Structures Research Report 2021-153961/153962

University of Florida
Civil and Coastal Engineering

UF

University of Florida
Civil and Coastal Engineering

Final report November 2021

MASH Validation Testing of Low Profile Barrier

Principal investigator:
Gary R. Consolazio, Ph.D.

Co-Principal investigator:
Kurtis R. Gurley, Ph.D.

Department of Civil and Coastal Engineering
University of Florida
P.O. Box 116580
Gainesville, Florida 32611

Sponsor:
Florida Department of Transportation (FDOT)
Olivia Townsend, P.E. – Project manager
Derwood Sheppard, P.E. – Co-Project Manager

Contract:
UF Project No. P0153961, P0153962
FDOT Contract No. BDV31-977-129

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

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 (2,000 lb)	0.907	Megagrams	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	ºC
FORCE and PRESSURE or STRESS				
kip	1,000 pound force	4.45	kilonewtons	kN
lbf	pound force	4.45	newtons	N
lbf/in^2	pound force per square inch	6.89	kilopascals	kPa
ksi	kips force per square inch	6.89	Megapascals	MPa

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MASH Validation Testing of Low Profile Barrier		5. Report Date November 2021 6. Performing Organization Code
7. Author(s) Gary R. Consolazio, Kurtis R. Gurley		8. Performing Organization Report No. 2021/153961-153962
9. Performing Organization Name and Address University of Florida Department of Civil and Coastal Engineering 365 Weil Hall, P.O. Box 116580 Gainesville, FL 32611-6580		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDV31-977-129
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Management Center 605 Suwannee Street, MS 30 Tallahassee, FL 32399-0450		13. Type of Report and Period Covered Final Report Jan. 2020 – June 2021 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The Florida low profile barrier—consisting of multiple interconnected portable concrete segments—is typically utilized in construction zones to separate traffic from construction activities. The original development and validation (crash testing) of the barrier were in accordance with applicable standards at the time (NCHRP Report 350). In the present study, the performance of the Florida low profile barrier was re-assessed in accordance with the current requirements of the AASHTO Manual for Assessing Safety Hardware (MASH), specifically at Test Level 2 (TL-2) impact conditions. Numerical finite element simulations of vehicle-barrier impacts were used to estimate barrier performance, and full-scale MASH-compliant crash testing was used to experimentally validate barrier performance. Full-scale crash testing, conducted using MASH-compliant test vehicles (1100-kg car and 2270-kg pickup truck), demonstrated that the Florida low profile barrier satisfactorily met all required MASH performance criteria (vehicle redirection, stability, and roll angle; and occupant risk) for longitudinal barrier tests 2-10 and 2-11.

17. Key Words Barrier, work zone, vehicle impact, crash simulation, occupant risk, friction		18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 101	22. Price

Form DOT F 1700.7 (8-72). Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors thank the Florida Department of Transportation (FDOT) for providing the funding that made this research possible.

EXECUTIVE SUMMARY

The Florida low profile barrier—consisting of multiple interconnected portable concrete segments—is typically utilized in construction zones to separate traffic from construction activities. The original development and validation (crash testing) of the barrier were in accordance with applicable standards at the time (NCHRP Report 350, 1993). In the present study, the performance of the Florida low profile barrier was re-assessed in accordance with the current requirements of the AASHTO Manual for Assessing Safety Hardware (MASH), specifically at Test Level 2 (TL-2) impact conditions. Numerical finite element simulations of vehicle-barrier impacts were used to estimate barrier performance, and full-scale MASH-compliant crash testing was used to experimentally validate barrier performance. Full-scale crash testing, conducted using MASH-compliant test vehicles (1100-kg car and 2270-kg pickup truck), demonstrated that the Florida low profile barrier satisfactorily met all required MASH performance criteria (vehicle redirection, stability, and roll angle; and occupant risk) for longitudinal barrier tests 2-10 and 2-11.

TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

LIST OF TABLES

Table | Page

CHAPTER 1
INTRODUCTION

In prior studies (Consolazio et al. 2003a, 2003b), a low profile safety barrier was developed for use in roadside work zones. Finite element crash simulations and full-scale physical crash testing were used to design the system and validate its performance according to nationally accepted standards (NCHRP Report 350 (1993), Test Level 2 requirements).

The AASHTO Manual for Assessing Safety Hardware (MASH; AASHTO 2016) is an update to, and supersedes, NCHRP Report 350 for purposes of evaluating roadside safety hardware devices. Selected revisions incorporated into MASH include: a) changes to the test vehicles, b) changes to selected impact conditions, and c) changes of selected evaluation criteria. Importantly, relative to NCHRP Report 350, the test vehicles masses included in MASH are larger—the 820C (820-kg) test vehicle (passenger car) was replaced by the 1100C (1100-kg) vehicle, and the 2000P (2000-kg) test vehicle (pickup truck) was replaced by the 2270P (2270-kg) vehicle.

In this study, the performance of the Florida low profile barrier was re-assessed under MASH Test Level 2 (TL-2) impact conditions. Numerical finite element simulations of vehicle-barrier impacts were conducted to estimate system performance. Subsequently, full-scale vehicle-barrier crash tests were performed to validate compliance with MASH TL-2 requirements.

CHAPTER 2
PRE-CRASH-TEST NUMERICAL IMPACT SIMULATIONS

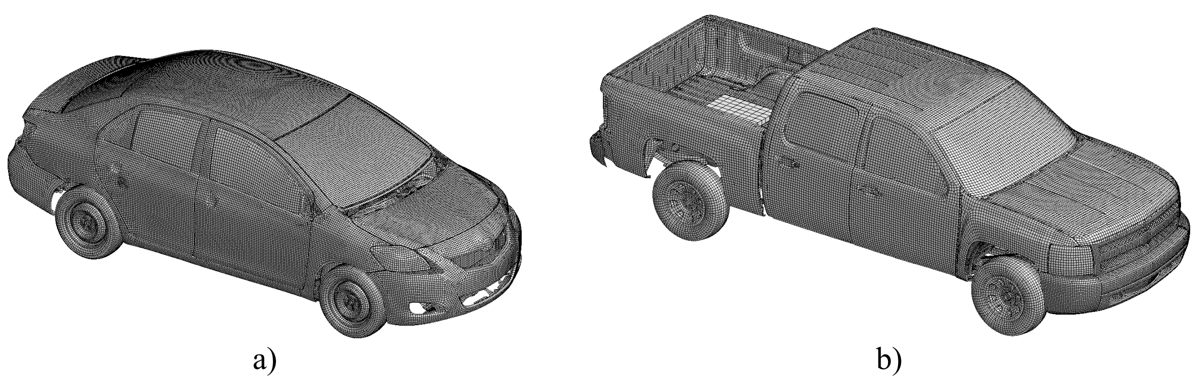
2.1 Introduction

In preparation for conducting full-scale crash tests, the performance of the Florida low profile barrier was numerically estimated, using finite element crash simulation techniques, in accordance with the longitudinal barrier requirements that are included in MASH. Details of the numerical simulations were reported in Consolazio and Han (2018) and are summarized here for convenience to the reader.

In conducting the impact simulations, coefficients of friction were parametrically varied so that barrier performance over a range of possible site conditions could be estimated. Raw simulation results were processed to quantify performance measures relating to vehicle stability (roll angle), barrier performance (lateral deflection), and occupant risk (occupant impact velocity and occupant ridedown acceleration).

2.2 Vehicle models

In each analysis, one of the MASH test vehicles (an 1100-kg car or a 2270-kg truck) (Figure 2-1) was simulated, using LS-DYNA (Livermore Software Technology Corporation 2018), impacting a series of ten low profile barrier segments. The vehicle models of the 1100-kg passenger car (denoted 1100C by MASH 2016) and the 2270-kg pickup truck (denoted 2270P by MASH 2016) were obtained from the Center for Collision Safety and Analysis (CCSA). For each vehicle type (1100C, 2270P), CCSA makes available 'detailed' high-resolution models (>1 million elements) and 'coarse' reduced-resolution models (>250,000 elements). For purposes of simulating the re-directional vehicle-barrier impacts in this study, the reduced-resolution CCSA models (Figure 2-3) were found to provide sufficient accuracy.



a) b)

Figure 2-1 Finite element models of test vehicles:
(a) 1100-kg small car (Toyota Yaris); (b) 2270-kg pickup truck (Chevrolet Silverado)

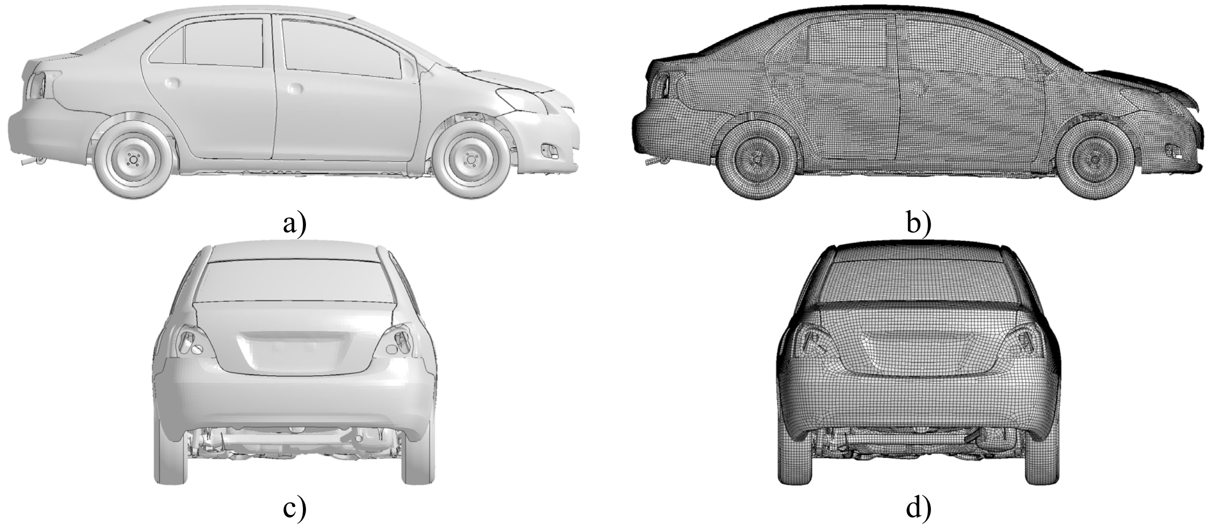


Figure 2-2 Finite element model of 1100-kg passenger car (Toyota Yaris):
(a) Side view (geometry); (b) Side view (mesh);
(c) Rear view (geometry); (d) Rear view (mesh)

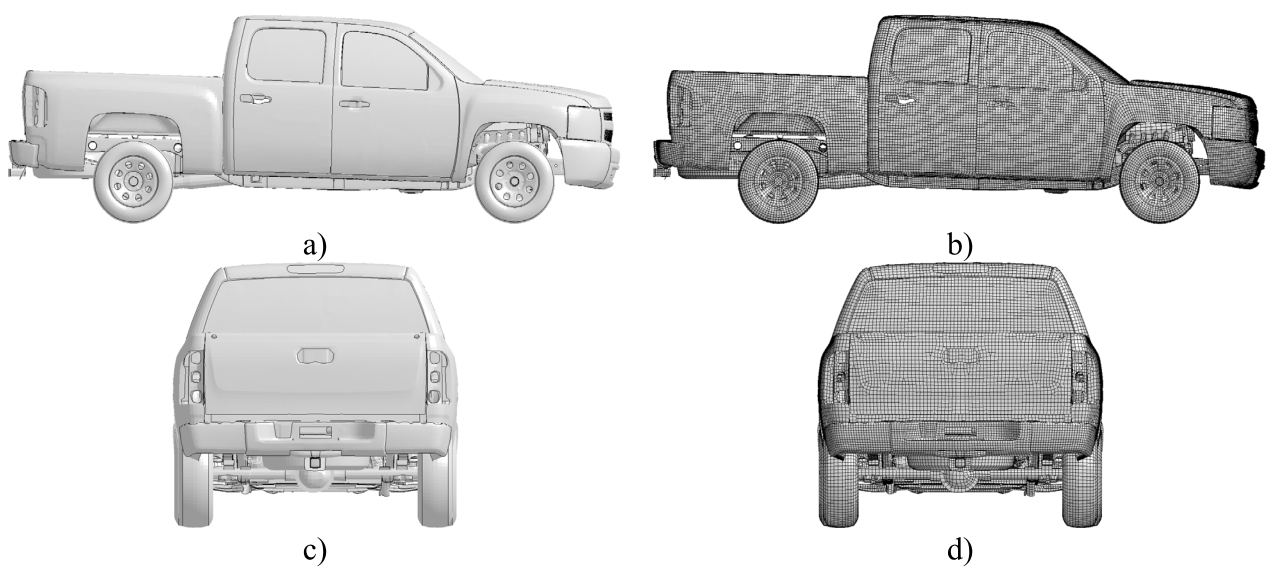
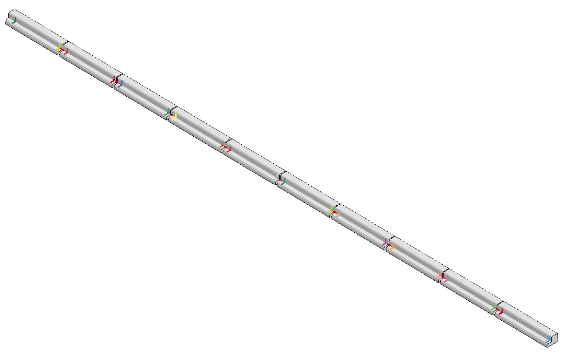


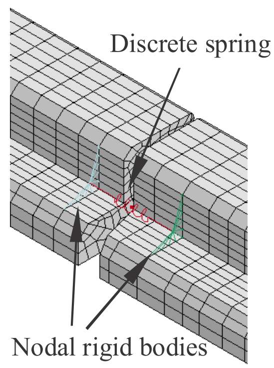
Figure 2-3 Finite element model of 2270-kg pickup truck (Chevrolet Silverado):
(a) Side view (geometry); (b) Side view (mesh);
(c) Rear view (geometry); (d) Rear view (mesh)

2.3 Barrier model

In each vehicle-barrier impact simulation, an assembly consisting of a series of ten (10) low profile barrier segments was used, as shown in Figure 2-4a. In a physical installation, individual barrier segments would be connected together using high-strength steel (150 ksi) threaded bars. In the finite element models, each threaded bar was modeled using 'discrete' spring elements which were capable of representing nonlinear and inelastic (yielding) stress-strain behavior. Separate sets of nodes at adjacent barrier segments were placed into 'nodal rigid body' definitions to approximate the physical dimension of threaded bar bearing surfaces. Discrete spring elements of diameter 1.25 in. connected two adjacent nodal rigid bodies (Figure 2-4b) at each interface between barrier segments. Each spring element (threaded bar) was assigned a tensile failure strain of 0.04 (4%), as well as zero compressive stiffness (to model the physical manner in which the threaded bars interact with the bearing surfaces on the barrier segments; see Consolazio et al., 2003b).



a)



b)

Figure 2-4 Finite element model of barrier (non-impact side shown):
(a) Ten low profile barrier segments; (b) Discrete springs at connection between barrier segments

2.4 Impact conditions simulated

Numerical models corresponding to MASH longitudinal barrier 'length of need' impact test conditions 2-10 and 2-11 are shown in Figures 2-5 and Figure 2-6, respectively. Impact condition 2-10 involved a 25-deg. oblique impact at 44 mph (70 kph) of an 1100C passenger car striking the barrier. Primary performance indicators of concern for condition 2-10 generally relate to occupant risk parameters (i.e., occupant impact velocity [OIV] and occupant ridedown acceleration [ORA]), and are reported in the following section. Contact detections were defined for vehicle and barrier components that could potentially come into contact during impact, and corresponding friction coefficients were specified, as listed in Table 2-1. Since the Florida low profile barrier primarily utilizes inertial (mass-related) resistance to redirect vehicles, the degree of lateral barrier deflection is partially influenced by frictional resistance between the bottom of the barrier and the roadway. To estimate the sensitivity of lateral barrier deflection (as well as OIV and ORA) to friction coefficient, multiple levels of friction were investigated.

