced walls, median and roadside versions. The basic design requirement was that the model must be similar in appearance to current designs. To meet the latter requirement, the team used the original wall designs as baselines (starting points) and made updates as believed necessary to meet MASH test and evaluation criteria.

Figure 3 – Views of a Stone-Faced Bridge Rail (with fence)

Figure 4 – Example of Measurements Taken on an Existing Stone-Faced Barrier

The process of developing the conceptual designs was started by performing an in-depth analysis of the original designs and assessing their strength and ability to meet the MASH TL3 impact criteria. The designs were evaluated using first principles analysis, which involved applying the basic laws of physics to examine the potential for a design to meet the current MASH impacts (i.e., the higher requirements due to the most recent MASH criteria). The analysis indicated the minimum barrier strength needed to withstand the loads subjected by the vehicle on the barrier during the impacts. These estimates were then used to update the barrier/transition designs to meet the strength requirements. While updating the designs, the original dimensions (height and width) of the barriers were kept as close as possible to the original designs by strengthening the reinforcement (e.g., rebars) instead of increasing the barrier cross-section. Figure 5 shows basic dimensions of the original SFCB median design and Figure 6 shows those for the roadside version.

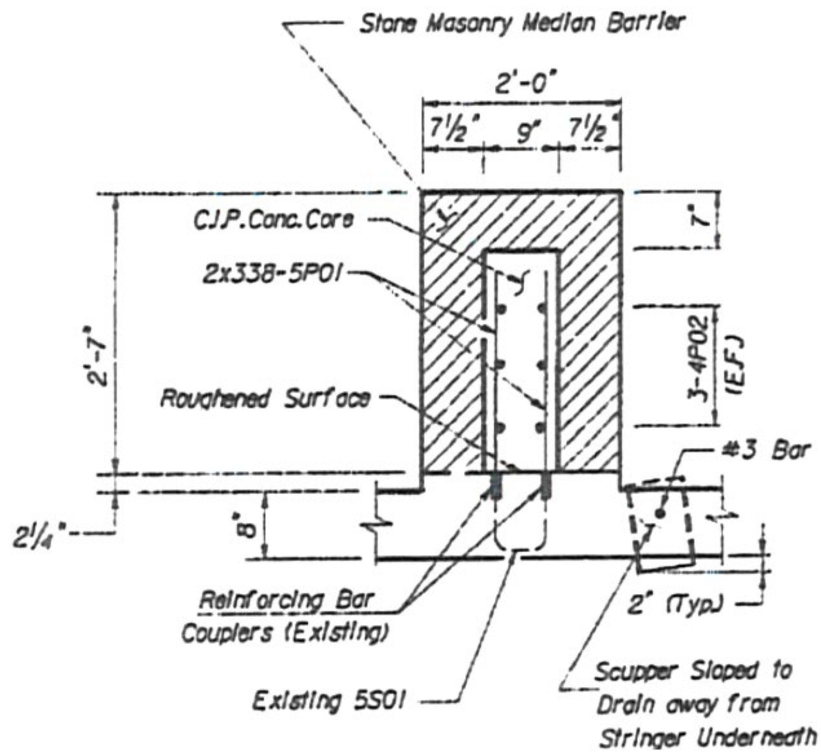


Figure 5 – Basic Dimensions of Existing Stone-Faced Barrier

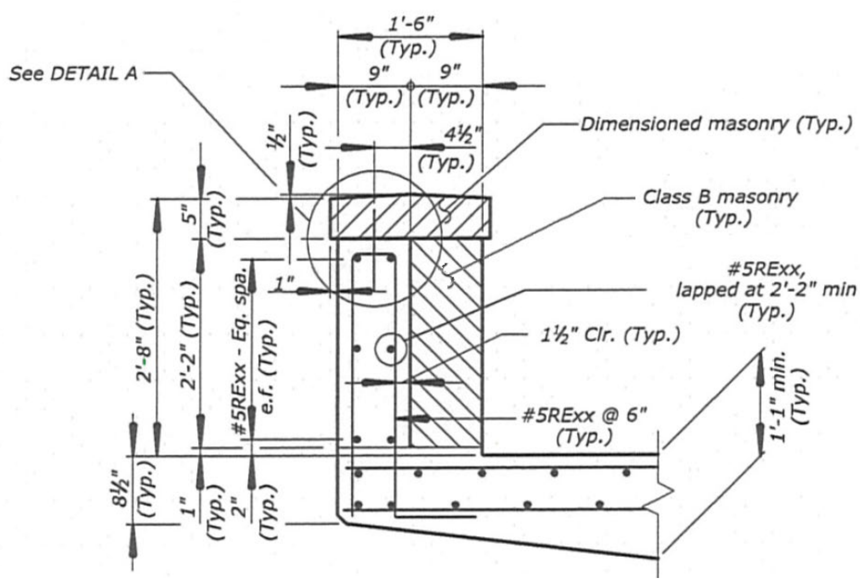


Figure 6 – Design Details for a Stone-Faced Concrete Core Bridge Rail

A critical question for this effort was how much difference is there in the sliding resistance and vehicle stability to the standard smooth-faced concrete barrier and a stone-faced barrier. While many methods could be employed to establish such a metric, to expedite this project, it was decided to use a simple test of the two conditions in actual test impacts at the FOIL. Figures 7 and 8 show two test set-ups. In the first, a large passenger vehicle (Toyota Venza) is set to impact a vertical concrete barrier with a typical smooth face at a 25-degree angle. The left view reflects the vehicle just before impact on its 25-degree angle approach. The right image shows the smooth, vertical face of the barrier. Figure 8 shows a similar set-up for a stone-faced section. A section of stone-faced panel is installed in front on the smooth-faced wall near the impact area to measure the differences in the sliding effects in the impact. The stone-faced barrier configuration in the test was made as close as possible to existing stone-faced barriers.

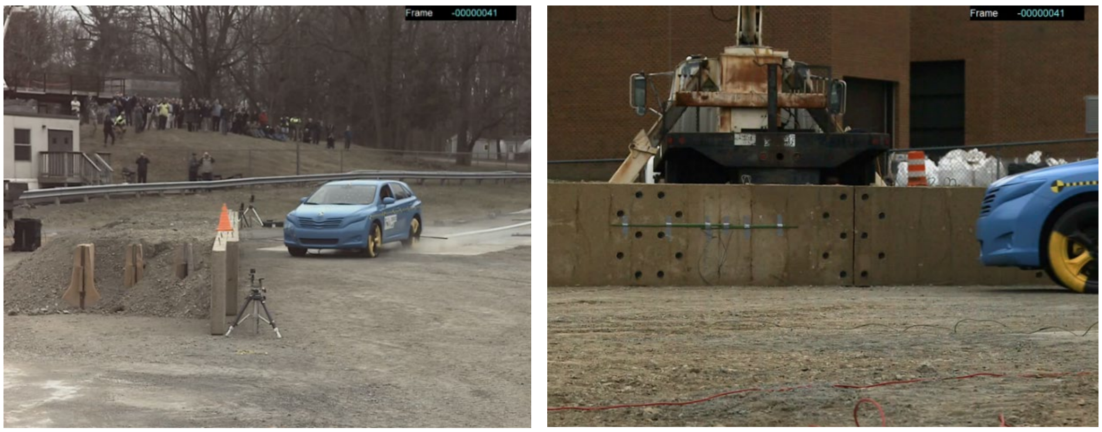


Figure 7 – Angular Impact Set-up for Large-Sedan with Smooth-faced Barrier

Figure 8 – Angular Impact Set-up for Large Sedan into a Stone-faced Barrier

Using high-speed video imaging from multiple angles it was possible to visualize variations between the two tests. Figure 9 shows a sequential view from the two tests (with and without stones). Using high-sensitivity accelerometers and rate transducers installed on the vehicle, measurements of the vehicle movement in the x, y, and z planes was recorded for the duration of the impact period. Comparison of the accelerometer and rate transducer traces provided a metric of the degree of difference between a smooth face and rough, stone face. The tests indicated that there was no significant difference in performance between the smooth-faced barrier and stone-faced barrier tests. In both tests, there was no significant instability of the vehicle, and the occupant risk numbers were below the MASH critical numbers.

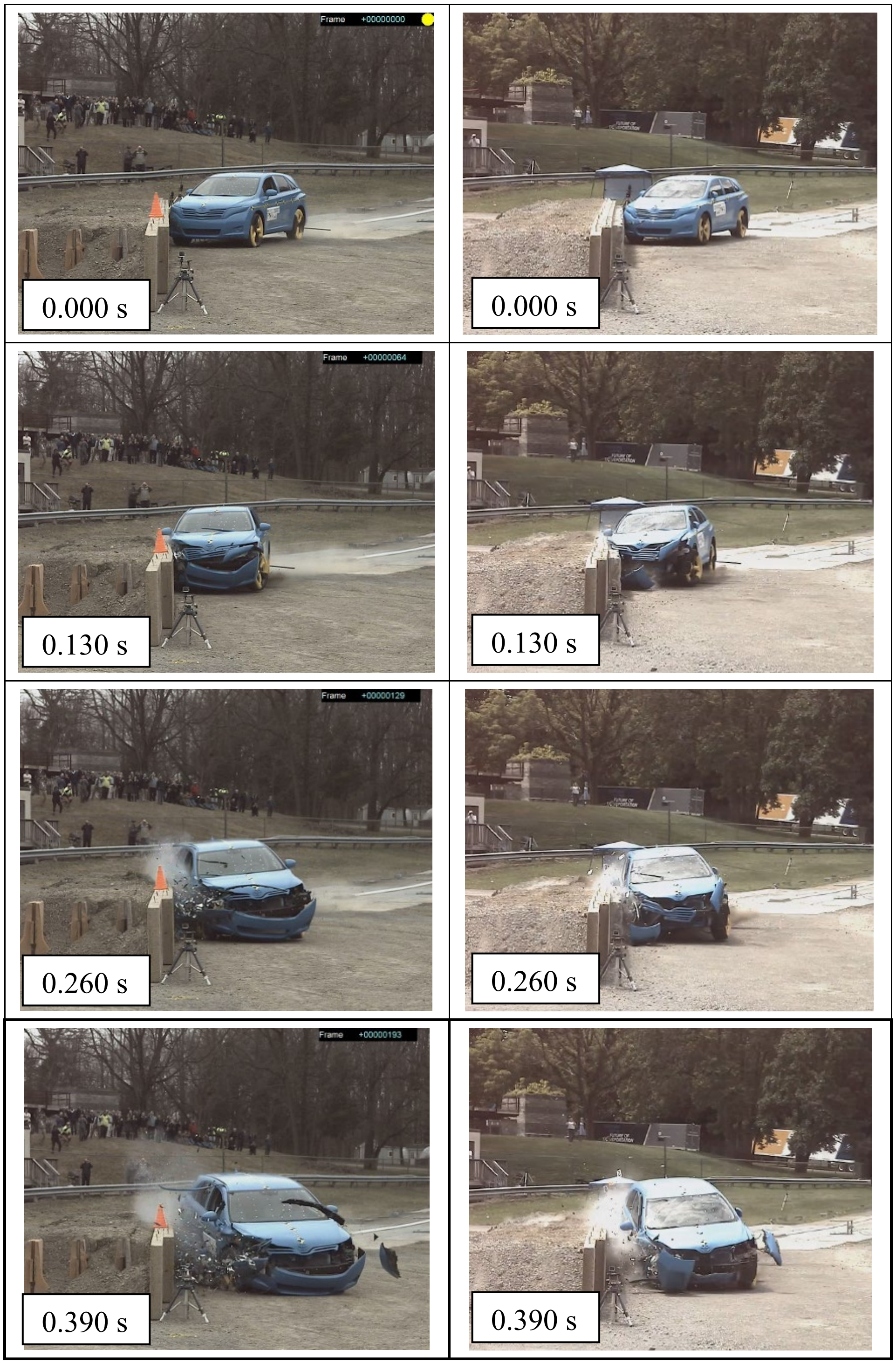


Figure 9 – Comparisons of Smooth-faced to Stone-faced Barrier Tests

The intent of the two impact tests was to measure the difference in the sliding resistance of the identical vehicles between surfaces and identify any potential for vehicle snagging with the stone-faced wall. These tests were also used to calibrate the computer models. Three-dimensional scans from a section of an existing stone-faced barrier were used to create computer models of generic stone-faced barriers. Figure 10 shows the wall from the crash test and the one from the model which was developed using the scanned geometry. Figure 11 shows the simulation setup used to calibrate the stone-faced model.

Figure 10 –Stone-faced Barrier from Test (Left) and Simulations (Right)

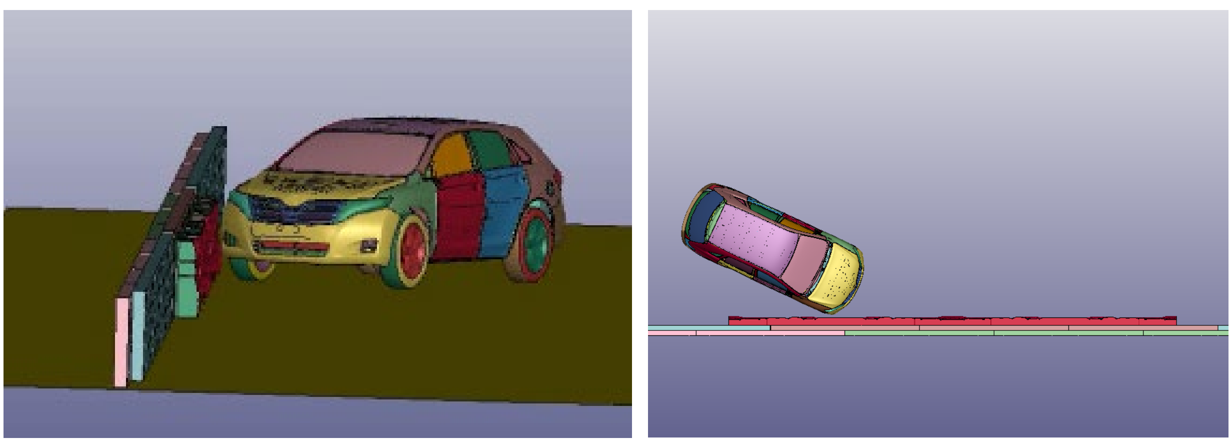


Figure 11 – Comparisons of Smooth-faced to Stone-faced Barrier Tests

The tests with the Toyota Venzas provided measurements that were used to calibrate the barrier with the stone-faced models to reflect the added roughness of the stone-faced barrier. A model of the same vehicle used in the tests (Toyota Venza) was used in the calibrations. Figure 12 shows comparisons of the simulation to the test for the case of the smooth-faced barrier. Figure 13 shows the simulation to test comparisons for the stone-faced wall. Both simulations show similar behavior to the tests.

These analyses provided specific metrics uniquely characterizing "stone-faced barriers," the incorporation of these into FE modes, confirmation of the viability of these metrics to reflect the differences associated with these designs, and insights into the expected performance of barriers with this feature. The subsequent analyses of safety performance of stone-faced barriers provide a basis for MASH evaluations and effective future use.

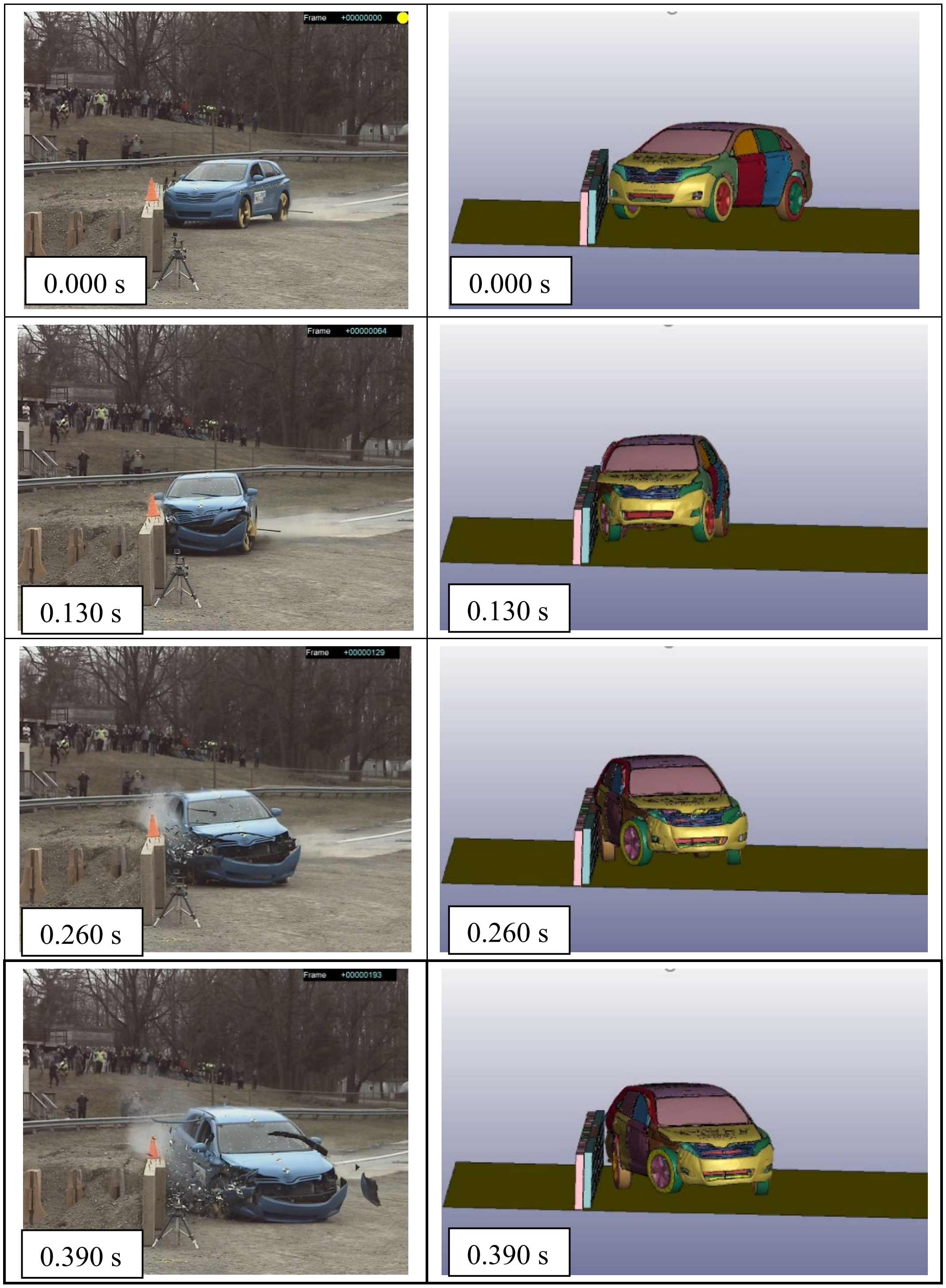


Figure 12 – Comparisons of Simulation to Test for the Smooth-faced Barrier

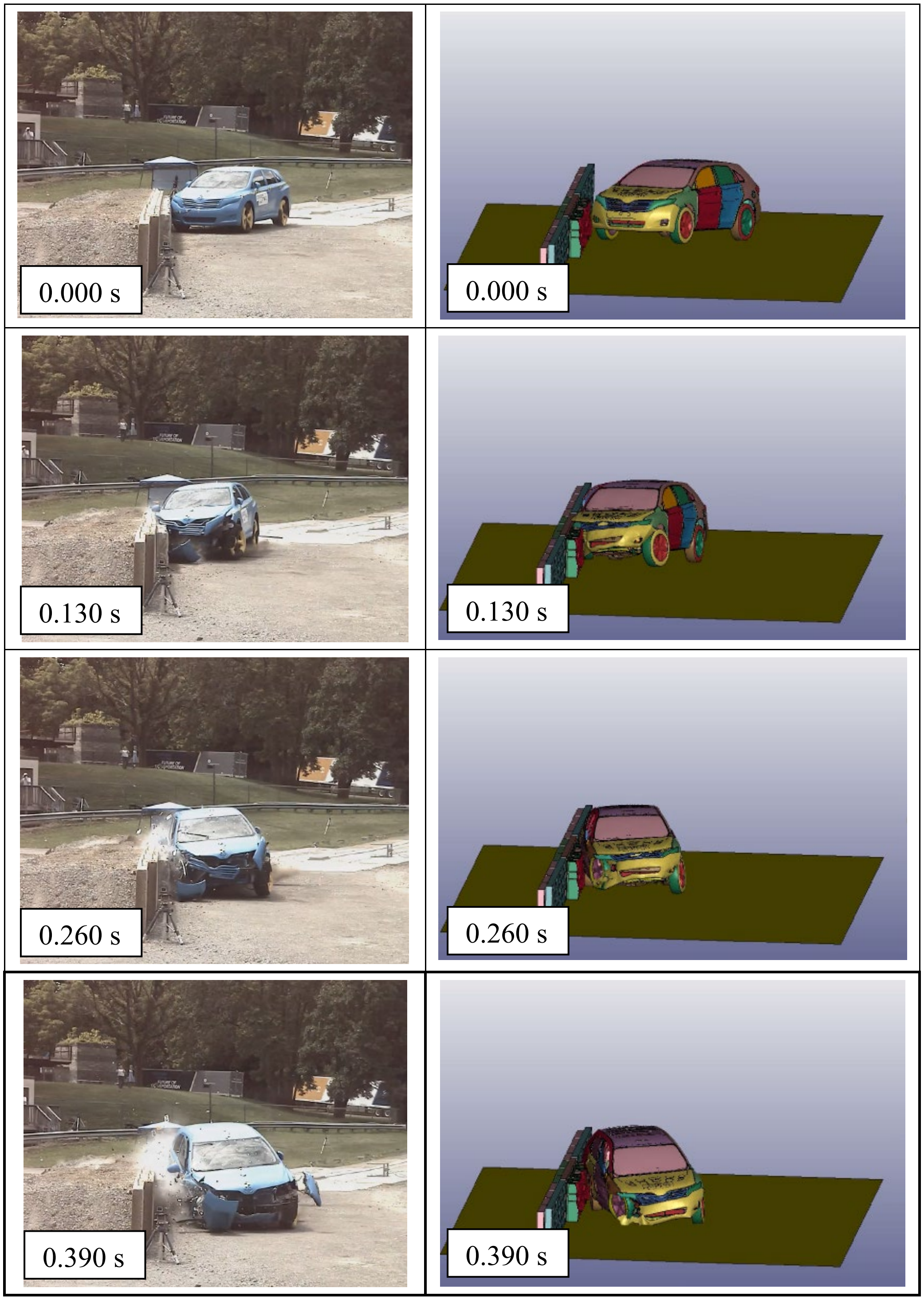


Figure 13 – Comparisons of Simulation to Test for the Stone-faced Barrier

3 Numerical Analyses of the SFCB MASH Devices

Once the conceptual stone-faced wall models and analysis were completed, detailed finite element models were created for the crash simulation analyses of specific applications of the SFCBs. This required finite element models of both the impacting vehicles and the barrier system elements. The research team has compiled an extensive library of vehicle and barrier models for the simulation of virtually any highway situation and crash scenario. The research team used available FE vehicle models for simulating the crashworthiness of the selected SFCB applications for the impacts associated with the prescribed in the MASH testing protocols. These vehicle models have been in wide-spread use by RSH developers and safety researchers across the world. For the MASH TL-3 impact condition, the two test vehicles recommended under MASH are 2270P pickup truck and the 1100C passenger. Table 1 describes the two vehicle models used in this project. All simulations were performed in accordance with the MASH TL-3 impact conditions (100 km/hr speed, and 25 deg angle).

Table 1 – Models Representing MASH Test Vehicles

Description	**Vehicle Image**
2010 Toyota Yaris Model – 1100C Small Car • 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 Silverado Model – 2270P Pick-up Truck • Weight – 2,270 kg, CG (1,545 mm rear, 710 mm high) • Model Parameters o Parts – 676 o Elements/Nodes – 261,647/250,932 o Shells/Beams/Solids – 235,921/2,463/12,525	

The research efforts to evaluate the SFCBs have been undertaken with considerable care to the efficacy of the finite element models and the application of various procedures that systematically compare incremental and overall impact conditions, various impact metrics, and conformance to safety standards. This includes the use of the rigorous, statistical methodologies documented in NCHRP Report 179 [6]. This approach was used to address a variety of aspects of this project including:

- Assess the stone roughness effects
- Ascertain the adequacy of the barrier core designs
- Ascertain the adequacy of SFCB to meet MASH requirements

These are summarized in the following sections.

3.1 Stone Roughness Effects

The calibrated stone-faced models were used to study the effects of the stone-face roughness on the MASH test vehicles. Simulations of the small car (1100C) and the pickup truck (2270P) vehicle models impacting the stone-faced barrier. The barrier used in the simulations is similar the one used in the calibration test with the Toyota Venza vehicle. The stone-faced layer was placed in front a rigidly fixed barrier. The impact speeds and impact angles in both tests were 100 km/hr and 25 degrees respectively. Figure 14 shows the simulation setup for the 1100C vehicle and Figure 15 shows the setup for the 2270P vehicle. Results from the simulation with the 1100C vehicle are shown in Figure 16 and the results from the 2270P simulations are shown in Figure 17. The simulations indicated that the stone-faced barrier did not lead to vehicle instability during the impact. The occupant risk number were also found to be below the MASH critical numbers.

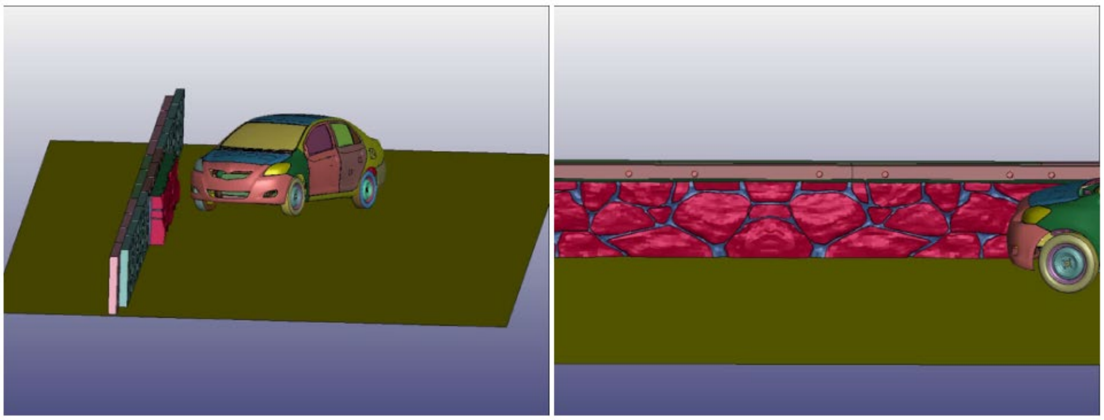


Figure 14 – Simulation Setup of 1100C Vehicle impacting Stone-faced Barrier

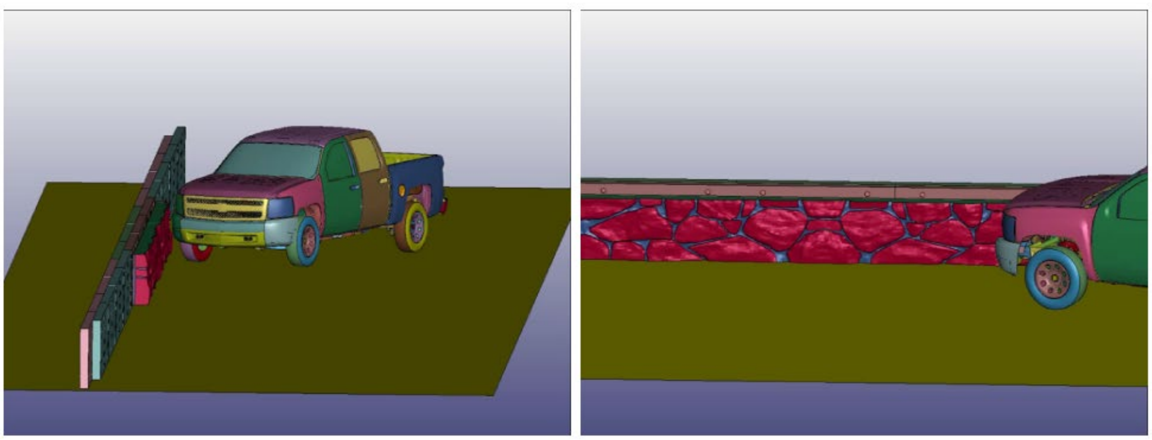


Figure 15 – Simulation Setup of 2270P Vehicle impacting Stone-faced Barrier

To investigate the effects of variations in the size and shape of the stones, simulations with varied stone configuration were performed. The results from these simulations were used to develop recommendations for the stone configuration that reduces the likelihood of vehicle snagging as it impacts the wall and hence reducing the occupant risk metrics and vehicle instability. These guidelines are included with the SFCB Final design.

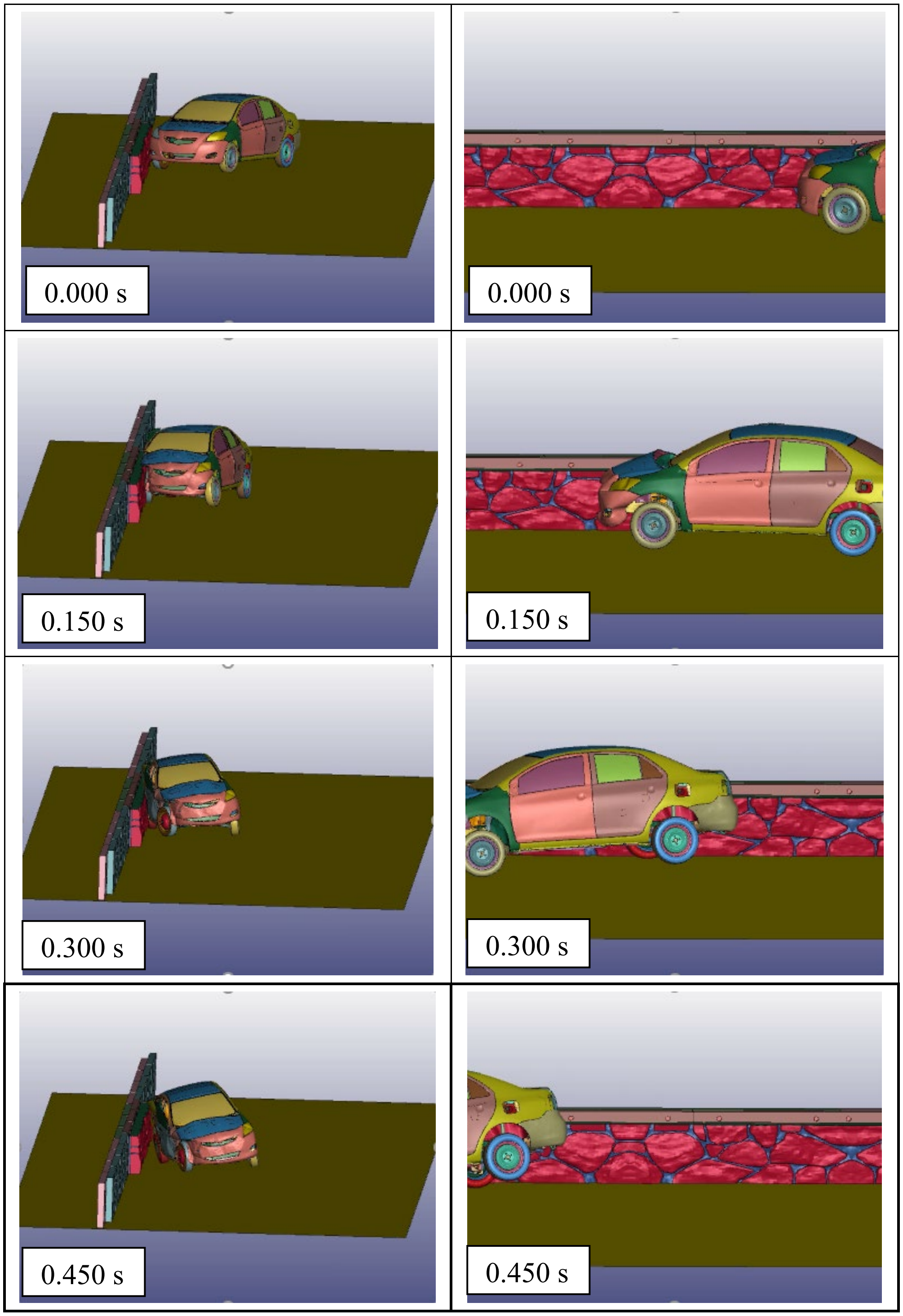


Figure 16 – Stone-faced Barrier Simulation Results with 1100C Vehicle

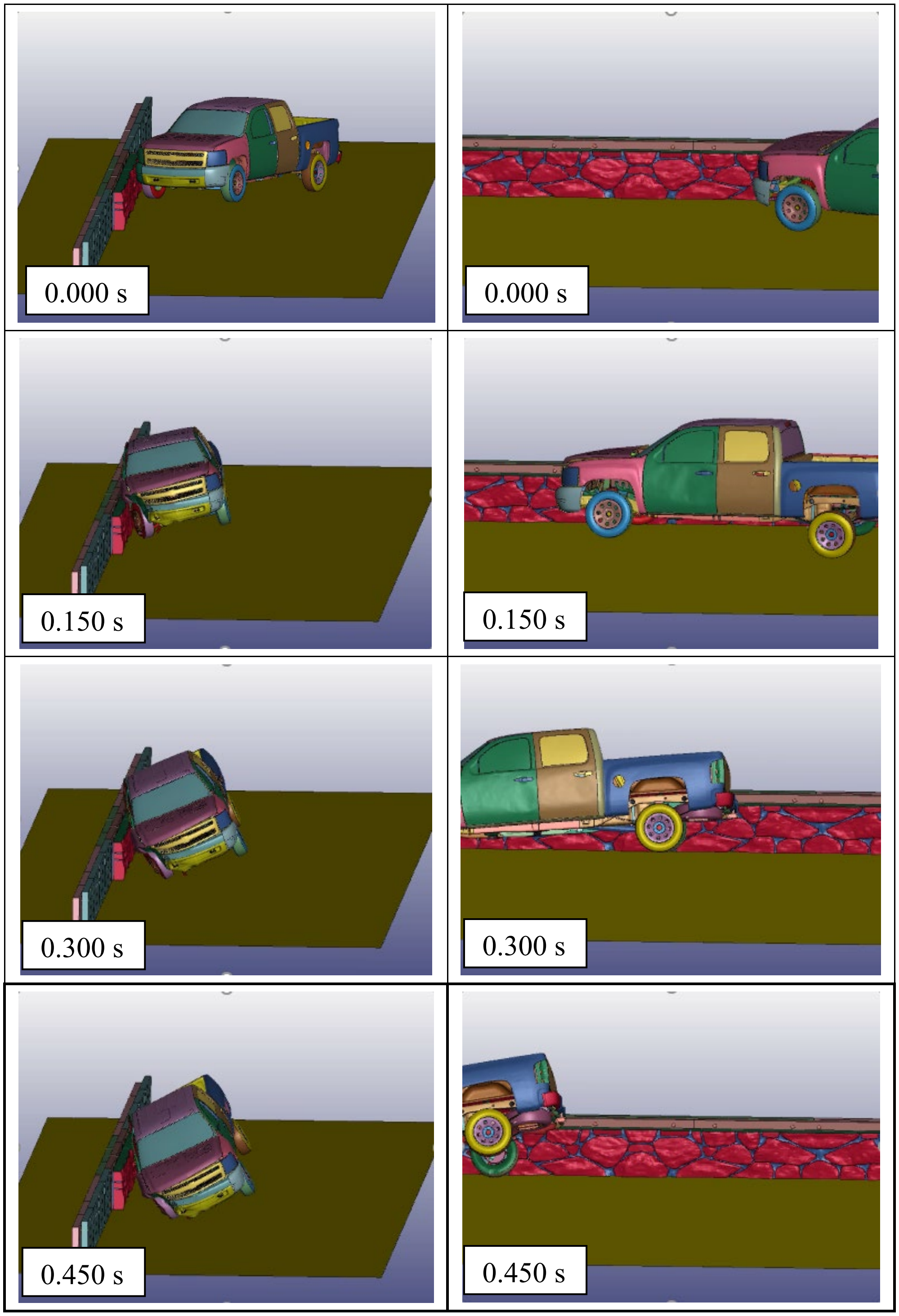
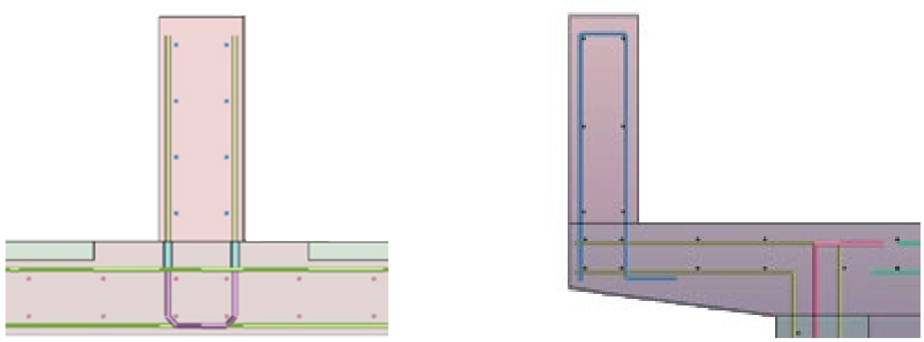


Figure 17 – Stone-faced Barrier Simulation Results with 2270P Vehicle

3.2 Barrier Core Adequacy

The basic design for the SFCB involves a reinforced poured concrete core element with rebar reinforcement. Evaluating the adequacy of the concrete core involved assessing its strength to withstand the impact load. This was achieved by performing impact simulations with the larger vehicle (2270P) impacting barrier with different concrete core heights. Both the median and the roadside versions of the wall were analyzed. Simulations with only the concrete core (without the stone-faced layer) were performed to isolate the effects of the core without the influence of the stone layer. The simulations were carried out with only the more critical 2270P vehicle in these investigations because it induces higher load on the barrier. The Analysis started with the original concrete configurations and updated as needed to withstand the impact load. Figure 18 shows the final configurations from the simulations. Figure 19 shows the set-ups for the analyses of 24-, 26-, and 28-inch-high core structures. Sequential images at different stages of the simulation at different heights are shown in Figure 20. The figure shows the results from the median barrier design, but similar results were obtained for roadside barrier design. The results show that the wall thickness and reinforcing rebar are adequate to withstand the impact load from the truck for all heights investigated. The simulations, however, showed that the vehicle was unstable would likely roll for the 24-, 26-, and 28-inch core heights. This indicates that overall height of the SFCBs (with stones) would need to be higher than 28 inches.