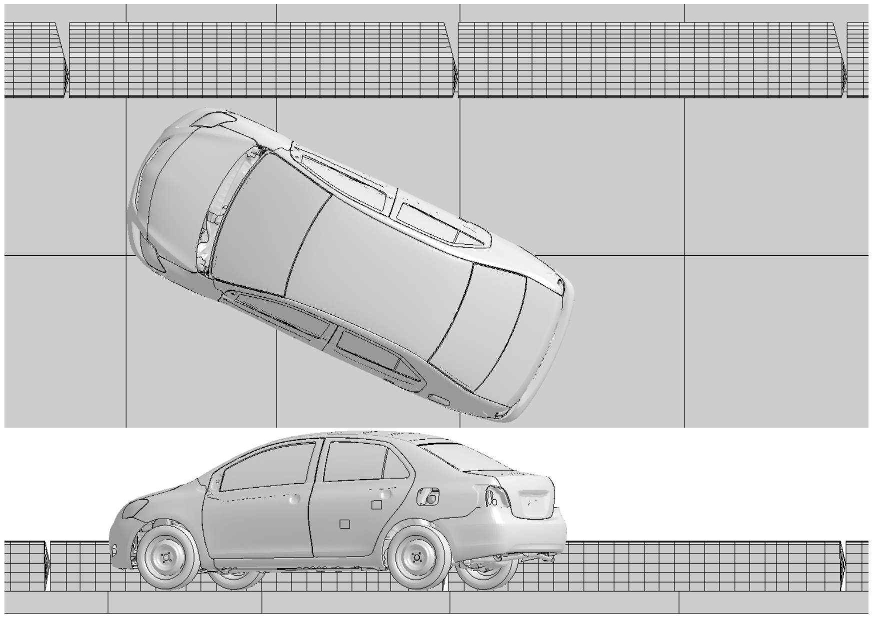


Figure 2-5 Finite element model of impact condition 2-10 (1100-kg car, 25-deg. angle, 44 mph)

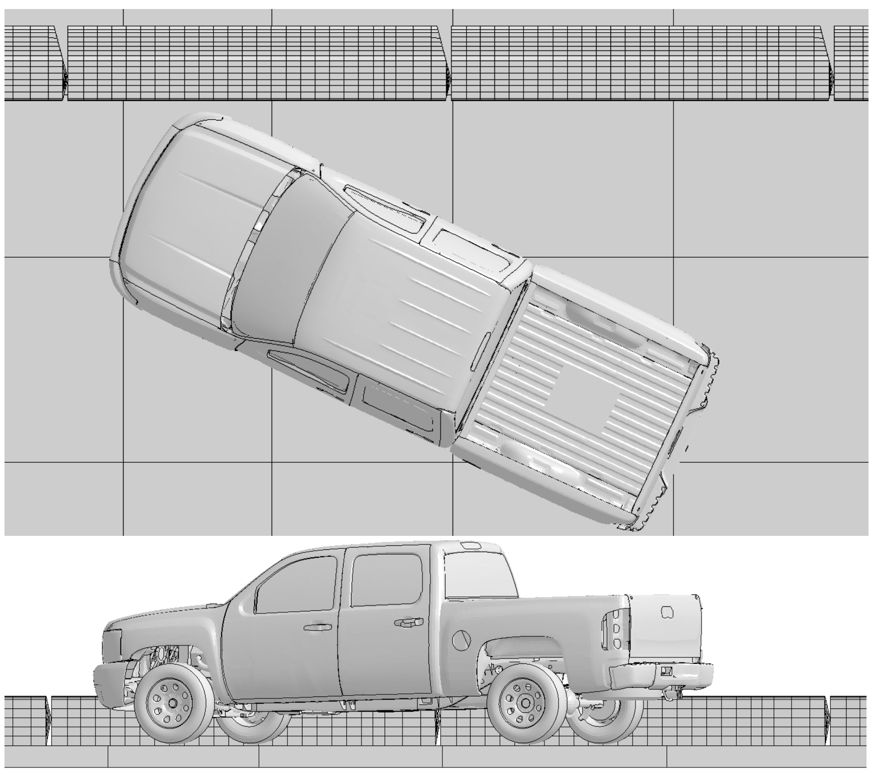


Figure 2-6 Finite element model of impact condition 2-11 (2270-kg truck, 25-deg. angle, 44 mph)

Table 2-1 Contact frictional coefficients (impact condition 2-10: 1100C passenger car)

Contact interface	Coefficient of friction
Vehicle (steel) to barrier	0.15
Tire (rubber) to barrier	0.20
Tire (rubber) to roadway	0.20
Barrier segment to barrier segment	0.60
Barrier to roadway	0.40, 0.60

Impact condition 2-11 involves a 25-deg. oblique impact at 44 mph (70 kph) of a 2270P pickup truck striking the barrier. Primary performance indicators of concern for condition 2-11 relate to vehicle stability (roll angle), barrier connector-bolt strength and integrity, and lateral barrier deflection. Occupant risk parameters (OIV and ORA) were also quantified for this impact condition. However, due to the larger vehicle mass of the 2270P truck (relative to the 1100C car), OIV and ORA values for impact condition 2-11 were expected to be less severe than those arising in impact condition 2-10. Contact detections were defined for vehicle and barrier components that could potentially come into contact during impact, and corresponding friction coefficients were specified, as listed in Table 2-2. Lateral barrier deflection, vehicle roll angle, and occupant OIV and ORA are all influenced by the friction. To estimate maximum vehicle roll angle, maximum barrier lateral deflection, and maximum OIV and ORA, multiple levels of friction were investigated.

Table 2-2 Contact frictional coefficients (impact condition 2-11: 2270P pickup truck)

Contact interface	Coefficient of friction
Vehicle (steel) to barrier	0.15
Tire (rubber) to barrier	0.20, 0.40
Tire (rubber) to roadway	0.20
Barrier segment to barrier segment	0.60
Barrier to roadway	0.20, 0.40, 0.60

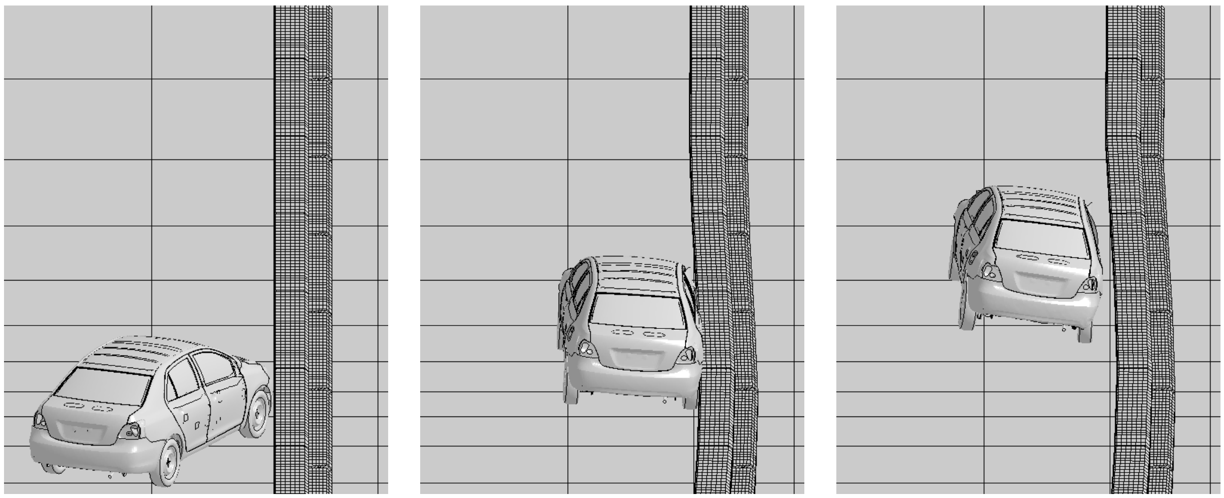
2.5 Results

2.5.1 Results for impact condition 2-10

Simulation results for impact condition 2-10 (1100-kg car, 25 deg., 44 mph) for various values of friction are summarized in Table 2-3. Maximum segment connector bolt (threaded bar) strain was 0.009 (0.9%), which was well below the bolt failure strain 0.040 (4%). Maximum vehicle roll angle was well below the MASH roll angle limit of 75 deg. Results from the impact case that produced the maximum roll angle are shown in Figure 2-7, where smooth redirection of the vehicle is indicated. For an oblique vehicle impact against a longitudinal concrete barrier, lateral OIV and ORA values typically control, as opposed to longitudinal OIV and ORA values. As noted in Table 2-3, the lateral OIV and ORA values were below the MASH preferred limits of 30 ft/sec, and 15 g respectively, and well below the maximum permissible limits of 40 ft/sec, and 20.49 g.

Table 2-3 Simulation results for impact condition 2-10

Friction coefficients		Max. barrier lateral disp. (in.)	Max. bolt strain	Max. roll angle (deg.)	Lateral OIV (ft/sec)	Lateral ORA (g)
Barrier to roadway	Tire to barrier					
0.4	0.2	7.2	0.009	10.7	21.9	11.6
0.6	0.2	5.4	0.009	11.0	22.2	11.1



t = 0.0 sec t = 0.2 sec t = 0.4 sec

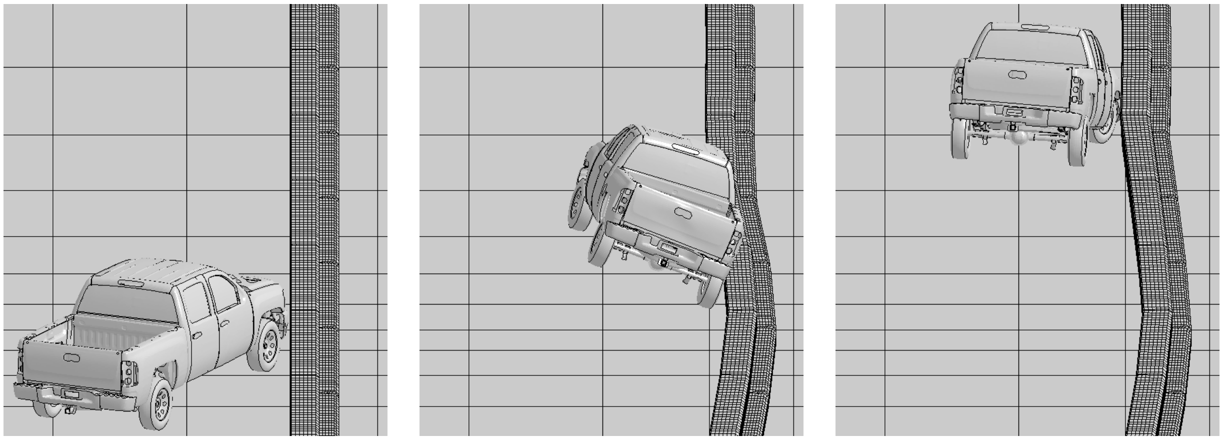
Figure 2-7 Simulation results for case producing maximum roll angle (impact condition 2-10, barrier-to-roadway friction = 0.6, tire-to-barrier friction = 0.2)

2.5.2 Results for impact condition 2-11

Simulation results for impact condition 2-11 (2270-kg truck, 25 deg., 44 mph) for various values of friction are summarized in Table 2-4. Maximum segment connector bolt (threaded bar) strain was 0.024 (2.4%), which was well below the bolt failure strain 0.040 (4%). Maximum vehicle roll angle was well below the MASH roll angle limit of 75 deg. Results from the impact case that produced the maximum roll angle are shown in Figure 2-8, where smooth redirection of the vehicle is indicated. As noted in Table 2-4, the lateral OIV and ORA values were below the MASH preferred limits of 30 ft/sec, and 15 g respectively, and well below the maximum permissible limits of 40 ft/sec, and 20.49 g.

Table 2-4 Simulation results for impact condition 2-11

Friction coefficients		Max. barrier lateral disp. (in.)	Max. bolt strain	Max. roll angle (deg.)	Lateral OIV (ft/sec)	Lateral ORA (g)
Barrier to roadway	Tire to barrier					
0.2	0.2	27.8	0.024	13.2	18.5	9.9
0.4	0.2	16.8	0.020	15.6	18.5	9.8
0.6	0.2	12.5	0.018	17.0	18.7	10.8
0.6	0.4	13.5	0.022	12.7	18.3	10.8



t = 0.0 sec t = 0.4 sec t = 0.8 sec

Figure 2-8 Simulation results for case producing maximum roll angle (impact condition 2-11, barrier-to-roadway friction = 0.6, tire-to-barrier friction = 0.2)

2.6 Summary

All results presented above were obtained from numerical impact simulations that were conducted *prior* to full-scale crash testing. Based in part on these simulation results, the decision was made experimentally validate the performance of the Florida low profile barrier by conducting full-scale MASH-compliant crash testing.

CHAPTER 3
FULL-SCALE CRASH TESTING

The Texas A&M Transportation Institute (TTI) Proving Ground was selected to conduct AASHTO MASH-compliant vehicle crash testing of the Florida low profile barrier. The following Test level 2 (TL-2) crash tests were conducted by TTI:

- AASHTO MASH Test 2-10, 1100C passenger car, 2420 lb., 44 mph, 25 deg. impact
- AASHTO MASH Test 2-11, 2270P pickup truck, 5000 lb., 44 mph, 25 deg. impact

For purposes of conducting the tests, TTI acquired a total of sixteen (16) Florida low profile barrier segments, each 12-ft long, resulting in a total test installation length of 192 ft. Barrier segments were acquired from a Florida precast concrete product producer and were assembled together in a straight line configuration. The test site was comprised of a concrete aircraft parking apron adjacent to an out-of-service runway. Based on information provided by TTI, the coefficient of friction at the test site was estimated as μ=0.7.

Vehicles used to conduct the crash tests, and corresponding test dates, were:

- 2016 Nissan Versa (1100C passenger car), test date : 2021-02-03
- 2016 Ram 1500 pickup (2270P pickup truck), test date: 2021-02-01

AASHTO MASH performance criteria that are applicable to LON (length of need) TL-2 tests of longitudinal barriers include the following [see MASH (AASHTO, 2016) Tables 2-2 and 5-1]:

Structural adequacy: Criterion 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: Criterion D

Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.

Occupant risk: Criterion F

The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.

Occupant risk: Criterion H

Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/sec, or maximum allowable value of 40 ft/sec.

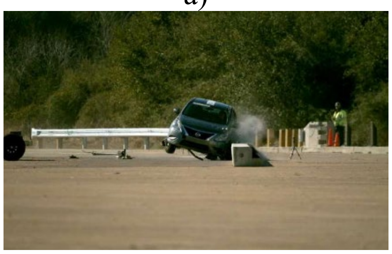
Occupant risk: Criterion I

The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.

Physical crash testing demonstrated that the Florida low profile barrier satisfactorily met all of the required AASHTO MASH performance criteria for Test 2-10 (Figure 3-1) and Test 2-11 (Figure 3-2). Included in Appendix A is the TTI crash report which provides detailed presentations of all crash test conditions and results.

a)

b)



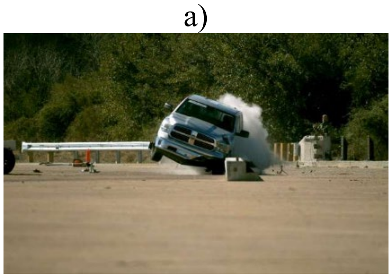
c)

d)

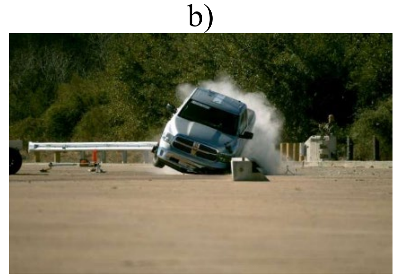
Figure 3-1 Full-scale crash Test 2-10: (a) t = 0.0 sec; (b) t = 0.2 sec, (c) t = 0.4 sec; (d) t = 0.6 sec

a)

b)



c)



d)

Figure 3-2 Full-scale crash Test 2-11: (a) t = 0.0 sec; (b) t = 0.2 sec, (c) t = 0.4 sec; (d) t = 0.6 sec

CHAPTER 4
COMPARISON OF SIMULATION RESULTS AND TEST RESULTS

4.1 Introduction

In this chapter, a comparison is provided between selected impact simulation results and physical crash test results. It is important to note that differences existed between the assumptions made in conducting the pre-crash-test impact simulations, and in the physical crash test conditions. Given these differences in impact condition, it is anticipated that differences will be observed in the results obtained.

Key differences between the simulations and the physical crash tests involved the types of vehicles utilized. While all vehicles investigated in this study (via simulation and crash testing) were suitable MASH 1100C and 2270P vehicles, the specific vehicle types used in the numerical simulations were not identical to those used in the TTI physical crash tests. Specific vehicle types were as follows:

- <u>MASH 1100C vehicle:</u>
  Numerical simulation = Toyota Yaris; Physical crash test = Nissan Versa

- <u>MASH 2270P vehicle:</u>
  Numerical simulation = Chevy Silverado; Physical crash test = Ram 1500

In addition to differences in vehicle types, differences in assumed versus actual frictional coefficients existed. The pre-crash-test numerical impact simulations were conducted using multiple frictional values so that barrier performance could be estimated over varying site conditions. As noted earlier, *barrier-to-roadway* friction values simulated in the numerical studies included values of μ=0.2, μ=0.4, and μ=0.6. At the TTI crash test site, the *barrier-to-roadway* friction value was estimated as μ=0.7. For comparison purposes, numerical simulations utilizing a *barrier-to-roadway* friction coefficient of μ=0.6 (closest available value to μ=0.7) were selected for comparison. Further, for both the 2-10 and 2-11 impact conditions, simulations utilizing a *tire-to-barrier* coefficient of friction of μ=0.2 were selected for comparison to test results.

4.2 Comparison and discussion

A comparison of key simulation results and crash test results is provided in Table 4-1. Taking into account the differences in vehicle types, friction values, vehicle masses, impact speeds, and impact angles, good agreement is observed between simulation and physical test results for maximum lateral deflection (Δ_{max}), maximum roll angle (ϕ_{max}), and occupant impact velocity (OIV). Importantly, the simulated and measured maximum lateral barrier deflections differed by less than 20%, despite differences in vehicle type.

In regard to occupant ridedown acceleration (ORA), more significant differences are observed between the simulated and measured results, with the simulations yielding conservative estimates of occupant risk. The observed differences in ORA are attributed to corresponding differences in the level of filtering (smoothing) that was applied to each set of acceleration data. Higher levels of filtering tend to reduce peak accelerations—by removing very short duration acceleration spikes—which in turn may reduce ORA.

Acceleration data obtained from the full-scale crash tests were filtered (by TTI) using methods that are in accordance with AASHTO MASH. In contrast, a lower level of filtering was applied to acceleration data obtained from the numerical impact simulations. The decision to use reduced filtering in processing the simulated acceleration data was made with the intent of yielding conservative occupant risk estimates. Had the pre-crash-test numerically estimated ORA values been close to the maximum permissible limits specified by AASHTO MASH, a higher level of filtering, as permitted by MASH, would have been applied to the simulation-based acceleration data and the ORA values would have been recomputed. However, given that the simulation-based ORA values were well below the AASHTO limits, refinements to the acceleration filtering were not deemed necessary.

Table 4-1 Comparison of pre-crash-test numerical estimates to crash test results

	Impact condition 2-10, 1100C car				Impact condition 2-11, 2270P truck		
	Pre-test FEA (Toyota Yaris)	TTI crash test (Nissan Versa)	Diff. (%)		Pre-test FEA (Chevy Silverado)	TTI crash test (Ram 1500)	Diff. (%)
Δ_{max}	5.4 in.	6.4 in.	17%	Δ_{max}	12.5 in.	13.2 in.	5%
ϕ_{max}	11.0 deg	11.0 deg	0%	ϕ_{max}	17.0 deg	20.0 deg	16%
OIV	22.2 ft/sec	20.7 ft/sec	7%	OIV	18.7 ft/sec	16.7 ft/sec	11%
ORA	11.1 g	6.7 g	49%	ORA	10.8 g	3.5 g	102%

Δ_{max} = maximum lateral dynamic barrier deflection (in.)
ϕ_{max} = maximum vehicle roll angle (deg.)
OIV = lateral occupant impact velocity (ft/sec)
ORA = lateral occupant ridedown acceleration (g)

CHAPTER 5
SUMMARY AND RECOMMENDATIONS

In this study, the performance of the Florida low profile barrier was assessed under AASHTO MASH Test Level 2 (TL-2) impact conditions. Numerical finite element simulations of vehicle-barrier impacts were used to estimate barrier performance, and full-scale MASH-compliant crash testing was used to experimentally validate barrier performance. Full-scale crash testing, conducted using MASH-compliant test vehicles (1100-kg car and 2270-kg pickup truck), demonstrated that the Florida low profile barrier satisfactorily met all required MASH performance criteria (vehicle redirection, stability, and roll angle; and occupant risk) for longitudinal barrier tests 2-10 and 2-11.

It is recommended that the lateral barrier deflection data presented in this report, obtained from a combination of numerical impact simulations and physical crash testing, be used to establish an appropriate working width that must be provided at installations of the Florida low profile barrier. It is also recommended that maximum construction tolerance limits be established for important dimensions of the Florida low profile barrier geometry (e.g., the inverted slope of the impact face).

REFERENCES

AASHTO (2016), *Manual for Assessing Safety Hardware*, 2nd ed., American Association of State Highway and Transportation Officials, 2nd ed, Unites States of America.

Consolazio, G.R., Chung, J.H., Gurley, K.R. (2003a), "Impact Simulation and Full-scale Crash Testing of a Low Profile Concrete Work Zone Barrier", *Computers and Structures*, Vol. 81, No.13, pp. 1359-1374.

Consolazio, G.R., Gurley, K.R., Ellis, R., Wilkes, J. (2003b), *Temporary Low Profile Barrier for Roadside Safety: Phase II*, Structures Research Report No. 827-3, Engineering and Industrial Experiment Station, University of Florida, Gainesville, Florida.

Consolazio, G.R. and Han, Z. (2018), "Analytical Assessment of Low Profile Concrete Work Zone Barrier Performance Under MASH Impact Conditions", Unpublished internal UF research report.

Livermore Software Technology Corporation (2018), *LS-DYNA Keyword User's Manual*, Livermore, CA.

NCHRP (1993), *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*, Transportation Research Board, National Cooperative Highway Research Program, Washington, D.C.

APPENDIX A: CRASH TEST REPORT

Texas A&M Transportation Institute
Proving Ground

Test Report No. 690905-UOF1&2
Test Report Date: March 2021

MASH TL-2 EVALUATION OF PORTABLE CONCRETE CONSTRUCTION ZONE BARRIER

by

D. Lance Bullard, Jr., P.E.
Senior Research Engineer

Wanda L. Menges
Research Specialist

William Schroeder
Engineering Research Associate

Bill L. Griffith
Research Specialist

and

Darrell L. Kuhn, P.E.
Research Specialist

Contract No.: 1909352
Test No.: 690905-UOF2 and UOF1
Test Date: 2021-02-01 and 2021-02-03

Sponsored by
University of Florida

TEXAS A&M TRANSPORTATION INSTITUTE PROVING GROUND

Mailing Address:
Roadside Safety & Physical Security
Texas A&M University System
3135 TAMU
College Station, TX 77843-3135

Located at:
Texas A&M University System RELLIS Campus
Building 7091
1254 Avenue A
Bryan, TX 77807

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01

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 University of Florida, The Texas A&M University System, or the Texas A&M Transportation Institute (TTI). This report does not constitute a standard, specification, or regulation. In addition, the above listed agencies/companies 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.

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

The Proving Ground Laboratory within TTI's Roadside Safety and Physical Security Division ("TTI Lab") strives for accuracy and completeness in its crash test reports. On rare occasions, unintentional or inadvertent clerical errors, technical errors, omissions, oversights, or misunderstandings (collectively referred to as "errors") may occur and may not be identified for corrective action prior to the final report being published and issued. If, and when, the TTI Lab discovers an error in a published and issued final report, the TTI Lab will promptly disclose such error to University of Florida, and both parties shall endeavor in good faith to resolve this situation. The TTI Lab will be responsible for correcting the error that occurred in the report, which may be in the form of errata, amendment, replacement sections, or up to and including full reissuance of the report. The cost of correcting an error in the report shall be borne by the TTI Lab. Any such errors or inadvertent delays that occur in connection with the performance of the related testing contract will not constitute a breach of the testing contract.

THE TTI LAB WILL NOT BE LIABLE FOR ANY INDIRECT, CONSEQUENTIAL, PUNITIVE, OR OTHER DAMAGES SUFFERED BY UNIVERSITY OF FLORIDA OR ANY OTHER PERSON OR ENTITY, WHETHER SUCH LIABILITY IS BASED, OR CLAIMED TO BE BASED, UPON ANY NEGLIGENT ACT, OMISSION, ERROR, CORRECTION OF ERROR, DELAY, OR BREACH OF AN OBLIGATION BY THE TTI LAB.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MASH TL-2 EVALUATION OF PORTABLE CONCRETE CONSTRUCTION ZONE BARRIER		5. Report Date March 2021 6. Performing Organization Code
7. Author(s) D. Lance Bullard, Jr., Wanda L. Menges, William Schroeder, Bill L. Griffith, and Darrell L. Kuhn		8. Performing Organization Report No. Test Report No. 690905-UOF1&2
9. Performing Organization Name and Address Texas A&M Transportation Institute Proving Ground 3135 TAMU College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 1909352
12. Sponsoring Agency Name and Address University of Florida 365 West Hall Gainesville, FL 32611		13. Type of Report and Period Covered Technical Report: August 2020 – February 2021 14. Sponsoring Agency Code
15. Supplementary Notes Project Title: Portable Concrete Construction Zone Barrier Name of Contacting Representative: Gary R. Consolazio, Ph.D.		

16. Abstract

The purpose of the tests reported herein was to assess the performance of University of Florida's portable concrete construction zone barrier according to the safety-performance evaluation guidelines included in the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware, Second Edition* (*MASH*). The crash tests were performed in accordance with *MASH* Test Level 2 (TL-2), which requires two crash tests:

1. ***MASH* Test 2-10**: An 1100C vehicle weighing 2420 lb impacting the longitudinal barrier while traveling at 44 mi/h and 25 degrees.
2. ***MASH* Test 2-11**: A 2270P vehicle weighing 5000 lb impacting the longitudinal barrier while traveling at 44 mi/h and 25 degrees.