(a) Median Configuration (b) Roadside Configuration

Figure 18 – Concrete Core Configurations with Steel Reinforcements for the two SFCBs

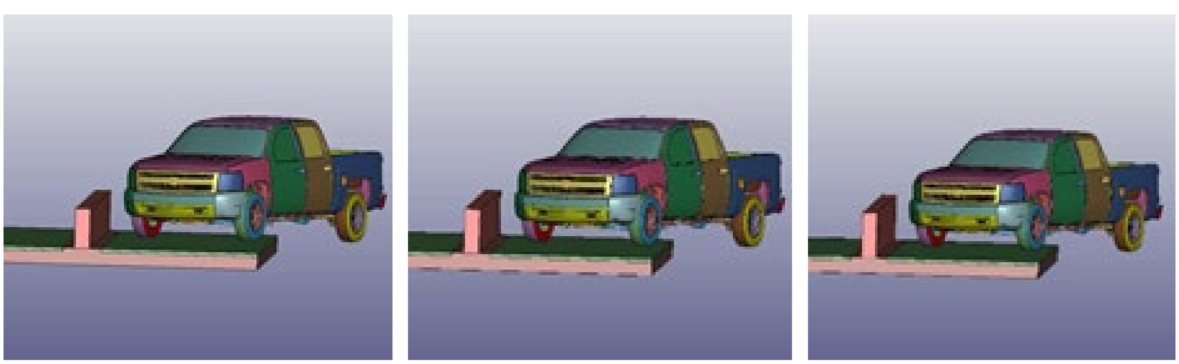


Figure 19 – Simulations of Different Core Heights: 24, 26, and 28 inches

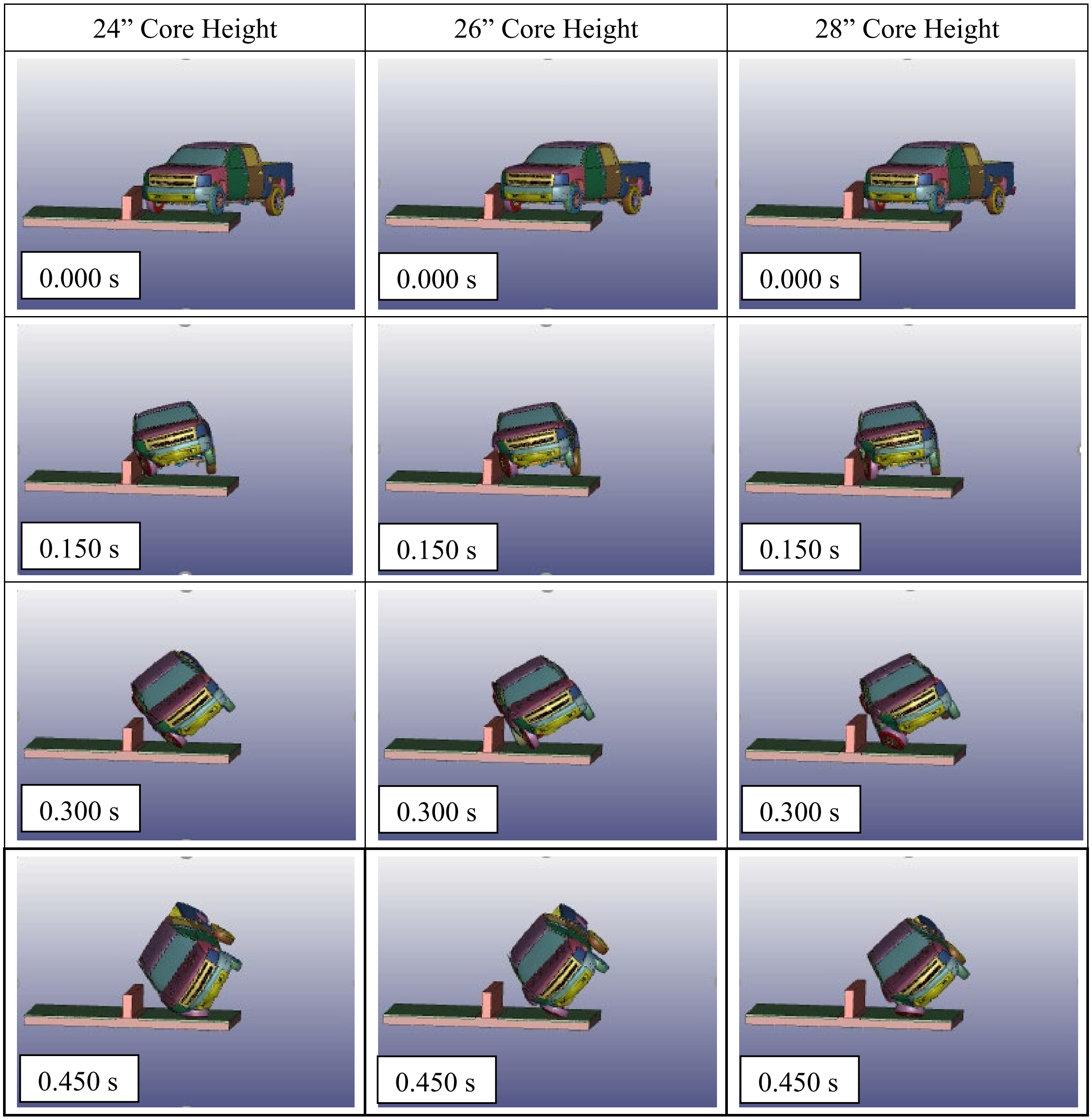


Figure 20 – Simulation Results with different Core Heights

3.3 Adequacy of SFCBs to Meet MASH Requirements

In the last part of analyses, simulations the SFCBs, with both stone-faced layer and concrete core, were evaluated in accordance with the MASH. The barrier safety performance was evaluated on the basis of three factors: structural adequacy, occupant risk, and post-impact vehicle trajectory. For longitudinal, MASH states that the following evaluation criteria (A,D,F,H, and I) have to be met:

<u>Structural Adequacy</u>

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

<u>Occupant Risk</u>

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 MASH Section 5.3 and Appendix E.
F. The vehicle should remain upright during and after a 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 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 (Preferred), 20.49 G (Maximum).

<u>Vehicle Trajectory</u>

The vehicle shall exit the barrier within exit box.

The results from each simulation were used to evaluate the barrier performance based on the above criteria. Iterative simulations with design variations were carried out until all criteria are met. Additionally, assessing the effects of variability in materials and geometric tolerances, the impact scenarios in the simulations provided insights on the inherent tolerances of the designs. These efforts applied a variety of models that were considered appropriate in level of details and quality. The efforts to analyze crashworthiness focused on meeting MASH TL-3 requirements. The models and simulation results are summarized in the following section.

As pervious mentioned, two versions of the SFCB designs are analyzed under this study: a median version and a roadside version. Additionally, transition designs between these two SFCBs and the SBT guardrail were evaluated in accordance with the same MASH TL3 requirements. Hence a total four devices were modeled and evaluated in this study:

1. Median SFCB,
2. Roadside SFCB,
3. Transitions between the Median SFCB and a SBT Guardrail, and
4. Transitions between the Roadside SFCB and a SBT Guardrail.

3.3.1 Median SFCB MASH Evaluations

The first system that was evaluated under this study is the median SFCB. A detailed computer model of this system was created and used in the evaluations. The first version of the model was based on the original SFCB design and updates were made, as needed, until the simulation results demonstrated that there is a high potential that the barrier would meet the MASH requirements. The final version of the model and the results from the final design are presented in below. Figure 21 shows cross-sectional and isometric views of the barrier model. The model was combined with the vehicle model as shown in Figure 22. The impact The focus in these simulations was with the with 2270P vehicle because it is more critical for this type of barrier than the 1100C vehicle.

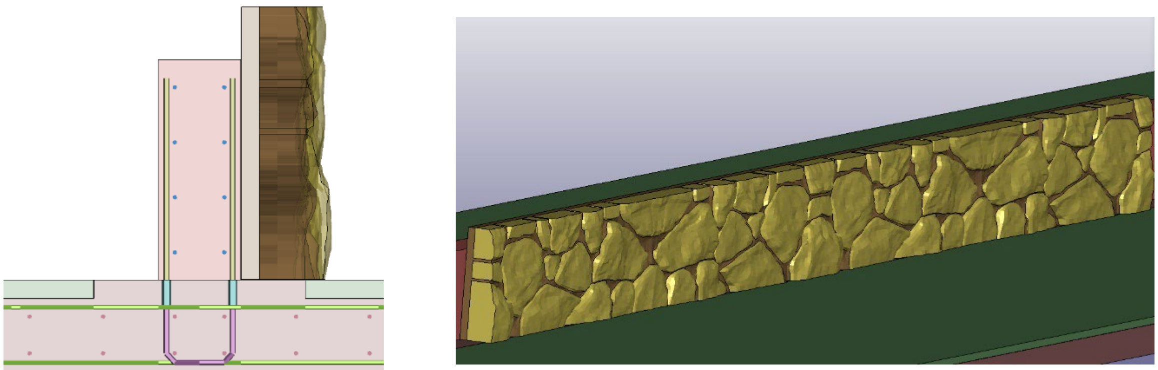


Figure 21 – Model of Median SFCB

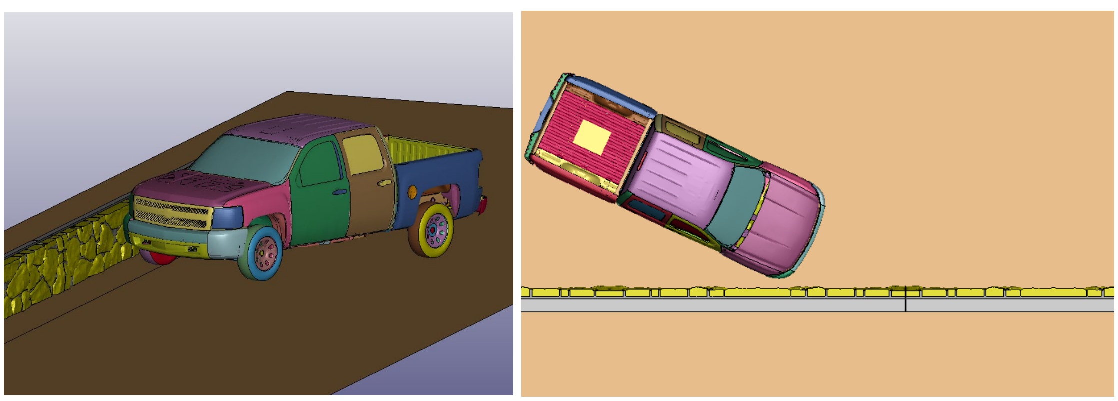


Figure 22 – Model of Median SFCB Combine with Vehicle Model

The MASH test designation for this impact is Test 3-11. This consisted of a 2270P pickup truck impacting the Median SFCB at a speed of 100 km/hr and at a 25-degree angle. Figure 23 presents sequential pictures from the simulation. Table 2 shows the MASH metrics from the simulations. The simulation results indicated that the barrier met all MASH evaluation criteria for impact configuration 3-11.

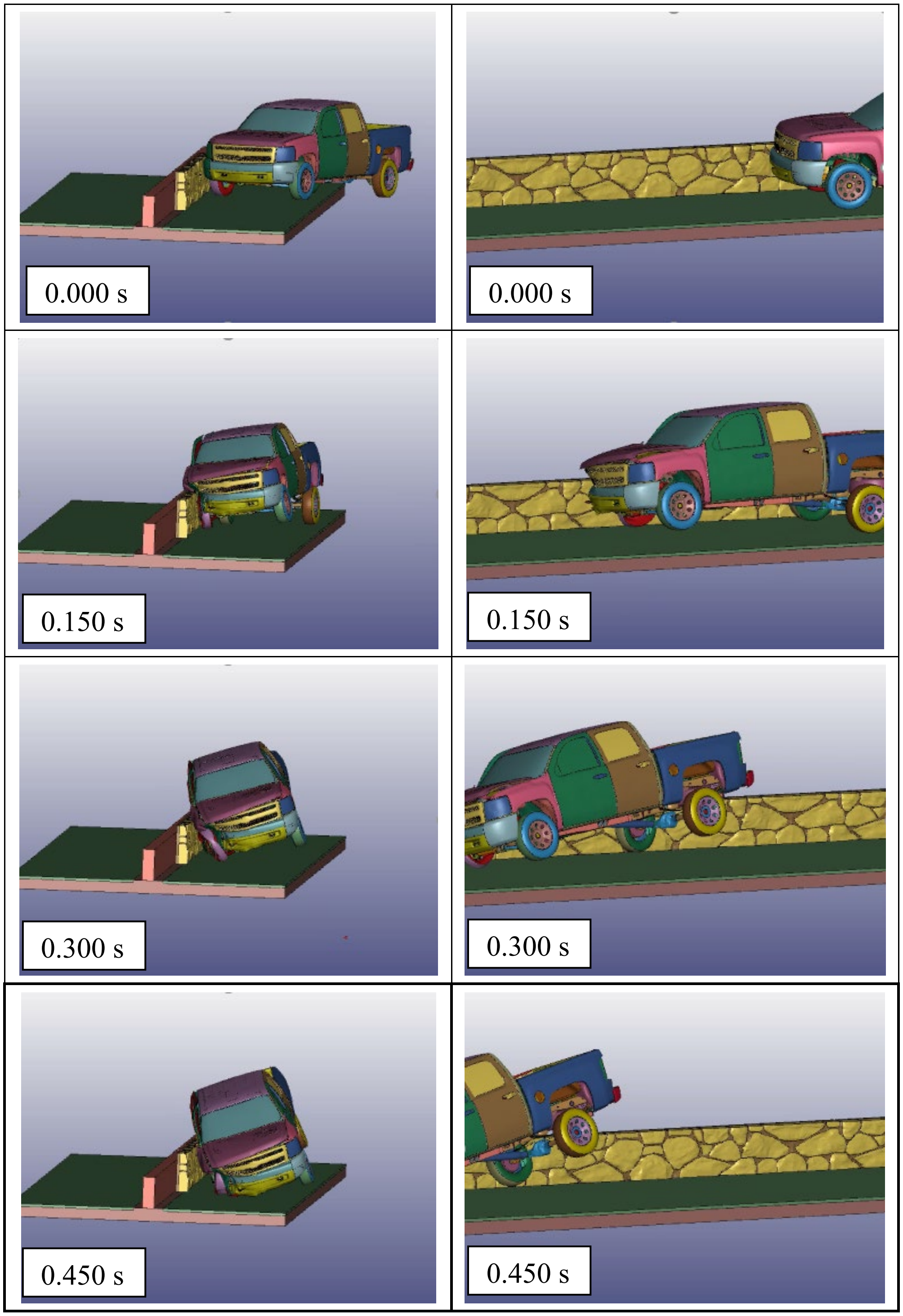


Figure 23 – Sequential Images from Median SFCB Simulation with 2270P Vehicle

Table 2 – MASH Metrics from Median SFCB Simulation with 2270P Vehicle

<table>
<tr><th colspan="3">Evaluation Criteria</th><th>Analysis Result</th></tr>
<tr><td>Structural Adequacy</td><td>A</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>Pass</td></tr>
<tr><td rowspan="4">Occupant Risk</td><td>D</td><td>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.</td><td>Pass</td></tr>
<tr><td>F</td><td>The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>Pass</td></tr>
<tr><td>H</td><td>Occupant Impact Velocities (OIV): 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)
• Longitudinal OIV (m/s): 6.6
• Lateral OIV (m/s): 7.1</td><td>Pass</td></tr>
<tr><td>I</td><td>Occupant Ridedown Accelerations (ORA): 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.
• Longitudinal ORA (g): 13.0
• Lateral ORA (g): 11.6</td><td>Pass</td></tr>
</table>

3.3.2 Roadside SFCB MASH Evaluations

The second system that was evaluated is the Roadside SFCB. Similar to the median barrier, a detailed computer model of this system was created and used in the evaluations. The first version of the model was based on the original roadside SFCB design. This version was found to meet MASH with no modifications to the original design. Figure 24 shows cross-sectional and isometric views of the barrier model. The model was combined with the vehicle model as shown in Figure 25. The focus in these simulations again was with the with 2270P vehicle because it is more critical for this type of barrier than the 1100C vehicle.

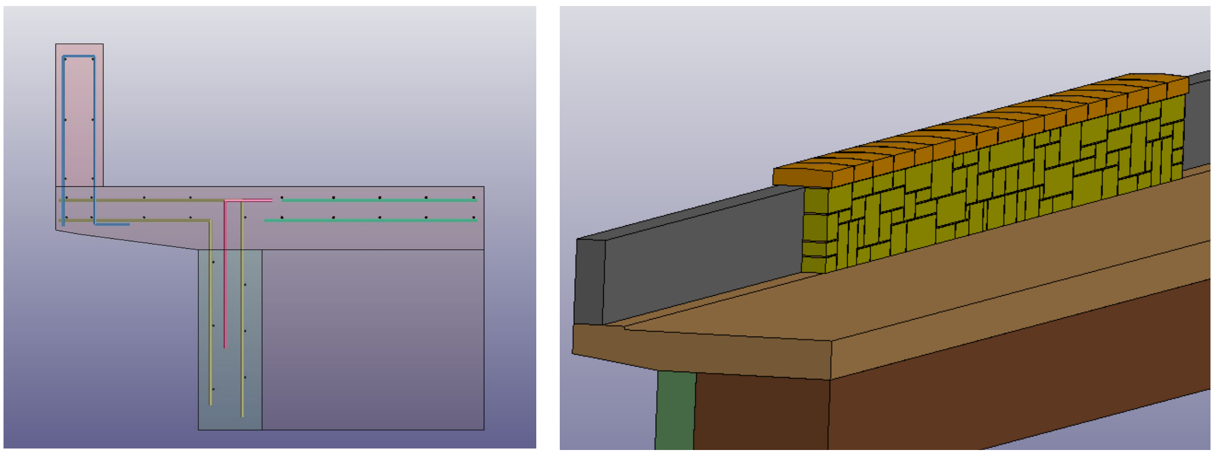


Figure 24 – Model of Roadside SFCB

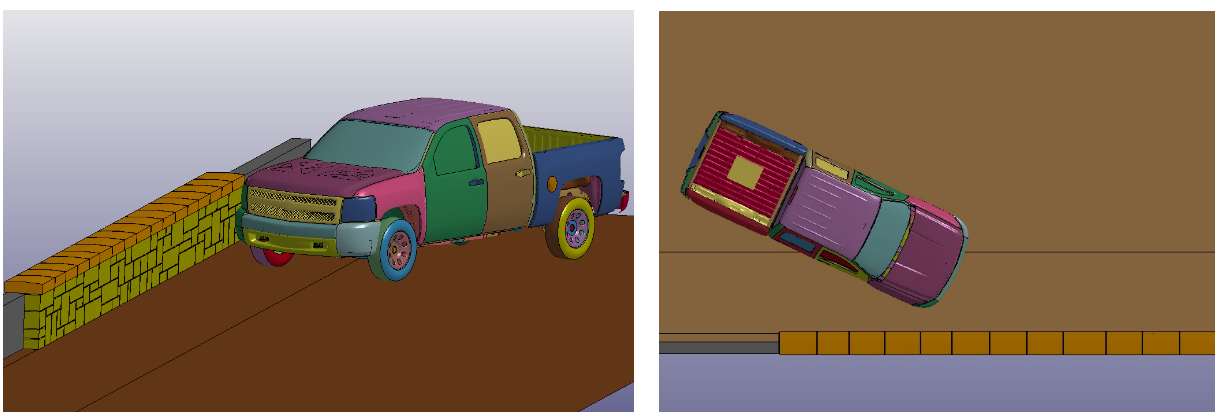


Figure 25 – Model of Roadside SFCB Combine with Vehicle Model

The simulation consisted of a 2270P pickup truck impacting the Median SFCB at a speed of 100 km/hr at a 25-degree angle. Figure 26 presents sequential pictures from the simulation. Table 3 shows the MASH metrics from the simulations. The simulation results indicated that the barrier met all MASH evaluation criteria for impact configuration 3-11.

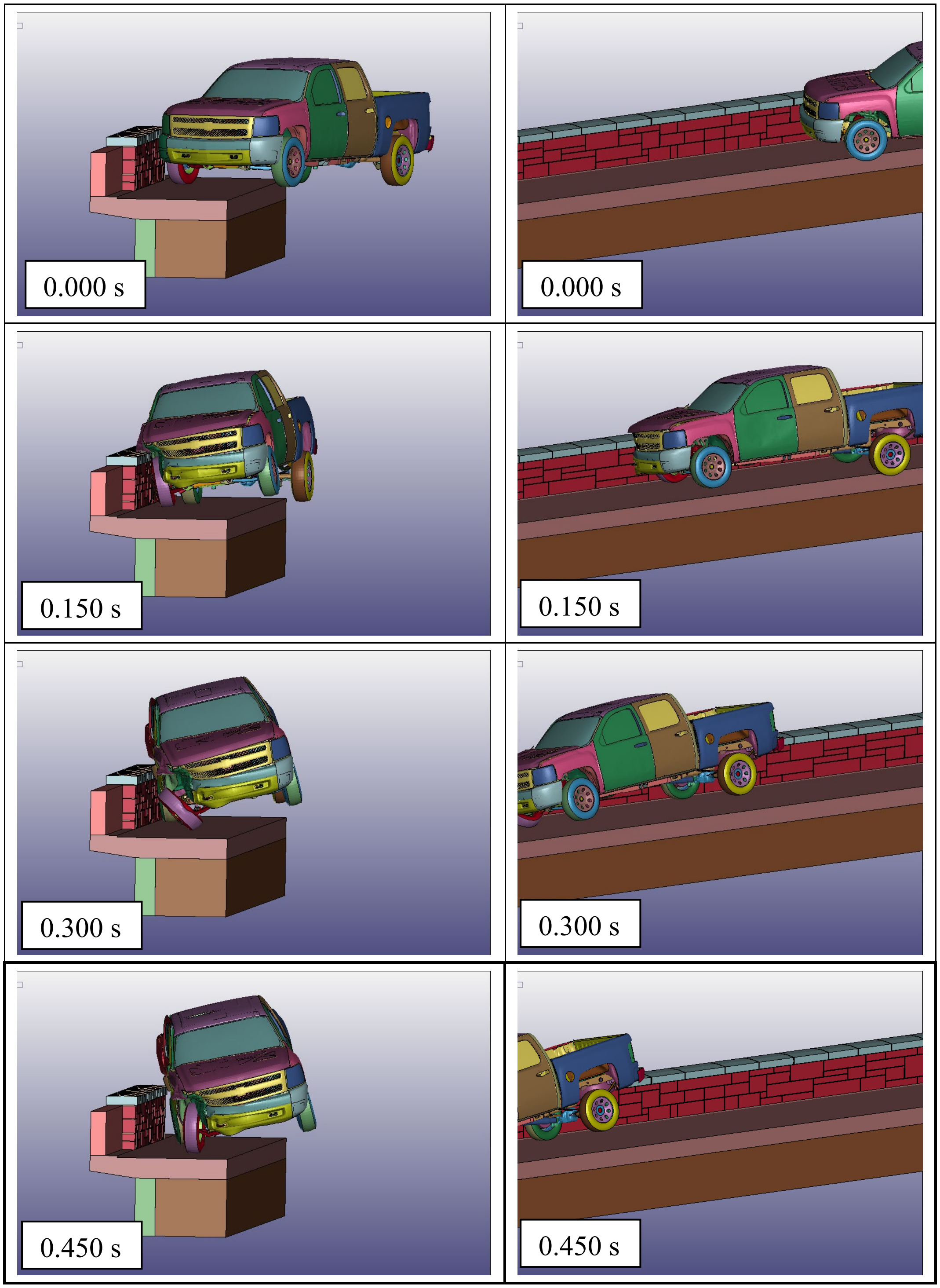


Figure 26 – Sequential Images from Roadside SFCB Simulation with 2270P Vehicle

Table 3 – MASH Metrics from Roadside SFCB Simulation with 2270P Vehicle

Evaluation Criteria			Analysis Result
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
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.	Pass
	F	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed **75 degrees**.	Pass
	H	**Occupant Impact Velocities (OIV)**: 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**) • **Longitudinal OIV (m/s):** 5.1 • **Lateral OIV (m/s):** 7.2	Pass
	I	**Occupant Ridedown Accelerations (ORA)** : 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**. • **Longitudinal ORA (g):** 7.6 • **Lateral ORA (g):** 14.8	Pass

3.3.3 Median Transition between SFCB and SBT Guardrail

The third system that was evaluated is the Transition between the Median SFCB and the SBT Guardrail. Detailed computer model of this system was created and used in the evaluations. Since no prior versions of this type of transition existed, a new design was developed. Most of the components used in the transition design were standard components that have been used in other roadside hardware, mainly components from the SBT guardrail. Iterative simulations were carried out until a design that meets MASH was reached. Figure 27 shows different views from the median transition design. The model was combined with the vehicle models as shown in Figure 28. Simulations were performed with both 2270P and 1100C vehicles because both are critical for this type of system.

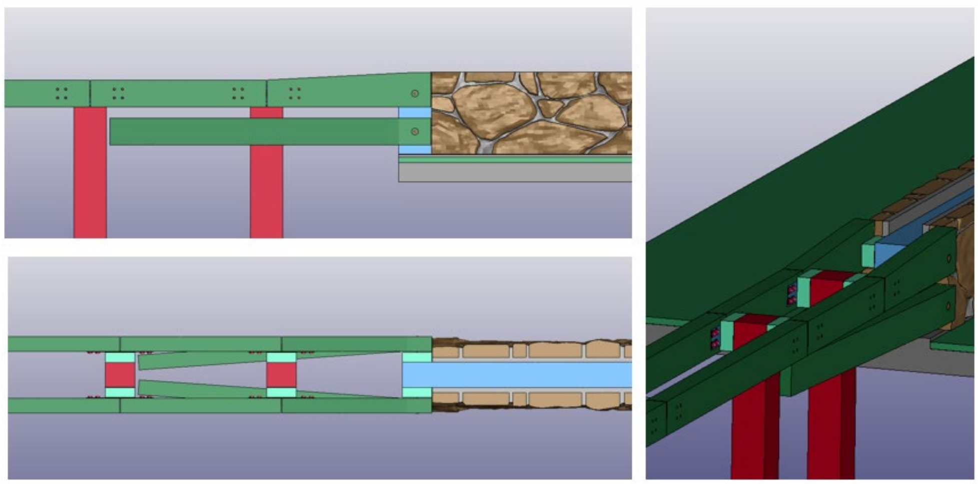
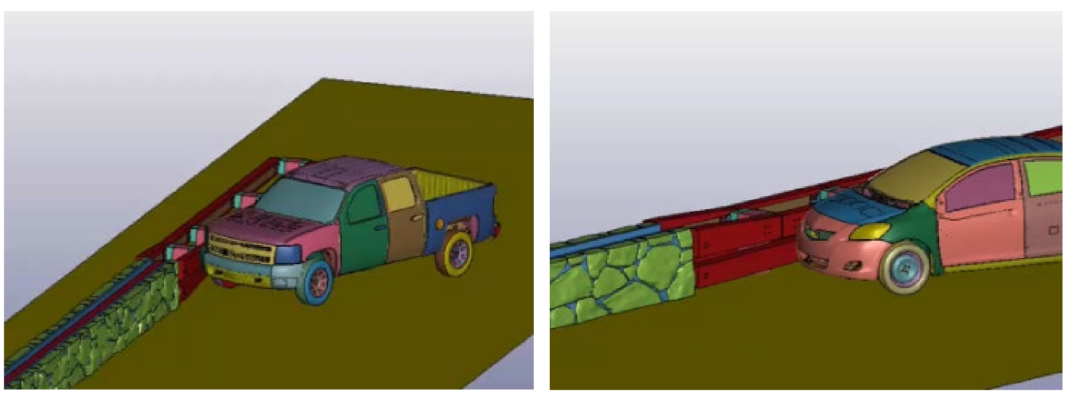


Figure 27 – Model of Median Transition between SFCB and SBT Guardrail



(a) with 2270P Vehicle (b) with 1100C Vehicle

Figure 28 –Median SFCB to SBT Guardrail Transition with Vehicle Models

The simulation consisted of a 2270P (Test 3-11) and 1100C (Test 3-10) vehicles impacting the Median SFCB at a speed of 100 km/hr at a 25-degree angle. Figure 29 presents sequential pictures from the simulation with the 2270P vehicle. Table 4 shows the MASH metrics from the same simulation. Figure 30 presents sequential pictures from the simulation with the 1100C vehicle and Table 5 shows the MASH metrics. The simulation results indicated that the barrier met all MASH evaluation criteria for impact configurations 3-11 and 3-10.

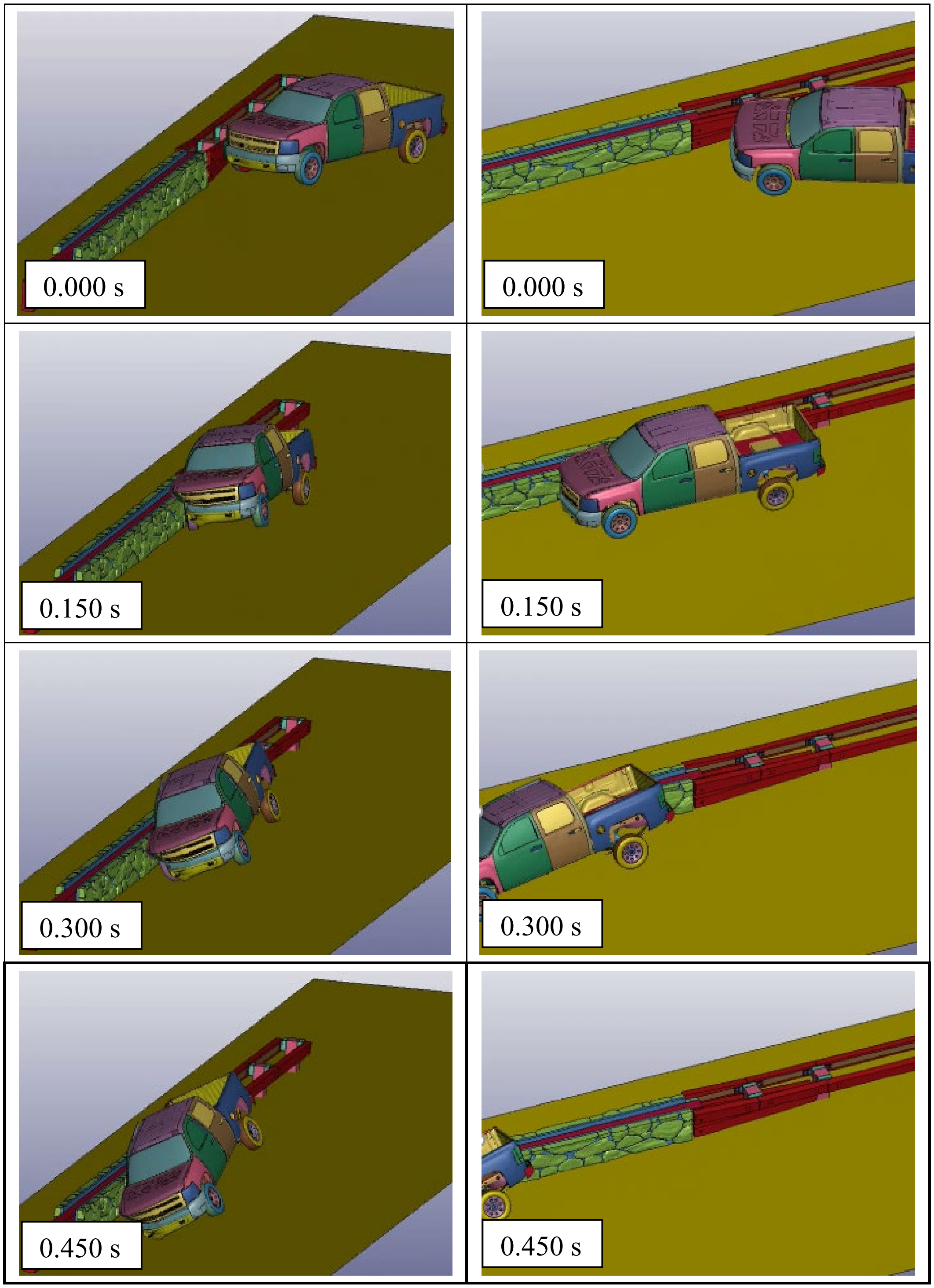


Figure 29 – Results Median SFCB to SBT Guardrail Transition with 2270P Vehicle

Table 4 – Median SFCB to SBT Guardrail Transition MASH 3-11 Metrics

Evaluation Criteria			Analysis Result
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
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.	Pass
	F	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed **75 degrees**.	Pass
	H	**Occupant Impact Velocities (OIV)**: 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**) • **Longitudinal OIV (m/s):** 4.9 • **Lateral OIV (m/s):** 6.8	Pass
	I	**Occupant Ridedown Accelerations (ORA)** : 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**. • **Longitudinal ORA (g):** 9.5 • **Lateral ORA (g):** 13.9	Pass

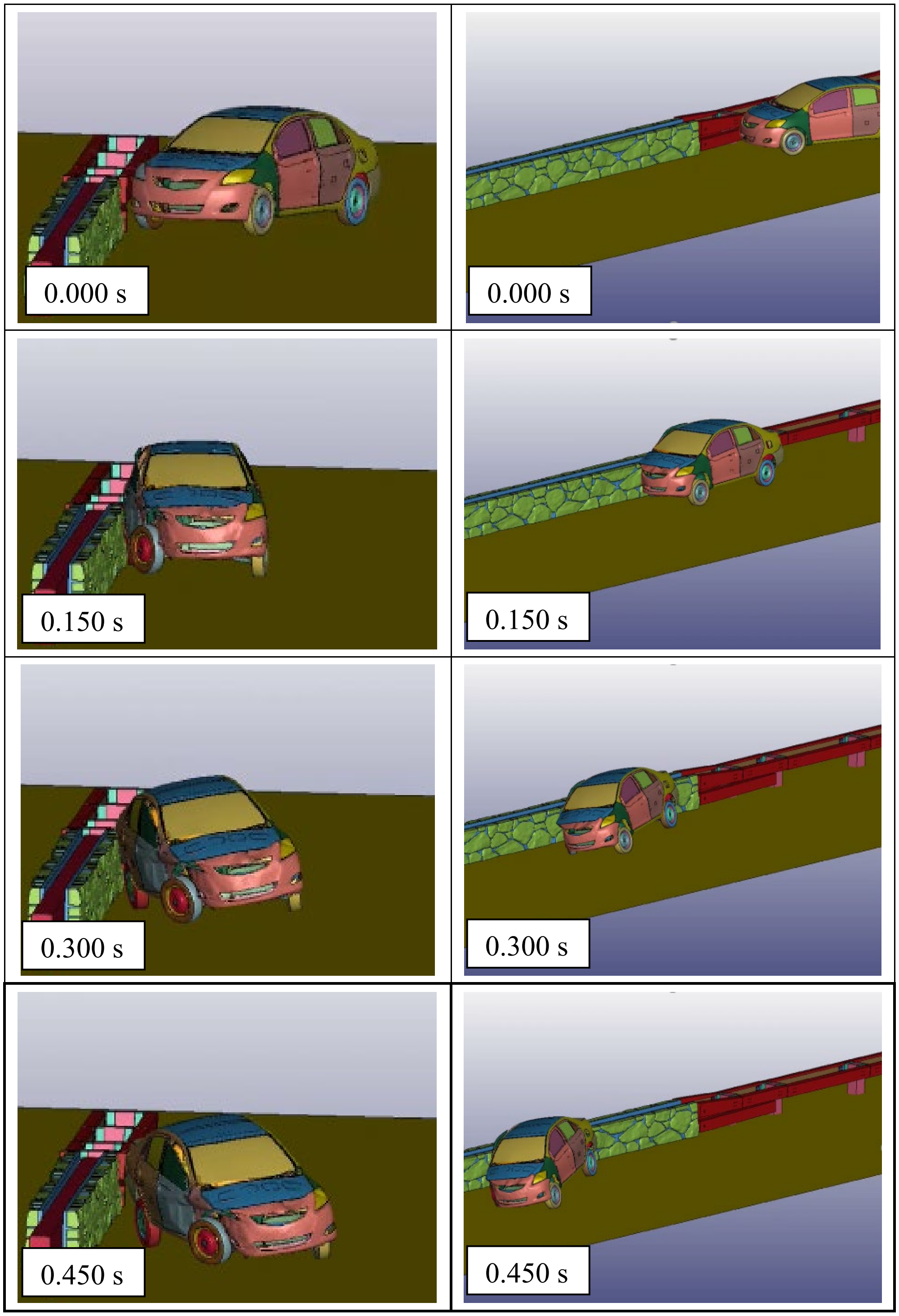


Figure 30 – Results from Median SFCB to SBT Guardrail Transition with 1100C Vehicle

Table 5 – Median SFCB to SBT Guardrail Transition MASH 3-10 Metrics

Evaluation Criteria			**Analysis Result**
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
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.	Pass
	F	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed **75 degrees**.	Pass
	H	**Occupant Impact Velocities (OIV)**: 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**) • **Longitudinal OIV (m/s):** 6.2 • **Lateral OIV (m/s):** 9.5	Pass
	I	**Occupant Ridedown Accelerations (ORA)** : 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**. • **Longitudinal ORA (g):** 5.3 • **Lateral ORA (g):** 12.5	Pass

3.3.4 Roadside Transition between SFCB and SBT Guardrail

The four and last system that was evaluated is the Transition between the Roadside SFCB and the SBT Guardrail. Detailed computer model of this system was created and used in the evaluations. The first version of the model was based on the original roadside Transition design. This version was found to meet MASH with no modifications to the original design. Figure 31 shows different views of the transition model. The model was combined with the vehicle models as shown in Figure 32. Simulations were performed with both the 2270P and 1100C vehicles because both are critical for this type of system.