This report provides details on the portable concrete construction zone barrier, the crash tests and results, and the performance assessment of the portable concrete construction zone barrier for *MASH* TL-2 longitudinal barrier evaluation criteria.

University of Florida's portable concrete construction zone barrier met the performance criteria for *MASH* TL-2 longitudinal barriers.

17. Key Words		18. Distribution Statement	
Longitudinal barrier, portable barrier, portable concrete barrier, PCB, temporary concrete barrier, TCB, median barrier, construction zone barrier, crash testing, roadside safety, MASH		Copyrighted. Not to be copied or reprinted without consent from University of Florida.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 78	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

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

*SI is the symbol for the International System of Units

REPORT AUTHORIZATION

REPORT REVIEWED BY:

DocuSigned by: Glenn Schroeder
E692F9CB5047487...

Glenn Schroeder, Research Specialist
Drafting & Reporting

DocuSigned by: Ken Reeves
60D556935596468...

Ken Reeves, Research Specialist
Electronics Instrumentation

DocuSigned by: Gary Gerke
FBA2101E9F6B4B7...

Gary Gerke, Research Specialist
Construction

DocuSigned by: Richard Badillo
0F51DA60AB144F9...

Richard Badillo, Research Specialist
Photographic Instrumentation

DocuSigned by: Scott Dobrovolny
1C613885787C44C...

Scott Dobrovolny, Research Specialist
Mechanical Instrumentation

DocuSigned by: Wanda L. Menges
B92179622AF24FE...

Wanda L. Menges, Research Specialist
Research Evaluation and Reporting

DocuSigned by: Bill Griffith
44A122CB271845B...

Bill L. Griffith, Research Specialist
Deputy Quality Manager

DocuSigned by: Darrell Kuhn
D4CC23E85D5B4E7...

Darrell L. Kuhn, P.E., Research Specialist
Quality Manager

DocuSigned by: Matt Robinson
EAA22BFA5BFD417...

Matthew N. Robinson, Research Specialist
Test Facility Manager & Technical Manager

DocuSigned by: D. Lance Bullard
1968BD6587A049C...

D. Lance Bullard, Jr., P.E.
Senior Research Engineer

This page intentionally left blank.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

Chapter 1. INTRODUCTION

The purpose of the tests reported herein was to assess the performance of University of Florida's portable concrete construction zone barrier according to the safety-performance evaluation guidelines included in the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware, Second Edition* (*MASH*) (*1*). The crash tests were performed in accordance with *MASH* Test Level 2 (TL-2) longitudinal barriers, which requires two crash tests:

1. ***MASH* Test 2-10**: An 1100C vehicle weighing 2420 lb impacting the longitudinal barrier while traveling at 44 mi/h and 25 degrees.
2. ***MASH* Test 2-11**: A 2270P vehicle weighing 5000 lb impacting the longitudinal barrier while traveling at 44 mi/h and 25 degrees.

This report provides details on the portable concrete construction zone barrier, the crash tests and results, and the performance assessment of the portable concrete construction zone barrier for *MASH* TL-2 longitudinal barrier evaluation criteria.

This page intentionally left blank.

Chapter 2. SYSTEM DETAILS

2.1. TEST ARTICLE AND INSTALLATION DETAILS

The installation consisted of sixteen 12-ft long precast low-profile barriers. The total installation length was approximately 192 ft. The upstream (“keyway”) end of each barrier segment was vertically flat, and the downstream (“key end”) end of each barrier segment was convex. An 8×8×½-inch angle was embedded longitudinally on the field side for the length of each segment. The barrier segments were connected to each other via two methods: 1) a tension link was threaded through bearing plates welded to the 8×8×½-inch angle on the field side of the barriers, and 2) a threaded rod on the downstream (“key end”) end of the barriers slid into a vertical slot on the upstream (“keyway”) end of its adjoining barrier. The traffic side of the barrier was 18 inches tall, with a 1-inch reverse slope on its front face. The height on the field side of the barriers was 5 inches. The total width of each barrier was 2 ft-4 inches.

Figure 2.1 presents the overall information on the portable concrete construction zone barrier, and Figure 2.2 provides photographs of the installation. Appendix A provides further details on the portable concrete construction zone barrier. Drawings were provided by University of Florida, barriers were provided by Seminole Pre-Cast, and installation was performed by TTI Proving Ground personnel.

2.2. DESIGN MODIFICATIONS DURING TESTS

No modification was made to the installation during the testing phase.

2.3. MATERIAL SPECIFICATIONS

The specified compressive strength of the concrete used in the barriers was 5000 psi. Core samples were taken from barriers 6 and 7 for each of the tests:

- Strength for barriers 6 and 7 from 690905-UOF1 was 8,620 psi and 5,280 psi respectively.
- Strength for barriers 6 and 7 from 690905-UOF2 was 10,080 psi and 9,110 psi respectively.

Appendix B provides material certification documents for the materials used to install/construct the portable concrete construction zone barrier.

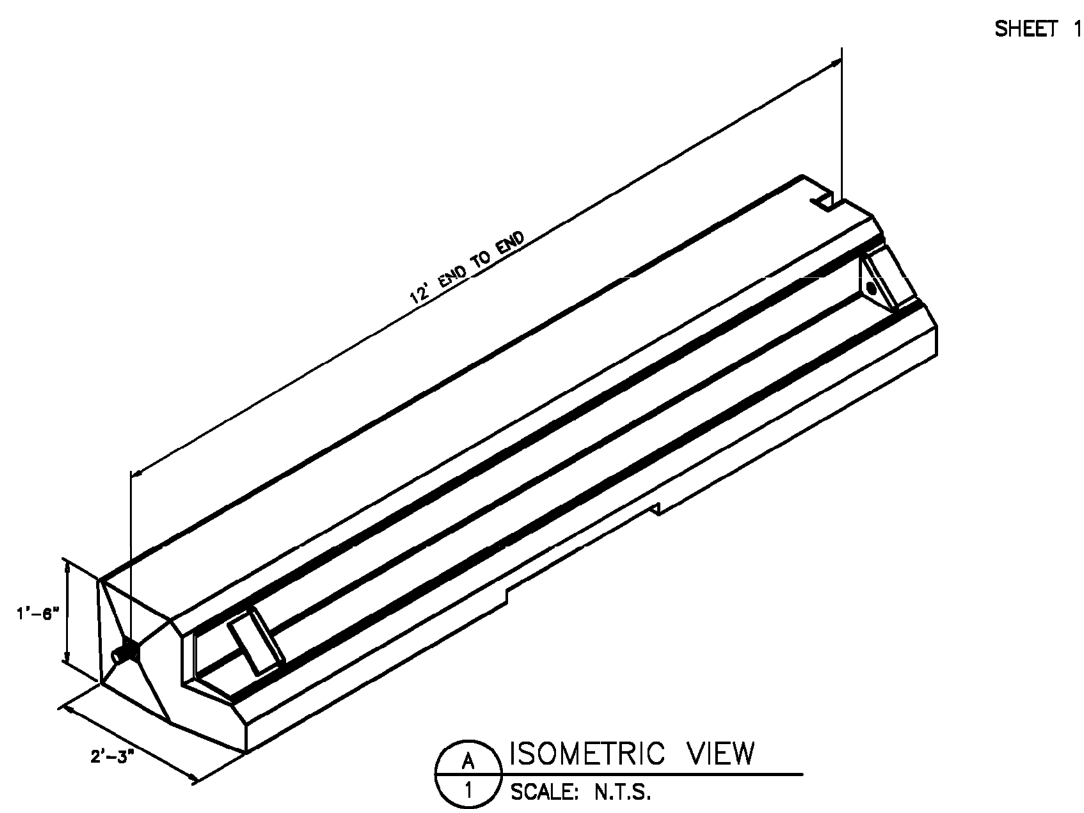


Figure 2.1. General Details of Portable Concrete Construction Zone Barrier.

Figure 2.2. Portable Concrete Construction Zone Barrier prior to Testing.

This page intentionally left blank.

Chapter 3. TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1. CRASH TEST PERFORMED/MATRIX

Table 3.1 shows the test conditions and evaluation criteria for *MASH* TL-2 for longitudinal barriers. The target critical impact points (CIPs) for each test were determined using the information provided in *MASH* Section 2.2.1 and Section 2.3.2. Figure 3.1 and Figure 3.2 show the target CIP for *MASH* Tests 2-10 and 2-11 on the portable concrete construction zone barrier.

Table 3.1. Test Conditions and Evaluation Criteria Specified for *MASH* TL-2 Longitudinal Barriers.

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria
			Speed	Angle	
Longitudinal Barrier	2-10	1100C	44 mi/h	25°	A, D, F, H, I
	2-11	2270P	44 mi/h	25°	A, D, F, H, I

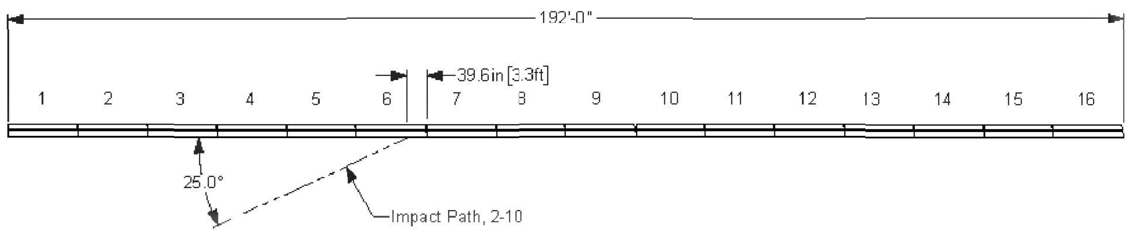


Figure 3.1. Target CIP for *MASH* Test 2-10 on Portable Concrete Construction Zone Barrier.

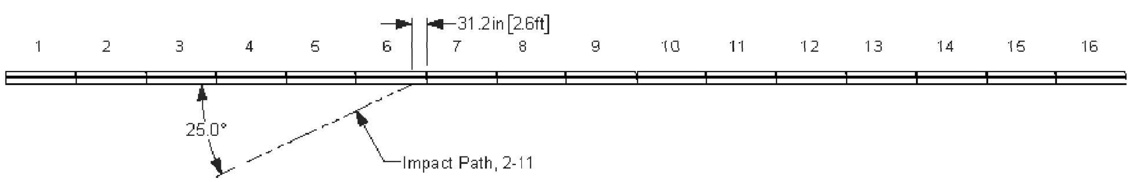


Figure 3.2. Target CIP for *MASH* Test 2-11 on Portable Concrete Construction Zone Barrier.

The crash tests and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 4 presents brief descriptions of these procedures.

3.2. EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-2 and 5-1 of *MASH* were used to evaluate the crash tests reported herein. Table 3.1 lists the test conditions and evaluation criteria required for *MASH* TL-2, and Table 3.2 provides detailed information on the evaluation criteria. An evaluation of the crash test results is presented in Chapter 7.

Table 3.2. Evaluation Criteria Required for *MASH* TL-2 Longitudinal Barriers.

Evaluation Factors	Evaluation Criteria	*MASH* Test
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.*	*2-10 and 2-11*
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 undue hazard to other traffic, pedestrians, or personnel in a work zone.* *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.*	*2-10 and 2-11*
	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	*2-10 and 2-11*
	H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.	*2-10 and 2-11*
	I. The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.	*2-10 and 2-11*

Chapter 4. TEST CONDITIONS

4.1. TEST FACILITY

The full-scale crash tests reported herein were performed at the TTI Proving Ground, an International Standards Organization (ISO)/International Electrotechnical Commission (IEC) 17025-accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing Certificate 2821.01. The full-scale crash tests were performed according to TTI Proving Ground quality procedures, as well as *MASH* guidelines and standards.

The test facilities of the TTI Proving Ground are located on The Texas A&M University System RELLIS Campus, which consists of a 2000-acre complex of research and training facilities situated 10 mi northwest of the flagship campus of Texas A&M University. The site, formerly a United States Army Air Corps base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, highway pavement durability and efficacy, and roadside safety hardware and perimeter protective device evaluation. The site selected for construction and testing of the portable concrete construction zone barrier was along the edge of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks nominally 6 inches deep. The aprons were built in 1942, and the joints have some displacement but are otherwise flat and level.

4.2. VEHICLE TOW AND GUIDANCE SYSTEM

Each vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point and through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2:1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released and ran unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site.

4.3. DATA ACQUISITION SYSTEMS

4.3.1. Vehicle Instrumentation and Data Processing

Each test vehicle was instrumented with a self-contained onboard data acquisition system. The signal conditioning and acquisition system is a 16-channel Tiny Data Acquisition System (TDAS) Pro produced by Diversified Technical Systems Inc. The accelerometers, which measure the x, y, and z axis of vehicle acceleration, are strain gauge type with linear millivolt output proportional to acceleration. Angular rate sensors, measuring vehicle roll, pitch, and yaw rates, are ultra-small, solid-state units designed for crash test service. The TDAS Pro hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each of the 16 channels is capable of providing precision amplification, scaling, and filtering based on transducer specifications and calibrations. During the test, data are recorded from each channel at a rate of 10,000 samples per second with a resolution of one part in 65,536. Once data are recorded, internal batteries back these up inside the unit in case the primary battery cable is severed. Initial contact of the pressure switch on the vehicle bumper provides a time zero mark and initiates the recording process. After each test, the data are downloaded from the TDAS Pro unit into a laptop computer at the test site. The Test Risk Assessment Program (TRAP) software then processes the raw data to produce detailed reports of the test results.

Each of the TDAS Pro units is returned to the factory annually for complete recalibration and to ensure that all instrumentation used in the vehicle conforms to the specifications outlined by SAE J211. All accelerometers are calibrated annually by means of an ENDEVCO® 2901 precision primary vibration standard. This standard and its support instruments are checked annually and receive a National Institute of Standards Technology (NIST) traceable calibration. The rate transducers used in the data acquisition system receive calibration via a Genisco Rate-of-Turn table. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel per SAE J211. Calibrations and evaluations are also made anytime data are suspect. Acceleration data are measured with an expanded uncertainty of ±1.7 percent at a confidence factor of 95 percent (k = 2).