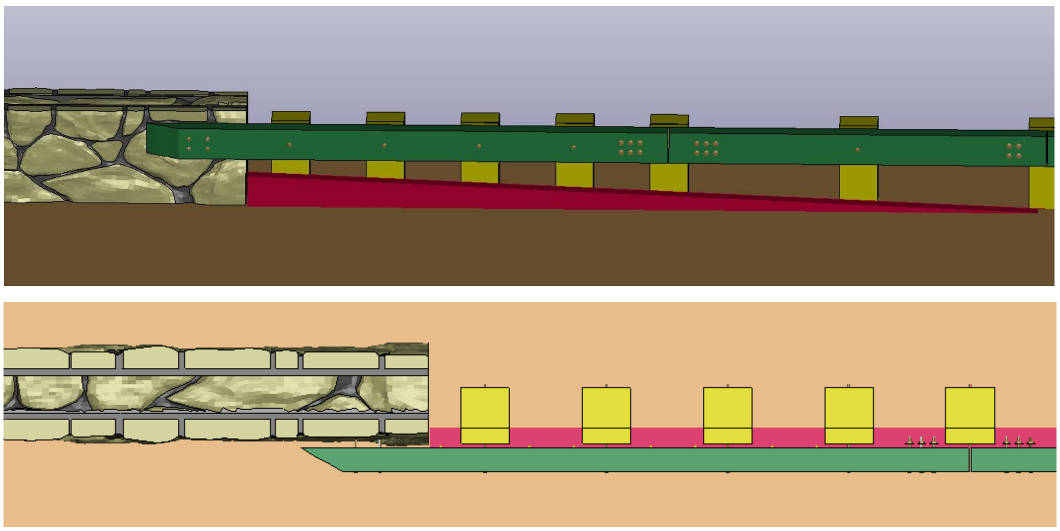
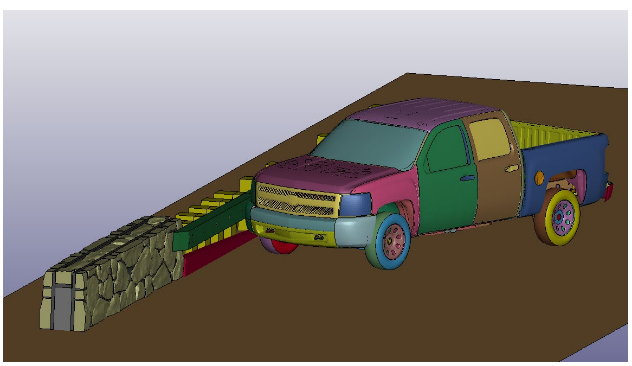
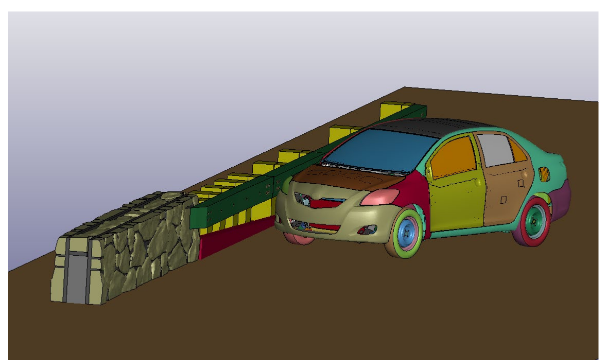


Figure 31 – Model of Roadside Transition between SFCB and SBT Guardrail



(a) with 2270P Vehicle



(b) with 1100C Vehicle

Figure 32 – Roadside SFCB to SBT Guardrail Transition with Vehicle Models

Like the median transition, the simulations for the roadside transition consisted of a 2270P (Test 3-11) and 1100C (Test 3-10) vehicles impacting the Roadside Transition at a speed of 100 km/hr and at a 25-degree angle. Figure 33 presents sequential pictures from the simulation with the 2270P vehicle. Table 6 shows the MASH metrics from the same simulation. Figure 34 presents sequential pictures from the simulation with the 1100C vehicle and Table 7 shows the MASH metrics. The simulation results indicated that the barrier met all MASH evaluation criteria for impact configurations 3-11 and 3-10.

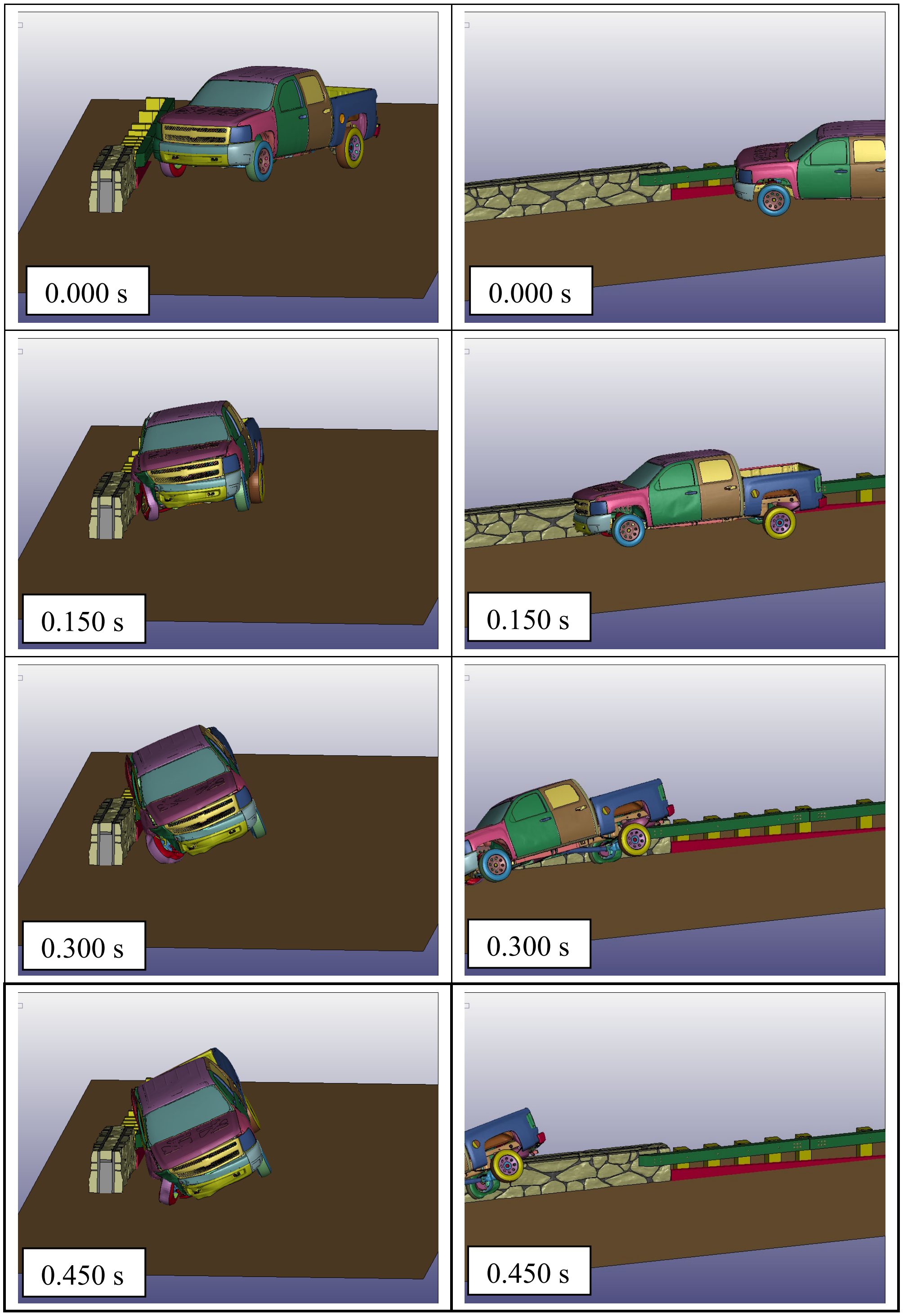


Figure 33 – Results from Roadside SFCB to SBT Guardrail Transition with 2270P Vehicle

Table 6 – Roadside SFCB to SBT Guardrail Transition MASH 3-11 Metrics

Evaluation Criteria			**Analysis Result**
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
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.	Pass
	F	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed **75 degrees**.	Pass
	H	**Occupant Impact Velocities (OIV)**: 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**) • **Longitudinal OIV (m/s):** 4.3 • **Lateral OIV (m/s):** 7.5	Pass
	I	**Occupant Ridedown Accelerations (ORA)** : 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**. • **Longitudinal ORA (g):** 7.1 • **Lateral ORA (g):** 13.0	Pass

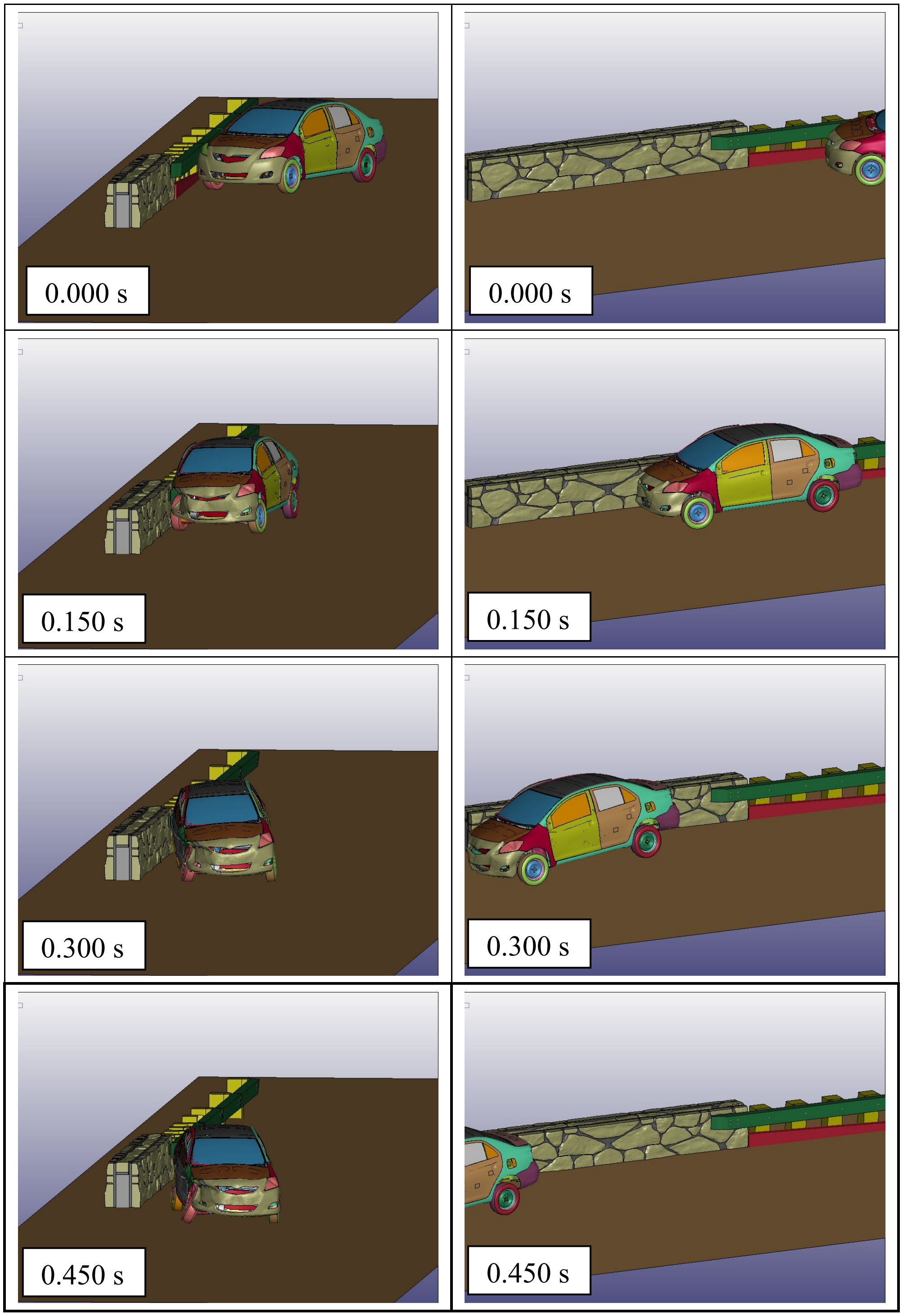


Figure 34 – Results from Roadside SFCB to SBT Guardrail Transition with 1100C Vehicle

Table 7 – Roadside SFCB to SBT Guardrail Transition MASH 3-10 Metrics

Evaluation Criteria			Analysis Result
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
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.	Pass
	F	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed **75 degrees**.	Pass
	H	**Occupant Impact Velocities (OIV)**: 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**) • **Longitudinal OIV (m/s):** 5.5 • **Lateral OIV (m/s):** 9.3	Pass
	I	**Occupant Ridedown Accelerations (ORA)** : 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**. • **Longitudinal ORA (g):** 4.6 • **Lateral ORA (g):** 13.2	Pass

4 Validating Simulation Analyses with Crash Tests

To validate the simulation findings, full-scale crash testing was conducted to evaluate the median stone-faced wall design developed. Two tests were conducted at the FHWA Federal Outdoor Impact Laboratory (FOIL). The FOIL is a full-scale outdoor crash test facility, primarily designed to test the impacts of vehicles with roadside safety hardware. The test vehicles are pulled into the barriers using a specially designed, hydraulic propulsion system. The vehicles are accelerated on a 220 ft fixed concrete track. The propulsion system is capable of pulling a 8,000kg vehicle up to 50 mph. The 2,270 kg test vehicle can be brought to a speed above 70 mph. Test articles are constructed according to specifications at the end of the accelerator in a manner that allows impacts at a designated angle. There is sufficient area to construct an appropriate length of barrier to achieve the strength and vehicle runout area. The test vehicles are released into a test article strategically positioned at the end of the accelerator. The large runout area allows the post-impact trajectory of vehicles to be observed. Barriers up to 450 ft in length (usually at 25 degrees relative to the track) have been installed in the area at the end of the track.

The two tests were setup 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. Multiple high-speed cameras were used in the full-scale crash tests. One camera was placed over the impact region to capture an overhead view. Additional cameras are placed at different 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 provides the basis for computing the occupant ride-down acceleration and occupant impact velocities, key metrics to understand occupant crash risks. Additionally, two tri-axial rate transducers were used to measure the vehicle roll, pitch, and yaw. Contact switches were installed on the vehicle and test article to synchronize time zero during the impact for the sensor data and high-speed imagery.

For each test, a detailed report documenting all aspects of the test was generated in accordance with the MASH requirements to provide to document the test results as a basis for certifications. These reports are included as Appendices A and B of this report. The following sections provide a summary of the results of the two tests conducted and the conclusions drawn. The videos, data, and analyses summaries are available from the FHWA and/or NPS.

4.1 Test Article Design and Installation Details

Figure 35 shows the design and installation details for Median SFCB that was tested for MASH TL-3 requirements under this project. The figure depicts a median barrier core with a stone face that featured:

- A reinforced concrete core that provided a 26” high and 10” wide vertical core over a 24” wide and 24” deep foundation. Loop and u-shaped rebar elements are tied to longitudinal rebars (eight in the upright element and sixteen in the base).
- Concrete for the barrier provided 4500 psi strength.
- Stones that are as large as possible and were used in the installation. Mortar joints between the stones were no more than 2 inches wide and stone protrusions limited to 0.5 inches. The stones were placed such that they did not extrude more than 3” from the mortar outer face.

A section of the SFCB was constructed following these design requirements at the FHWA Federal Outdoor Impact Lab (FOIL) to conduct the necessary MASH Tests 3-10 and 3-11. Figure 36 shows the MASH Test 3-11 impact test set-up involving the 2270P vehicle (pick-up truck). Figure 37 shows the set-up for MASH Test 3-10 with 1100C small sedan.

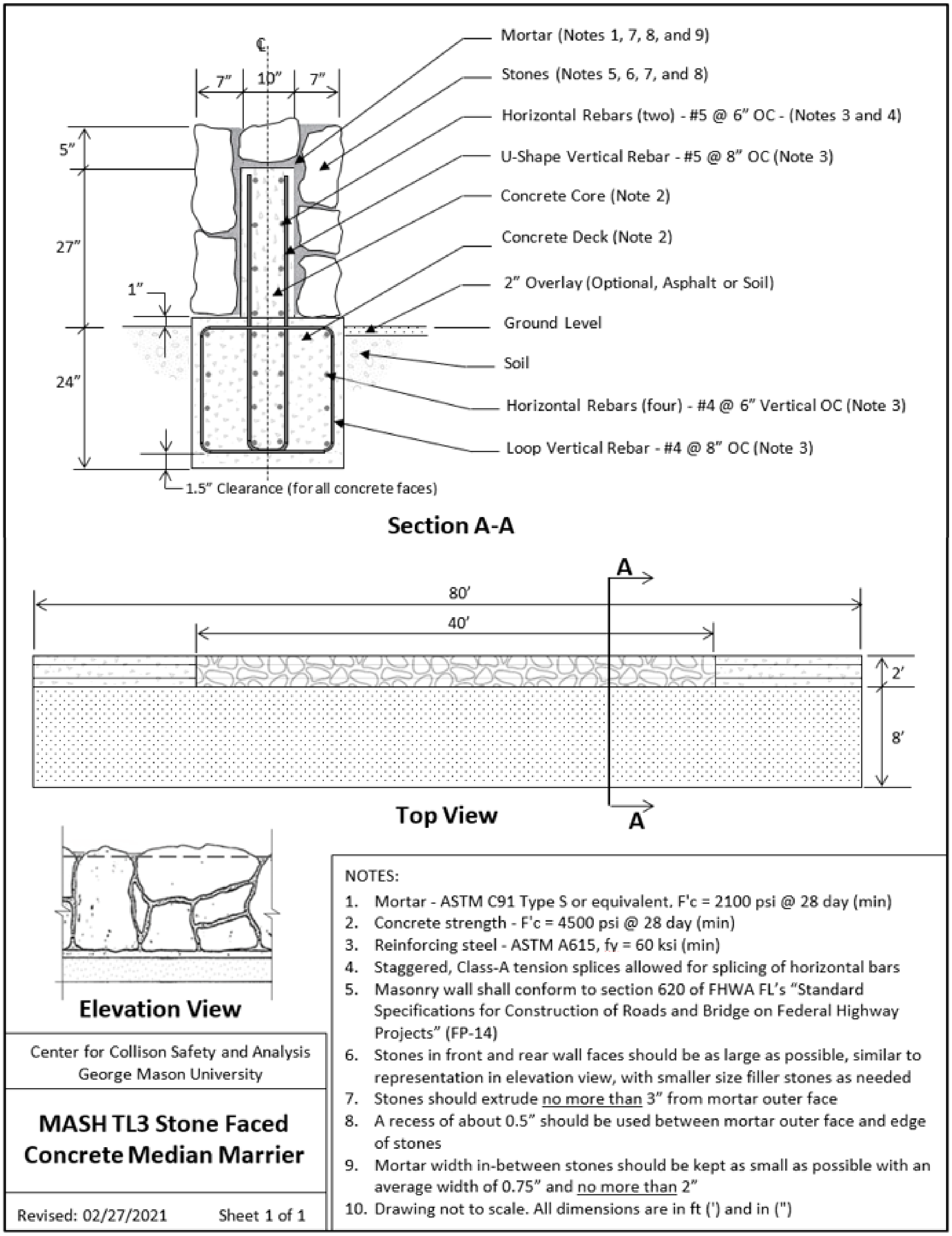


Figure 35 – SFCB Design details for the Barrier Test Installation

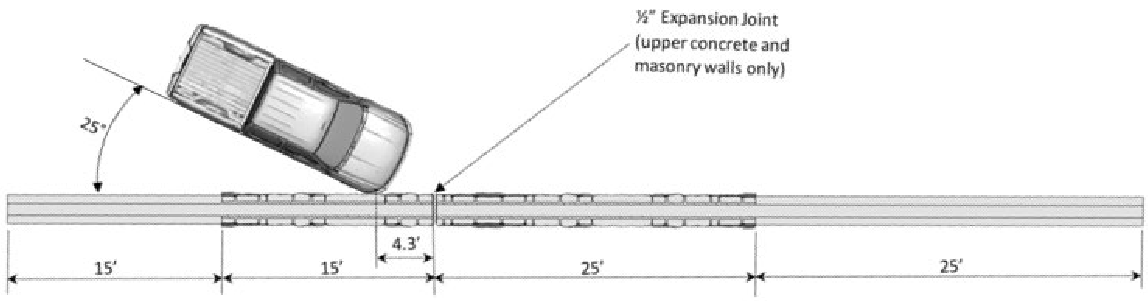


Figure 36 – Test Setup Diagram for FOIL Test 21004 (Test 3-11)

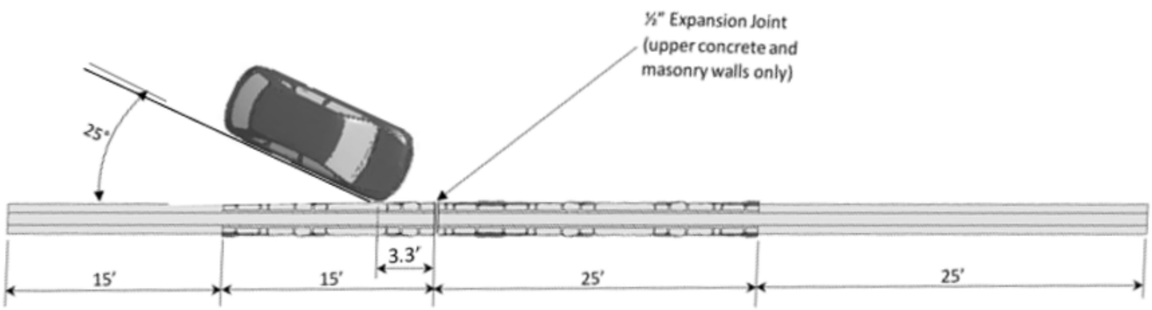


Figure 37 – Test Set-up diagram for FOIL Test 21005

4.2 Material Specifications & Soil Conditions

The stone-faced barrier system was fabricated using standard roadside safety hardware elements as specified. The materials and hardware elements delivered to the FOIL met the basic standards in accordance with suppliers or certifications that are on file at the FOIL. The foundation for the SFCB was laid in the designated positions in the impact area of the FOIL, as depicted. The soils at the FOIL have been classified as typical VDOT materials. Soil tests confirmed the compaction and moisture content of the soils were in appropriate ranges as recommended in MASH and consistent with previous testing at the FOIL. These soil tests were conducted with a nuclear density device and involved repeated measurements at multiple positions around the test installation. The FOIL Summary Report documents these results. Independent soil analyses are filed at the FOIL.

4.3 MASH Test Requirements and Acceptance Criteria

As noted, researchers determined that overall evaluation of the SFCB would require successful passing of two MASH tests, namely Tests 3-11 and 3-10. The results from these tests were intended to determine the barrier's capacity for containing and/or redirecting a large pick-up truck and a small sedan. These vehicle types have been selected in MASH to account for a large portion of the vehicles on the road. Both the tests involved vehicles impacting the SFCB at a 25-degree angle at 100 km/hr (62.4 mph). These tests, as all others conducted at the FOIL facility were setup and executed according to prescribed FOIL protocols (including facility ISO requirements) and MASH standards. These were individually documented in FOIL Test Reports 21004 and 21005, but they are summarized here. Table 8 reflects the test parameters indicating the variations in vehicles, speed, and angles for the two Median SFCB tests. Under MASH critical requirements for Structural Adequacy, Occupant Risk, and Vehicle Trajectory must be met to "pass." The requirements for these criteria are provided in Table 9.

Table 8 – MASH Tests Conducted for the Median SFCB

Test Number	Test Date	MASH Impact	Test Vehicle	Impact Speed	Impact Angle
21004	04/20/21	3-11	Pickup Truck	100 km/hr	25
21005	04/27/21	3-10	Small Sedan	100 km/hr	25

Table 9 – MASH Tests 3-10/11 Evaluation Requirements by Category

Evaluation Category	Requirement
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 (roof ≤4.0 in.; windshield = ≤3.0 in.; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 in.; forward of A-pillar ≤12.0 in.; front side door area above seat ≤9.0 in.; front side door below seat ≤12.0 in.; floor pan/transmission tunnel area ≤12.0 in.).
	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 • **Preferred** 30 ft/s **Maximum:** 40 ft/s
	I. Occupant ridedown accelerations should satisfy the following: • Longitudinal and Lateral Occupant Ridedown Accelerations • **Preferred:** 15.0 G **Maximum:** 20.49 G
Vehicle Trajectory	For redirective devices, the vehicle should be smoothly redirected and exit the barrier within the "exit box" criteria (not less than 32.8 ft); document all tests. Vehicle rebound distance and velocity for crash cushions.

4.4 Crash Testing for MASH Test 3-11 – FOIL Test 21004

As was cited earlier, two typical vehicles would be selected for the testing to validate the simulation studies that indicated the viability of the stone-faced barriers. The strategy was to test the larger vehicle first, as the higher weight for similar impact angles would be more likely to cause failure. If the large vehicle failed, it might suggest that more analyses was necessary before any further testing took place. Hence, MASH Test 3-11 with the 2270P large pick-up truck was selected as the first test. The following sections describe the set-up and executions of this test. A subset of the results is provided, but the full set of results can be obtained in the detailed test report and/or the acquisition of the videos and data sets.

4.4.1 Test Vehicle – 2270P

Figure 38 shows the 2014 Dodge Ram 1500 quad-cab pickup used for the crash test. Test inertial and gross static weight of the vehicle were the same and were 4,945 lb (2282 kg). The height to the lower and upper edge of the vehicle bumper was 10.8 in. and 25 in. respectively. The height to the vehicle's center of gravity was 28.4 in.

The FOIL's cable tow guidance system was used to direct the vehicle towards the barrier such that, at release, the vehicle would be moving at the desired impact speed in a freewheeling and unrestrained mode for an impact with the barrier.

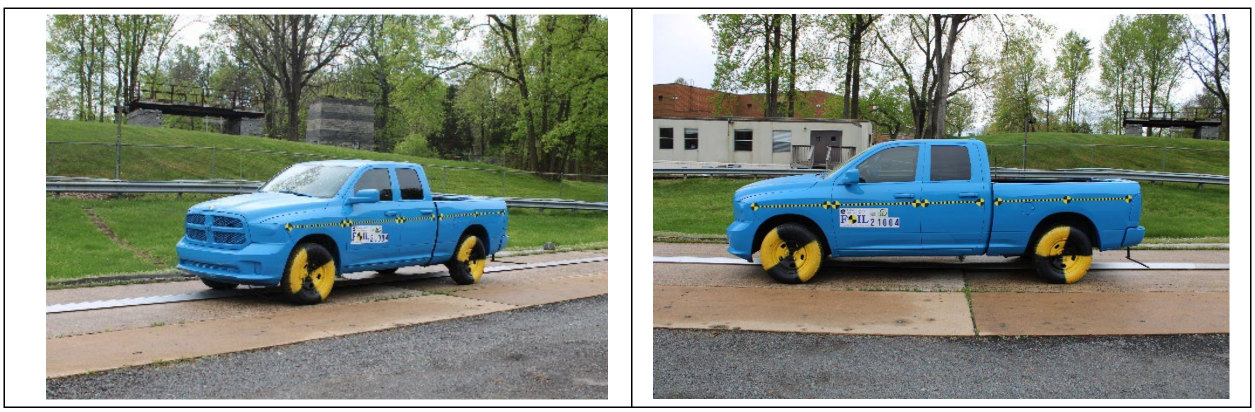


Figure 38 – Pre-Crash Views of the Test Vehicle

4.4.2 Test Article

Figure 39 shows a view of the installed SFCB prior to the test. An 80' length of reinforced concrete barrier wall and foundation was constructed at the FOIL following the specifications. The median barrier configuration of a stone-facing was applied to 40 feet of the barrier. This was determined to be an adequate length to cover the vehicle-to-SFCB interface based upon the simulation studies. The vehicle was expected to slide over the random stone pattern for a short distance before being redirected away from the barrier. The random pattern of the stonework in apparent in the various views. During installation, the specifications for size of the stones, the width of separations between the stones, and the depth of the mortar followed the requirements cited earlier.

Figure 39 – View of the Median SFCB Article Installed for MASH Test 3-11

Figure 40 shows views of the test vehicle in proximity to the test article to document the static interface of vehicle and the system elements. It can be noted that the front bumper impacts the barrier at mid-height. Projecting a line along the stone face indicates that various sizes of stones would interact with the bumper and the side of the vehicle during the crash. Pictures documenting the construction of the test article are available along with any related compaction, material strengths, or other features of the test article that may become relevant.

Figure 40 – Views of the Test Vehicle in Proximity to the Test Article Prior to Test

4.4.3 Crash Test Observations

Seven high-speed, digital cameras were deployed for the test to capture various views of the crash event to record the barrier interaction with the vehicle. Of these, the overhead and frontal sequential views of the crash provide the best indications of the barrier performance. In the series of overhead views shown in Figure 41, the initial contact occurred at time 0.00 seconds (as planned) with the right front corner (bumper) of the vehicle. The path of the vehicle began to alter and by 0.070 seconds as the right front fender had crushed to the point at the front of the windshield. That crush continued and by 0.290 seconds the vehicle was diverted and sliding parallel to the face of the barrier and starting to move away from it. The photos show no evidence of damage to the windshield over that time. The redirection was relatively smooth, despite the rough stone face. Figure 42 shows the impact from the downstream ground-level camera. It provides views of the damage to the right front fender and front of the vehicle. The view shows the limited vehicle roll and pitch that occurred during the impact.

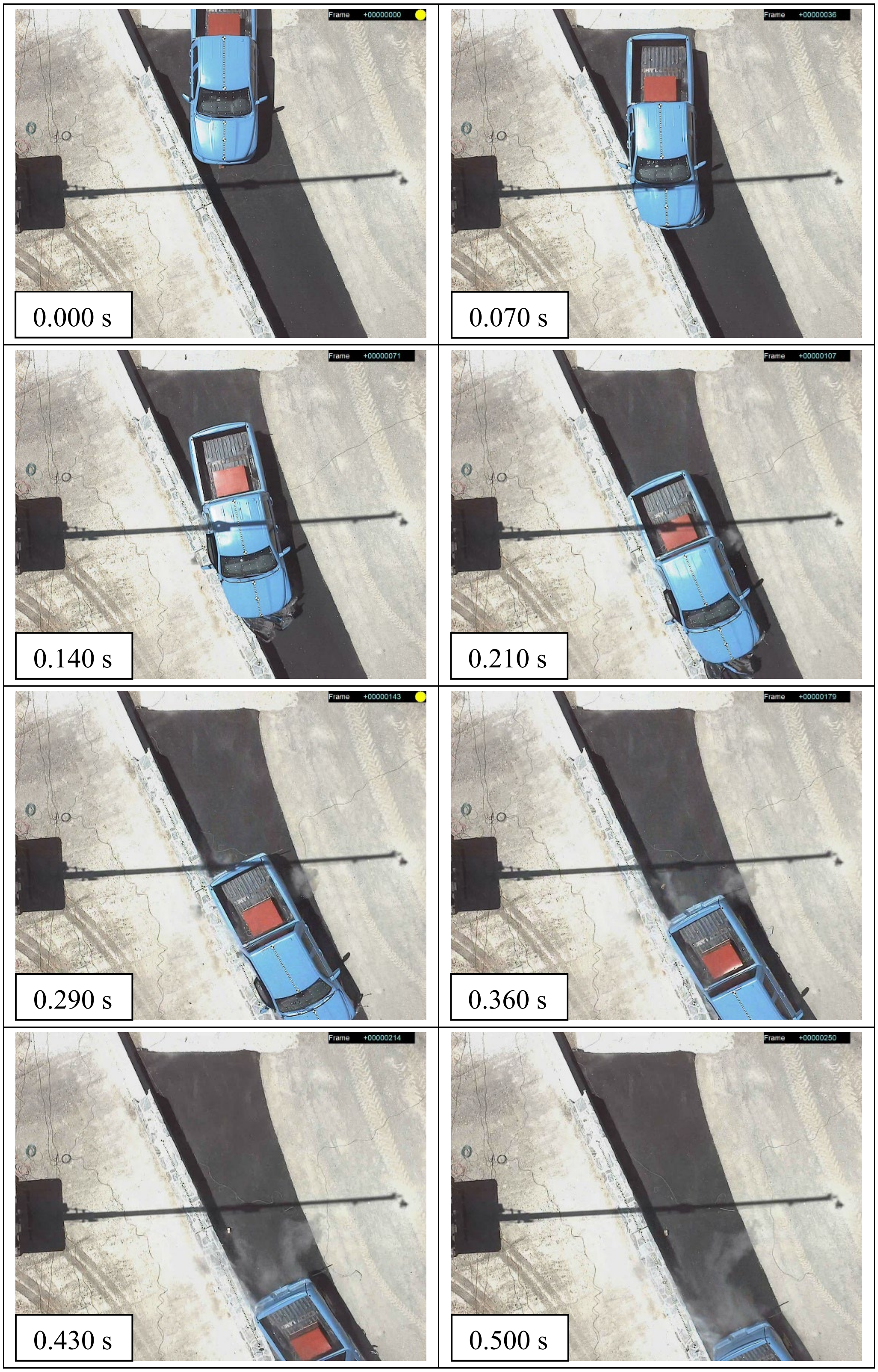


Figure 41 – FOIL Test 21004 (MASH 3-11) Sequential Overhead Images of Impact.

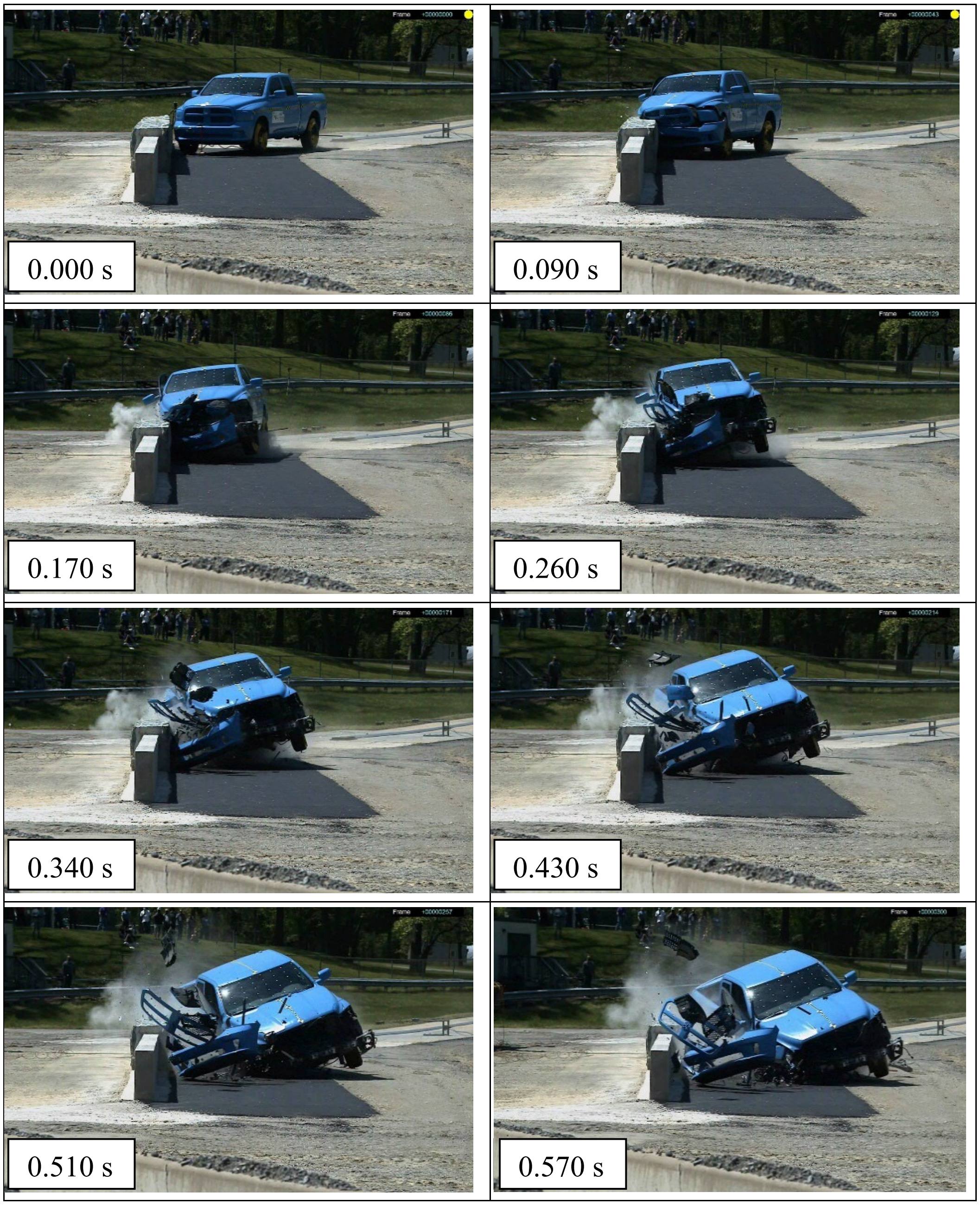


Figure 42 – Frontal Views of the Test 31001 Impact

Figure 43 provides views of the limited damage to the barrier from two perspectives of the SFCB after the crash test. There are scars and scrapes of the stone at the impact area, but none of these are deep. There is no apparent fracture or displacement of the stones after the test. Post impact inspection of the stone face indicated little damage or dislodging of stones in the barrier. Figure 44 shows the test vehicle after the test. It is apparent that the right front wheel was sheared off during the impact. The left side door seems to have been slightly affected, but there visually seems to be little damage to the occupant compartment.

Figure 43 – Views of the Median SFCB Test Installation after Crash Test

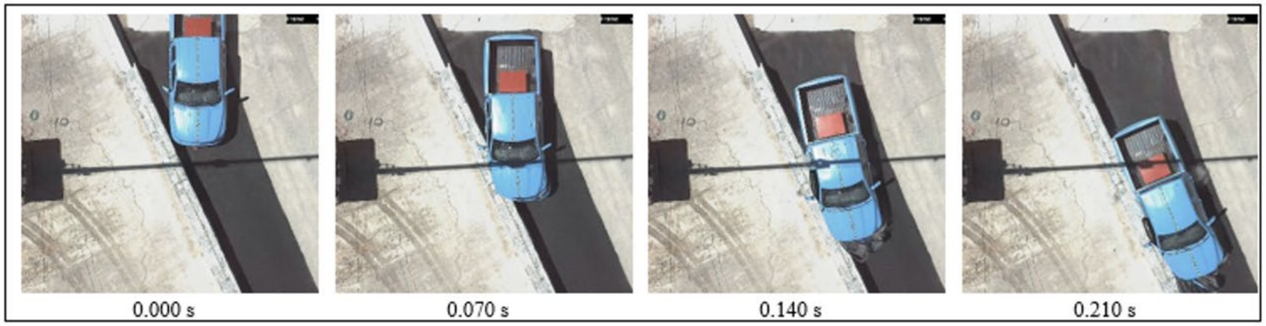
Figure 44 – Views of Damage to the Vehicle Resulting from the Crash Test

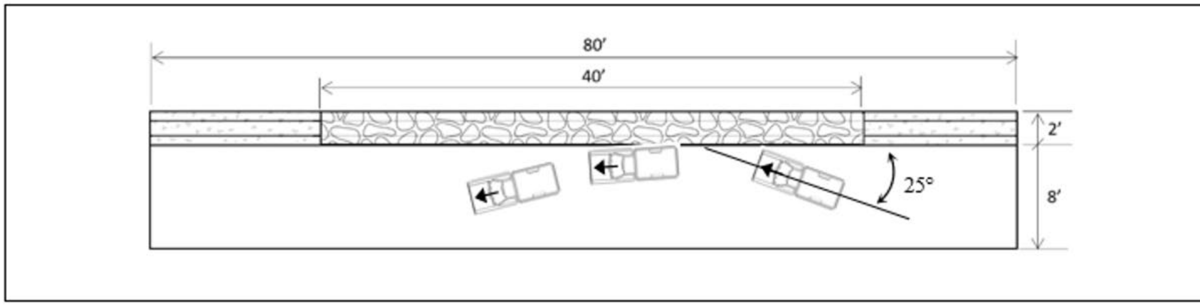
4.4.4 MASH Evaluation

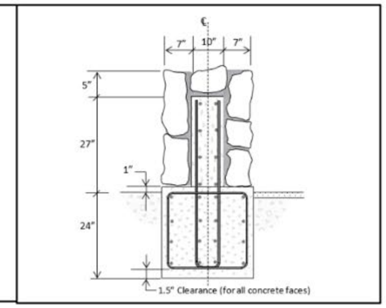
The visual and measured results of FOIL Test 21004 provided positive evidence that the barrier performed effectively. The last step to determining whether the SFCB meets the MASH criteria, is the comparison of the measured Occupant Risk values to the MASH limits to deem it acceptable for use on the highways. Table 10 cites the specific MASH requirements for Test 3-11 in the first column and indicates the test results and the specific conclusions drawn from the test results. The last column notes that the results indicated that the barrier met all the MASH requirements (i.e., Passed). A one-page test summary sheet for Crash Test 21004 is provided in Figure 45. It reflects the measured test metrics and the comparisons to the MASH criteria.

Table 10 – Review of MASH results for FOIL Test 21004 (MASH 3-11)

MASH Requirement	Results	Status
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.	The Median SFCB smoothly redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation.	*Pass*
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.	Scrapes and slight gouges in the stone face of the SFCB were apparent, but none appeared to have cracked or dislodged. There was no intrusions or penetration or potential for such to the occupant compartment.	*Pass*
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH (roof ≤4.0 in.; windshield = ≤3.0 in.; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 in.; forward of A-pillar ≤12.0 in.; front side door area above seat ≤9.0 inc.; front side door below seat ≤12.0 in.; floor pan/transmission tunnel area ≤12.0 in.).	All occupant compartment deformations were less that MASH critical numbers.	*Pass*
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75°.	The 2270P vehicle remained upright during and after the collision event. Maximum roll & pitch angles were 18.4 and -5.4 degrees, respectively.	*Pass*
H. Longitudinal & Lateral Occupant Impact Velocities should satisfy the following: Preferred 30 ft/s Maximum: 40 ft/s	Longitudinal occupant impact velocity was 7.3 ft/s, and lateral occupant impact velocity was 6.8 ft/s.	*Pass*
I. Longitudinal and Lateral Occupant Ridedown Accelerations should satisfy the following: Preferred 15.0 G Maximum: 20.49 G	Maximum longitudinal occupant ridedown acceleration was -5.7 G, and maximum lateral occupant ridedown acceleration was -6.7 G.	*Pass*
For redirective devices, it is desirable that the vehicle be smoothly redirected and exit the barrier within the "exit box" criteria (not less than 32.8 ft), and should be documented. Also report vehicle rebound distance and velocity for crash cushions.	The vehicle exited the installation, skidding to a stop. The vehicle exited the barrier within the "exit box".	*Pass*







General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 21004-
- Date 04/20/2021

Test Article:
- Type............................ Stone Faced Bridge Rail Design
  - Name or Mfg. .... Generic
- Installation Length ...... 80 ft. (24.4 m) Concrete
  40 ft. (12.2 m) Stone
- Key Elements .... Concrete, Stone, 21a Soil
  - Size/dimension .... 32 in (813 mm) stone wall height
  - Material .... Stone, concrete, steel
  - Other .... Concrete foundation and wall

Test Vehicle:
- Type/Designation 2270P
- Make and Model.......... 2014 Ram 1500 Quad Cab Pickup
  - VIN No..................... 1C6RR6FTXES391758
  - Curb .... 5093 lb. (2310 kg)
- Test Inertial .... 5031 lb. (2282 kg)
- Gross Static .... 5031 lb. (2282. kg)

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

Impact Conditions:
- Speed......................... 63.3 mph (102.0 km/hr)
- Angle .... 25 degrees
- Location/Orientation ..... Vehicle right front corner aligned with the front face of the barrier 4.3 ft. (1.3 m) upstream from expansion joint.

Exit Conditions:
- Speed .... 47.6 mph (76.7 km/hr)
- Angle .... 7.1 degrees
- Exit Box Criterion .... Vehicle exited within box

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

Occupant Risk:
- Longitudinal OIV .... 24.0 ft/s (7.3 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 22.3 ft/s (6.8 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal ORA ...... -5.7 G ≤ 20.49 G
- Lateral ORA .... -6.7 G ≤ 20.49 G
- THIV .... 32.6 ft/s (22.2 mph) 9.9 m/s (35.8 km/hr)
- PHD .... 8.7 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0 in (0 cm)
- Dynamic .... 1.2 in (3.0 cm)
- Working Width .... 1.2 in (3.0 cm)

Vehicle Damage:
- VDS 1RFQ5
- CDC 01RYEW2
- Max. Deformation
  - Exterior .... 9.13 in (23.2 cm)
  - Windshield .... 0.90 in (2.3 cm)
  - Occupant Comp. ..... 7.80 in (19.8 cm)

Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle...........18.4 deg ≤ 75 deg
- Max. Pitch Angle ....5.4 deg ≤ 75 deg
- Max. Yaw Angle ....36.4 deg

Overall Performance: Pass

Figure 45 – FOIL Test 21004 Summary Sheet

4.5 Crash Testing for MASH Test 3-10 – FOIL Test 21005

FOIL Test 21005 was conducted to certify that the SFCB would meet the requirements for MASH Test 3-10, the designated test vehicle needed to reach the planned impact speed and contact at the designated point aligned with the stone-faced section of the 80-foot test length of concrete barrier (test article). The 2015 Kia Rio small sedan test vehicle was accelerated on the FOIL track to a speed of 100 km/hr (62.5 mph), when it contacted the system at an angle of 25 degrees at the planned impact point on the barrier (Figure 37).

4.5.1 Test Vehicle – 1100C

Figure 46 shows the 2015 Kia Rio sedan used for the crash test. The inertial and gross static weight of the vehicle were similar and were 1123 kg. The height to the lower and upper edge of the vehicle bumper was 46.8 cm. and 39.8 cm. respectively. The height to the vehicle's center of gravity was 54.2 cm.

The FOIL cable tow and guidance system was used to direct the vehicle towards test barrier installation and released it to be freewheeling and unrestrained just prior to impact.

Figure 46 – Pre-Crash Views of the Test Vehicle

4.5.2 Test Article

Figure 47 shows views of the installed Median SFCB prior to the test. An 80' length of reinforced concrete barrier wall and foundation was constructed at the FOIL following the specifications cited in Figure 35. The median barrier configuration of a stone-facing was applied to 40 feet of the barrier. This was determined to be an adequate length to cover the vehicle-to-SFCB interface based upon the simulation studies. The vehicle was expected to slide over the random stone pattern for a short distance before being redirected away from the barrier. The random pattern of the stonework in apparent in the various views. During installation, the specifications for the width of separations between the stones and the depth of the mortar followed the requirements cited in Figure 47.

Figure 48 shows views of the test vehicle in proximity to the barrier to document the static interface of vehicle and the system elements. Pictures documenting the construction of the test article are available along with any related compaction, material strengths, or other features of the test article that may become relevant.

Figure 47 – View of the SFCB Article Installed for MASH Test 3-10

Figure 48 – Test 21005 Pre-impact Views of Test Vehicle Relative to SFCB

4.5.3 Crash Test Observations

The test was performed on February 27, 2021, at 1:00 pm under good weather conditions for testing. High-speed digital cameras deployed for the test captured various, continuous views of the crash event to record the barrier interaction with the vehicle. Two views of the test and results are provided in the overhead view in Figure 49 and ground level view from the rear as shown in Figure 50. The initial contact occurred at time 0.00 seconds (as planned) with the right front corner (bumper) of the vehicle. The path of the vehicle began to alter and by 0.060 seconds as the right front fender had crushed to the point at the front of the windshield. That crush continued and by 0.230 seconds the vehicle was diverted and sliding parallel to the face of the barrier and starting to move away from it. The photos show no evidence of damage to the windshield over that time. The vehicle appears to be sliding along the barrier slightly moving away from it as it goes out of view 0.400 seconds after initial contact from this vantage point. The redirection was relatively smooth.

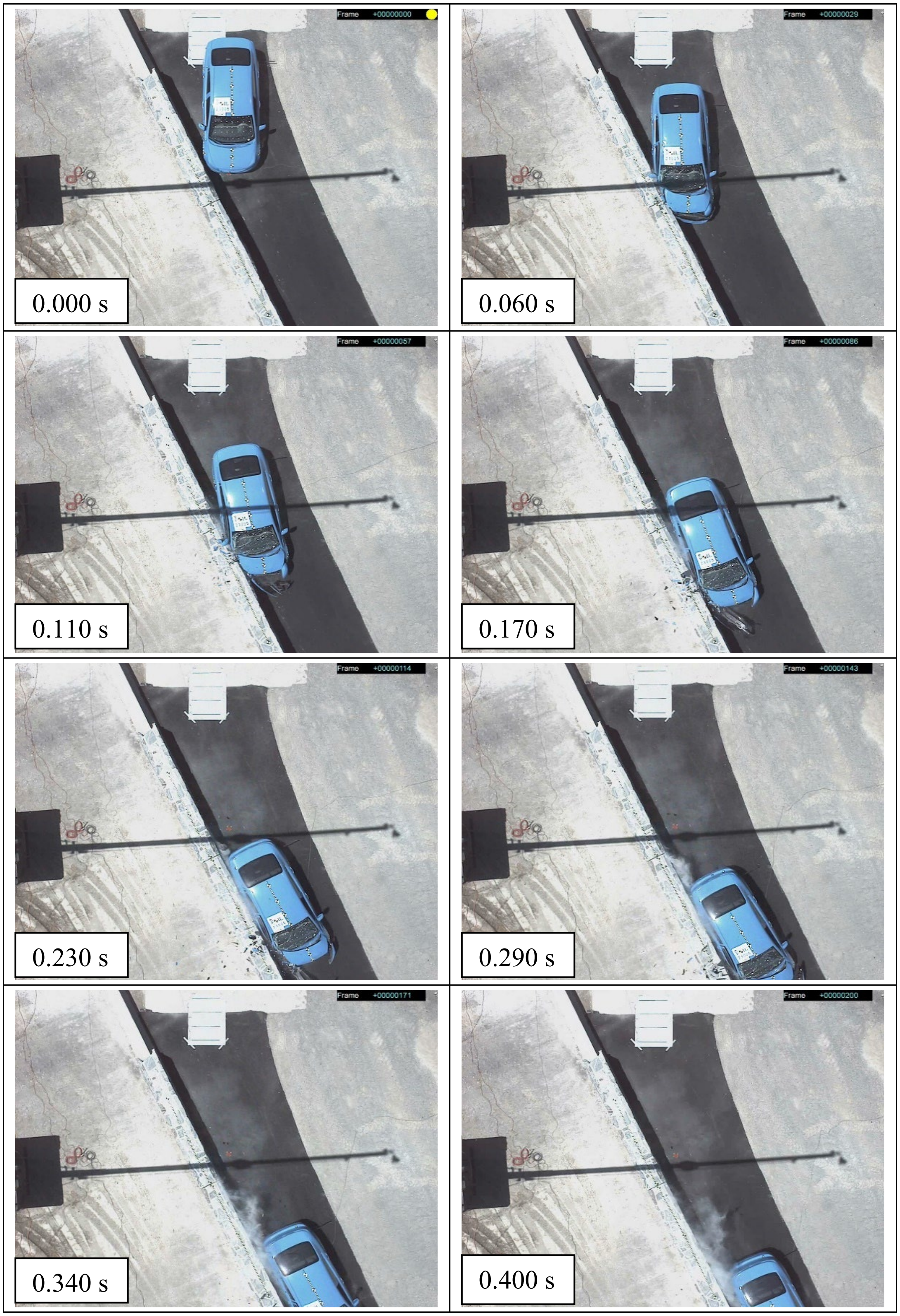


Figure 49 – FOIL Test 21005 Sequential Overhead Images of Impact

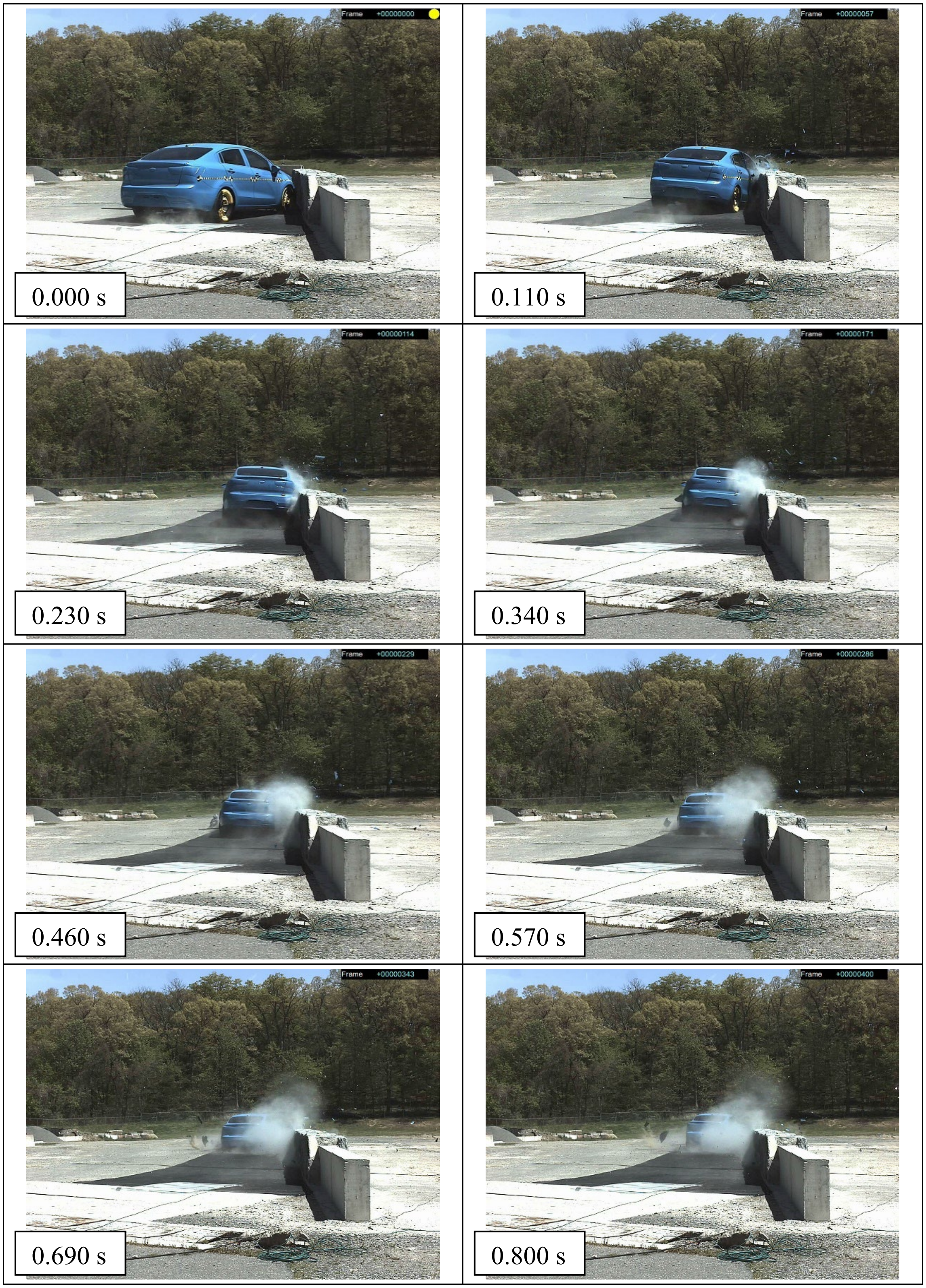


Figure 50 – Test 21005 Sequential Rear View Images of Impact.

Figure 51 shows there was no appreciable damage to the barrier, other than scrapes and the vehicle came to a controlled stop. Figure 52 shows views of the considerable damage to the vehicle. Despite the damage, it the occupant compartment remained uncompromised in the test.

Figure 51 – View Showing Only Limited Damage to Barrier

Figure 52 – Views of Damage to the Vehicle Resulting from the Crash Test

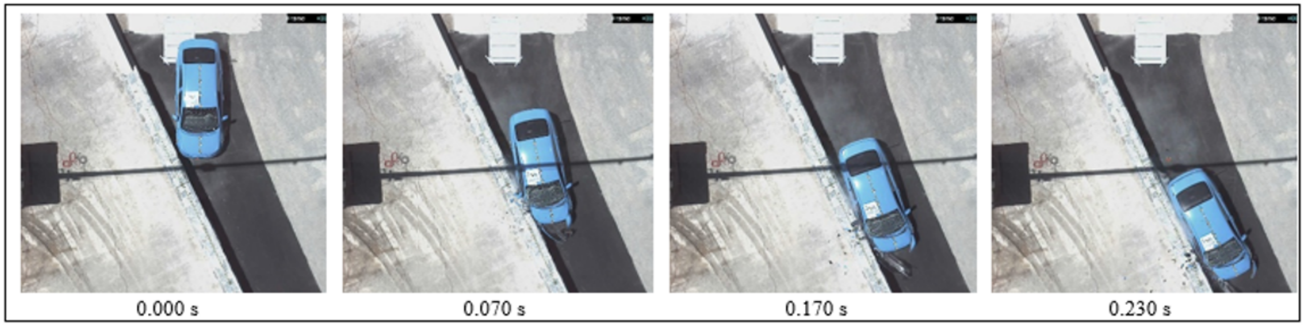
4.5.4 MASH Evaluation

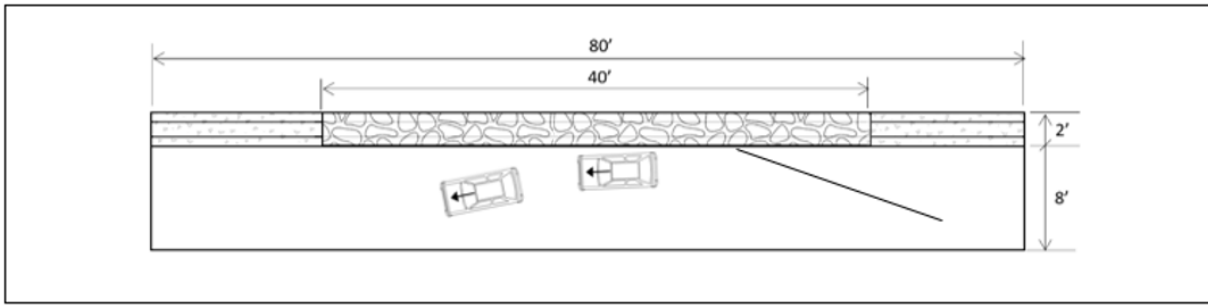
The visual and measured results of FOIL Test 21005 provided positive evidence that the barrier performed effectively. The last step to determining whether the SFCB meets the MASH criteria, is the comparison of the measured Occupant Risk values to the MASH limits to deem it acceptable for use on the highways. Table 10 cites the specific MASH requirements for Test 3-11 in the first column and indicates the test results and the specific conclusions drawn from the test results. The last column notes that the results indicated that the barrier met all the MASH requirements (i.e., Passed). A one-page test summary sheet for Crash Test 21004 is provided in Figure 45. It reflects the measured test metrics and the comparisons to the MASH criteria.

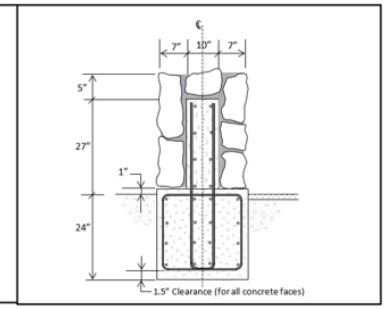
The results of FOIL Test 21005 provide one step toward determining whether the Median SFCB meets the MASH criteria, as required to deem it acceptable for use on the highways. Table 11 cites the specific MASH requirements for Test 3-10 in the first column. The Results column indicates the specific conclusions drawn from the test outcome. The last column notes whether results meet the requirements. In all cases, a PASS was considered appropriate. A one-page test summary sheet for Crash Test 21005 is provided in Figure 53. It reflects the measured test metrics and the comparisons to the MASH criteria.

Table 11 – Review of MASH results for FOIL Test 21005 (MASH 3-10)

MASH Requirement	Results	Status
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.	The SFCB smoothly redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation.	*Pass*
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.	No elements of the test article penetrated or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.	*Pass*
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH (roof ≤4.0 in.; windshield = ≤3.0 in.; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 in.; forward of A-pillar ≤12.0 in.; front side door area above seat ≤9.0 inc.; front side door below seat ≤12.0 in.; floor pan/transmission tunnel area ≤12.0 in.).	All occupant compartment intrusions were less than the MASH critical values.	*Pass*
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75°.	The vehicle remained upright during and after the collision event. • Maximum Roll: 10.8 deg ≤ 75 deg • Maximum Pitch: 4.0 deg ≤ 75 deg	*Pass*
H. Longitudinal & Lateral Occupant Impact Velocities should satisfy the following: Preferred 30 ft/s Maximum:_40 ft/s	Longitudinal occupant impact velocity was 7.3 ft/s, and lateral occupant impact velocity was 6.8 ft/s.	*Pass*
I. Longitudinal and Lateral Occupant Ridedown Accelerations should satisfy the following: Preferred 15.0 G Maximum: 20.49 G	Maximum longitudinal occupant ridedown acceleration was -5.7 G, and maximum lateral occupant ridedown acceleration was -6.7 G.	*Pass*
For redirective devices, it is desirable that the vehicle be smoothly redirected and exit the barrier within the “exit box” criteria (not less than 32.8 ft), and should be documented. Also report vehicle rebound distance and velocity for crash cushions.	The vehicle exited the installation, skidding to a stop. The vehicle exited the barrier within the “exit box”.	*Pass*







General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 21005
- Date 04/27/2021

Test Article:
- Type............................ Stone Faced Bridge Rail Design
  Name or Mfg .... Generic
- Installation Length .... 80 ft. (24.4 m) Concrete
  40 ft.(12.2 m) Stone
- Key Elements .... Concrete, Stone, 21a Soil
  Size/dimension .... 32 in (813 mm) stone wall height
  Material .... Carderock Stone
  Other .... Concrete foundation and wall

Test Vehicle:
- Type/Designation 1100C
- Make and Model .... 2015 Kia Rio
  VIN No. KNADM4A38F6515059
  Curb .... 2522 lb (1144 kg)
- Test Inertial .... 2476 lb (1123 kg)
- Gross Static .... 2641 lb (1198. kg)

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

Impact Conditions:
- Speed.......................... 60.5 mph (97.6 km/hr)
- Angle.......................... 25 degrees
- Location/Orientation .... Vehicle right front corner aligned with the front face of the barrier 3.3 ft. (1.0 m) upstream from expansion joint.

Exit Conditions:
- Speed .... 43.0 mph (69.2 km/hr)
- Angle .... 3.5 degrees
- Exit Box Criterion .... Vehicle exited within box

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

Occupant Risk:
- Longitudinal OIV .... 24.0 ft/s (8.1 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 22.3 ft/s (8.5 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal ORA ...... -5.5 G ≤ 20.49 G
- Lateral ORA .... -8.6 G ≤ 20.49 G
- THIV .... 38.3 ft/s (26.2 mph) 11.7 m/s (42.1 km/hr)
- PHD .... 9.5 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0 in (cm)
- Dynamic .... 0.8 in (cm)
- Working Width .... 0.8 in (cm)

Vehicle Damage:
- VDS 1RFQ5
- CDC 01RYEW3
- Max. Deformation
  Exterior .... 8.4 in (21.3 cm)
  Windshield .... 2.1 in (7.8 cm)
  Occupant Comp. ...... 3.6 in (9.1 cm)

Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle.......... 10.8 deg ≤ 75 deg
- Max. Pitch Angle .... 4.0 deg ≤ 75 deg
- Max. Yaw Angle .... 28.5 deg

Overall Performance: Pass

Figure 53 – FOIL Test 21005 Summary Sheet

5 Project Summary and Conclusions

This effort demonstrated that conceptual models of stone-faced median barriers and the elements of a system could be modeled for crash simulation analyses and the models applied to provide safety performance for such barrier and their appurtenances. The modeling effort developed digital representations of currently used stone-face concrete barriers (SFCBs). It demonstrated the application of the model to depict the crash behavior of two different versions of the SFCBs: a median and a roadside design. The models were also used to investigate transition designs for connecting these barriers to the commonly used Steel Backed Timber Guardrail (SBTG) designs. A total of four system were analyzed (1- median SFCB, 2- roadside SFCB, 3- Transition between the median SFCB and SBTG, and 4- Transition between the roadside SFCB and the SBTG.

Computer simulations were performed to analyze these four systems. The analyses started with the original designs of these systems and the designs were updated as needed to meet the MASH criteria for TL3 impacts. Through computer simulations, a design for each of the four systems that has a high potential to meet the MASH requirements was developed. Full-scale crash testing was performed on one of the developed systems (the Median SFCB). Two tests, depicting MASH Tests 3-11 and 3-10, were conducted. The two tests confirmed that the developed design meets all MASH requirement for TL3 impacts.

6 References

1. American Association of State Highway and Transportation Officials (AASHTO). A Policy on Geometric Design of Highways and Streets, Washington, D.C., 2004.
2. American Association of State Highway and Transportation Officials (AASHTO). Roadside Design Guide, AASHTO. Washington, D.C., 2011.
3. American Association of State Highway and Transportation Officials (AASHTO). Manual for Assessment of Safety Hardware (MASH). AASHTO. Washington, D.C., 2016.
4. Texas Transportation Institute, NCHRP Report 554 Bullard, L.D., Sheikh N.M., Bligh R.P., Haug, R.R., Schutt, J.R., Storey, B.J., Aesthetic Concrete Barrier Design, NCHRP Report No. 554, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2006.
5. Midwest Roadside Safety Facility, UNL, "Crash Testing & Evaluation of the HDOT 34 inch Tall Aesthetic Concrete Bridge Rail, MASH Tests 3-10 & 3-11", Research Report TRP-03-420-19, Lincoln, NB, October 21, 2019.
6. White M., Jewell J., Peter R., "Crash Testing of Various Textured Barriers", California Department of Transportation, September 2002.

Appendix A: MASH TEST 3-11 of a Median Stone-Faced Concrete Barrier

Authors:

**Dhafer Marzougui, Christopher Story, Kenneth Opiela
Fadi Tahan, and Cing-Dao (Steve) Kan
Center for Collision Safety and Analysis
George Mason University**

FOIL Test No. 21004

CCSA Report No. R-22001A

Sponsored by:
National Park Service,
Eastern Federal Lands Branch, FHWA
and

Office of Safety Research & Development
Turner Fairbank Highway Research Center
Federal Highway Administration
U.S. Department of Transportation

January 2022

DISCLAIMER

The contents of this report reflect the views of the authors who are solely responsible for the facts and accuracy of the data, and the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration of the U.S. Department of Transportation, or the George Mason University Center for Collision Safety and Analysis. This report does not constitute a standard, specification, or regulation. In addition, the above listed agencies assume no liability for its contents or use thereof. The names of specific products or manufacturers listed herein do not imply endorsement of those products or manufacturers.

ACKNOWLEDGEMENTS

This study was sponsored by the National Park Service (NPS), Eastern Federal Lands (EFL) Branch of FHWA, in cooperation with Office of Safety Research & Development at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA), of the US Department of Transportation (US DOT).

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2002)

SUMMARY

This report documents the procedures and result of a crash test described below:

Report Title	**MASH TEST 3-11 of a Median Stone-Faced Concrete Barrier – FOIL Crash Test 21004**
Test Type	Full-Scale Crash Test: Vehicle Impacting Barrier
What is Tested	Median Stone-Faced Concrete Barrier
Purpose/Objective	Ascertain that a concrete barrier with stone-facing that can be used as a median barrier or bridge rail offering an aesthetic appearance consistent with the objectives for park service roads can also meet the national crashworthiness requirements under MASH at Test Level 3.
Impacting Item/Vehicle	2270P MASH pickup truck-type vehicle.
Impact Speed and Conditions	Speed 62 mph, centerline of the vehicle aligned 25 degrees to the concrete median barrier having a natural stone-face along the face of the barrier.
Test Procedures and Standards Information	*Manual for Assessing Safety Hardware* (MASH), 2016 Edition
Test Criteria	TL-3 Impact Rating for Condition 3-11
Test Number	FOIL Test No. 21004
Test Date	February 10, 2021
Test Location	Federal Outdoor Impact Laboratory (FOIL) Turner-Fairbank Highway Research Center (TFHRC) FHWA U.S. DOT 6300 Georgetown Pike, McLean, VA 22101-2296
Conducted by	Center for Collision Analyses and Safety (CCSA) George Mason University (GMU) 4087 University Drive, Fairfax, VA 22030
Report Authors	Dhafer Marzougui, Christopher Story, Kenneth Opiela Fadi Tahan, and Cing-Dao (Steve) Kan
Test Results Summary	MASH Test 3-11. Test 21004. Pick-up truck was smoothly redirected, without significant vehicle instability. PASSED MASH requirements.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0. INTRODUCTION

1.1. Problem Statement

The National Park Service (NPS) objectives include providing access in scenic or historic areas in a manner the compliment the environment. Many NPS roads have become important links in growing metropolitan areas and therefore carry greater volumes of traffic at higher speeds than originally conceived. In the interests meeting safety and aesthetic goals, enhanced designs for RSH have evolved. The increasing emphasis on agencies to assure the highest level of highway safety under guidelines such as the Manual for Assessing Safety Hardware (MASH) provided the impetus for this research.

Most concrete barriers used as RSH feature a smooth face, except for the necessary expansion or connection joints. The relatively smooth concrete surface readily allows an impacting vehicle to slide along the barrier as speed and impact energy are dispersed. The rough, natural stone face of the Stone-Faced Concrete Barrier (SFCB) developed by EFL obviously results in greater resistance to sliding along the barrier. This raised questions about its safety efficacy. Due to the limited testing and evaluation efforts insights on the effects of barrier surface treatments on the performance of barriers like the SFCB, computer simulations and crash testing were performed to confirm that the desired MASH requirements including post-impact effects are achieved.

1.2. Study Objectives

This report documents the findings of one test conducted in a larger effort focused on testing the efficacy of the Stone-faced Concrete Barriers (SFCB) used on highways under the jurisdiction of the Federal Lands and National Park Service. Aesthetic barriers such as the rough stone-faced walls and steel-backed timber (STB) guardrail have been developed and tested for use in parks and other historic or scenic areas. The growth of urban areas has some roads, where these barriers are being used, carrying greater amounts of traffic at higher speeds than originally anticipated. This effort is aimed at determining whether the typical stone-faced concrete barriers that are widely used on roads under the jurisdiction of the National Park Service (NPS) meet the latest safety requirements (MASH 2016)

2.0. SYSTEM DETAILS

2.1. Test Article and Installation Details

Figure 1 shows the design and installation details for SFCMB that was tested for MASH TL-3 requirements under this project. The figure depicts a median barrier design with a vertical face that features:

- A reinforced concrete core that provides a 26” high and 10” wide barrier vertical element over a 24” wide and 25” deep foundation. Loop and u-shaped rebar element are tied to longitudinal rebars (eight in the upright element and sixteen in the base.
- Concrete for the barrier should be 4500 psi strength.
- Stones that are as large as possible and no more than 3” deep are mortared to the concrete vertical element. Mortar joints are specified to be no more than 2” wide and protrusion should be limited to 0.5 inches.

A section of the SFCMB was constructed following these design requirements at the FHWA Federal Outdoor Impact Lab (FOIL) to conduct the necessary MASH tests on the crash-worthiness of these barriers. Figure 2 shows the planned set-up for MASH Test 3-11.