TRAP uses the data from the TDAS Pro to compute the occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and highest 10-millisecond (ms) average ridedown acceleration. TRAP calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with an SAE Class 180-Hz low-pass digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals, and then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation being initial impact. Rate of rotation data is measured with an expanded uncertainty of ±0.7 percent at a confidence factor of 95 percent (k = 2).

4.3.2. Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the front seat on the impact side of the 1100C vehicle. The dummy was not instrumented.

According to *MASH*, use of a dummy in the 2270P vehicle is optional, and no dummy was used in the test.

4.3.3. Photographic Instrumentation Data Processing

Photographic coverage of each test included three digital high-speed cameras:

- One overhead with a field of view perpendicular to the ground and directly over the impact point.

- One placed upstream from the installation at an angle to have a field of view of the interaction of the rear of the vehicle with the installation.
- A third placed with a field of view parallel to and aligned with the installation at the downstream end.

A flashbulb on the impacting vehicle was activated by a pressure-sensitive tape switch to indicate the instant of contact with the portable concrete construction zone barrier. The flashbulb was visible from each camera. The video files from these digital high-speed cameras were analyzed to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A digital camera recorded and documented conditions of each test vehicle and the installation before and after the test.

This page intentionally left blank.

Chapter 5. *MASH* TEST 2-10 (CRASH TEST NO. 690905-UOF1)

5.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 2-10 involves a 1100C vehicle weighing 2420 lb ± 55 lb impacting the CIP of the longitudinal barrier at an impact speed of 44 mi/h ± 2.5 mi/h and an angle of 25 degrees ± 1.5 degrees. The CIP for *MASH* Test 2-10 on the portable concrete construction zone barrier was 3.3 ft ± 1 ft upstream of the center of the joint between barriers 6 and 7. Figure 3.1 and Figure 5.1 depict the target impact setup.

Figure 5.1. Barrier/Test Vehicle Geometrics for Test No. 690905-UOF1.

The 1100C vehicle weighed 2402 lb, and the actual impact speed and angle were 44.4 mi/h and 25.6 degrees. The actual impact point was 3.6 ft upstream of the center of the joint between barriers 6 and 7. Minimum target impact severity (IS) was 25 kip-ft, and actual IS was 30 kip-ft.

5.2. WEATHER CONDITIONS

The test was performed on the morning of February 3, 2021. Weather conditions at the time of testing were as follows: wind speed: 11 mi/h; wind direction: 174 degrees (vehicle was traveling at a heading of 350 degrees); temperature: 61°F; relative humidity: 80 percent.

5.3. TEST VEHICLE

Figure 5.2 shows the 2016 Nissan Versa used for the crash test. The vehicle's test inertia weight was 2402 lb, and its gross static weight was 2567 lb. The height to the lower edge of the vehicle bumper was 7.0 inches, and the height to the upper edge of the bumper was 22.25 inches. Table C.1 in Appendix C.1 gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 5.2. Test Vehicle before Test No. 690905-UOF1.

5.4. TEST DESCRIPTION

Table 5.1 lists events that occurred during Test No. 690905-UOF1. Figures C.1 and C.2 in Appendix C.2 present sequential photographs during the test.

Table 5.1. Events during Test No. 690905-UOF1.

Time (s)	Events
0.0000	Vehicle impacts the barrier
0.0390	Vehicle begins to redirect
0.0770	Right front tire lifts off of the pavement
0.0830	Right rear tire lifts off of the pavement
0.2540	Vehicle traveling parallel with the barrier
0.2630	Rear of vehicle contacts the barrier
0.4250	Vehicle loses contact with the barrier while traveling at 34.6 mi/h, at a trajectory of 6.8 degrees, and a heading of 4.6 degrees
0.5310	Right front tire returns to the pavement

For longitudinal barriers, it is desirable for the vehicle to redirect and exit the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the barrier, the vehicle came to rest 105 ft downstream of the point of impact and 51 ft toward traffic lanes.

5.5. DAMAGE TO TEST INSTALLATION

Figure 5.3 and Figure 5.4 show the damage to the portable concrete construction zone barrier. Orange paint was used to indicate existing spalling, and silver paint was used to cover up scuffing from the previous test. Red lines were also used to outline the cracks from the previous test.

There was some scuffing at impact and at the secondary impact location 69 inches downstream from the upstream end of barrier 8. Barrier 5 at its upstream slot location had a 17¾-inch long crack extending 3¼ inches from the top traffic side edge of the slot downstream. Barrier 6 had an existing crack which widened to ¼-inch and extended further downstream ending at 34¼ inches downstream from the upstream end of the barrier. Barrier 10 had some spalling at its downstream field-side toe.

Figure 5.3. Portable Concrete Construction Zone Barrier after Test No. 690905-UOF1.

Figure 5.4. Damage to Field Side of Barrier after Test No. 690905-UOF1.

Table 5.2 shows barrier displacements after the test. Working width* was 27.1 inches, and height of working width was 5.0 inches. Maximum dynamic deflection during the test was 6.4 inches, and maximum permanent deformation was 6.25 inches.

Table 5.2. Displacement of Barrier after Test No. 690905-UOF1.

Joint	Barrier	Displacement Toward Field-Side
4-5	4	3 inches
	5	2½ inches
5-6	5	4¾ inches
	6	5 inches
6-7	6	6¼inches
	7	6¼ inches
7-8	7	5½ inches
	8	4¾ inches
8-9	8	2½ inches
	9	2½ inches

* Per *MASH*, "The working width is the maximum dynamic lateral position of any major part of the system or vehicle. These measurements are all relative to the pre-impact traffic face of the test article." In other words, working width is the total barrier width plus the maximum dynamic intrusion of any portion of the barrier or test vehicle past the field side edge of the barrier.

5.6. DAMAGE TO TEST VEHICLE

Figure 5.5 shows the damage sustained by the vehicle. The front bumper, left front wheel rim, left front fender, left front and rear doors, left rear wheel rim, and rear bumper were damaged. No fuel tank damage was observed. Maximum exterior crush to the vehicle was 3.0 inches in the front and side planes at the left front corner at bumper height. No occupant compartment deformation or intrusion was observed. Figure 5.6 shows the interior of the vehicle. Tables C.2 and C.3 in Appendix C.1 provide exterior crush and occupant compartment measurements.

Figure 5.5. Test Vehicle after Test No. 690905-UOF1.

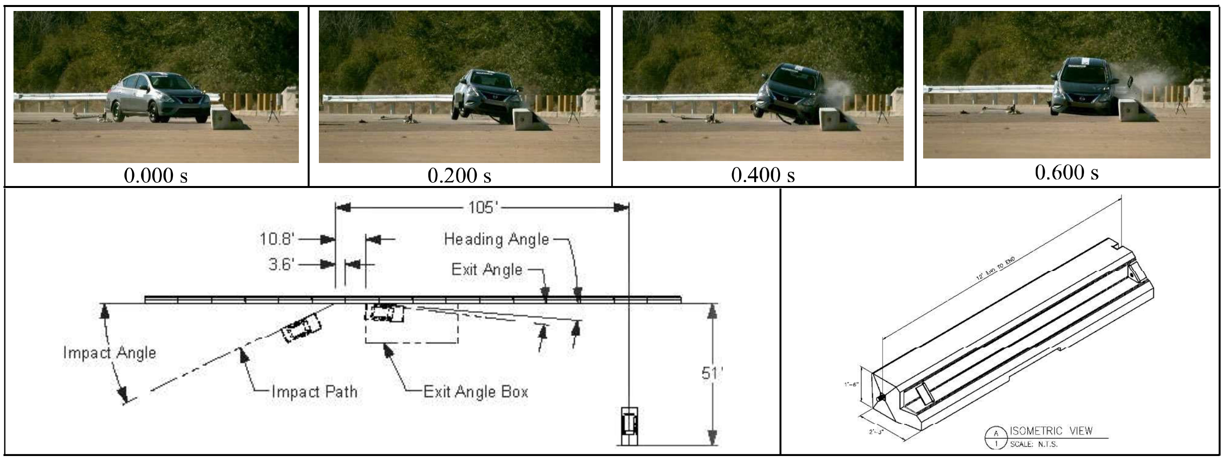
Figure 5.6. Interior of Test Vehicle after Test No. 690905-UOF1.

5.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 5.3. Figure C.3 in Appendix C.3 shows the vehicle angular displacements, and Figures C.4 through C.6 in Appendix C.4 show acceleration versus time traces. Figure 5.7 summarizes pertinent information from the test.

Table 5.3. Occupant Risk Factors for Test No. 690905-UOF1.

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	15.4 ft/s	at 0.1035 s on left side of interior
Lateral	20.7 ft/s	
Occupant Ridedown Accelerations		
Longitudinal	2.1 g	0.2871 - 0.2971 s
Lateral	6.7 g	0.2902 - 0.3002 s
Theoretical Head Impact Velocity (THIV)	7.8 m/s	at 0.1010 s on left side of interior
Acceleration Severity Index (ASI)	1.5	0.0568 - 0.1068 s
Maximum 50-ms Moving Average		
Longitudinal	−7.6 g	0.0424 - 0.0924 s
Lateral	11.3 g	0.0281 - 0.0781 s
Vertical	−2.6 g	0.0254 - 0.0754 s
Maximum Roll, Pitch, and Yaw Angles		
Roll	11°	0.4154 s
Pitch	12°	5.0000 s
Yaw	106°	4.8883 s



General Information
Test Agency....................... Texas A&M Transportation Institute (TTI)
Test Standard Test No........ *MASH* Test 2-10
TTI Test No. 690905-UOF1
Test Date........................... 2021-02-03

Test Article
Type .... Longitudinal Barrier—PCB
Name................................. Portable Concrete Construction Zone Barrier
Installation Length.............. 192 ft
Material or Key Elements.... 16 precast low-profile concrete barriers connected in tension with plates and threaded rods

Soil Type and Condition..... Concrete pavement, damp

Test Vehicle
Type/Designation............... 1100C
Make and Model .... 2016 Nissan Versa
Curb................................... 2394 lb
Test Inertial........................ 2402 lb
Dummy .... 165 lb
Gross Static....................... 2567 lb

Impact Conditions
Speed .... 44.4 mi/h
Angle .... 25.6°
Location/Orientation........... 3.6 ft upstream of joint 6-7

Impact Severity.................... 30 kip-ft

Exit Conditions
Speed .... 34.6 mi/h
Trajectory/Heading Angle... 6.8°/4.6°

Occupant Risk Values
Longitudinal OIV .... 15.4 ft/s
Lateral OIV......................... 20.7 ft/s
Longitudinal Ridedown....... 2.1 g
Lateral Ridedown .... 6.7 g
THIV .... 7.8 m/s
ASI..................................... 1.5
Max. 0.050-s Average
Longitudinal .... −7.6 g
Lateral............................. 11.3 g
Vertical............................ −2.6 g

Post-Impact Trajectory
Stopping Distance.................... 105 ft downstream 51 ft twd traffic lanes

Vehicle Stability
Maximum Roll Angle .... 11°
Maximum Pitch Angle .... 12°
Maximum Yaw Angle .... 106°
Vehicle Snagging...................... No
Vehicle Pocketing .... No

Test Article Deflections
Dynamic.................................... 6.4 inches
Permanent .... 6.25 inches
Working Width........................... 27.1 inches
Height of Working Width .... 5.0 inches

Vehicle Damage
VDS 11LFQ3
CDC 11FLEW3
Max. Exterior Deformation......... 3.0 inches
OCDI.. LF0000000
Max. Occupant Compartment Deformation .... None

Figure 5.7. Summary of Results for *MASH* Test 2-10 on Portable Concrete Construction Zone Barrier.

This page intentionally left blank.

Chapter 6. *MASH* TEST 2-11 (CRASH TEST NO. 690905-UOF2)

6.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 2-11 involves a 2270P vehicle weighing 5000 lb ± 110 lb impacting the CIP of the longitudinal barrier at an impact speed of 44 mi/h ± 2.5 mi/h and an angle of 25 degrees ± 1.5 degrees. The CIP for *MASH* Test 2-11 on the portable concrete construction zone barrier was 2.6 ft ± 1 ft upstream of the center of the joint between barriers 6 and 7. Figure 3.2 and Figure 6.1 depict the target impact setup.

Figure 6.1. Barrier/Test Vehicle Geometrics for Test No. 690905-UOF2.

The 2270P vehicle weighed 5016 lb, and the actual impact speed and angle were 42.5 mi/h and 26.4 degrees. The actual impact point was 3.6 ft upstream of the center of the joint between barriers 6 and 7. Minimum target IS was 52 kip-ft, and actual IS was 60 kip-ft.

6.2. WEATHER CONDITIONS

The test was performed on the morning of February 1, 2021. Weather conditions at the time of testing were as follows: wind speed: 7 mi/h; wind direction: 309 degrees (vehicle was traveling at a heading of 350 degrees); temperature: 53°F; relative humidity: 59 percent.

6.3. TEST VEHICLE

Figure 6.2 shows the 2016 RAM 1500 pickup truck used for the crash test. The vehicle's test inertia weight was 5016 lb, and its gross static weight was 5016 lb. The height to the lower edge of the vehicle bumper was 11.75 inches, and height to the upper edge of the bumper was 27.0 inches. The height to the vehicle's center of gravity was 28.37 inches. Tables D.1 and D.2 in Appendix D.1 give additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 6.2. Test Vehicle before Test No. 690905-UOF2.

6.4. TEST DESCRIPTION

Table 6.1 lists events that occurred during Test No. 690905-UOF2. Figures D.1 and D.2 in Appendix D.2 present sequential photographs during the test.

Table 6.1. Events during Test No. 690905-UOF2.

Time (s)	Events
0.0000	Vehicle impacts the barrier
0.0377	Left front tire lifts off of the pavement
0.0520	Vehicle begins to redirect
0.1000	Right front tire lifts off of the pavement
0.1310	Right rear tire lifts off of the pavement
0.3070	Vehicle traveling parallel with the barrier
0.3830	Rear bumper contacts the barrier
0.6290	Vehicle loses contact with the barrier while traveling at 33.5 mi/h, at a trajectory of 10.3 degrees, and a heading of 8.0 degrees
0.7090	Right front tire returns to the pavement
1.0700	Right rear tire returns to the pavement

For longitudinal barriers, it is desirable for the vehicle to redirect and exit the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the barrier, the vehicle came to rest 107 ft downstream of the point of impact against the traffic face of the barrier.

6.5. DAMAGE TO TEST INSTALLATION

Figure 6.3 shows the damage to the barrier. There was scuffing from impact until the vehicle's final resting position. There was a secondary contact 25½ inches downstream from the joint of barriers 8 and 9. Barrier 6 had a ½-inch wide crack 20½ inches long on its upstream traffic side extending from the top of the barrier to grade. Barrier 6 also had some spalling from impact until its center. Barrier 11 had a crack on its upstream field side toe which extended through to grade. Barriers 4 and 7 had cracks extending from their slots.

Table 5.2 shows barrier displacements after the test. Working width* was 40.5 inches, and height of working width was 5.0 inches. Maximum dynamic deflection during the test was 13.2 inches, and maximum permanent deformation was 12.5 inches.

Figure 6.3. Barrier after Test No. 690905-UOF2.

* Per *MASH*, "The working width is the maximum dynamic lateral position of any major part of the system or vehicle. These measurements are all relative to the pre-impact traffic face of the test article." In other words, working width is the total barrier width plus the maximum dynamic intrusion of any portion of the barrier or test vehicle past the field side edge of the barrier.

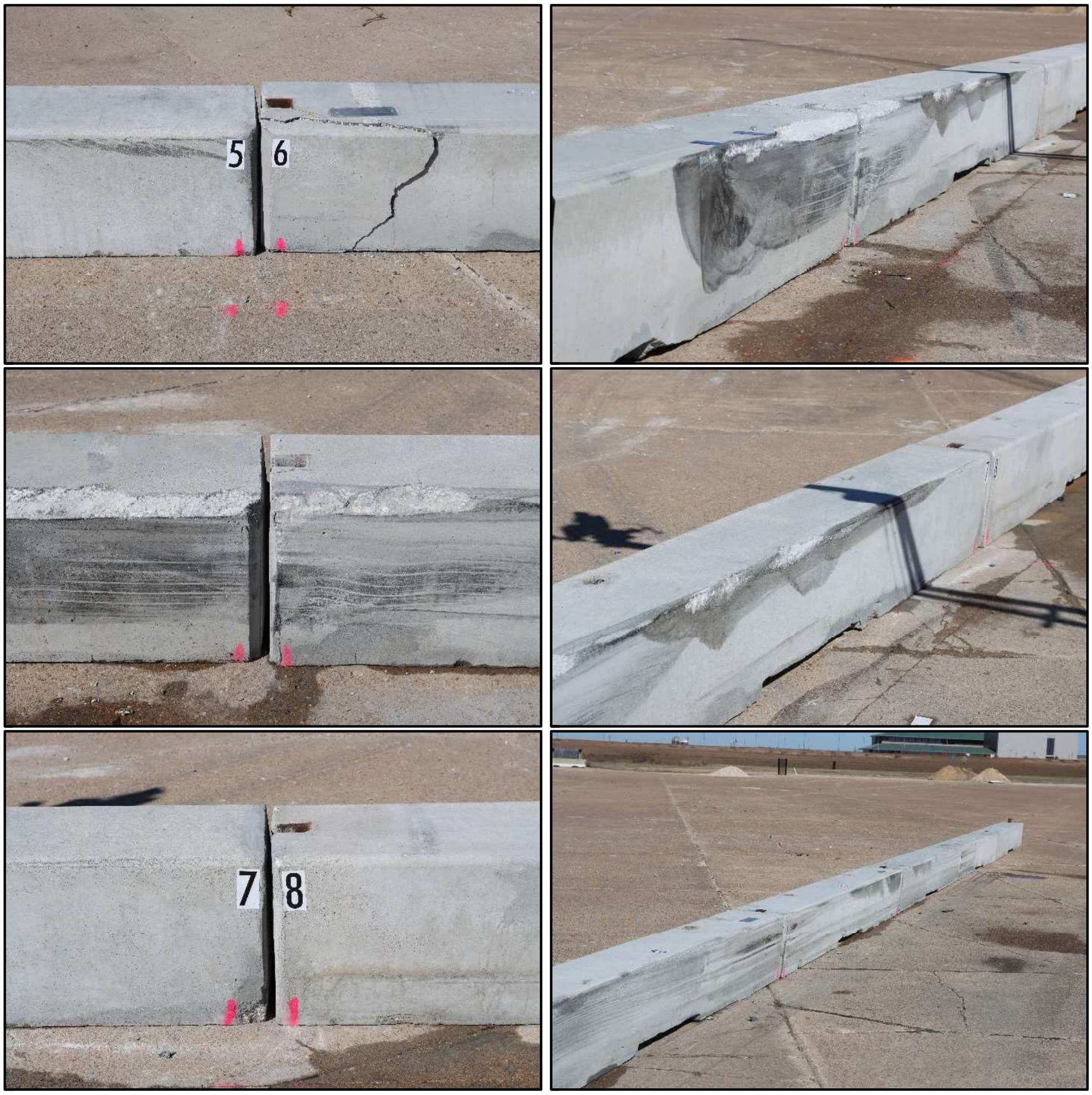


Figure 6.4. Damage to Traffic Side after Test No. 690905-UOF2.

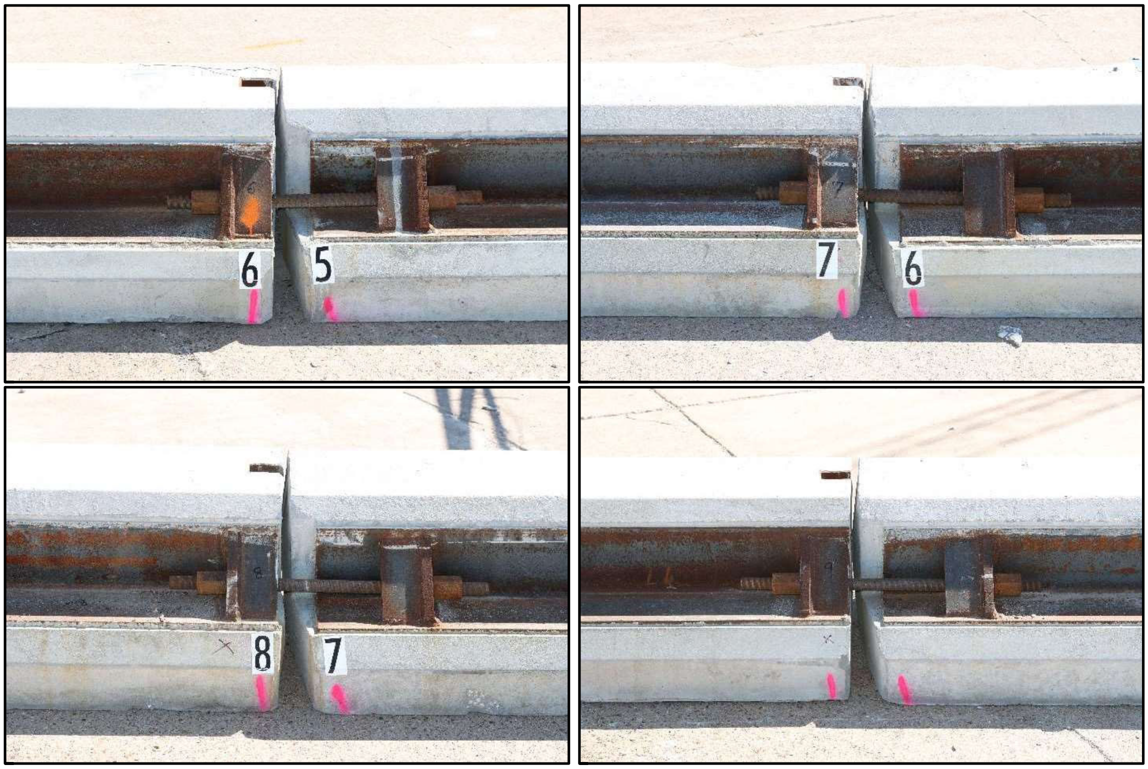


Figure 6.5. Damage to Field Side after Test No. 690905-UOF2.

Table 6.2. Displacement of Barrier after Test No. 690905-UOF2.

Joint	Barrier	Displacement Toward Field-Side
2-3	2	0 inch
	3	⅜ inch
3-4	3	3 inches
	4	3 inches
4-5	4	7 inches
	5	7 inches
5-6	5	11 inches
	6	11½ inches
6-7	6	12½ inches
	7	12½ inches
7-8	7	10¼ inches
	8	10¼ inches
8-9	8	6¼ inches
	9	6¼ inches
9-10	9	3½ inches
	10	3½ inches
10-11	10	½ inch
	11	½ inch

6.6. DAMAGE TO TEST VEHICLE

Figure 6.4 shows the damage sustained by the vehicle. The front bumper, left front fender, left tire and rim, left lower control arm, left front and rear doors, left rear cab corner, left rear rim, and left exterior bed were damaged. No fuel tank damage was observed. Maximum exterior crush to the vehicle was 10.0 inches in the front and side planes at the right front corner at bumper height. No occupant compartment deformation or intrusion was observed. Figure 6.5 shows the interior of the vehicle. Tables D.3 and D.4 in Appendix D.1 provide exterior crush and occupant compartment measurements.

Figure 6.6. Test Vehicle after Test No. 690905-UOF2.

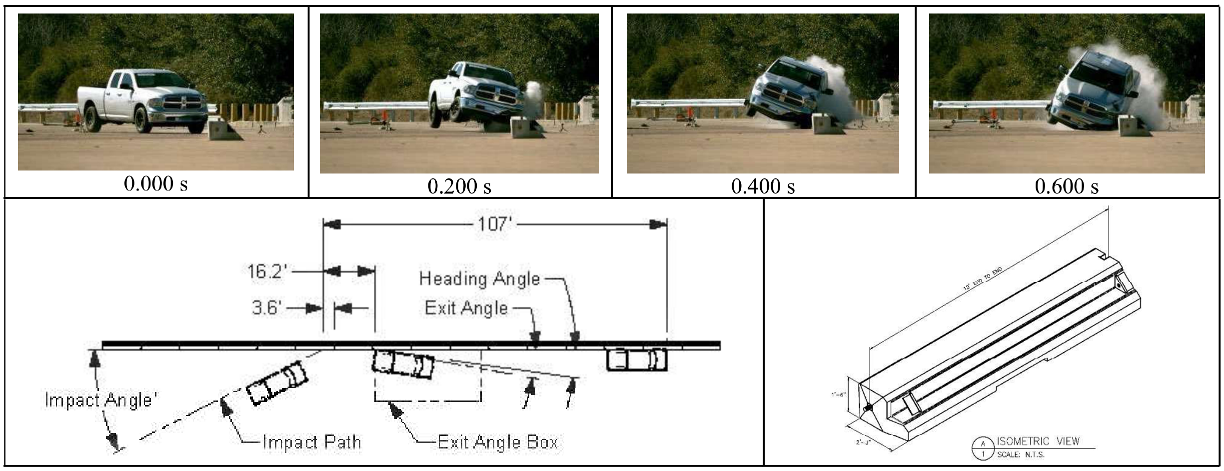
Figure 6.7. Interior of Test Vehicle after Test No. 690905-UOF2.

6.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 6.3. Figure D.3 in Appendix D.3 shows the vehicle angular displacements, and Figures D.4 through D.6 in Appendix D.4 show acceleration versus time traces. Figure 6.6 summarizes pertinent information from the test.

Table 6.3. Occupant Risk Factors for Test No. 690905-UOF2.

Occupant Risk Factor	Value	Time
OIV		
Longitudinal	14.8 ft/s	at 0.1268 s on left side of interior
Lateral	16.7 ft/s	
Occupant Ridedown Accelerations		
Longitudinal	3.7 g	0.3986 - 0.4086 s
Lateral	3.5 g	0.4127 - 0.4227 s
THIV	6.7 m/s	at 0.1230 s on left side of interior
ASI	1.1	0.0660 - 0.1160 s
Maximum 50-ms Moving Average		
Longitudinal	−6.3 g	0.0521 - 0.1021 s
Lateral	7.7 g	0.0431 - 0.0931 s
Vertical	−2.2 g	0.0315 - 0.0815 s
Maximum Yaw, Pitch, and Roll Angles		
Roll	20°	0.5158 s
Pitch	11°	0.7836 s
Yaw	35°	0.4715 s



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	*MASH* Test 2-11
TTI Test No.	690905-UOF2
Test Date	2021-02-01
Test Article	
Type	Longitudinal Barrier—PCB
Name	Portable Concrete Construction Zone Barrier
Installation Length	192 ft
Material or Key Elements	16 precast low-profile concrete barriers connected in tension with plates and threaded rods
Soil Type and Condition	Concrete Pavement, Dry
Test Vehicle	
Type/Designation	2270P
Make and Model	2016 RAM 1500 Pickup
Curb	5155 lb
Test Inertial	5016 lb
Dummy	No dummy
Gross Static	5016 lb

Impact Conditions	
Speed	42.5 mi/h
Angle	26.4°
Location/Orientation	3.6 ft upstream of joint 6-7
Impact Severity	60 kip-ft
Exit Conditions	
Speed	33.5 mi/h
Trajectory/Heading Angle	10.3°/8.0°
Occupant Risk Values	
Longitudinal OIV	14.8 ft/s
Lateral OIV	16.7 ft/s
Longitudinal Ridedown	3.7 g
Lateral Ridedown	3.5 g
THIV	6.7 m/s
ASI	1.1
Max. 0.050-s Average	
Longitudinal	−6.3 g
Lateral	7.7 g
Vertical	−2.2 g

Post-Impact Trajectory	
Stopping Distance	107 ft downstream Against traffic face
Vehicle Stability	
Maximum Roll Angle	20°
Maximum Pitch Angle	11°
Maximum Yaw Angle	35°
Vehicle Snagging	No
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	13.2 inches
Permanent	12.5 inches
Working Width	40.5 inches
Height of Working Width	5.0 inches
Vehicle Damage	
VDS	11LFQ2
CDC	11FLEW2
Max. Exterior Deformation	10.0 inches
OCDI	LF0000000
Max. Occupant Compartment Deformation	None

Figure 6.8. Summary of Results for *MASH* Test 2-11 on Portable Concrete Construction Zone Barrier.