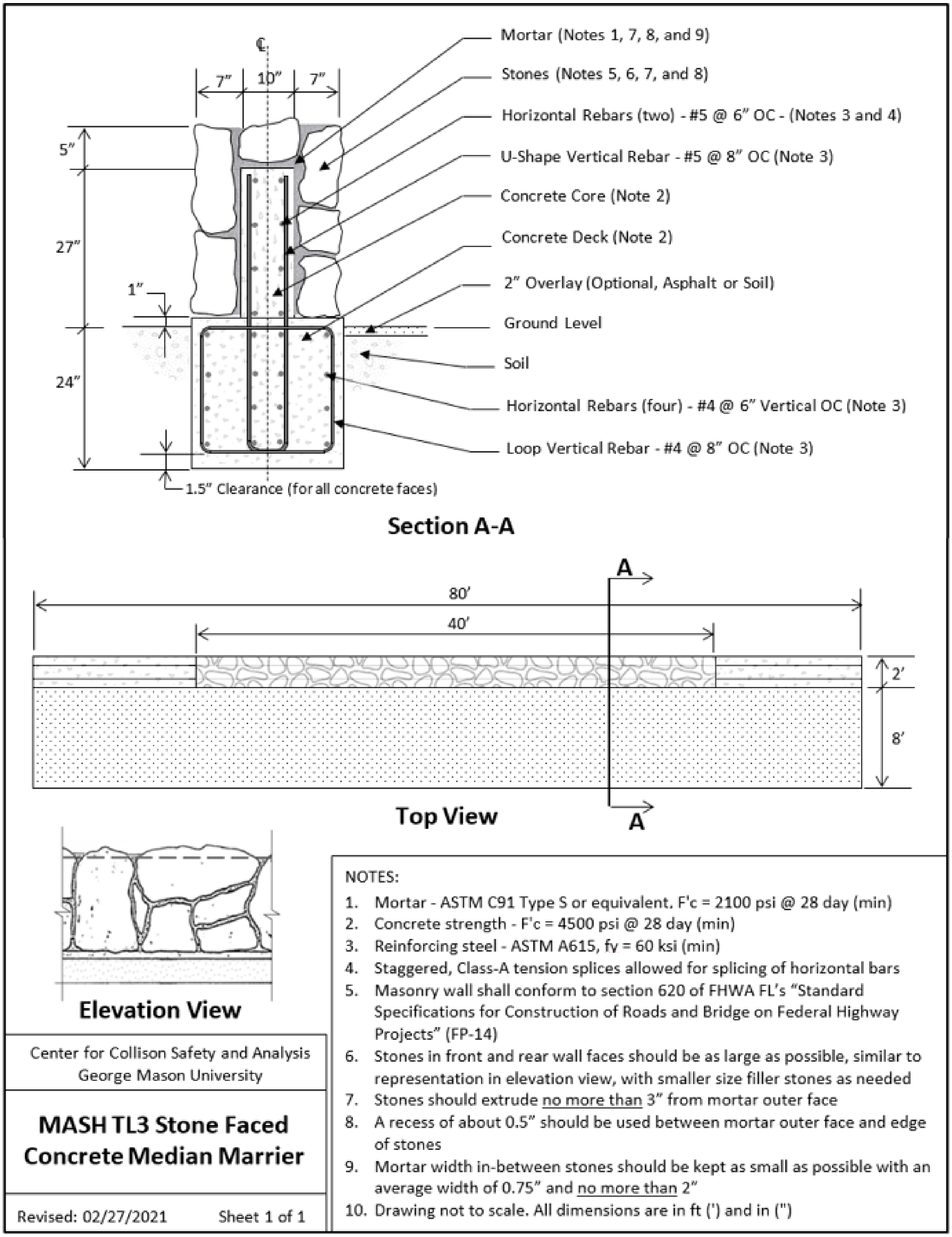


Figure 1. Median SFCB Test Installation Design Features

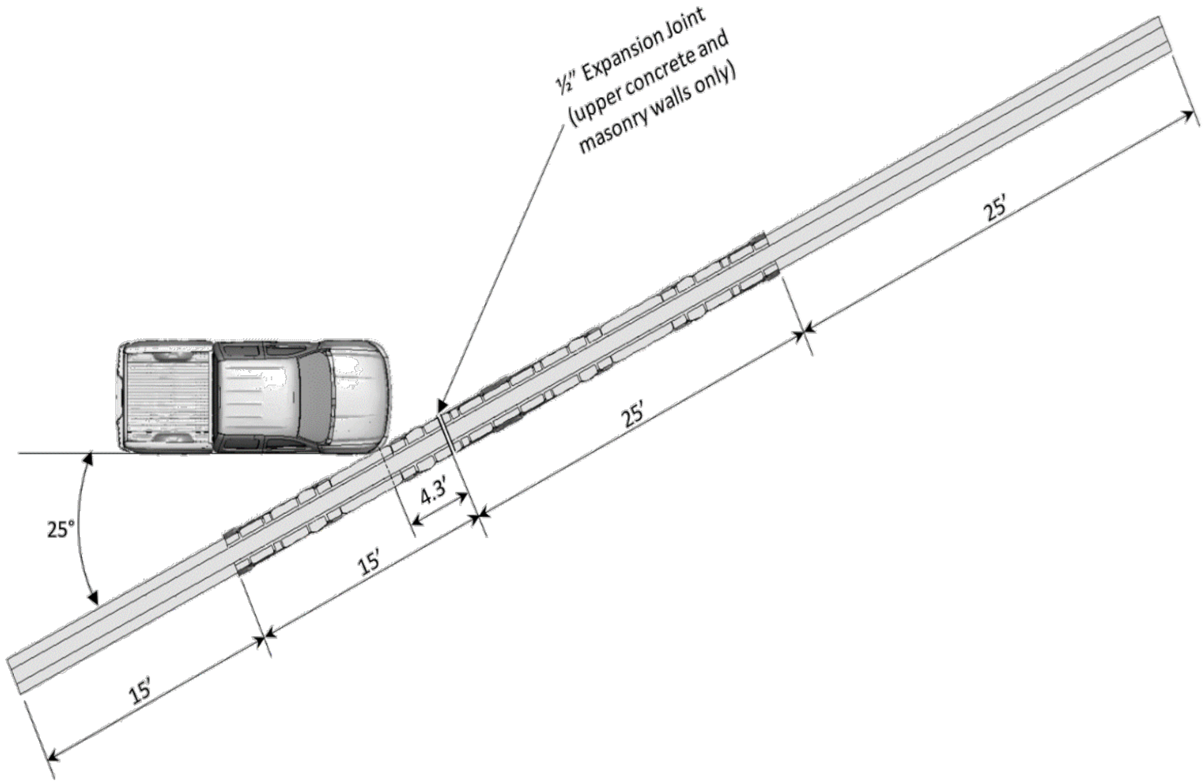


Figure 2. Median SFCB Test Installation Diagram for MASH Test 3-11.

2.2. Material Specifications

This system was fabricated using standard roadside safety hardware elements, as described above. The materials and hardware elements delivered met the basic standards in accordance with suppliers or certifications that are on file at the FOIL Office.

2.3. Soil Conditions

The foundation for the SFCMB was laid in the designated positions in the impact area of the FOIL, as depicted. The soils at the FOIL have been classified as typical VDOT materials. Soil tests confirmed the compaction and moisture content of the soils were in appropriate ranges consistent with previous testing at the FOIL. These tests, conducted with a nuclear density device, involved repeated measures at multiple positions around the test installation. The FOIL Summary Report documents these results. Independent soil analyses by Froehling & Robertson, Inc. are on file at the FOIL Office.

3.0. MASH TEST REQUIREMENTS AND ACCEPTANCE CRITERIA

As noted in Table 1 below, researchers determined that overall evaluation of this device would require successful passing of two MASH tests. This report only provides the background and results for MASH Test 3-11 (FOIL Test 21004). Test 3-11 is intended to determine the barrier's capacity for containing and/or redirecting the larger vehicle. All tests were setup and executed according to prescribed FOIL protocols (including facility ISO requirements) and MASH standards. These are individually documented in Test Reports (following MASH requirements). The Table 1 reflects variations in vehicles, speed, and angles for the planned tests.

Table 1. MASH Tests Conducted for Medan SFCB

Test Number	Date	MASH Test	Vehicle	Impact Speed	Impact Angle	Outcome
21004	04/20/21	3-11	Pickup Truck	100 km/hr	25	Pass
21005	04/27/21	3-10	Small Sedan	100 km/hr	25	Pass

Three criteria must be met under MASH requirements for Structural Adequacy, Occupant Risk, and Vehicle Trajectory. The specific requirements for these criteria are noted in Table 2.

Table 2. Test 3-11 Evaluation Requirements by Category.

Evaluation Category	Requirement
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 (roof ≤4.0 in.; windshield = ≤3.0 in.; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 in.; forward of A-pillar ≤12.0 in.; front side door area above seat ≤9.0 in.; front side door below seat ≤12.0 in.; floor pan/transmission tunnel area ≤12.0 in.).
	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 • **Preferred** 30 ft/s **Maximum:** 40 ft/s
	I. Occupant ridedown accelerations should satisfy the following: • Longitudinal and Lateral Occupant Ridedown Accelerations • **Preferred:** 15.0 G **Maximum:** 20.49 G
Vehicle Trajectory	For redirective devices, the vehicle should be smoothly redirected and exit the barrier within the “exit box” criteria (not less than 32.8 ft); document all tests. Vehicle rebound distance and velocity for crash cushions.

4.0. TEST CONDITIONS

4.1. FOIL Test Facility

All testing on this system was performed at the FOIL. The FOIL is an ISO17025-accredited (Cert. # AT-1565) research facility used to support FHWA Safety Research and Development programs and other federal security initiatives. ISO 17025 identifies high technical competence and management system requirements that guarantee test results. It demonstrates the FOIL's commitment to operational efficiency and quality management practices and verifies the quality, capability, and expertise of the FOIL. The FOIL is a multifaceted impact-testing facility, primarily designed to test the impacts of vehicles with roadside safety hardware, in accordance with the MASH guidelines and standards.

4.2. Vehicle Tow and Guidance Procedures

A specially designed FOIL hydraulic-propulsion system pulls the test vehicles into the barriers. The vehicles are accelerated on a 220 ft concrete track. The propulsion system is capable of pulling a 17,637 lbs. vehicle to over 50 mph. The 2270P test vehicle can be brought to speeds in excess of 70 mph. The test vehicles are released into a 160 x 320 ft runout area. Barriers up to 450 ft in length (usually at 25 degree relative to the track) can be installed in the runout area at the end of the track. Figure 4 provides an aerial view of the FOIL facility.

Figure 3. Aerial View of FHWA FOIL Layout

For the SFCB tests, the system was placed at an angle relative to the FOIL track to achieve the desired impact point and angle with the system. The system was installed adjacent to end of the track so the vehicle could be freewheeling and impact at the desired speed and point. Figure 1 (above) depicted the orientations of the barrier relative to the track of the vehicle (which followed the alignment of the FOIL accelerator. The vehicle was released from the accelerator at a point that allowed it to be "free-wheeling" at the desired impact velocity.

4.3. Test Vehicle Preparation

MASH Test 3-11 involved a test with a MASH 2270P vehicle impacting the test article at a speed of 62 mph (100.0 km/h) and an angle of 25.0 degrees relative to the traffic face of the barrier. The target impact point was the front right front of the truck just downstream of the beginning from the section of the concrete barrier to which stone rumble had been attached with mortar (following the specifications noted in Figure 1). The test vehicle was prepared for the test following standard procedures to drain fluids, and take accurate measurements of the vehicle, weight, tires, and related features. Vehicles are typically painted blue to maximize the visibility of the impact outcomes in the multiple video cameras setup for each test.

4.4. Data Acquisition Systems

4.4.1. Vehicle Instrumentation and Data Processing

Accelerometers, rate transducers, and speed measuring devices captured the vehicle and barrier responses during impact. Two tri-axial accelerometers mounted at the vehicle center of gravity measured the x-, y-, and z-accelerations of the vehicle. This data was used to compute the occupant ride-down acceleration and occupant-impact velocities. Additionally, two tri-axial rate transducers measured vehicle roll, pitch, and yaw. Contact switches installed on the vehicle and test article synchronized time zero for the sensor data and high-speed video imagery.

4.4.2. Photographic Instrumentation and Data Processing

Eight high-speed cameras were 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 different locations surrounding the impact region to capture left, right, front, rear and isometric views of the crash event. These images are downloaded immediately after the test to allow detailed scrutiny of the crash event and behavior of the barrier in slow motion.

4.5. Test Set-up Conditions

4.5.1. Test Vehicle

Figure 4 shows the 2014 Dodge Ram 1500 quad-cab pickup used for the crash test. Test inertial and gross static weight of the vehicle was 4,945 lb 2282 kg. The height to the lower and upper edge of the vehicle bumper was 10.8 in. and 25 in. respectively. The height to the vehicle's center of gravity was 28.4 in. Researchers used the cable reverse tow and guidance system to direct the vehicle into the installation that then released the vehicle in a freewheeling and unrestrained mode just prior to impact.

4.5.2. Test Article

Figure 5 shows several views of the installed SFCB prior to the test. An 80' length of reinforced concrete barrier wall and foundation was constructed at the FOIL following the specifications cited in Figure 2. The median barrier configuration of a stone-facing was applied to 40 feet of the barrier. This was determined to be an adequate length to cover the vehicle-to-SFCMB interface based upon the simulation studies. The vehicle was expected to slide over the random stone pattern for a short distance before being redirected away from the barrier. The random pattern of the stonework in apparent in the various views. During installation, the specifications for the width of separations between the stones and the depth of the mortar followed the requirements cited in Figure 1.

Figure 6 shows eight views of the test vehicle in proximity to the test article to document the static interface of vehicle and the system elements. It can be noted that the front bumper impacts the barrier at mid-height. Projecting a line along the stone face indicates that various sizes of stones would interact with the bumper and the side of the vehicle during the crash. Pictures documenting the construction of the test article are available along with any related compaction, material strengths, or other features of the test article that may become relevant.

Figure 4. Test 21004 Pre-impact Photos of Test vehicle.

Figure 5. Test 21004 Pre-impact Condition Views of SFCB

Figure 6. Test 21004 Pre-impact Views of Test Vehicle Relative to SFCB

5.0. CRASH TEST DOCUMENTATION

5.1. Test Designation and Impact Conditions

For Test 21004 to certify that the SFCB would meet the requirements for MASH Test 3-11, the designated test vehicle needed to reach the planned impact speed and contact at the designated point aligned with the stone-faced section of the 80-foot test length of concrete barrier (test article) as shown in Figure 1. The 2014 Dodge Ram 1500 quad-cab pickup test vehicle was accelerated on the FOIL track. It was traveling at a speed of 63 mph (100 kmph), when it contacted the system at an impact angle of 25 degrees at the planned impact point of the concrete barrier. Figure 2 (above) showed the test set-up for this impact test.

5.2. FOIL Crash Test 21004 Outcome (for MASH Test 3-11)

5.2.1. General Conditions at Time of Test

The test was performed on February 20, 2021, at 1:00 p.m. Weather conditions at the time of testing were as follows:

- Temperature: 74 degrees
- Relative Humidity: 77%
- Wind speed and direction: 13 mph - south
- Wind Chill: N/A
- Visibility: 10.0 miles
- Sky Condition: Mostly Sunny
- Surface Condition: Dry
- Three-day Precipitation History: > 0.01 inches

These were considered to be ideal conditions for testing and have negligible effects on the outcome of the test.

5.2.2. Crash Test Observations

The seven, high-speed, digital cameras deployed for the test captured various, continuous views of the crash event to record the effects of the barrier stone face on the interaction with the vehicle and its redirection and reduction of impact velocity.

A series of overhead views captured from one camera are shown in Figure 7. It can be seen that the initial contact occurred at time 0.00 seconds (as planned) with the right front corner (bumper) of the vehicle. [Note: the shadow of the overhead camera boom provides a useful benchmark.] The path of the vehicle began to alter and by 0.070 seconds as the right front fender had crushed to the point at the front of the windshield. That crush continued and by 0.290 seconds the vehicle was diverted and sliding parallel to the face of the barrier and starting to move away from it. The photos show no evidence of damage to the windshield over that time. The vehicle appears to be continuing to move away from the barrier as it goes out of view 0.500 seconds after initial contact from this vantage point. It would appear that the redirection was relatively smooth.

Figure 8 shows views of the impact from the ground level camera on the left (driver's) side. There appears to be a little pitch or roll of the vehicle, but the "puff" near the rear tire may indicate that the left rear tire very briefly left the road surface and then touched down.

Figure 9 shows the impact from the downstream ground-level camera. It provides better views of the damage to the right front fender and front. It appears that pieces of the grill, front bumper, and fender are loose and being dragged along. It provides a better view of the limited roll and pitch that occurred.

Figure 10 shows the impact sequence from the rear ground mounted camera. There is no evidence of stones or other parts being dislodged from the barrier. The lifting of the right rear of the vehicle (roll & pitch) are noted despite the dust from the impact.

Figures 11 and 12 show various views of the damage to the test vehicle and barrier installation occurring in the test.

Table 3 lists some of the events that occurred over the duration of the crash. Note: These various views of the crash indicate that the vehicle never lost contact with the system after first impact and came shows various views of the vehicle and system after impact.

Table 3. Events During FOIL Test 21004.

TIME (s)	EVENT
0.00	Vehicle front right bumper contacts the SFCMB at 63 mph.
0.200	Vehicle sliding fully parallel along the barrier have moved the length of the vehicle along the barrier. It appears that the right side of the vehicle is almost fully in contact with the barrier. No noticeable deflection of the barrier, crush of the passenger compartment, or damage to the windshield. Very little yaw, pitch, or roll noted.
0.290	Some movement of the vehicle away (rebound) from the barrier. A slight degree of pitch and roll is noted with outside rear wheel seeming to be just off the ground.
0.260-0.400	Vehicle continues to move along the rail with slight increases in forward pitch, probably caused by the vehicle contact with the "rough" barrier face also causing damage to vehicle bumper, grill, and rights side panels.
0.430	Vehicle shows more pitch as the it slides along the barrier.
0.570	Vehicle moves still farther along the barrier with more pitch and roll as it begins moving away from the barrier.
0.600 +	Vehicle appears to end contact with the system skidding along the surface. Vehicle later comes to rest upright about 50 feet from the end of the test set-up [not seen in the sequential views] after brakes were remotely applied.

Figures 3.11 and 3.12 show multiple close and distant views of the SFCNB after the crash test. There are scars and scrapes of the stone at the impact area, but none of these are deep. There is no apparent fracture or displacement of the stones after the test. Figure 3.13 shows that the test vehicle after the test. It is apparent that the right front wheel was sheared off during the impact. The left side door seems to have been slightly affected, but there visually seems to be little damage to the occupant compartment.

Last, Figures 3-14 and 3-15 provided the digital trace results from accelerometers installed at the CG of the test vehicle. These graphs show x, y, and z accelerations and roll, pitch and yaw angle over the duration of the impact event. These appear typical for crash tests.

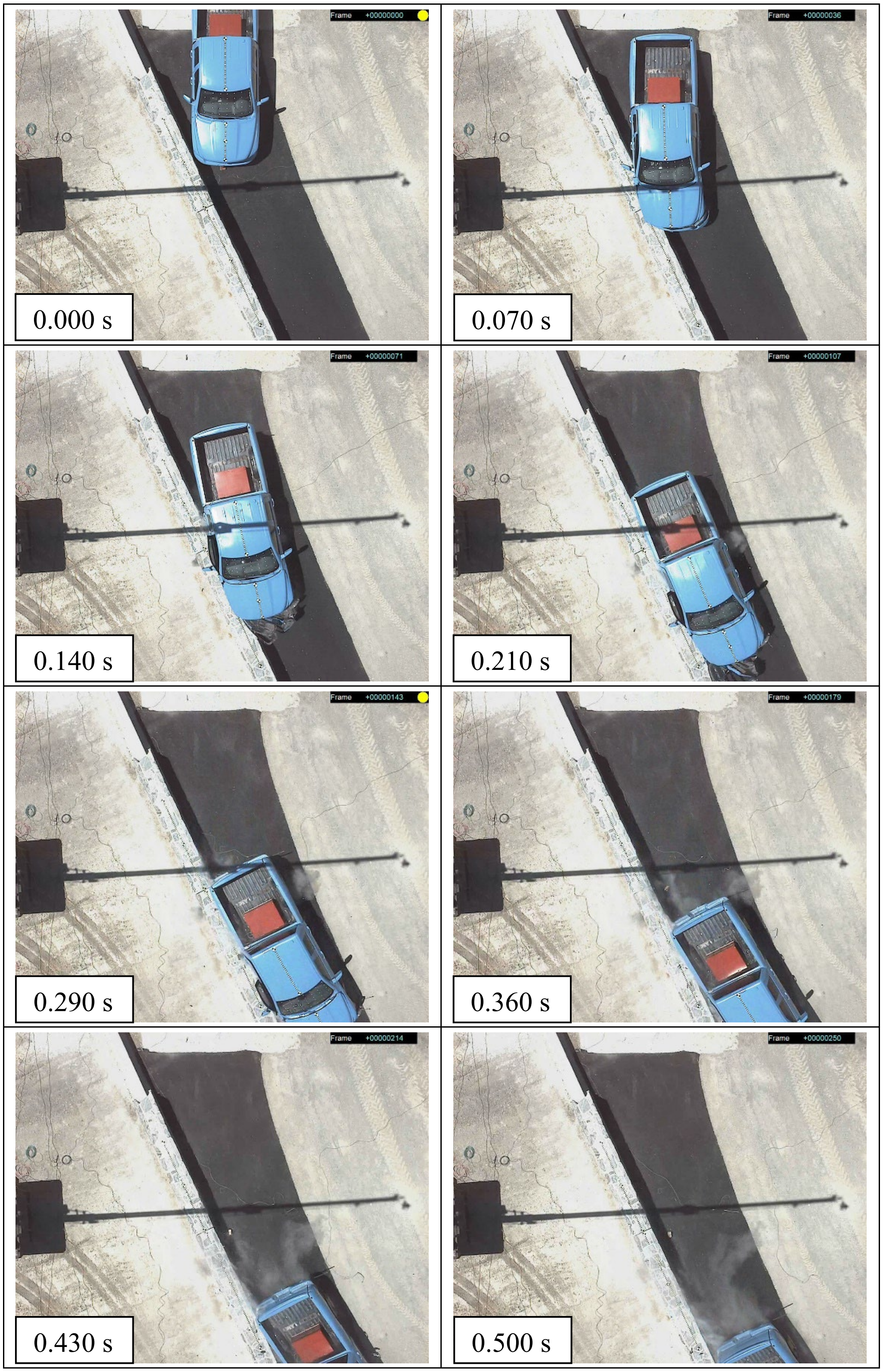


Figure 7. FOIL Test 21004 Sequential Overhead Images of Impact.