Chapter 7. SUMMARY AND CONCLUSIONS

7.1. ASSESSMENT OF TEST RESULTS

The crash tests reported herein were performed on the portable concrete construction zone barrier in accordance with *MASH* TL-2, which involves two tests. Table 7.1 and Table 7.2 provide an assessment of each test based on the applicable safety evaluation criteria for *MASH* TL-2 longitudinal barriers.

7.2. CONCLUSIONS

Table 7.3 shows that University of Florida's portable concrete construction zone barrier met the performance criteria for *MASH* TL-2 longitudinal barriers.

Table 7.1. Performance Evaluation Summary for *MASH* Test 2-10 on Portable Concrete Construction Zone Barrier.

Test Agency: Texas A&M Transportation Institute | Test No.: 690905-UOF1 | Test Date: 2021-02-03

***MASH* Test 2-10 Evaluation Criteria**	**Test Results**	**Assessment**
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.*	The portable concrete construction zone barrier contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the barrier. Maximum dynamic deflection during the test was 6.4 inches.	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.*	No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present undue hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.	No occupant compartment deformation or intrusion occurred.	
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 11 degrees and 12 degrees.	Pass
H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.	Longitudinal OIV was 15.4 ft/s, and lateral OIV was 20.7 ft/s.	Pass
I. The occupant ridedown accelerations should satisfy the following limits: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.	Longitudinal occupant ridedown acceleration was 2.1 g, and lateral occupant ridedown acceleration was 6.7 g.	Pass

Table 7.2. Performance Evaluation Summary for *MASH* Test 2-11 on Portable Concrete Construction Zone Barrier.

Test Agency: Texas A&M Transportation Institute — Test No.: 690905-UOF2 — Test Date: 2021-02-01

MASH Test 2-11 Evaluation Criteria	Test Results	Assessment
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.*	The portable concrete construction zone barrier contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the barrier. Maximum dynamic deflection during the test was 13.2 inches.	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.*	Although the barrier was cracked at one joint, there were no detached fragments or other debris to penetrate or show potential for penetrating the occupant compartment, or present undue hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.	No occupant compartment deformation or intrusion occurred.	
F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*	The 2270P vehicle remained upright during and after the collision period. Maximum roll and pitch angles were 20 degrees and 11 degrees.	Pass
H. *Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.*	Longitudinal OIV was 14.8 ft/s, and lateral OIV was 16.7 ft/s.	Pass
I. *The occupant ridedown accelerations should satisfy the following limits: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.*	Longitudinal occupant ridedown acceleration was 3.7 g, and lateral occupant ridedown acceleration was 3.5 g.	Pass

Table 7.3. Assessment Summary for *MASH* TL-2 Tests on Portable Concrete Construction Zone Barrier.

Evaluation Factors	Evaluation Criteria	Test No. 690905-UOF1	Test No. 690905-UOF2
Structural Adequacy	A	S	S
Occupant Risk	D	S	S
	F	S	S
	H	S	S
	I	S	S
	Test No.	***MASH* Test 2-10**	***MASH* Test 2-11**
	Pass/Fail	Pass	Pass

Note: S = Satisfactory.

REFERENCES

1. AASHTO. *Manual for Assessing Roadside Safety Hardware, Second Edition.* American Association of State Highway and Transportation Officials: Washington, DC, 2016.

This page intentionally left blank.

APPENDIX A. DETAILS OF PORTABLE CONCRETE CONSTRUCTION ZONE BARRIER

UNIVERSITY OF FLORIDA
PRECAST LOW-PROFILE BARRIER WALL

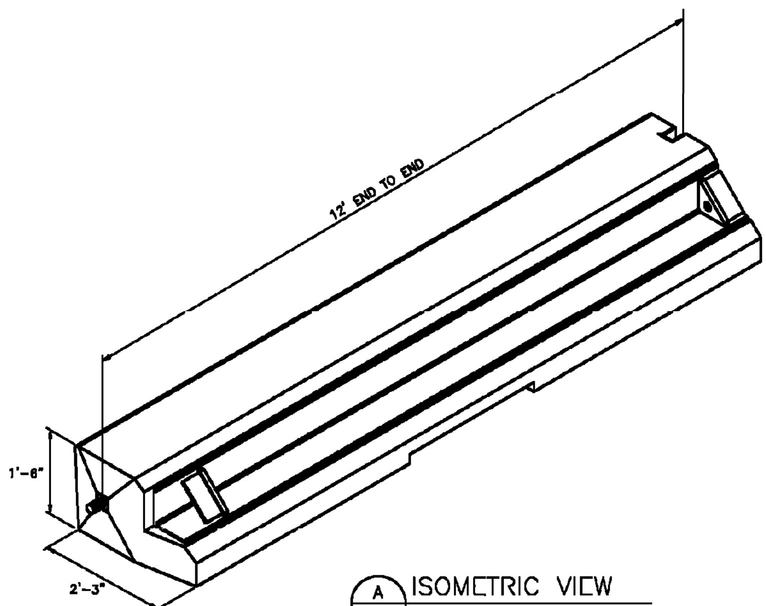
GENERAL NOTES:

1. CONCRETE
   A. CONCRETE MIX:
      fc'i = 3,000 psi AT FORM REMOVAL
      f'c = 5,000 psi AT 28 DAYS.
   B. CURING SHALL BE IN ACCORDANCE WITH CURRENT FLORIDA DOT STANDARDS.
   C. NEITHER TRANSPORT NOR INSTALLATION OF BARRIER SEGMENTS SHALL TAKE PLACE BEFORE THE 28 DAY CONCRETE STRENGTH HAS BEEN ACHIEVED. ⚠
2. ALL REBAR SHALL BE A615, GR60.
3. FABRICATION OF THE LOW PROFILE BARRIER WALL UNITS SHALL CONFORM TO THE REQUIREMENTS OF ACI 318-02.
4. MANUFACTURERS OF LOW PROFILE BARRIER WALL UNITS SHALL CONFORM TO THE CURRENT FLORIDA DEPARTMENT OF TRANSPORTATION REQUIREMENTS FOR QUALITY CONTROL. CONTACT THE FLORIDA DEPARTMENT OF TRANSPORTATION, STATE MATERIALS OFFICE FOR INFORMATION ON CURRENT REQUIREMENTS (352-955-6683).
5. EACH LOW PROFILE BARRIER WALL UNIT SHALL BE INSTALLED SO AS TO BE IN FIRM CONTACT WITH ADJOINING UNITS. NUTS ON TENSIONING RODS SHALL BE INSTALLED SNUG TIGHT.
6. THE LOW PROFILE BARRIER WALL IS APPLICABLE FOR DESIGN SPEEDS OF 45 MPH OR LESS.
7. LAYOUT AND CONFIGURATION OF LOW PROFILE BARRIER WALL INSTALLATIONS SHALL CONFORM TO THE CURRENT FLORIDA DEPARTMENT OF TRANSPORTATION DESIGN STANDARDS (SEE FDOT DESIGN STANDARD INDEX NO. 412) AND THE MANUAL FOR UNIFORM TRAFFIC CONTROL DEVICES.