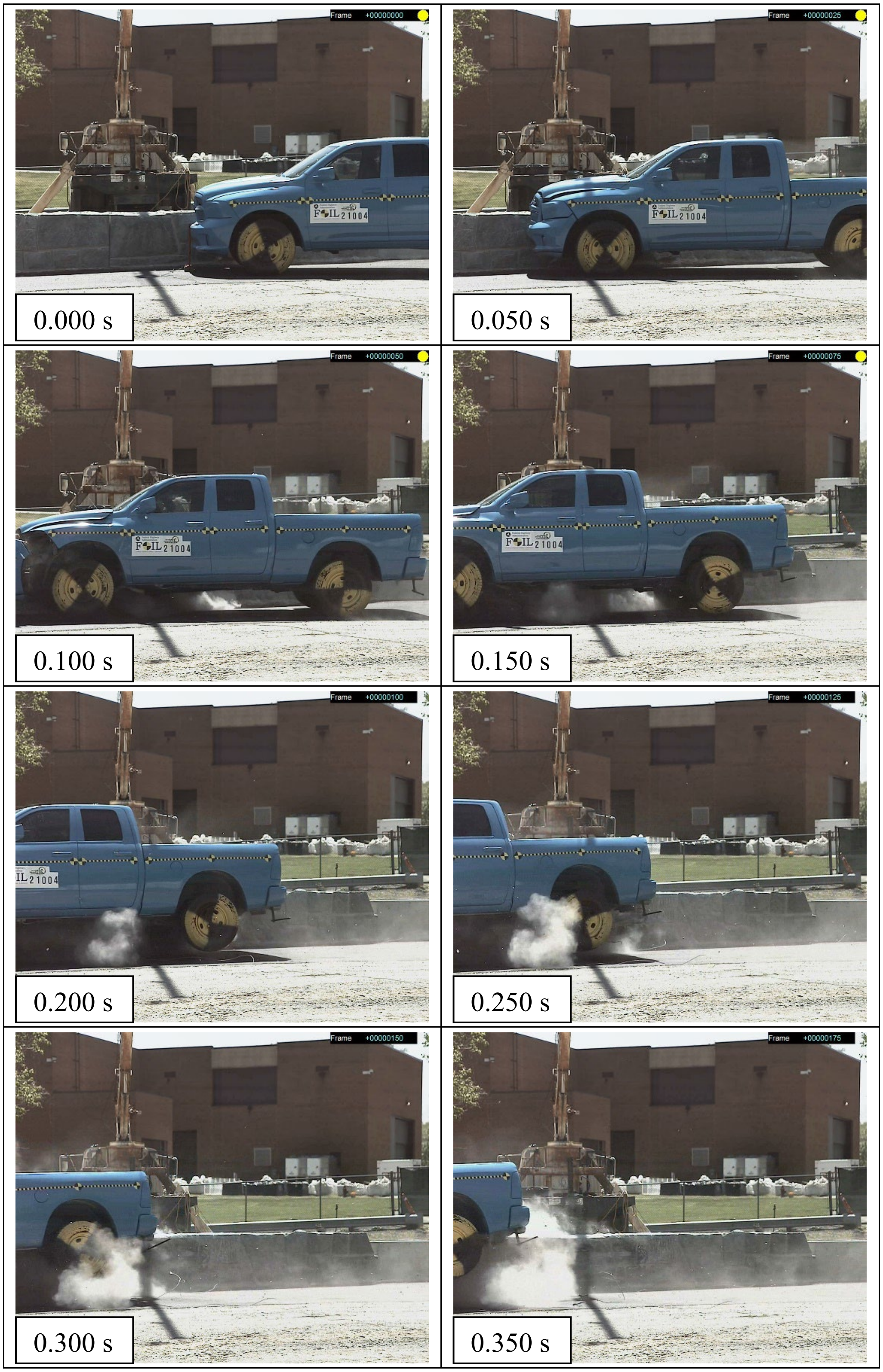


Figure 8. Test 21004 Sequential Views from Right Side Camera

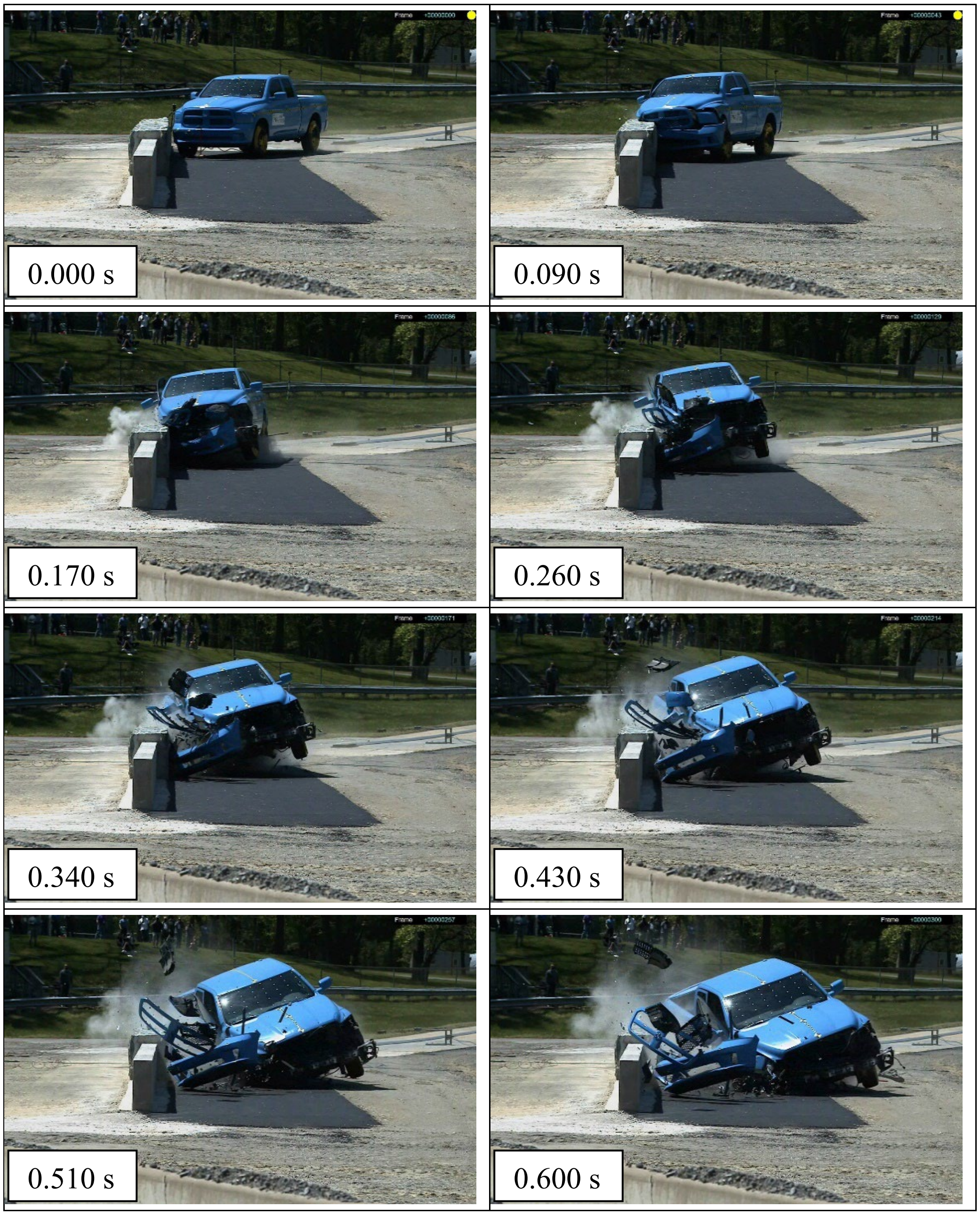


Figure 9. Test 21004 Sequential Views from Front Camera

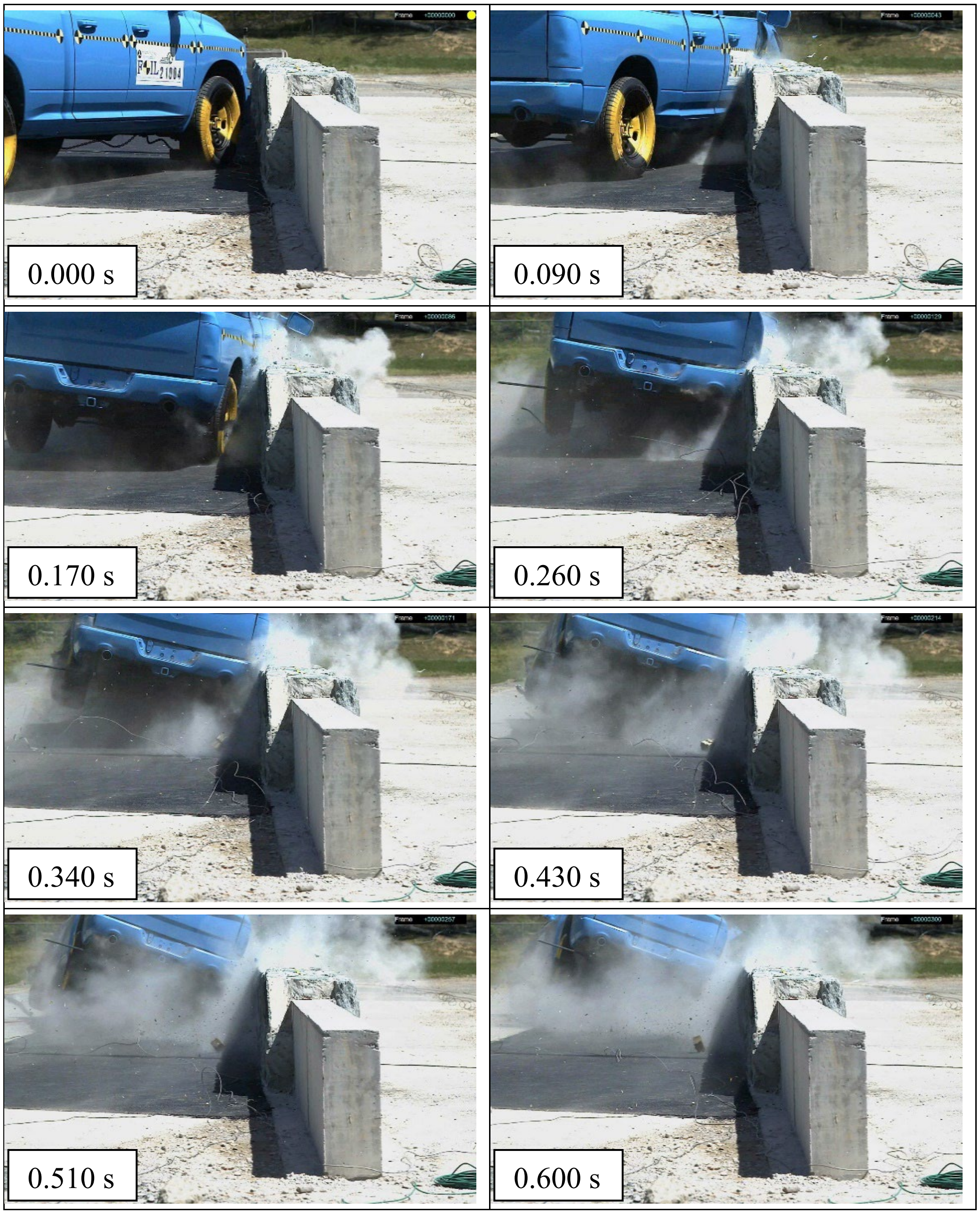


Figure 10. Test 21004 Rear Camera Views

Figure 11. Views of the SFCB Test Installation After Crash Test – 1 of 2

Figure 12. Views of the SFCB Test Installation After Crash Test – 2 of 2

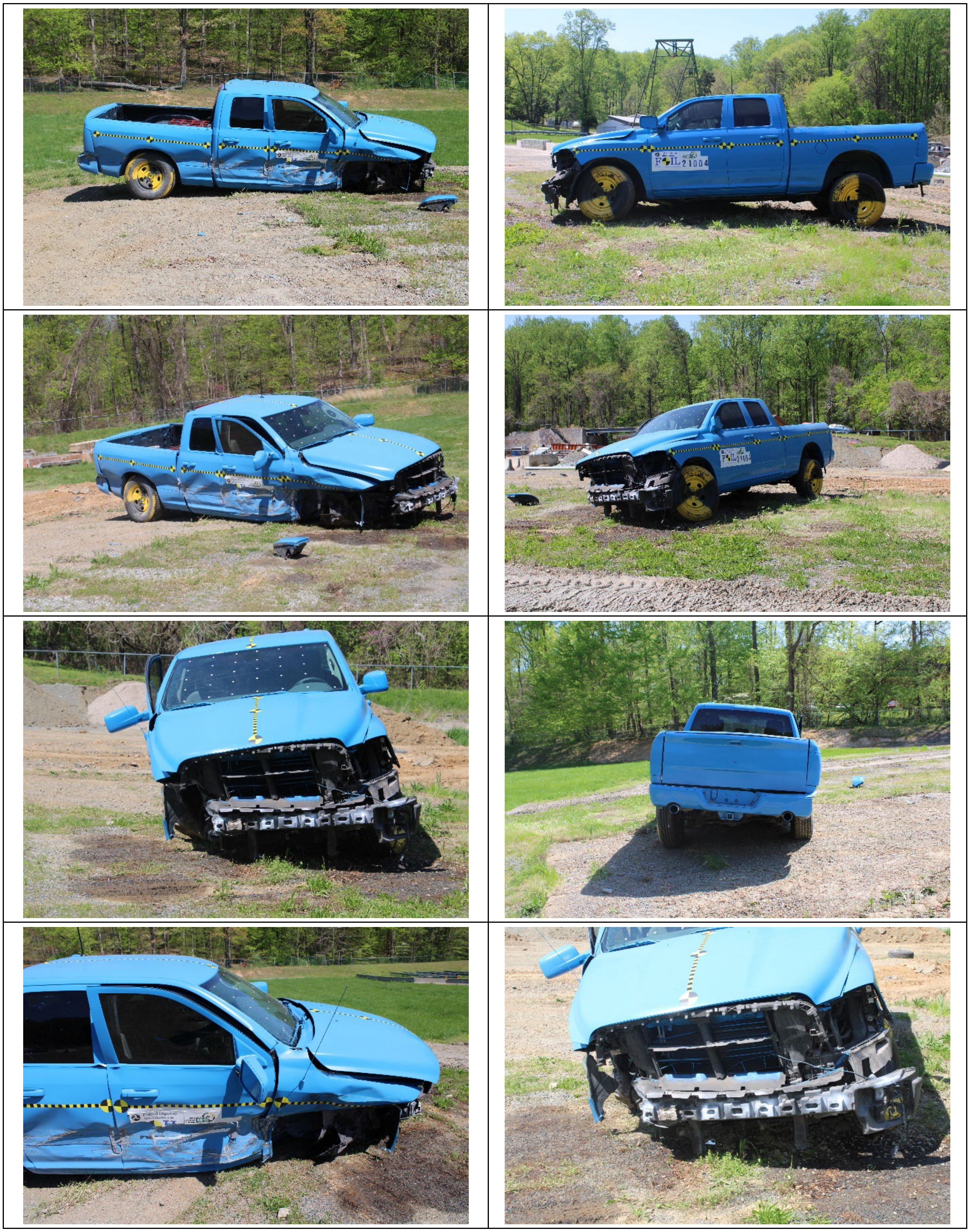


Figure 13. Views of Damage to the Vehicle Resulting from the Crash Test

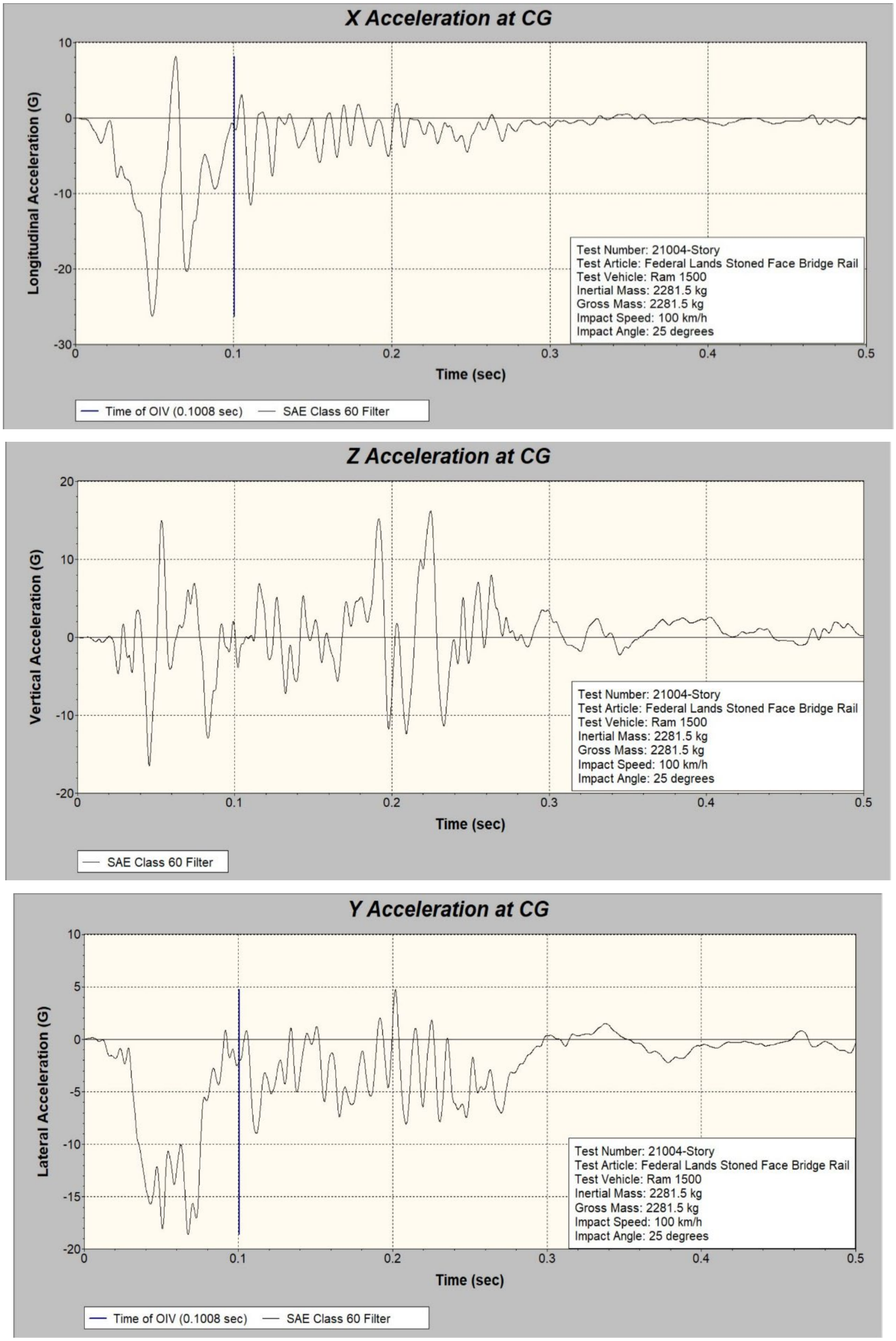


Figure 14. FOIL Test 21004 X-, Y-, and Z- Accelerations at CG

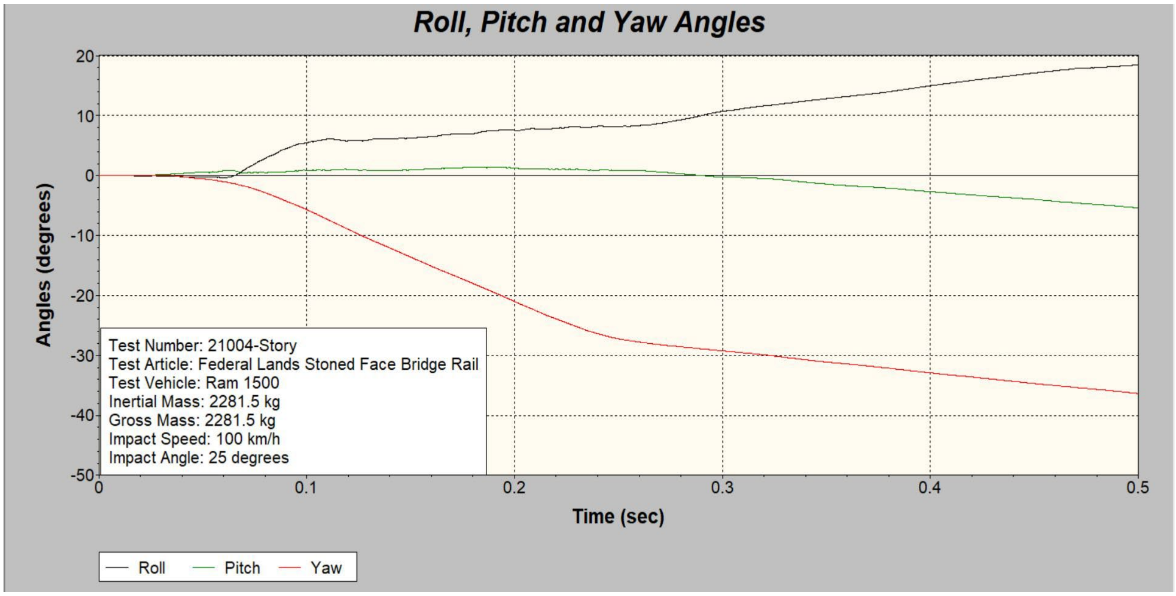


Figure 15. FOIL Test 21004 Measured Roll-, Pitch-, and Yaw-Angle Plots

5.4. MASH Evaluation

The results of FOIL Test 21004 provide one step toward determining whether the SFCMB meets the MASH criteria, as required to deem it acceptable for use on the highways. **Error! Reference source not found.** provides the critical occupant risk data captured. These metrics were derived from the accelerometer, located at the vehicle center of gravity.

Table 4. Occupant-Risk Factors—FOIL Test 21004.

Occupant Risk Factor		Value
Occupant Impact Velocity (OIV) ft/s	Longitudinal	7.3
	Lateral	6.8
Occupant Ridedown Acceleration G	Longitudinal	-5.7
	Lateral	-6.7
Theoretical Head Impact Velocity (THIV) km/hr		35.8
Post Head Deceleration (PHD) G		8.7
Acceleration Severity Index (ASI)		1.72
Maximum 50-ms Moving Average	Longitudinal	-11.3
	Lateral	-12.6
	Vertical	2.9
Maximum Roll, Pitch, and Yaw Angles degrees	Roll	18.4
	Pitch	-5.4
	Yaw	-36.4

Table 5 cites the specific MASH requirements for Test 3-11 in the first column. The Results column indicates the specific conclusions drawn from the test outcome. In all cases, a PASS was considered appropriate.

Table 5. Review of MASH Results for FOIL Test 21004

MASH Requirement	Results	Status
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.	The SFCB smoothly redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation.	*Pass*
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.	Scrapes and slight gouges in the stone face of the SFCB were apparent, but none appeared to cracked or dislodged. There was no intrusions or penetration or potential for such to the occupant compartment.	*Pass*
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH	All deformations and intrusions were less than the critical MASH numbers	*Pass*
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75°.	The vehicle remained upright during and after the collision event. Maximum roll & pitch angles were 18.4 and -5.4 degrees, respectively.	*Pass*
H. Longitudinal & Lateral Occupant Impact Velocities should satisfy the following: Preferred:_30 ft/s Maximum: 40 ft/s	Longitudinal occupant impact velocity was 7.3 ft/s, and lateral occupant impact velocity was 6.8 ft/s.	*Pass*
I. Longitudinal and Lateral Occupant Ridedown Accelerations should satisfy the following: Preferred 15.0 G t Maximum: 20.49 G	Maximum longitudinal occupant ridedown acceleration was -5.7 G, and maximum lateral occupant ridedown acceleration was -6.7 G.	*Pass*
For redirective devices, it is desirable that the vehicle be smoothly redirected and exit the barrier within the "exit box" criteria (not less than 32.8 ft), and should be documented. Also report vehicle rebound distance and velocity for crash cushions.	The vehicle exited the installation, skidding to a stop. No significant rebound occurred.	*Pass*

6.0. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

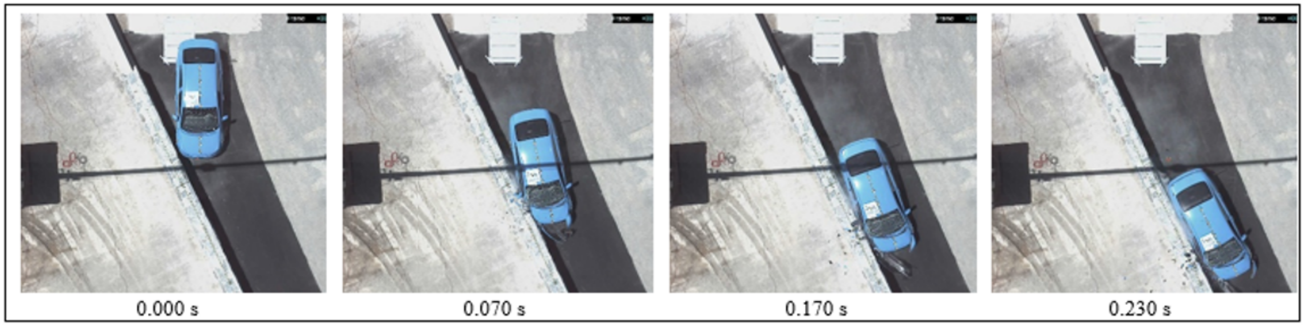
The Summary Sheet for FOIL Test 21004 (MASH 3-11) is provided in Figure 16. The test was deemed successful. It showed that the system design, functioned as expected in one of the most critical conditions by being able to smoothly redirect the vehicle. It was able to do so without significant vehicle instability. The rail remained connected, with little damage, and functioned as designed to redirect the vehicle (including away from the concrete parapet). The crucial occupant-risk values were in acceptable ranges, indicating that occupants would likely survive the crash. Parts were contained to not create other risks.

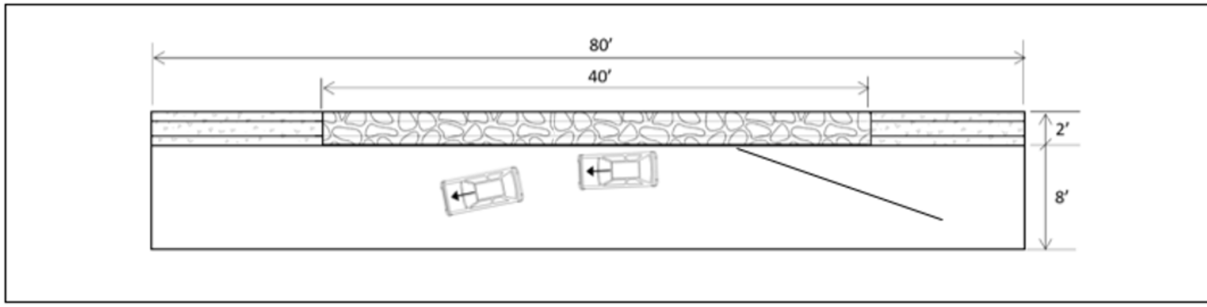
6.2 Recommendations

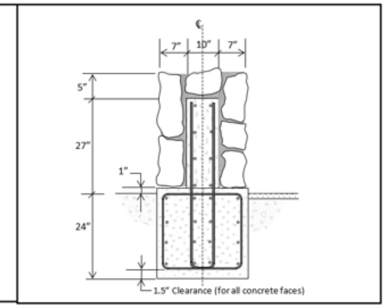
Given the success of this critical test, researchers proceeded to prepare and execute the other required test of the system with a small car.

7.0. REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO). *Manual for Assessment of Safety Hardware* (MASH). AASHTO. Washington, D.C., 2016.
2. American Association of State Highway and Transportation Officials (AASHTO). *Roadside Design Guide*, AASHTO. Washington, D.C., 2011.
3. American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*, Washington, D.C., 2004.







General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 21005
- Date 04/27/2021

Test Article:
- Type............................. Stone Faced Bridge Rail Design
  - Name or Mfg .... Generic
- Installation Length .... 80 ft. (24.4 m) Concrete
  40 ft.(12.2 m) Stone
- Key Elements .... Concrete, Stone, 21a Soil
  - Size/dimension .... 32 in (813 mm) stone wall height
  - Material .... Carderock Stone
  - Other .... Concrete foundation and wall

Test Vehicle:
- Type/Designation 1100C
- Make and Model .... 2015 Kia Rio
  - VIN No. KNADM4A38F6515059
  - Curb .... 2522 lb (1144 kg)
- Test Inertial .... 2476 lb (1123 kg)
- Gross Static .... 2641 lb (1198. kg)

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

Impact Conditions:
- Speed........................... 60.5 mph (97.6 km/hr)
- Angle........................... 25 degrees
- Location/Orientation .... Vehicle right front corner aligned with the front face of the barrier 3.3 ft. (1.0 m) upstream from expansion joint.

Exit Conditions:
- Speed .... 43.0 mph (69.2 km/hr)
- Angle .... 3.5 degrees
- Exit Box Criterion .... Vehicle exited within box

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

Occupant Risk:
- Longitudinal OIV .... 24.0 ft/s (8.1 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 22.3 ft/s (8.5 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal ORA ...... -5.5 G ≤ 20.49 G
- Lateral ORA .... -8.6 G ≤ 20.49 G
- THIV .... 38.3 ft/s (26.2 mph) 11.7 m/s (42.1 km/hr)
- PHD .... 9.5 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0 in (cm)
- Dynamic .... 0.8 in (cm)
- Working Width .... 0.8 in (cm)

Vehicle Damage:
- VDS 1RFQ5
- CDC 01RYEW3
- Max. Deformation
  - Exterior .... 8.4 in (21.3 cm)
  - Windshield .... 2.1 in (7.8 cm)
  - Occupant Comp. ...... 3.6 in (9.1 cm)

Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle........... 10.8 deg ≤ 75 deg
- Max. Pitch Angle .... 4.0 deg ≤ 75 deg
- Max. Yaw Angle .... 28.5 deg

Overall Performance: Pass

Figure 16. FOIL Test 21004 Summary Sheet

APPENDIX B: MASH TEST 3-10 of a Median Stone-Faced Concrete Barrier

Authors:

Dhafer Marzougui, Christopher Story, Kenneth Opiela
Fadi Tahan, and Cing-Dao (Steve) Kan
Center for Collision Safety and Analysis
George Mason University

FOIL Test No. 21005

CCSA Report No. R-22001B

Sponsored by:
National Park Service,
Eastern Federal Lands Branch, FHWA
and

Office of Safety Research & Development
Turner Fairbank Highway Research Center
Federal Highway Administration
U.S. Department of Transportation

January 2022

DISCLAIMER

ACKNOWLEDGEMENTS

This study was sponsored by the National Park Service (NPS), Eastern Federal Lands (EFL) Branch of FHWA, in cooperation with Office of Safety Research & Development at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA), of the US Department of Transportation (US DOT).

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2002)

SUMMARY

This report documents the procedures and result of a crash test described below:

Report Title	**MASH TEST 3-10 of a Median Stone-Faced Concrete Barrier – FOIL Crash Test 21005**
Test Type	Full-Scale Crash Test: Vehicle Impacting Barrier
What is Tested	Median Stone-Faced Concrete Barrier
Purpose/Objective	Ascertain that a concrete barrier with stone-facing that can be used as a median barrier or bridge rail offering an aesthetic appearance consistent with the objectives for park service roads can also meet the national crashworthiness requirements under MASH at Test Level 3.
Impacting Item/Vehicle	1100C MASH small-car vehicle.
Impact Speed and Conditions	Speed 62 mph, centerline of the vehicle aligned 25 degrees to the concrete median barrier having a natural stone-face along the face of the barrier.
Test Procedures and Standards Information	*Manual for Assessing Safety Hardware* (MASH), 2016 Edition
Test Criteria	TL-3 Impact Rating for Condition 3-10
Test Number	FOIL Test No. 21005
Test Date	February 27, 2021
Test Location	Federal Outdoor Impact Laboratory (FOIL) Turner-Fairbank Highway Research Center (TFHRC) FHWA U.S. DOT 6300 Georgetown Pike, McLean, VA 22101-2296
Conducted by	Center for Collision Analyses and Safety (CCSA) George Mason University (GMU) 4087 University Drive, Fairfax, VA 22030
Report Authors	Dhafer Marzougui, Christopher Story, Kenneth Opiela Fadi Tahan, and Cing-Dao (Steve) Kan
Test Results Summary	MASH Test 3-10. Test 21005. Small was smoothly redirected, without significant vehicle instability. PASSED MASH requirements.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0. INTRODUCTION

1.1. Problem Statement

The National Park Service (NPS) objectives include providing access in scenic or historic areas in a manner the compliment the environment. Many NPS roads have become important links in growing metropolitan areas and therefore carry greater volumes of traffic at higher speeds than originally conceived. In the interests meeting safety and aesthetic goals, enhanced designs for RSH have evolved. The increasing emphasis on agencies to assure the highest level of highway safety under guidelines such as the Manual for Assessing Safety Hardware (MASH) provided the impetus for this research.

Most concrete barriers used as RSH feature a smooth face, except for the necessary expansion or connection joints. The relatively smooth concrete surface readily allows an impacting vehicle to slide along the barrier as speed and impact energy are dispersed. The rough, natural stone face of the Stone-Faced Concrete Barrier (SFCB) developed by EFL obviously results in greater resistance to sliding along the barrier. This raised questions about its safety efficacy. Due to the limited testing and evaluation efforts insights on the effects of barrier surface treatments on the performance of barriers like the SFCB, computer simulations and crash testing were performed to confirm that the desired MASH requirements including post-impact effects are achieved.

1.2. Study Objectives

This report documents the findings of one test conducted in a larger effort focused on testing the efficacy of the Stone-faced Concrete Barriers (SFCB) used on highways under the jurisdiction of the Federal Lands and National Park Service. Aesthetic barriers such as the rough stone-faced walls and steel-backed timber (STB) guardrail have been developed and tested for use in parks and other historic or scenic areas. The growth of urban areas has some roads, where these barriers are being used, carrying greater amounts of traffic at higher speeds than originally anticipated. This effort is aimed at determining whether the typical stone-faced concrete barriers that are widely used on roads under the jurisdiction of the National Park Service (NPS) meet the latest safety requirements (MASH 2016)

2.0. SYSTEM DETAILS

2.1. Test Article and Installation Details

Figure 1 shows the design and installation details for SFCMB that was tested for MASH TL-3 requirements under this project. The figure depicts a median barrier design with a vertical face that features:

- A reinforced concrete core that provides a 26” high and 10” wide barrier vertical element over a 24” wide and 25” deep foundation. Loop and u-shaped rebar element are tied to longitudinal rebars (eight in the upright element and sixteen in the base.
- Concrete for the barrier should be 4500 psi strength.
- Stones that are as large as possible and no more than 3” deep are mortared to the concrete vertical element. Mortar joints are specified to be no more than 2” wide and protrusion should be limited to 0.5 inches.

A section of the SFCMB was constructed following these design requirements at the FHWA Federal Outdoor Impact Lab (FOIL) to conduct the necessary MASH tests on the crash-worthiness of these barriers. Figure 2 shows the planned set-up for MASH Test 3-10.

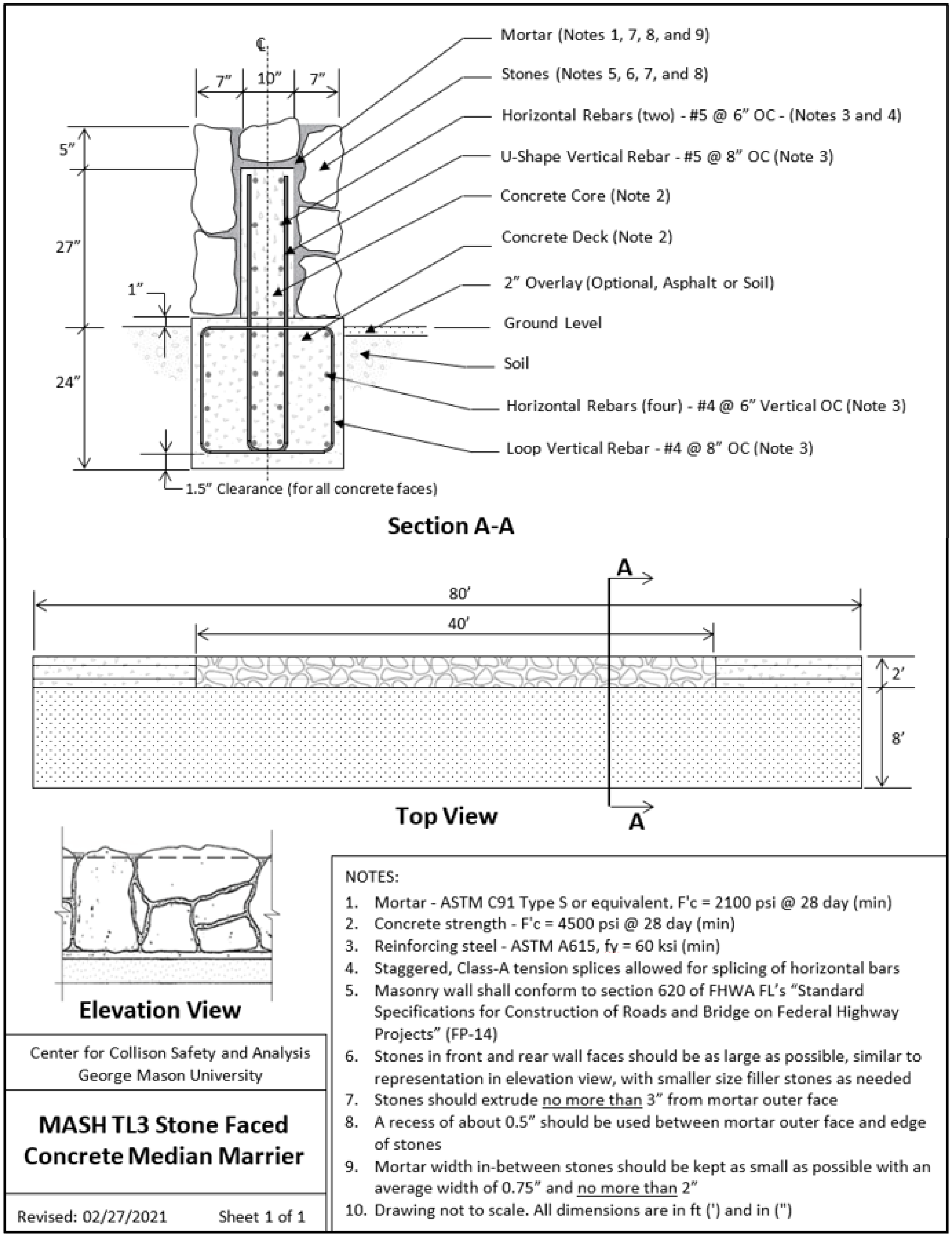


Figure 1. Median SFCB Test Installation Design Features

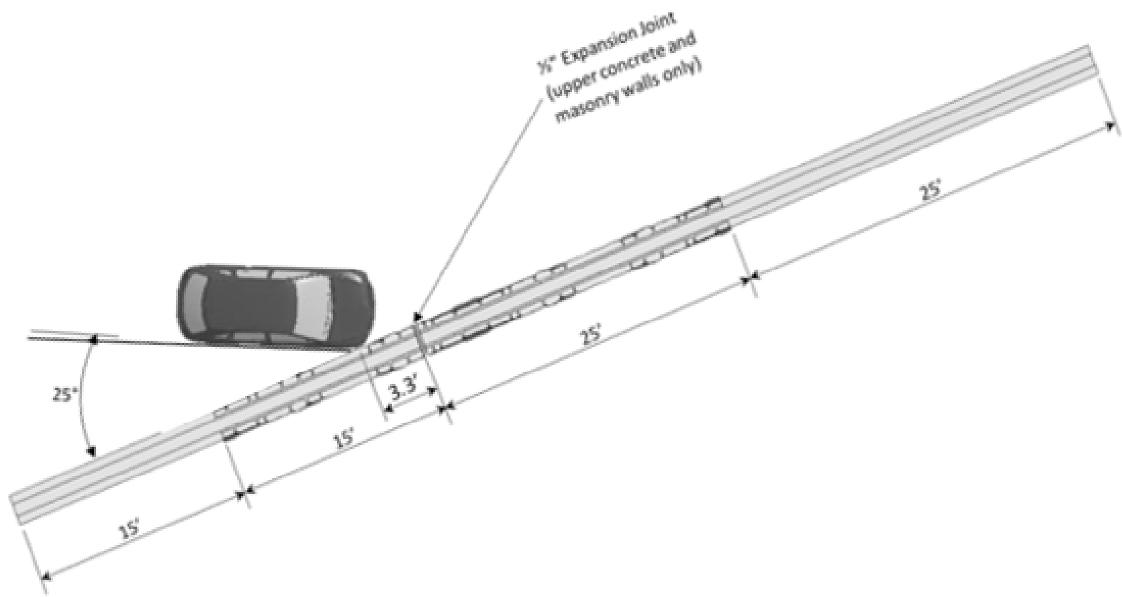


Figure 2. Median SFCB Test Installation Diagram for MASH Test 3-10.

2.2. Material Specifications

This system was fabricated using standard roadside safety hardware elements, as described above. The materials and hardware elements delivered met the basic standards in accordance with suppliers or certifications that are on file at the FOIL Office.

2.3. Soil Conditions

The foundation for the SFCB was laid in the designated positions in the impact area of the FOIL, as depicted. The soils at the FOIL have been classified as typical VDOT materials. Soil tests confirmed the compaction and moisture content of the soils were in appropriate ranges consistent with previous testing at the FOIL. These tests, conducted with a nuclear density device, involved repeated measures at multiple positions around the test installation. The FOIL Summary Report documents these results. Independent soil analyses by Froehling & Robertson, Inc. are on file at the FOIL Office**.**

3.0. MASH TEST REQUIREMENTS AND ACCEPTANCE CRITERIA

As noted in Table 1 below, researchers determined that overall evaluation of this device would require successful passing of two MASH tests. This report only provides the background and results for MASH Test 3-10 (FOIL Test 21005). Test 3-10 is intended to determine the barrier's capacity for containing and/or redirecting the small vehicle. All tests were setup and executed according to prescribed FOIL protocols (including facility ISO requirements) and MASH standards. These are individually documented in Test Reports (following MASH requirements). The Table 1 reflects variations in vehicles, speed, and angles for the planned tests.

Table 1. MASH Tests Conducted for the Stone-Faced Concrete Median Barrier (SFCMB)

Test Number	Date	MASH Test	Vehicle	Impact Speed	Impact Angle	Outcome
21004	04/20/21	3-11	Pickup Truck	100 km/hr	25	Pass
21005	04/27/21	3-10	Small Sedan	100 km/hr	25	Pass

Three criteria must be met under MASH requirements for Structural Adequacy, Occupant Risk, and Vehicle Trajectory. The specific requirements for these criteria are noted in Table 2.

Table 2. Test 3-10 Evaluation Requirements by Category.

Evaluation Category	Requirement
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 (roof ≤4.0 in.; windshield = ≤3.0 in.; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 in.; forward of A-pillar ≤12.0 in.; front side door area above seat ≤9.0 in.; front side door below seat ≤12.0 in.; floor pan/transmission tunnel area ≤12.0 in.).
	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 • **Preferred** 30 ft/s **Maximum:** 40 ft/s
	I. Occupant ridedown accelerations should satisfy the following: • Longitudinal and Lateral Occupant Ridedown Accelerations • **Preferred:** 15.0 G **Maximum:** 20.49 G
Vehicle Trajectory	For redirective devices, the vehicle should be smoothly redirected and exit the barrier within the "exit box" criteria (not less than 32.8 ft); document all tests. Vehicle rebound distance and velocity for crash cushions.

4.0. TEST CONDITIONS

4.1. FOIL Test Facility

All testing on this system was performed at the FOIL. The FOIL is an ISO17025-accredited (Cert. # AT-1565) research facility used to support FHWA Safety Research and Development programs and other federal security initiatives. ISO 17025 identifies high technical competence and management system requirements that guarantee test results. It demonstrates the FOIL's commitment to operational efficiency and quality management practices and verifies the quality, capability, and expertise of the FOIL. The FOIL is a multifaceted impact-testing facility, primarily designed to test the impacts of vehicles with roadside safety hardware, in accordance with the MASH guidelines and standards.

4.2. Vehicle Tow and Guidance Procedures

A specially designed FOIL hydraulic-propulsion system pulls the test vehicles into the barriers. The vehicles are accelerated on a 220 ft concrete track. The propulsion system is capable of pulling a 17,637 lbs. vehicle to over 50 mph. The 2270P test vehicle can be brought to speeds in excess of 70 mph. The test vehicles are released into a 160 x 320 ft runout area. Barriers up to 450 ft in length (usually at 25 degree relative to the track) can be installed in the runout area at the end of the track. Figure 4 provides an aerial view of the FOIL facility.

Figure 3. Aerial View of FHWA FOIL Layout

For the SFCB tests, the system was placed at an angle relative to the FOIL track to achieve the desired impact point and angle with the system. The system was installed adjacent to end of the track so the vehicle could be freewheeling and impact at the desired speed and point. Figure 1 (above) depicted the orientations of the barrier relative to the track of the vehicle (which followed the alignment of the FOIL accelerator). The vehicle was released from the accelerator at a point that allowed it to be "free-wheeling" at the desired impact velocity.

4.3. Test Vehicle Preparation

MASH Test 3-10 involved a test with a MASH 1100C vehicle impacting the test article at a speed of 62 mph (100.0 km/h) and an angle of 25.0 degrees relative to the traffic face of the barrier. The target impact point was hit by the front right fender of the car just downstream of the beginning from the section of the concrete barrier to which stone rumble had been attached with mortar (following the specifications noted in Figure 1). A 2015 Kia Rio sedan was used in the test. It weighed 1123kg after being prepared for the test following standard procedures to drain fluids, take accurate measurements of the vehicle, weight, tires, and related features. Vehicles are typically painted blue to maximize the visibility of the impact outcomes in the multiple video cameras setup for each test.

4.4. Data Acquisition Systems

4.4.1. Vehicle Instrumentation and Data Processing

Accelerometers, rate transducers, and speed measuring devices captured the vehicle and barrier responses during impact. Two tri-axial accelerometers mounted at the vehicle center of gravity measured the x-, y-, and z-accelerations of the vehicle. This data was used to compute the occupant ride-down acceleration and occupant-impact velocities. Additionally, two tri-axial rate transducers measured vehicle roll, pitch, and yaw. Contact switches installed on the vehicle and test article synchronized time zero for the sensor data and high-speed video imagery.

4.4.2. Photographic Instrumentation and Data Processing

Eight high-speed cameras were 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 different locations surrounding the impact region to capture left, right, front, rear and isometric views of the crash event. These images are downloaded immediately after the test to allow detailed scrutiny of the crash event and behavior of the barrier in slow motion.

4.5. Test Set-up Conditions

4.5.1. Test Vehicle

Figure 4 shows the 2015 Kia Rio sedan was used for the crash test. Test inertial and gross static weight of the vehicle were both 1123 kg. The height to the lower and upper edge of the vehicle bumper was 46.8 cm. and 39.8 cm. respectively. The height to the vehicle's center of gravity was 54.2 cm. Researchers used the cable reverse tow and guidance system to direct the vehicle into the installation that then released the vehicle in a freewheeling and unrestrained mode just prior to impact.

4.5.2. Test Article

Figure 5 shows several views of the installed SFCB prior to the test. An 80' length of reinforced concrete barrier wall and foundation was constructed at the FOIL following the specifications cited in Figure 2. The median barrier configuration of a stone-facing was applied to 40 feet of the barrier. This was determined to be an adequate length to cover the vehicle-to-SFCMB interface based upon the simulation studies. The vehicle was expected to slide over the random stone pattern for a short distance before being redirected away from the barrier. The random pattern of the stonework in apparent in the various views. During installation, the specifications for the width of separations between the stones and the depth of the mortar followed the requirements cited in Figure 1. Figure 6 shows eight views of the test vehicle in proximity to the test article to document the static interface of vehicle and the system elements. It can be noted that the front bumper impacts the barrier at mid-height. Projecting a line along the stone face indicates that various sizes of stones would interact with the bumper and the side of the vehicle during the crash. Pictures documenting the construction of the test article are available along with any related compaction, material strengths, or other features of the test article that may become relevant.

Figure 4. Test 21005 Pre-impact Photos and Setup of Test Vehicle

Figure 5. Test 21005 Pre-impact Pictures of SFCB

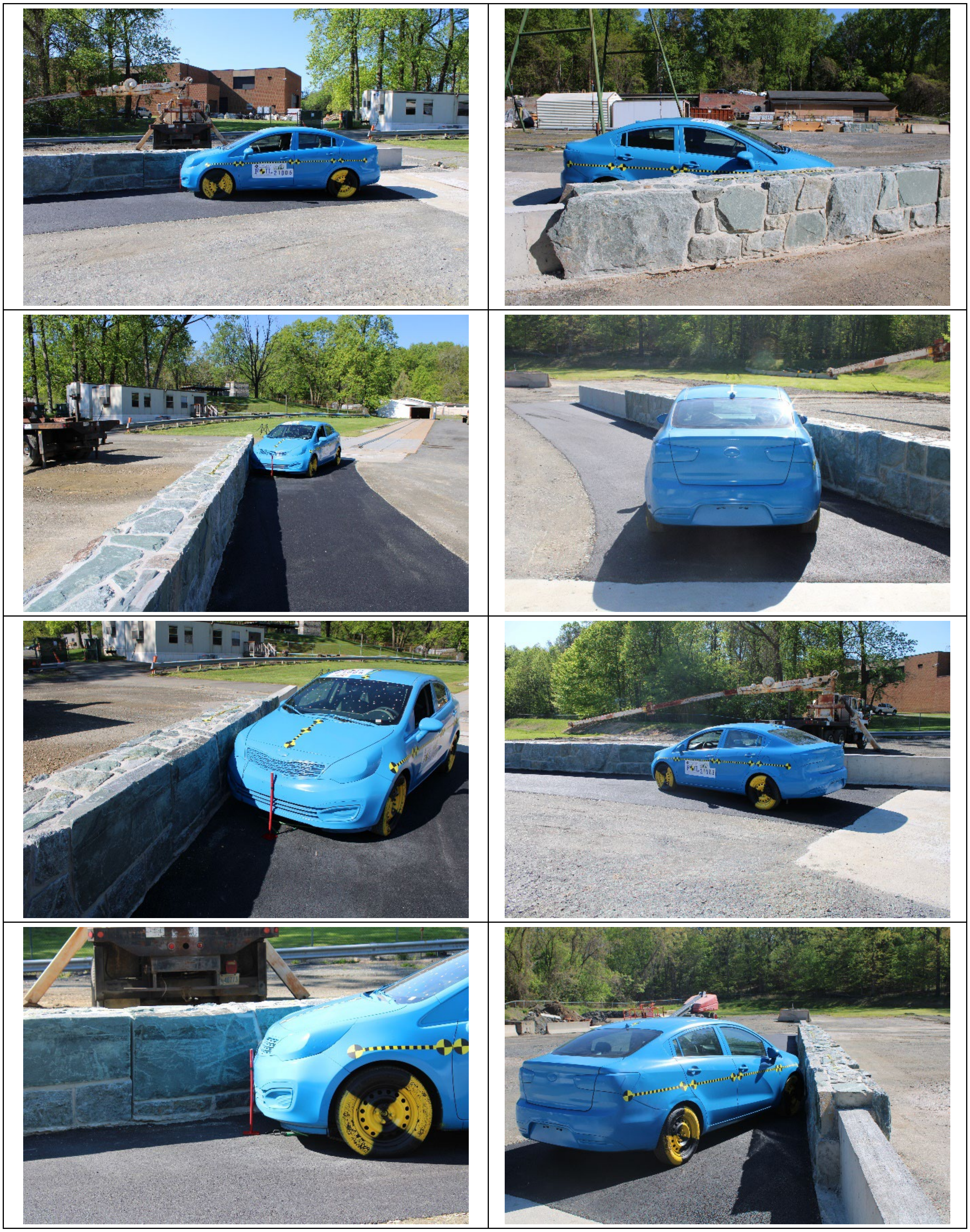


Figure 6. Test 21005 Pre-impact Views of Test Vehicle Relative to SFCB

5.0. CRASH TEST DOCUMENTATION

5.1. Test Designation and Impact Conditions

For Test 21005 to certify that the SFCB would meet the requirements for MASH Test 3-10, the designated test vehicle needed to reach the planned impact speed and contact at the designated point aligned with the stone-faced section of the 80-foot test length of concrete barrier (test article) as shown in Figure 1. The 2015 Kia Rio test vehicle was accelerated on the FOIL track. It was traveling at a speed of 100 km/hr (62.5 mph), when it contacted the system at an impact angle of 25 degrees at the planned impact point of the concrete barrier. Figure 2 showed the test set-up for this impact.

5.2. FOIL Crash Test 21005 Outcome (for MASH Test 3-10)

5.2.1. General Conditions at Time of Test

The test was performed on February 27, 2021, at 1:00 p.m. Weather conditions at the time of testing were as follows:

- Temperature: 85 degrees
- Relative Humidity: 49%
- Wind speed and direction: 12 mph - south
- Wind Chill: N/A
- Visibility: 10.0 miles
- Sky Condition: Sunny
- Surface Condition: Dry
- Three-day Precipitation History: <0.01 inches

These were considered to be ideal conditions for testing and have negligible effects on the outcome of the test.

5.2.2. Crash Test Observations

The seven, high-speed, digital cameras deployed for the test captured various, continuous views of the crash event to record the effects of the barrier stone face on the interaction with the vehicle and its redirection and reduction of impact velocity.

A series of overhead views captured from one camera are shown in Figure 7. It can be seen that the initial contact occurred at time 0.00 seconds (as planned) with the right front corner (bumper) of the vehicle. [Note: the shadow of the overhead camera boom provides a useful benchmark.] The path of the vehicle began to alter and by 0.060 seconds as the right front fender had crushed to the point at the front of the windshield. That crush continued and by 0.230 seconds the vehicle was diverted and sliding parallel to the face of the barrier and starting to move away from it. The photos show no evidence of damage to the windshield over that time. The vehicle appears to be sliding along the barrier slightly moving away from it as it goes out of view 0.400 seconds after initial contact from this vantage point. It would appear that the redirection was relatively smooth.

Figure 8 shows views of the impact from the ground level camera on the left (driver's) side. There appears to be a little pitch or roll of the vehicle, but it is obscured by the dust. The dust and distance from the camera make it hard to effectively discern any adverse effects.

Figure 9 shows the impact from the downstream ground-level camera. It provides better views of the damage to the right front fender and front. It appears that pieces of the grill, front bumper, and fender are loose and being dragged along. It provides a better view of the limited roll and pitch that occurred.

Figures 10 and 11 show various views of the damage to the test vehicle and barrier installation that occurred in the test.

Table 3 lists some of the events that occurred over the duration of the crash. Note: These various views of the crash indicate that the vehicle never lost contact with the system after first impact and came shows various views of the vehicle and system after impact.

Table 3. Events during FOIL Test 21005

TIME (s)	EVENT
0.000	Vehicle front right bumper contacts the SFCMB at 63 mph.
0.170	Vehicle sliding fully parallel along the barrier have moved the length of the vehicle along the barrier. It appears that the right side of the vehicle is almost fully in contact with the barrier. No noticeable deflection of the barrier, crush of the passenger compartment, or damage to the windshield. Very little yaw, pitch, or roll noted.
0.230	Some movement of the vehicle away (rebound) from the barrier. A slight degree of pitch and roll is noted with outside rear wheel seeming to be just off the ground.
0.260-0.800	Vehicle continues to move along the rail with slight increases in forward pitch, probably caused by the vehicle contact with the “rough” barrier face also causing damage to vehicle bumper, grill, and rights side panels.
0.800 +	Vehicle appears to end contact with the system skidding along the surface. Vehicle later comes to rest upright about 50 feet from the end of the test set-up [not seen in the sequential views] after brakes were remotely applied.

Last, Figures 12 and 13 provided the digital trace results from accelerometers installed at the CG of the test vehicle. These graphs show x, y, and z accelerations and roll, pitch and yaw angle over the duration of the impact event. These appear typical for crash tests.

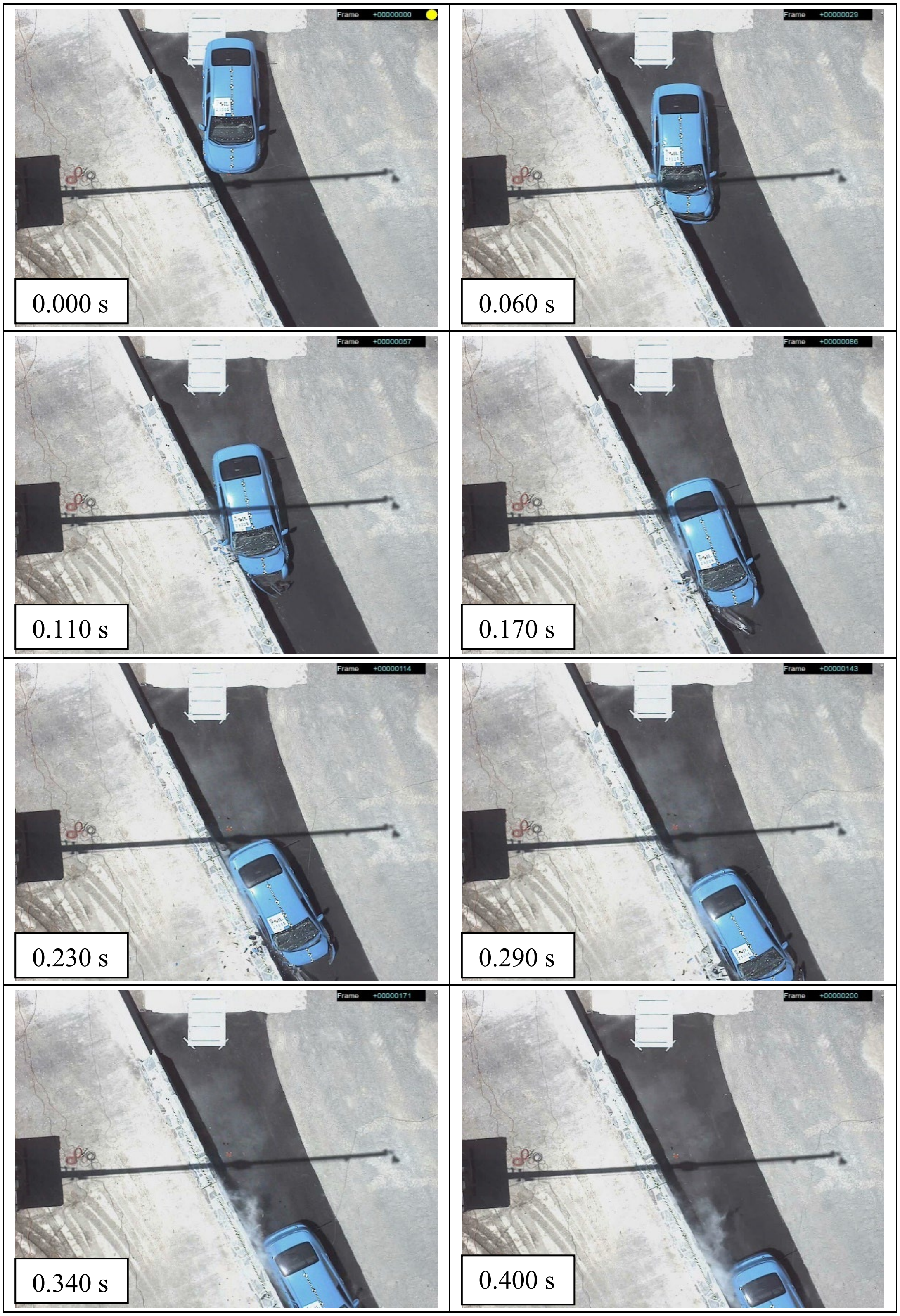


Figure 7. FOIL Test 21005 Sequential Overhead Images.

Figure 8. Test 21005 Sequential Views from Right Side Camera

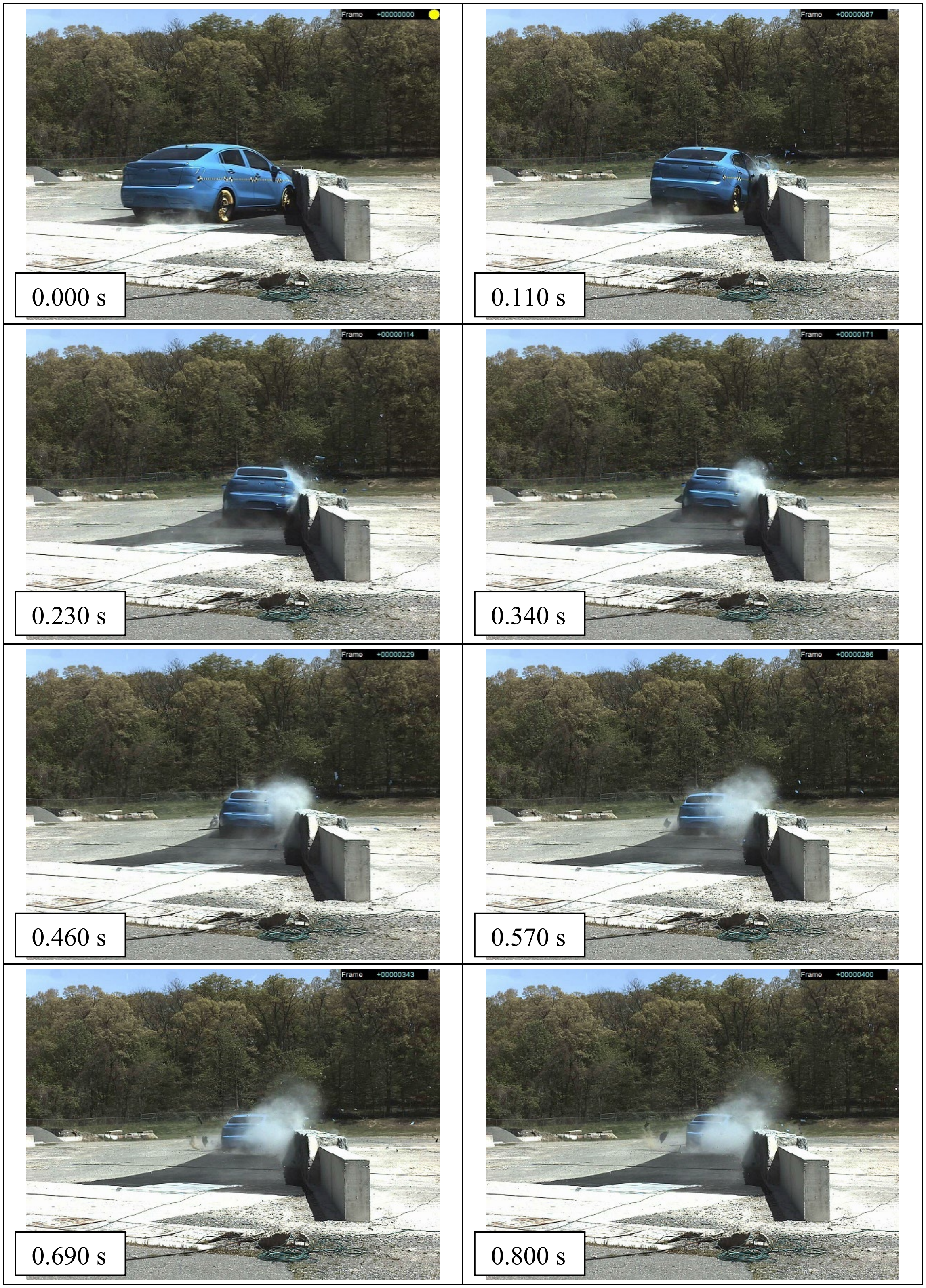


Figure 9. Test 21005 Sequential Views from Front Camera

Figure 10. Views of the SFCB Test Installation After Crash Test

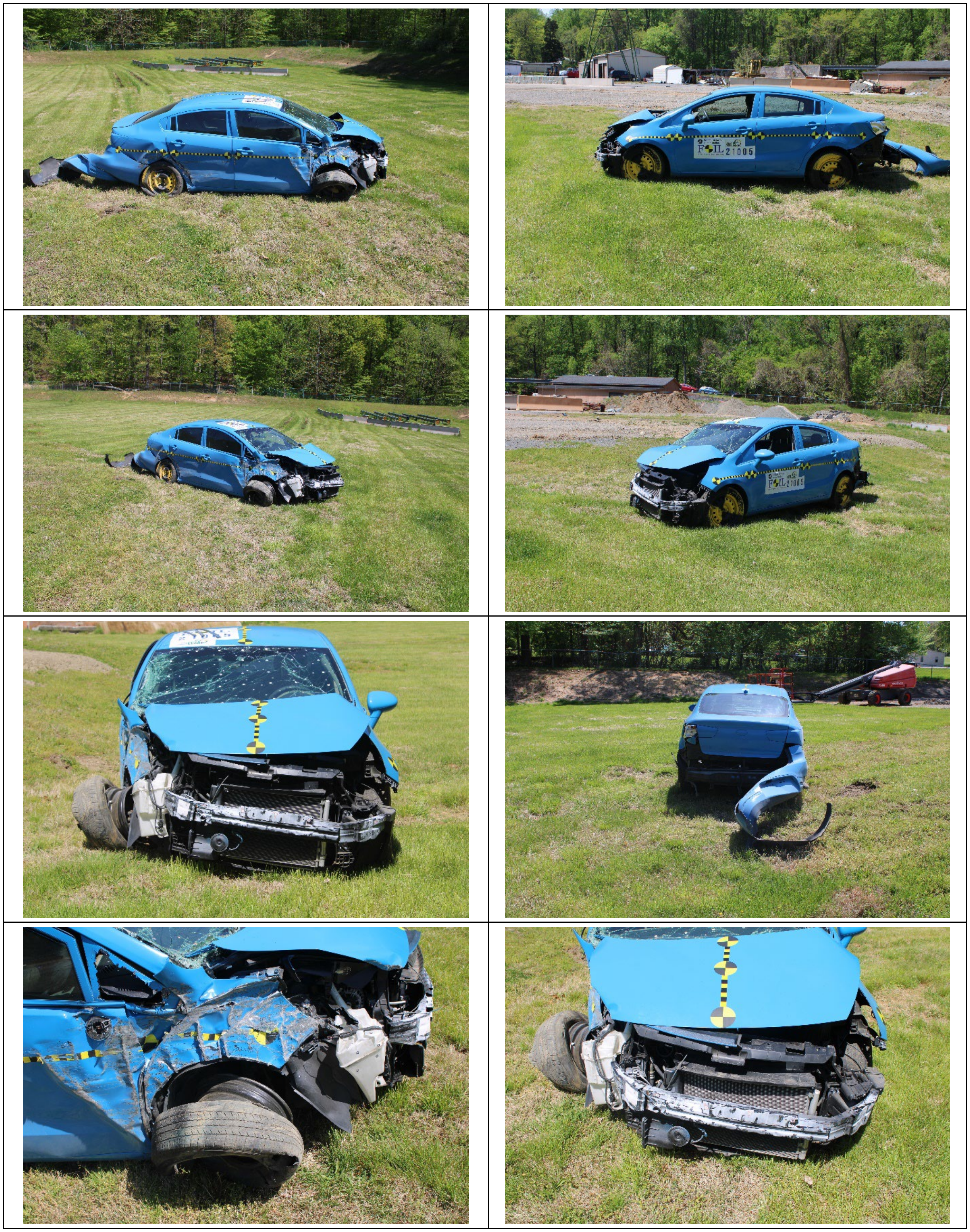
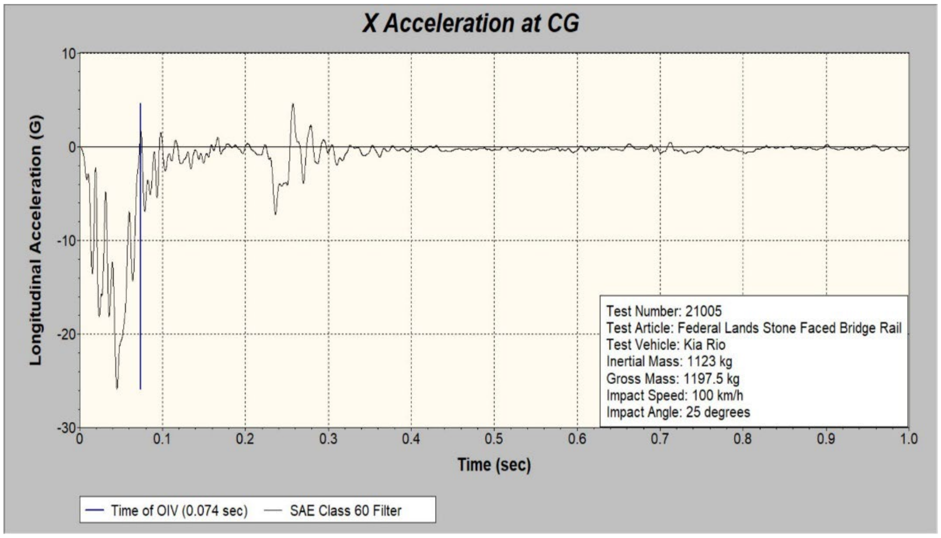
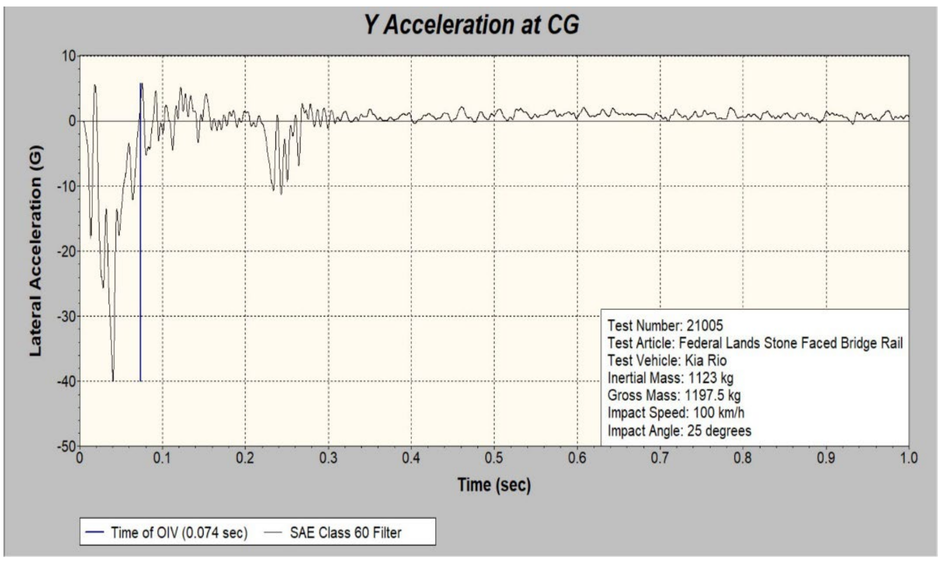


Figure 11. Views of Damage to the Vehicle Resulting from the Crash Test





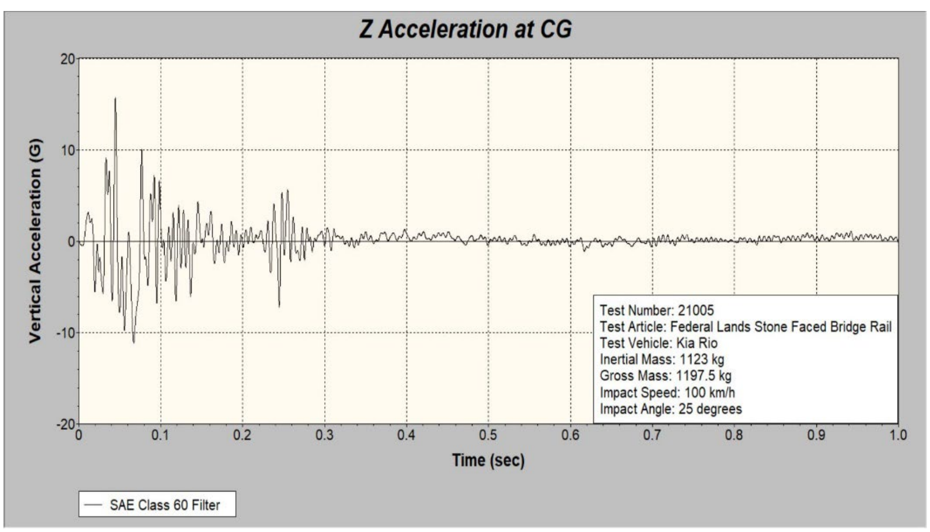


Figure 12. FOIL Test 21005 X-, Y-, and Z- Accelerations at CG.

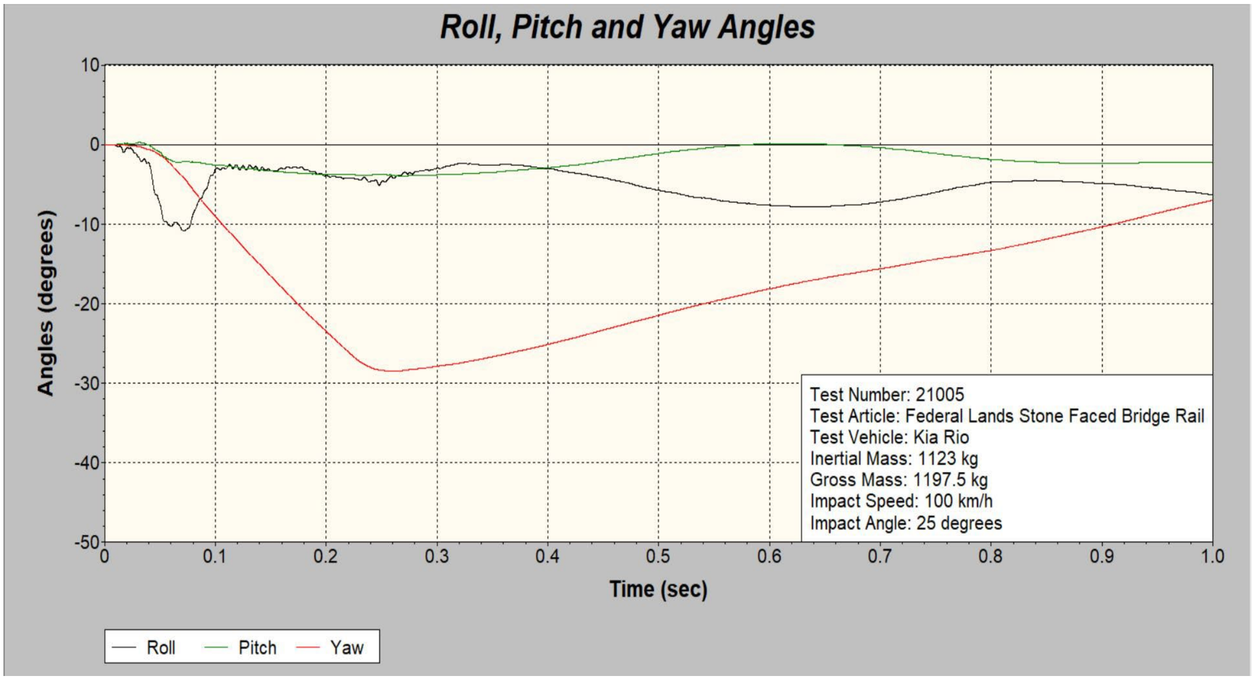


Figure 13. FOIL Test 21005 Measured Roll-, Pitch-, and Yaw-Angle Plots

5.4. MASH Evaluation

The results of FOIL Test 21005 provide one step toward determining whether the SFCB meets the MASH criteria, as required to deem it acceptable for use on the highways. Table 4 provides the critical occupant risk data captured. These metrics were derived from the accelerometer, located at the vehicle center of gravity.

Table 4. Occupant-Risk Factors—FOIL Test 21005.

Occupant Risk Factor		Value
Occupant Impact Velocity (OIV) ft/s	Longitudinal	7.3
	Lateral	6.8
Occupant Ridedown Acceleration G	Longitudinal	-5.7
	Lateral	-6.7
Theoretical Head Impact Velocity (THIV) km/hr		35.8
Post Head Deceleration (PHD) G		8.7
Acceleration Severity Index (ASI)		1.72
Maximum 50-ms Moving Average	Longitudinal	-11.3
	Lateral	-12.6
	Vertical	2.9
Maximum Roll, Pitch, and Yaw Angles degrees	Roll	18.4
	Pitch	-5.4
	Yaw	-36.4

Table 5 cites the specific MASH requirements for Test 3-10 in the first column. The Results column indicates the specific conclusions drawn from the test outcome. In all cases, a PASS was considered appropriate.

Table 5. Review of MASH Results for FOIL Test 21005

MASH Requirement	Results	Status
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.	The SFCB smoothly redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation.	*Pass*
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.	No elements of the test article penetrated or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.	*Pass*
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH	All deformations and intrusions were less than the critical MASH numbers	*Pass*
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75°.	The vehicle remained upright during and after the collision event. Maximum Roll: 10.8 deg ≤ 75 deg Maximum Pitch: 4.0 deg ≤ 75 deg	*Pass*
H. Longitudinal & Lateral Occupant Impact Velocities should satisfy the following: Preferred:_30 ft/s Maximum: 40 ft/s	Longitudinal OIV: 26.6 ft/s ≤ 40 ft/s Lateral OIV: 27.9 ft/s ≤ 40 ft/s	*Pass*
I. Longitudinal and Lateral Occupant Ridedown Accelerations should satisfy the following: Preferred 15.0 G t Maximum: 20.49 G	Longitudinal ORA: 5.5 G ≤ 20.49 G Lateral ORA: 8.6 G ≤ 20.49 G	*Pass*
For redirective devices, it is desirable that the vehicle be smoothly redirected and exit the barrier within the “exit box” criteria (not less than 32.8 ft), and should be documented. Also report vehicle rebound distance and velocity for crash cushions.	The vehicle exited the installation, skidding to a stop. No significant rebound occurred.	*Pass*

6.0. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

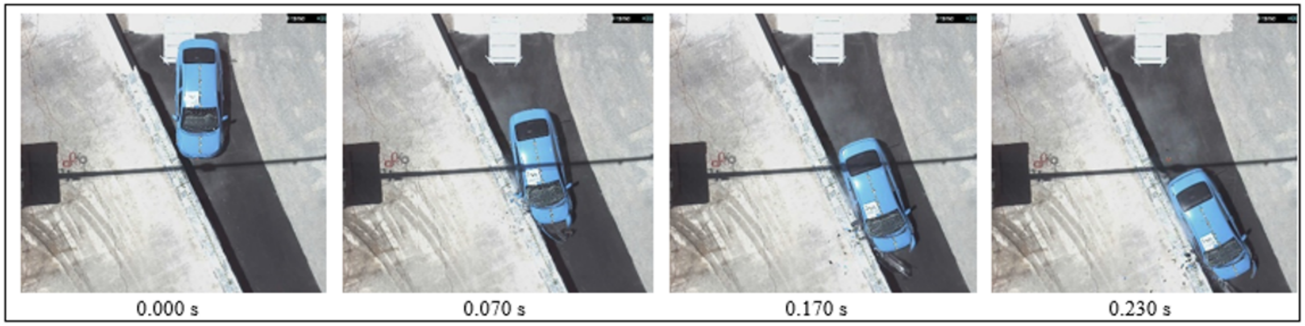
The Summary Sheet for FOIL Test 21005 (MASH 3-10) is provided in Figure 14. The test was deemed successful. It showed that the system design, functioned as expected in one of the most critical conditions by being able to smoothly redirect the vehicle. It was able to do so without significant vehicle instability. The rail remained connected, with little damage, and functioned as designed to redirect the vehicle (including away from the concrete parapet). The crucial occupant-risk values were in acceptable ranges, indicating that occupants would likely survive the crash. Parts were contained to not create other risks.

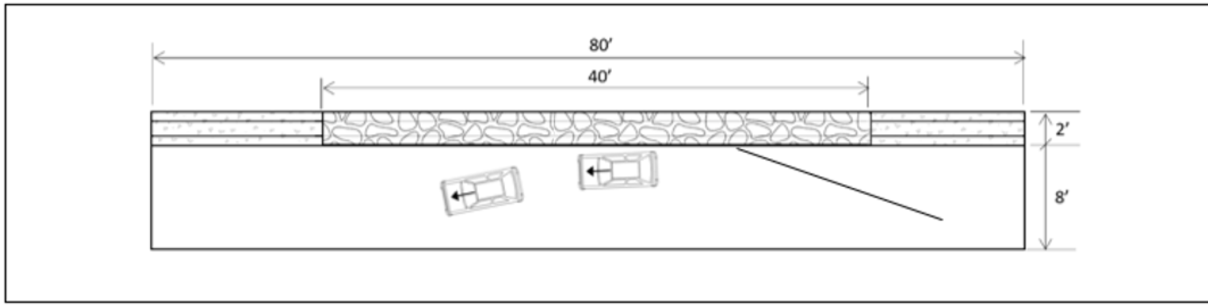
6.2 Recommendations

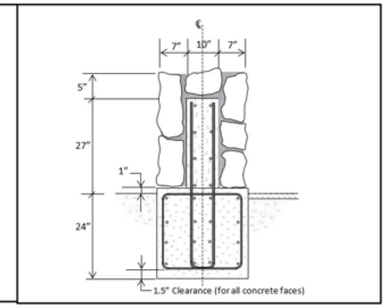
Given the success of this critical test and the previous 3-11 test, the system was found to meet the all MASH requirements for longitudinal barrier.

7.0. REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO). *Manual for Assessment of Safety Hardware* (MASH). AASHTO. Washington, D.C., 2016.
2. American Association of State Highway and Transportation Officials (AASHTO). *Roadside Design Guide*, AASHTO. Washington, D.C., 2011.
3. American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*, Washington, D.C., 2004.







General Information:
- Test Agency .... Federal Outdoor Impact Laboratory
- Test Number 21005
- Date 04/27/2021

Test Article:
- Type............................ Stone Faced Bridge Rail Design
  - Name or Mfg .... Generic
- Installation Length .... 80 ft. (24.4 m) Concrete
  40 ft.(12.2 m) Stone
- Key Elements .... Concrete, Stone, 21a Soil
  - Size/dimension .... 32 in (813 mm) stone wall height
  - Material .... Carderock Stone
  - Other .... Concrete foundation and wall

Test Vehicle:
- Type/Designation 1100C
- Make and Model .... 2015 Kia Rio
  - VIN No. KNADM4A38F6515059
  - Curb .... 2522 lb (1144 kg)
- Test Inertial .... 2476 lb (1123 kg)
- Gross Static .... 2641 lb (1198. kg)

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

Impact Conditions:
- Speed........................... 60.5 mph (97.6 km/hr)
- Angle........................... 25 degrees
- Location/Orientation .... Vehicle right front corner aligned with the front face of the barrier 3.3 ft. (1.0 m) upstream from expansion joint.

Exit Conditions:
- Speed .... 43.0 mph (69.2 km/hr)
- Angle .... 3.5 degrees
- Exit Box Criterion .... Vehicle exited within box

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

Occupant Risk:
- Longitudinal OIV .... 24.0 ft/s (8.1 m/s) ≤ 40 ft/s (12 m/s)
- Lateral OIV .... 22.3 ft/s (8.5 m/s) ≤ 40 ft/s (12 m/s)
- Longitudinal ORA ...... -5.5 G ≤ 20.49 G
- Lateral ORA .... -8.6 G ≤ 20.49 G
- THIV .... 38.3 ft/s (26.2 mph) 11.7 m/s (42.1 km/hr)
- PHD .... 9.5 G

Test Article Damage:
No significant damage to test article.

Test Article Deflections:
- Permanent Set .... 0 in (cm)
- Dynamic .... 0.8 in (cm)
- Working Width .... 0.8 in (cm)

Vehicle Damage:
- VDS 1RFQ5
- CDC 01RYEW3
- Max. Deformation
  - Exterior .... 8.4 in (21.3 cm)
  - Windshield .... 2.1 in (7.8 cm)
  - Occupant Comp. ...... 3.6 in (9.1 cm)

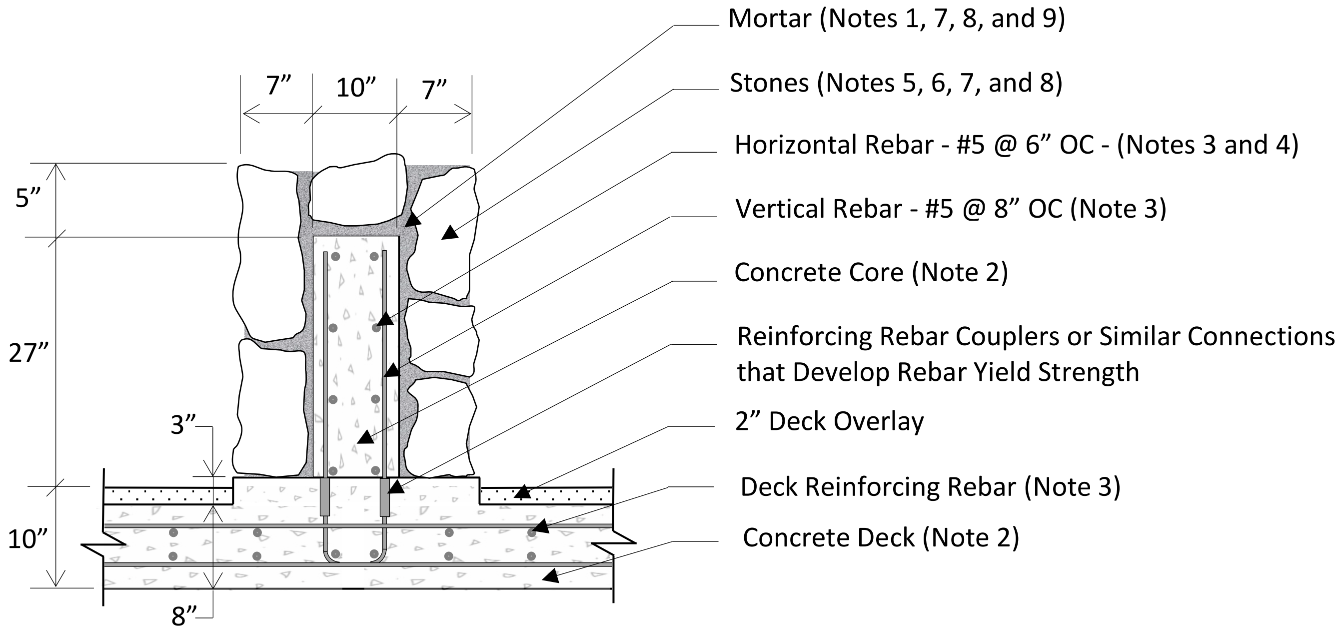
Vehicle Post-Impact Behavior:
- Vehicle Stability .... Satisfactory
- Max. Roll Angle........... 10.8 deg ≤ 75 deg
- Max. Pitch Angle .... 4.0 deg ≤ 75 deg
- Max. Yaw Angle .... 28.5 deg

Overall Performance: Pass

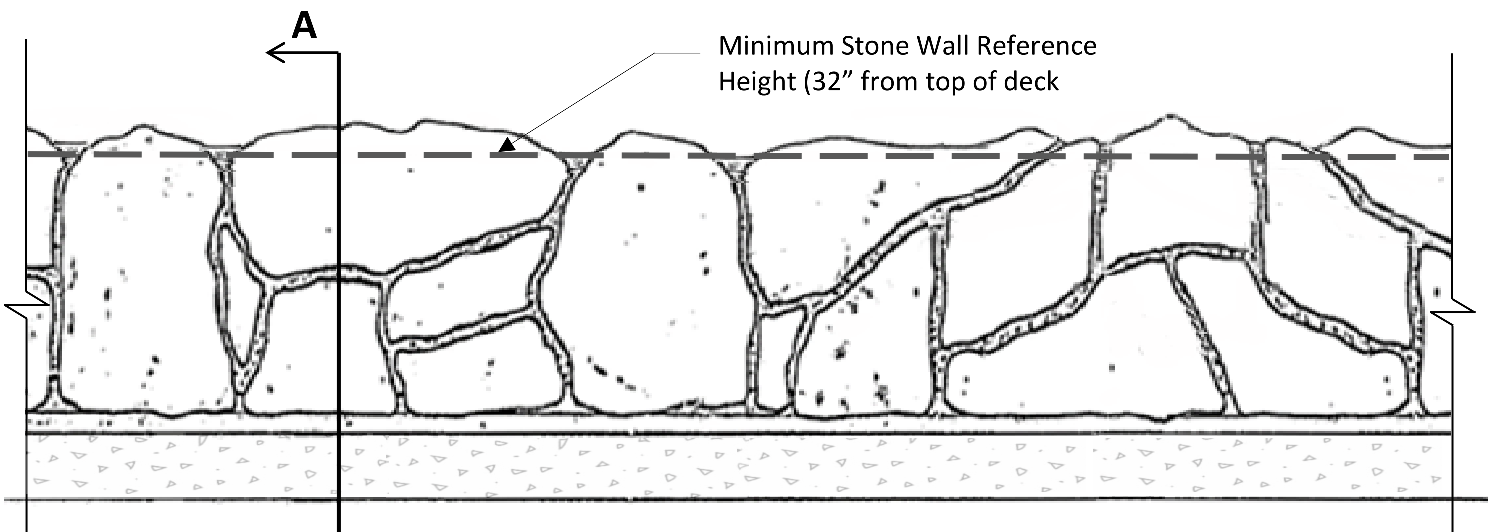
Figure 14. FOIL Test 21005 Summary Sheet

Appendix C: Design Drawings for the Stone-faced Concrete Barriers and Their Transitions

C-1: MASH TL3 Median Stone-faced Concrete Barrier



Section A-A



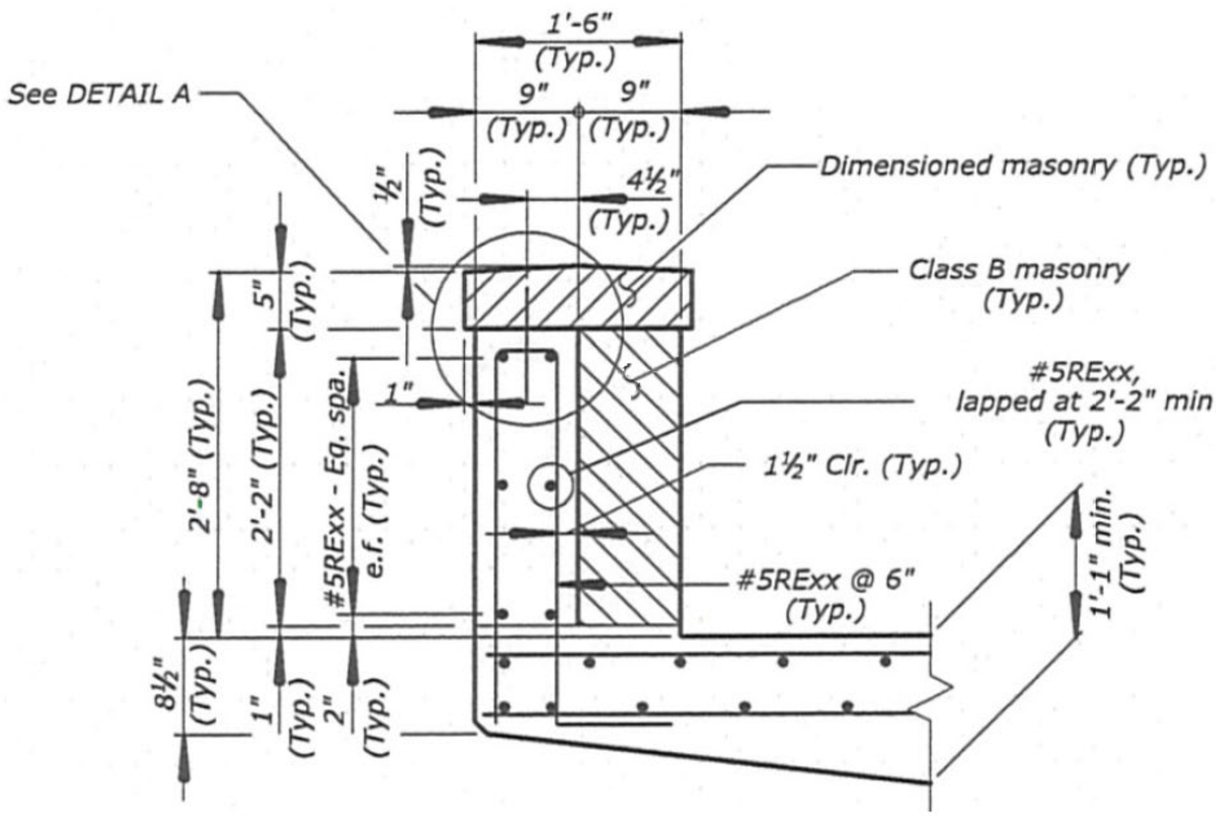
Elevation View

NOTES:

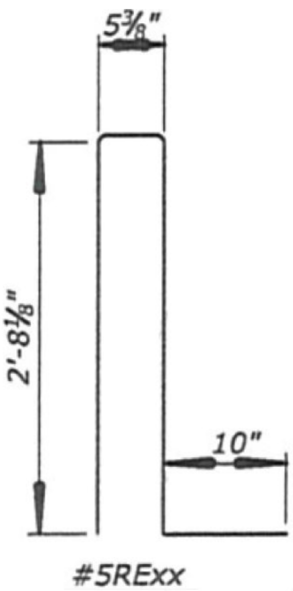
1. Mortar - ASTM C91 Type S or equivalent, F'c = 2100 psi @ 28 day (min)
2. Concrete strength - F'c = 4500 psi @ 28 day (min)
3. Reinforcing steel - ASTM A615, fy = 60 ksi (min)
4. Staggered, Class-A tension splices allowed for splicing of horizontal bars
5. Masonry wall shall conform to section 620 of FHWA FL’s “Standard Specifications for Construction of Roads and Bridge on Federal Highway Projects” (FP-14)
6. Stones in front and rear wall faces should be as large as possible, similar to representation in elevation view, with smaller size filler stones as needed
7. Stones should extrude <u>no more than</u> 3” from mortar outer face
8. A recess of about 0.5” should be used between mortar outer face and edge of stones
9. Mortar width in-between stones should be kept as small as possible with an average width of 0.75” and <u>no more than</u> 2”
10. Drawing not to scale. All dimensions are in ft (') and in (")

Center for Collison Safety and Analysis George Mason University
Median Stone-faced Concrete Barrier (MASH TL3)
Revised: 07/30/2022 Sheet 1 of 1

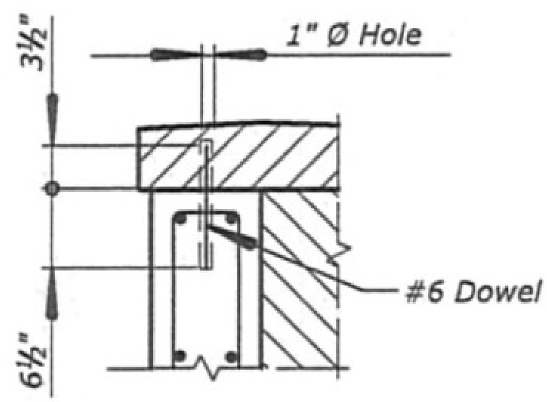
C-2: MASH TL3 Roadside Stone-faced Concrete Barrier



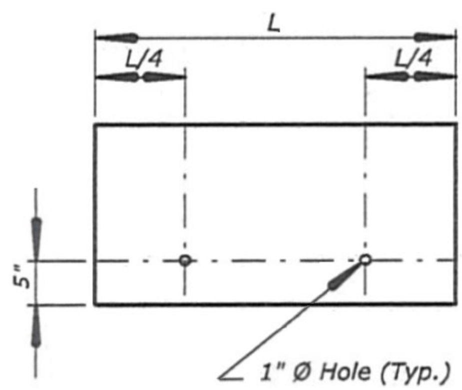
SECTION VIEW



REBAR DETAIL



DETAIL A



CAP STONE DETAIL

NOTES:

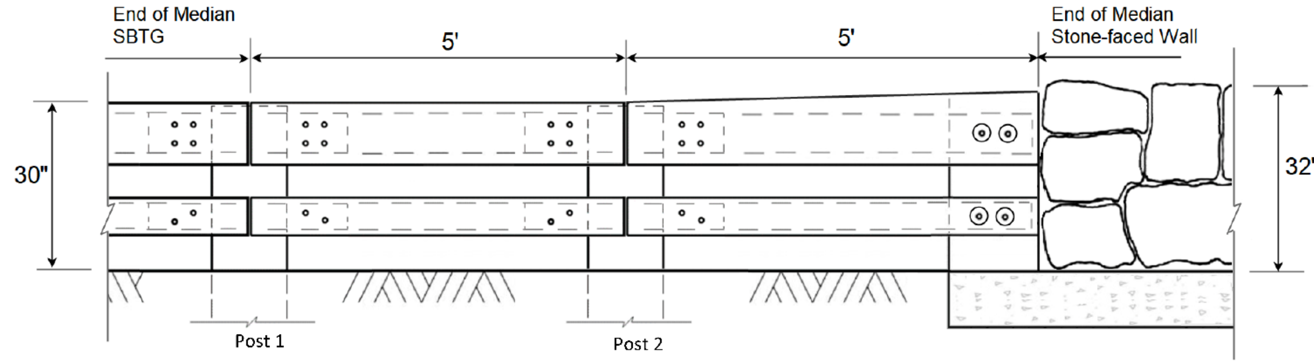
1. Concrete strength - F'c = 4000 psi @ 28 day (min)
2. Reinforcing steel - ASTM A615, fy = 60 ksi (min)
3. Staggered, Class-A tension splices allowed for splicing of horizontal bars
4. Masonry wall shall conform to section 620 of FHWA FL's "Standard Specifications for Construction of Roads and Bridge on Federal Highway Projects" (FP-14)
5. Mortar - ASTM C91 Type S or equivalent, F'c = 2100 psi @ 28 day (min)
6. Anchor #6 dowels (Detail A) with an epoxy grout system or approved equal
7. Drawing not to scale. All dimensions are in ft (') and in (")

Center for Collison Safety and Analysis
George Mason University

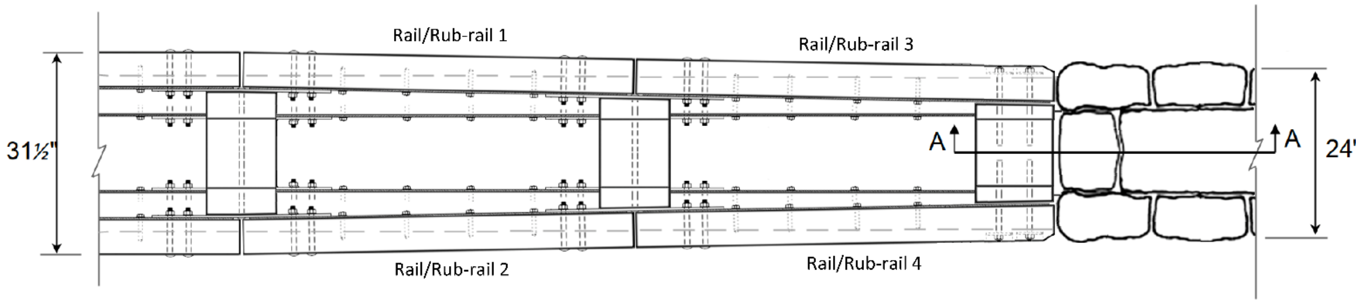
Smooth Stone Bridge Rail (MASH TL-3)

Revised: 01/20/2021 Sheet 1 of 1

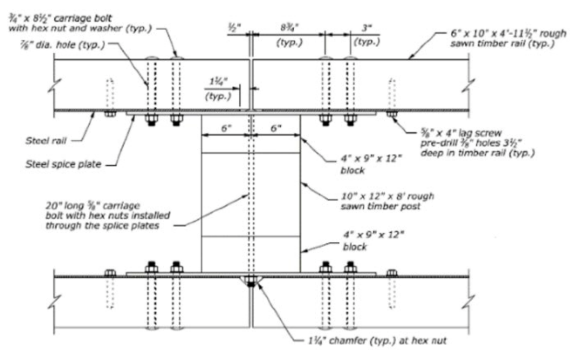
C-3: MASH TL3 Median Steel Backed Timber Guardrail to Median Stone-faced Wall Transition



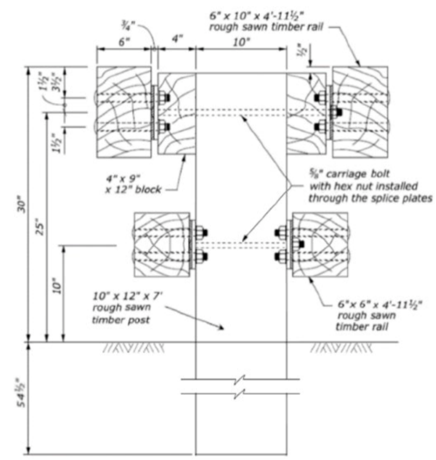
ELEVATION VIEW



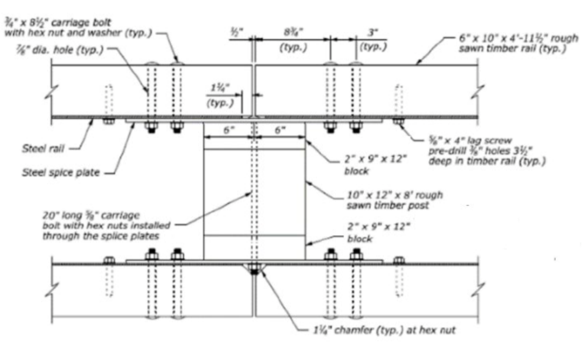
PLAN VIEW



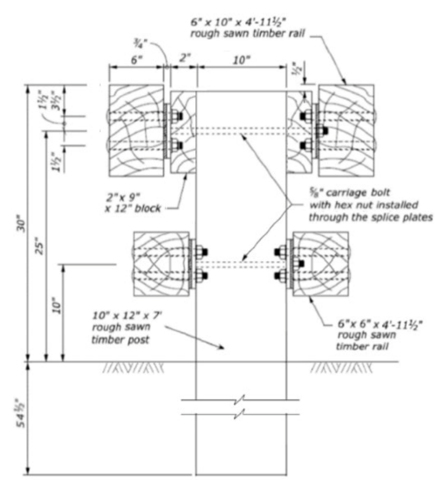
RAILS TO POST CONNECTION @ Post 1 – Plan View



RAILS TO POST CONNECTION @ Post 1 – Section View



RAILS TO POST CONNECTION @ Post 2 – Plan View

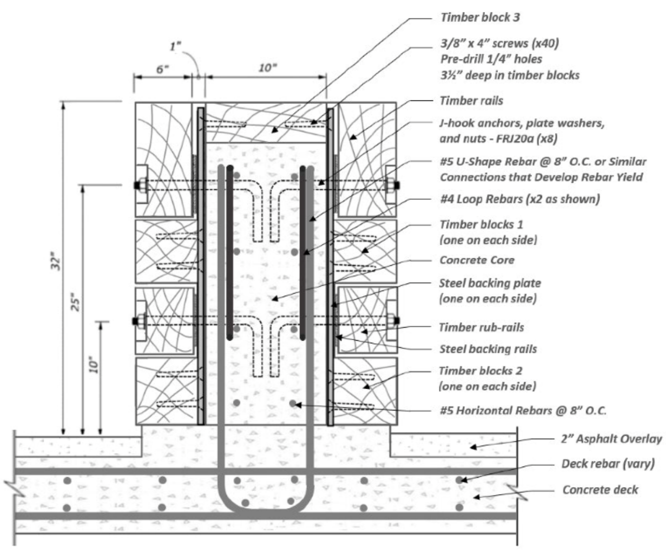


RAILS TO POST CONNECTION @ Post 2 – Section View

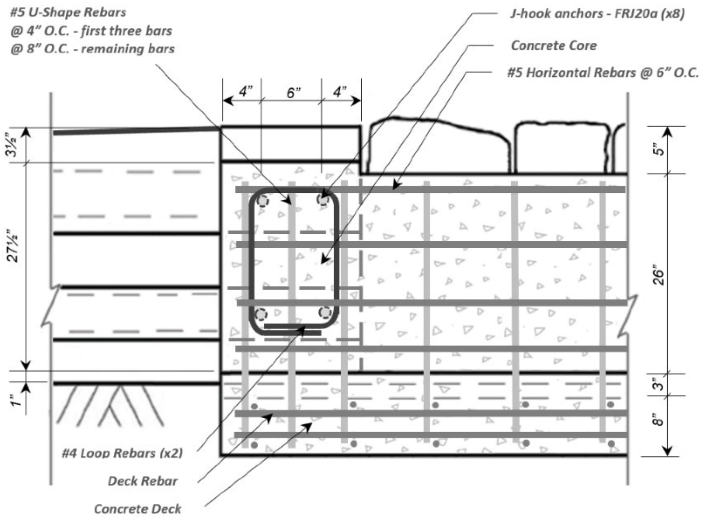
Center for Collison Safety and Analysis
George Mason University

Median SBTG to Median Stone-faced Wall Transition (MASH TL3)

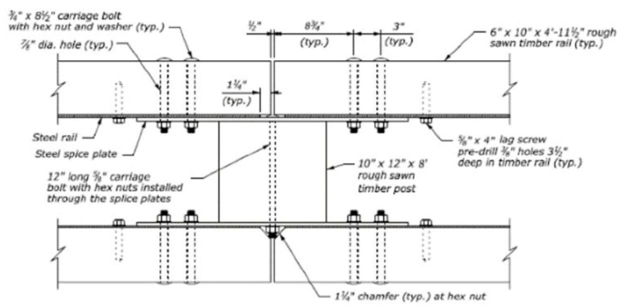
Revised: 7/18/2022 Sheet 1 of 3



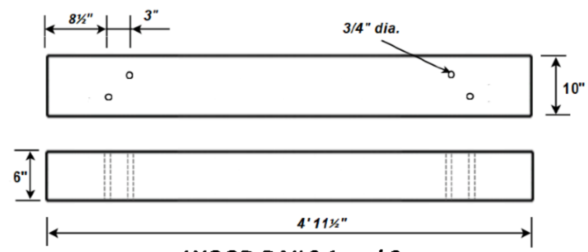
RAILS TO WALL-END CONNECTION – Section View 1



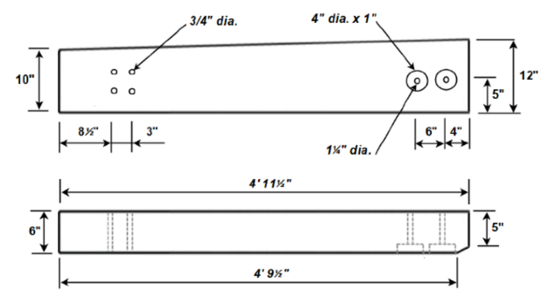
WALL-END REBAR SETUP – Section A-A



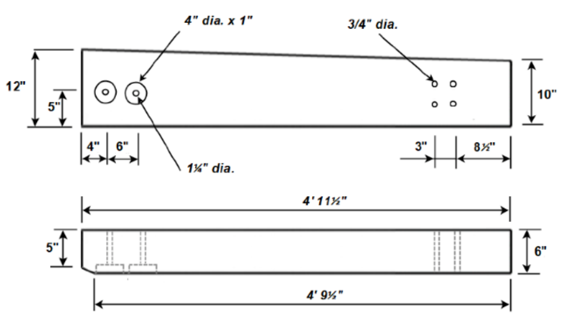
RUB-RAILS TO POST CONNECTION – Plan View



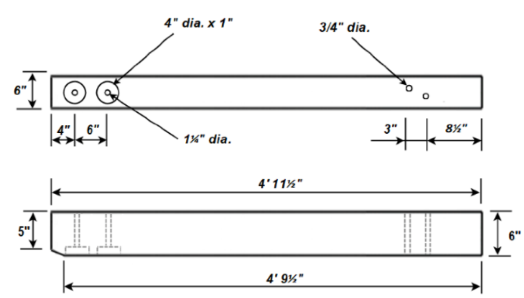
WOOD RAILS 1 and 2



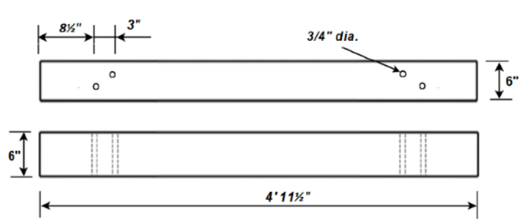
WOOD RAIL 4



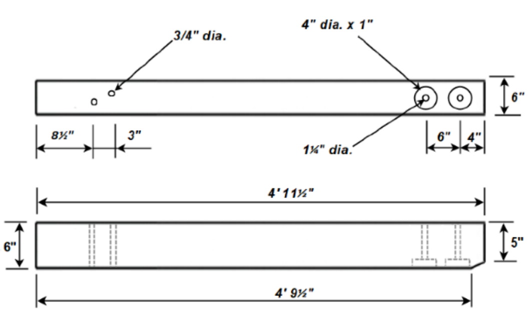
WOOD RAIL 3



WOOD RUB-RAIL 3

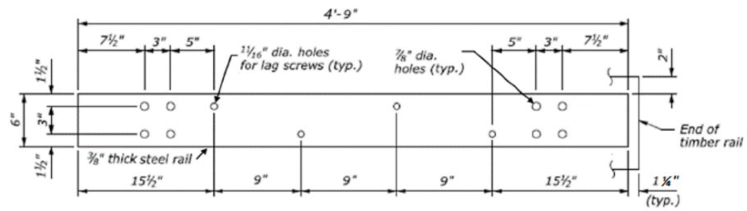


WOOD RUB-RAILS 1 & 2

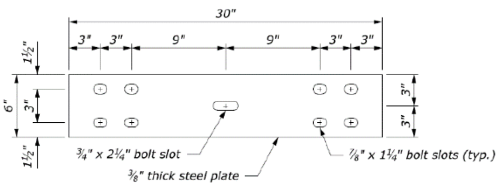


WOOD RUB-RAIL 4

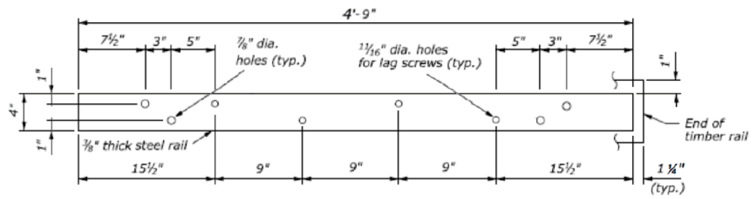
Center for Collison Safety and Analysis George Mason University
Median SBTG to Median Stone-faced Wall Transition (MASH TL3)
Revised: 7/18/2022 Sheet 2 of 3



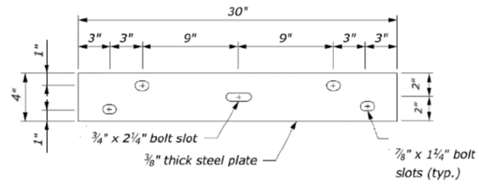
STEEL RAILS - Behind Rails 1 and 2



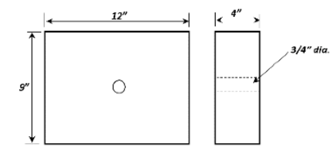
RAIL STEEL SPLICE PLATES – At Posts 1 and 2



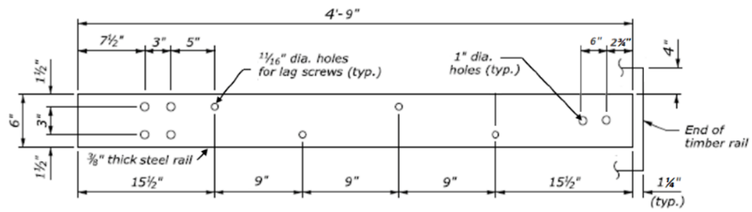
STEEL RAILS - Behind Rub-Rails 1 and 2



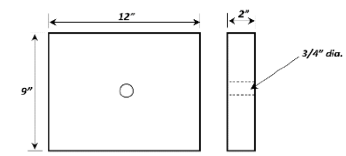
RUB-RAIL STEEL SPLICE PLATES – At Posts 1 and 2



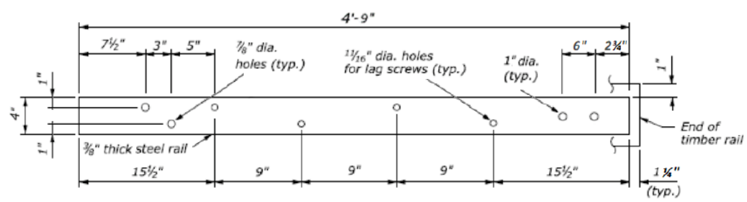
WOOD BLOCKOUTS @ POST 1



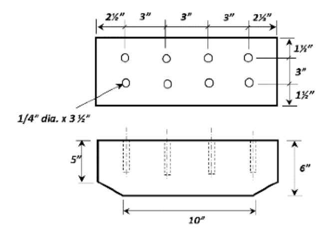
STEEL RAILS – Behind Rails 3 and 4



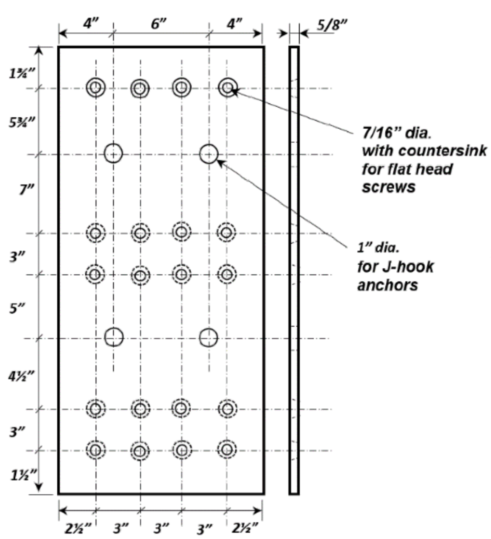
WOOD BLOCKOUTS @ POST 2



STEEL RAILS - Behind Rub-Rails 3 and 4



WOOD BLOCK 1 @ WALL-END



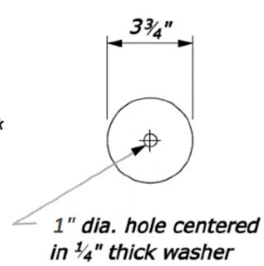
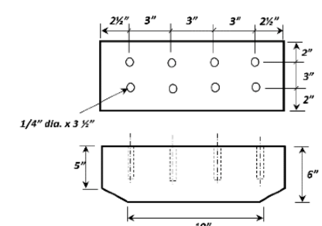
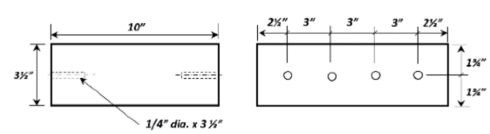


PLATE WASHERS (x4)



WOOD BLOCK 2 @ WALL-END

STEEL BACKING PLATE @ WALL-END



WOOD BLOCK 3 @ WALL-END

Center for Collison Safety and Analysis
George Mason University

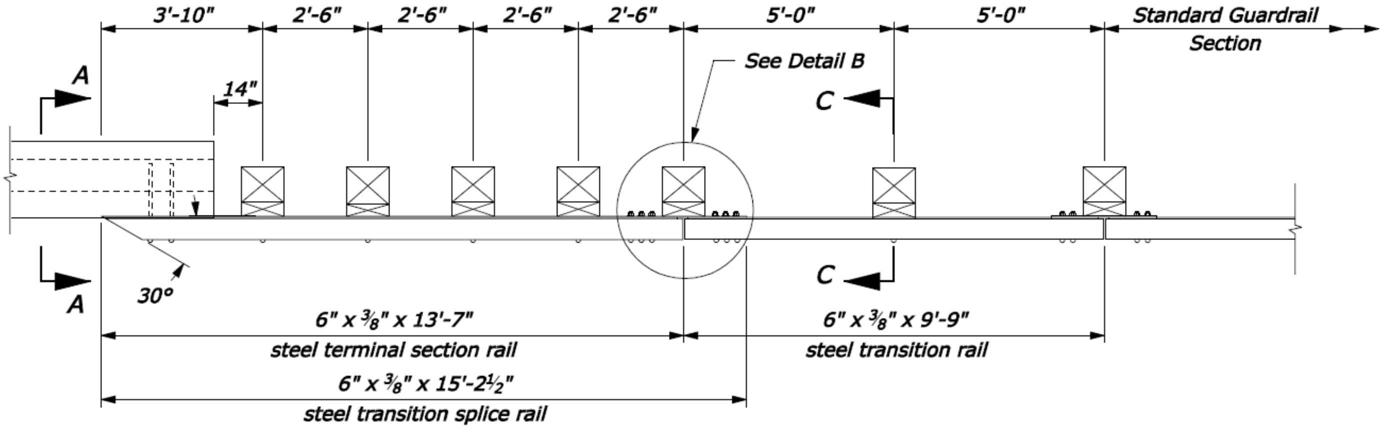
Median SBTG to Median Stone-faced Wall Transition (MASH TL3)

Revised: 7/18/2022 Sheet 3 of 3

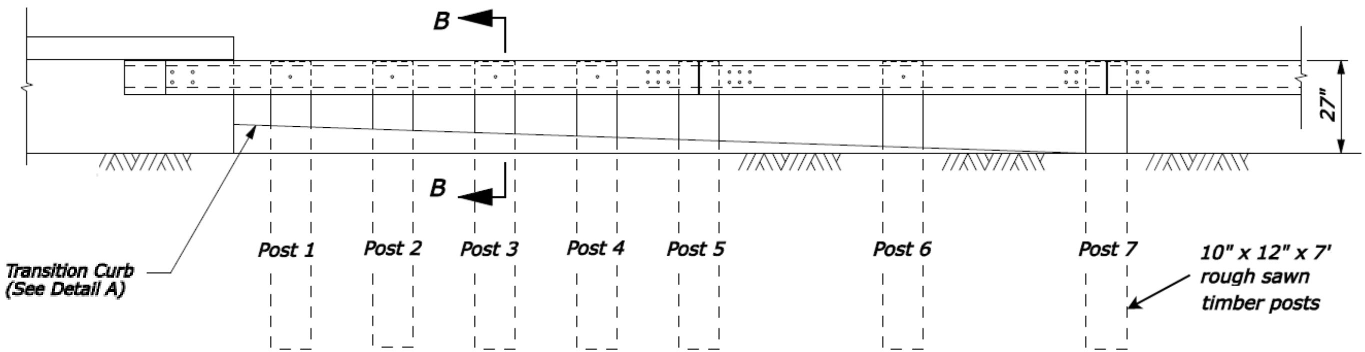
NOTES:

1. Use weathering steel for all structural steel and fastener hardware as specified
2. Pre-drill ¾" holes in blockouts, rails and posts for 5/8" carriage bolts
3. Concrete strength - F'c = 4500 psi @ 28 day (min)
4. Reinforcing steel - ASTM A615, fy = 60 ksi (min)
5. Drawing not to scale. All dimensions are in ft (') and in (")

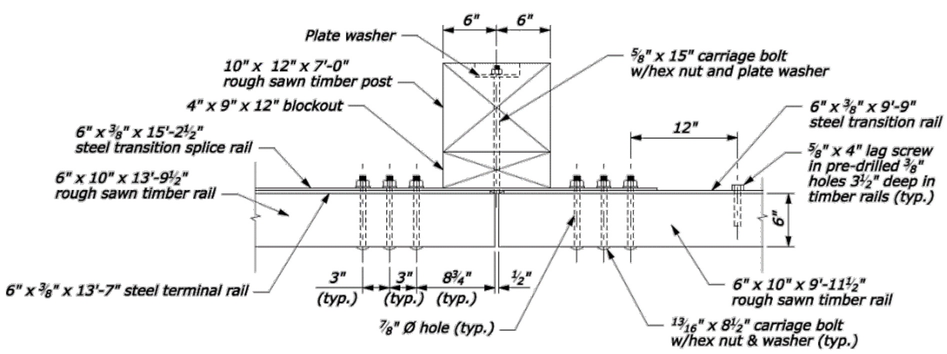
C-4: MASH TL3 Roadside Steel Backed Timber Guardrail to Roadside Stone-faced Wall Transition



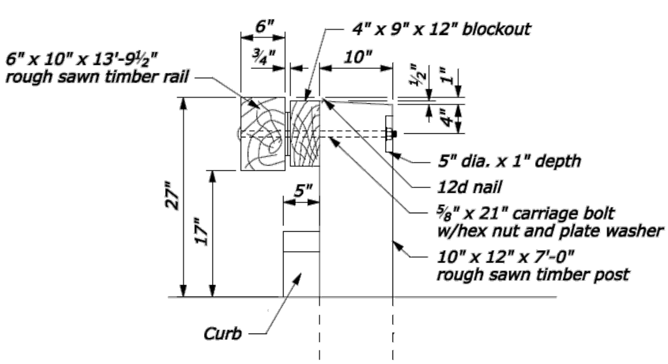
TOP VIEW



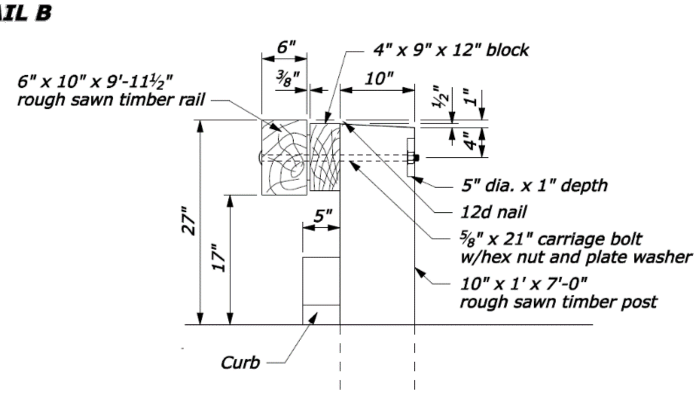
ELEVATION VIEW



DETAIL B



SECTION B-B



SECTION C-C

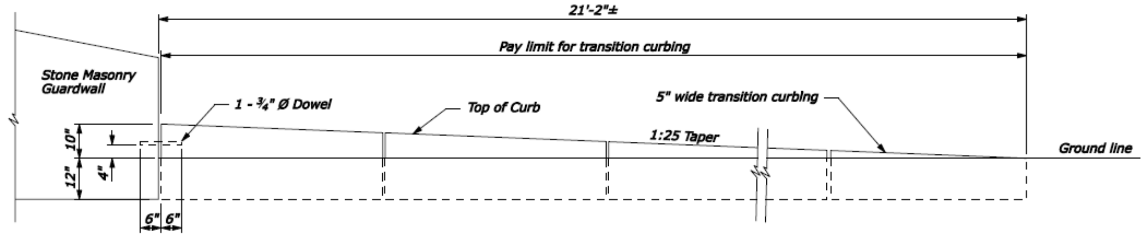
Center for Collison Safety and Analysis
George Mason University

Roadside SBTG to Roadside Stone-faced Wall Transition (MASH TL3)

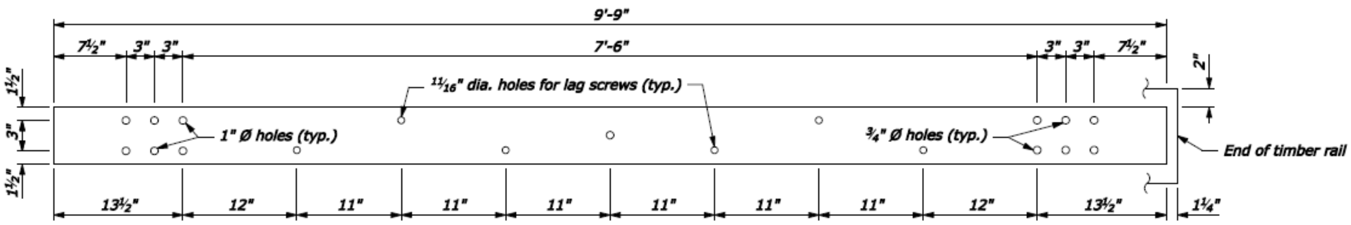
Revised: 7/30/2022 Sheet 1 of 2

NOTES:

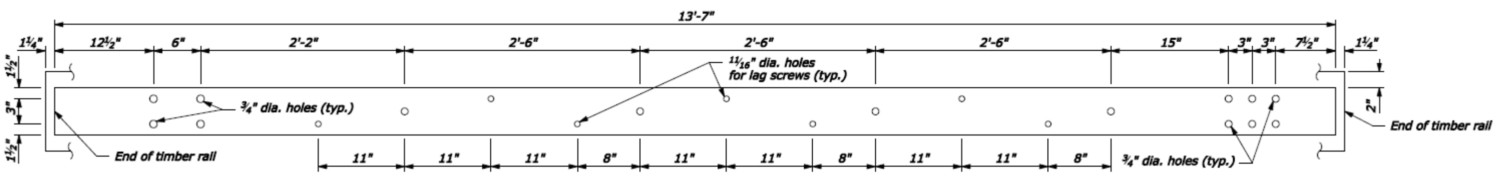
1. Use weathering steel for all structural steel and fastener hardware as specified
2. Pre-drill 7/8” holes in blockouts, rails and posts for 5/8” carriage bolts
3. Drawing not to scale. All dimensions are in ft (') and in (")



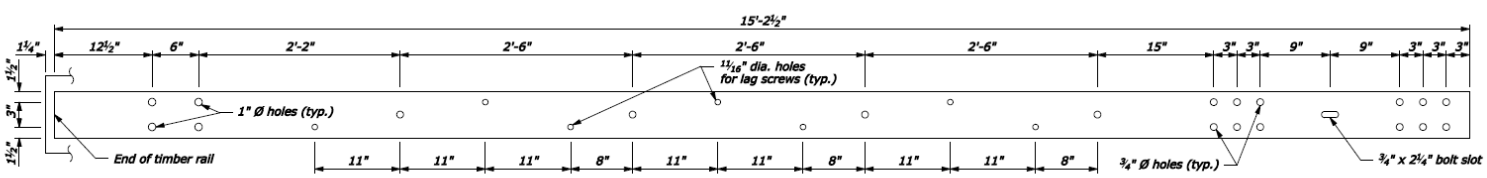
DETAIL A



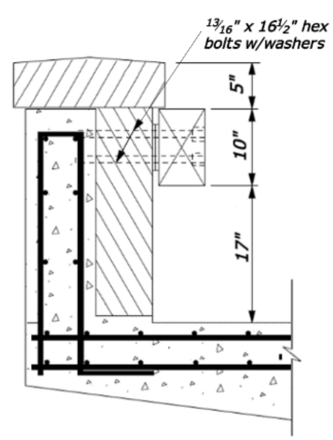
TRANSITION RAIL
6" x 3/8" x 9'-9"



TERMINAL SECTION RAIL
6" x 3/8" x 13'-7"



TRANSITION SPLICE RAIL
6" x 3/8" x 15'-2½"



SECTION A-A Parapet

Center for Collison Safety and Analysis
George Mason University

Roadside SBTG to Roadside Stone-faced Wall Transition (MASH TL3)

Revised: 7/30/2022 | Sheet 2 of 2