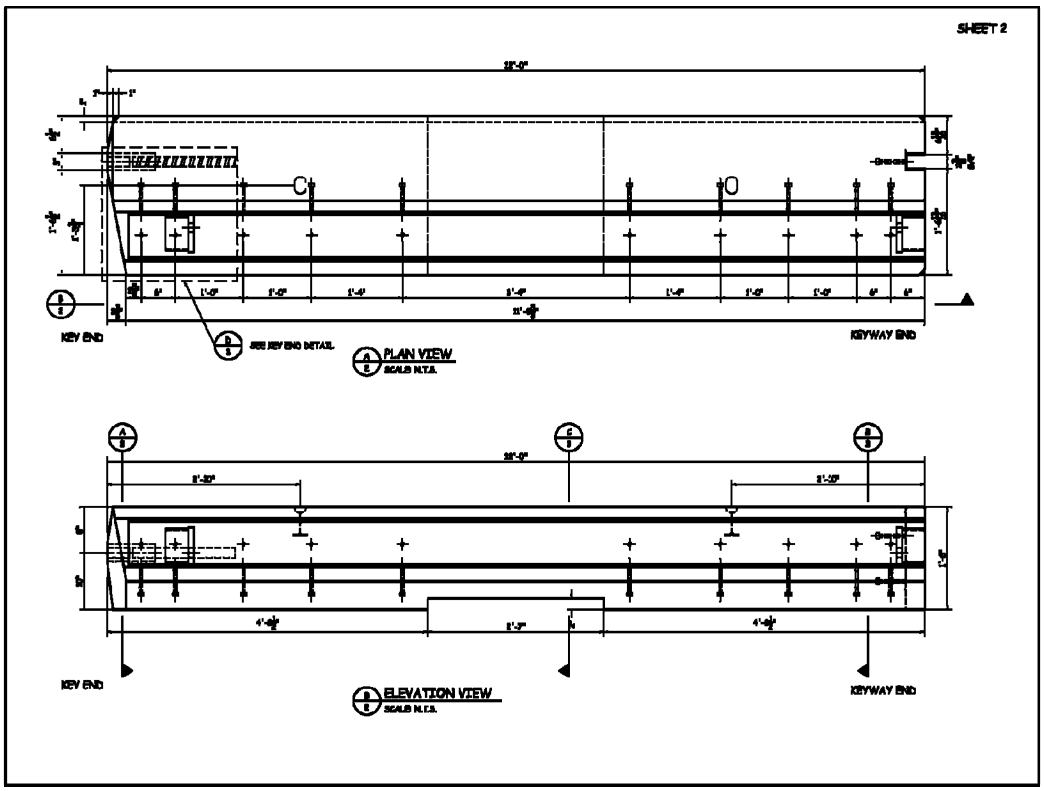
REVISIONS

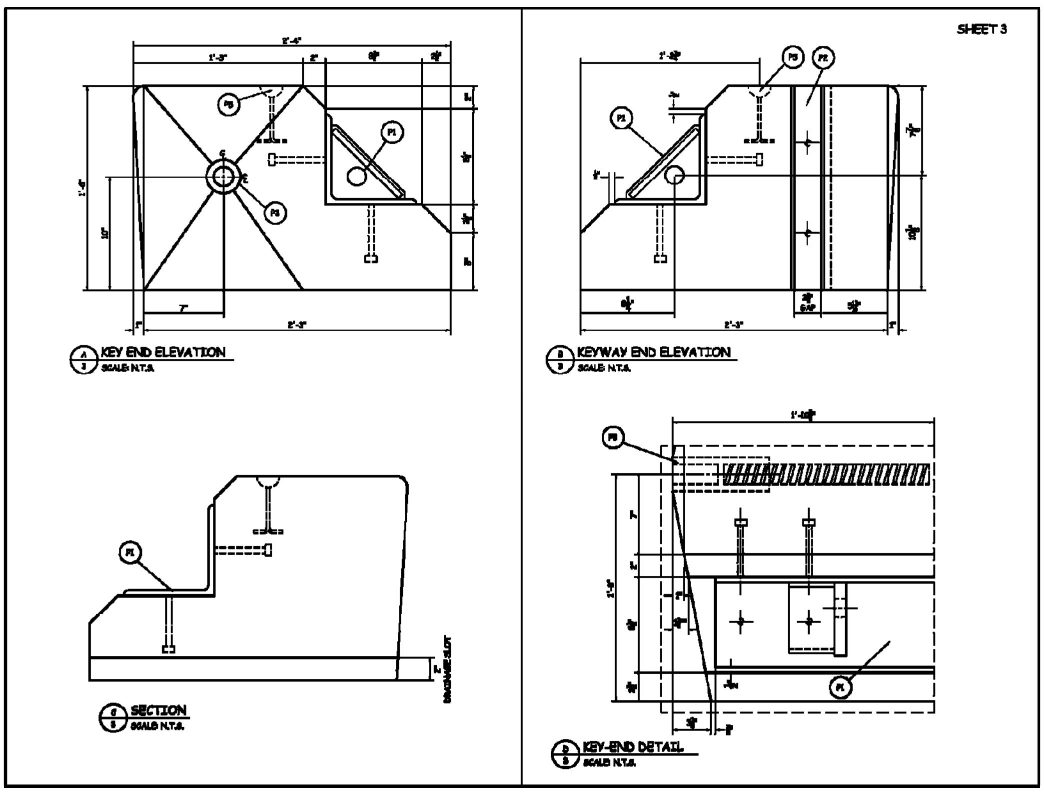
⚠ 11/05/2004

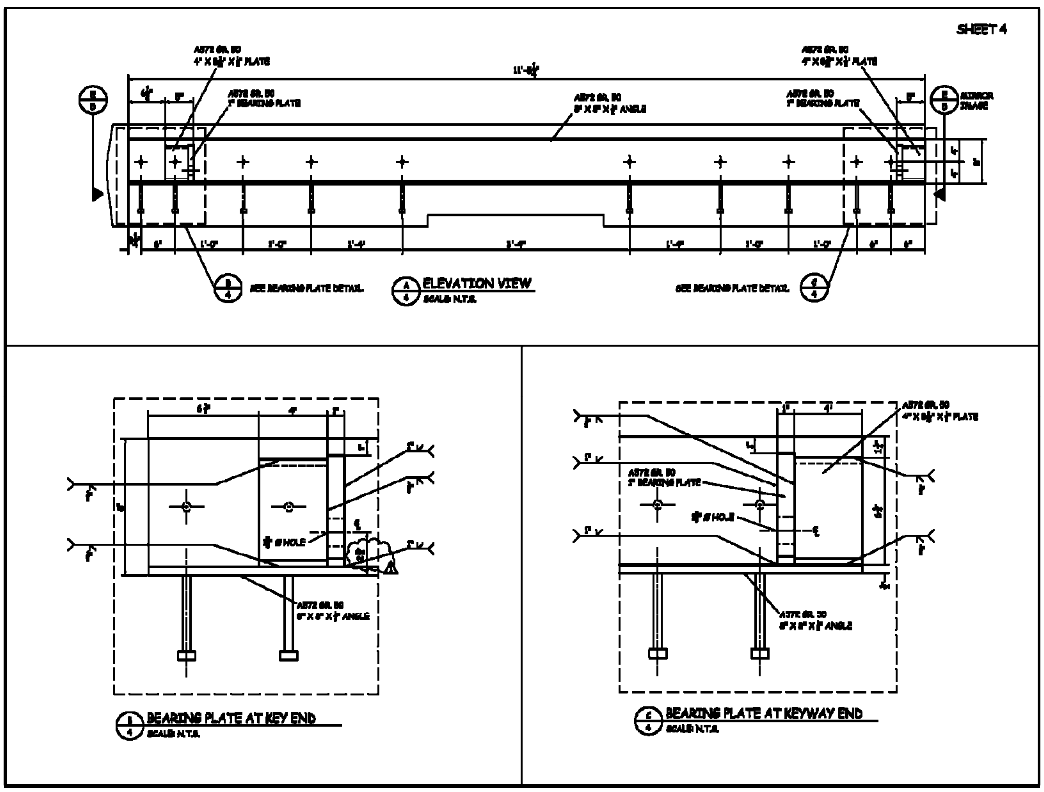
SHEET 1

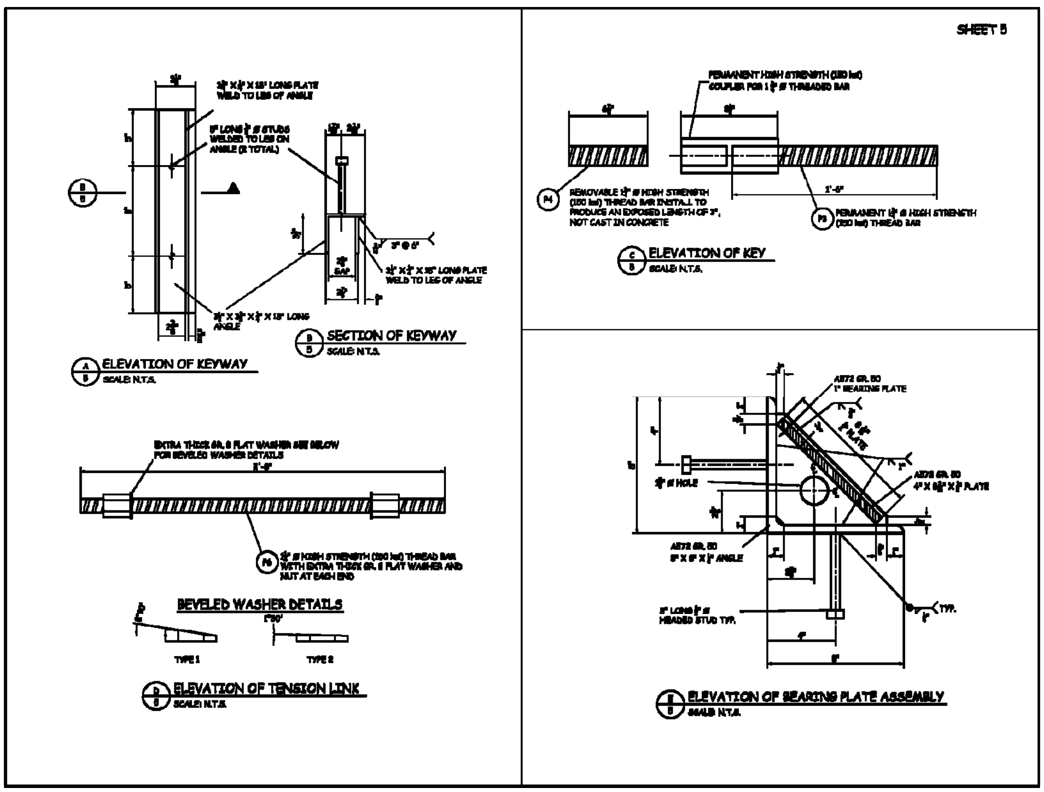


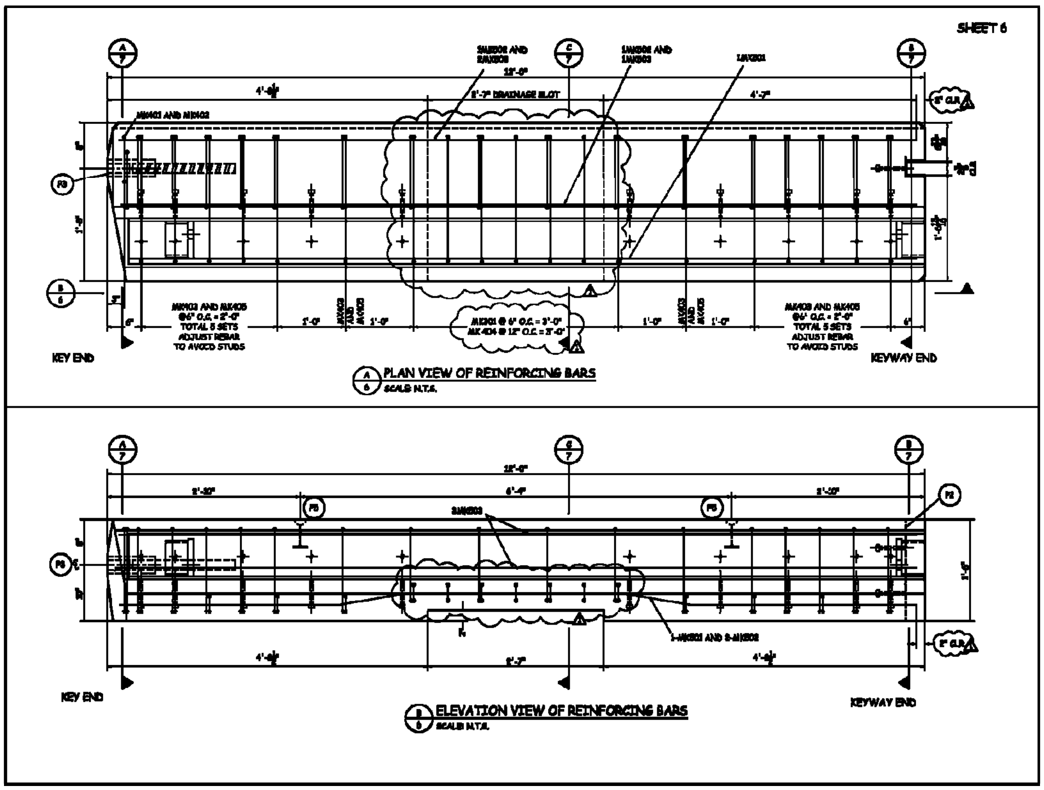
A/1 ISOMETRIC VIEW
SCALE: N.T.S.

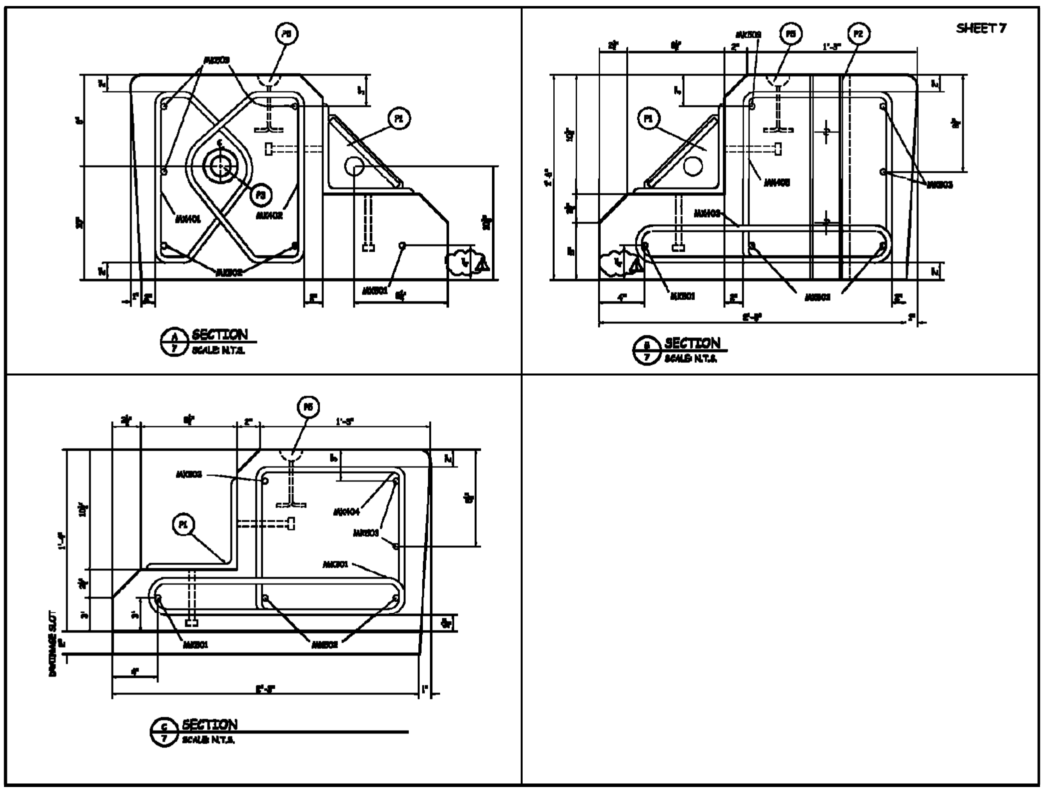

SHEET 2
KEY END
SEE KEY END DETAIL
PLAN VIEW
SCALE N.T.S.
KEYWAY END
KEY END
ELEVATION VIEW
SCALE N.T.S.
KEYWAY END

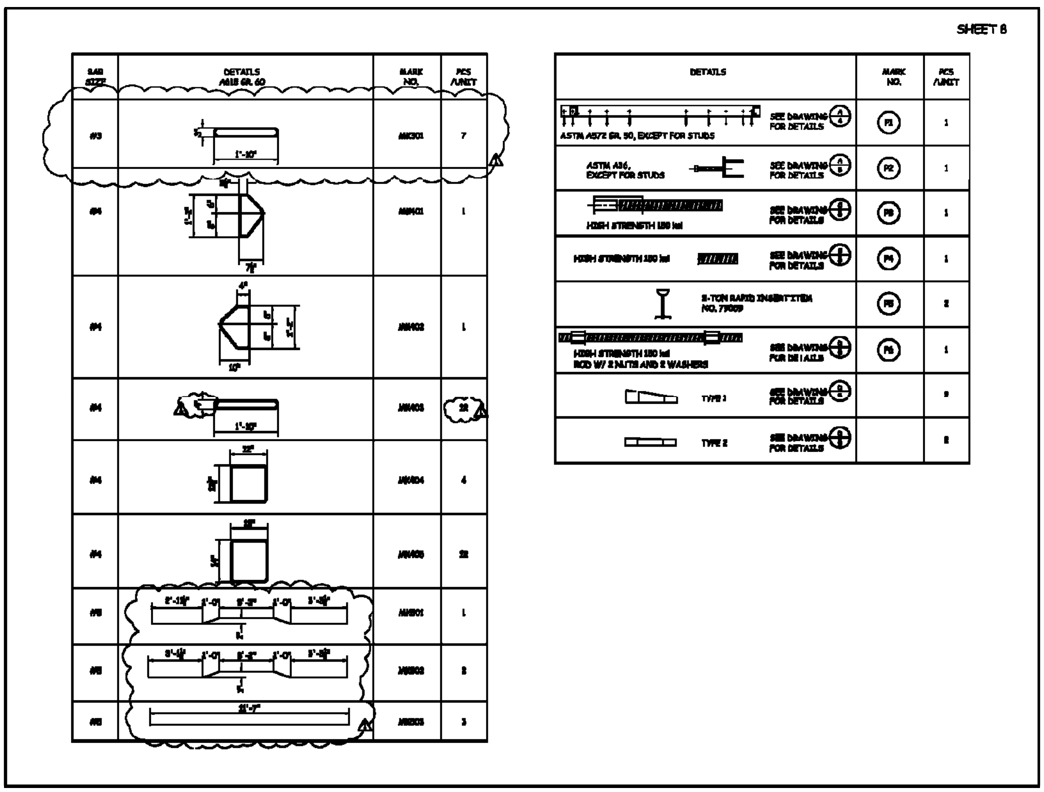

SHEET 3
KEY END ELEVATION
SCALE: N.T.S.
KEYWAY END ELEVATION
SCALE: N.T.S.
SECTION
SCALE: N.T.S.
KEY-END DETAIL
SCALE: N.T.S.


SHEET 4
ELEVATION VIEW
SEE BEARING PLATE DETAIL.
SEE BEARING PLATE DETAIL.
BEARING PLATE AT KEY END
BEARING PLATE AT KEYWAY END


SHEET 5
ELEVATION OF KEYWAY
SCALE: N.T.S.
SECTION OF KEYWAY
SCALE: N.T.S.
ELEVATION OF KEY
SCALE: N.T.S.
BEVELED WASHER DETAILS
TYPE 1
TYPE 2
ELEVATION OF TENSION LINK
SCALE: N.T.S.
ELEVATION OF BEARING PLATE ASSEMBLY
SCALE: N.T.S.


SHEET 6
KEY END
KEYWAY END
PLAN VIEW OF REINFORCING BARS
SCALE N.T.S.
ELEVATION VIEW OF REINFORCING BARS
SCALE N.T.S.


SHEET 7
A 7 SECTION
SCALE N.T.S.
B 7 SECTION
SCALE N.T.S.
C 7 SECTION
SCALE N.T.S.


SHEET 8
BAR SIZE
DETAILS A615 GR. 60
MARK NO.
PCS /UNIT
#3
1'-10"
#4
4"
10"
1'-10"
22"
#5
DETAILS
MARK NO.
PCS /UNIT
ASTM A572 GR. 50, EXCEPT FOR STUDS
SEE DRAWING FOR DETAILS
ASTM A36, EXCEPT FOR STUDS
HIGH STRENGTH 150 ksi
ROD W/ 2 NUTS AND 2 WASHERS
TYPE 2

This page intentionally left blank.

APPENDIX B. SUPPORTING CERTIFICATION DOCUMENTS

Concrete Core Test Report

Report Number: A1171057.0165
Service Date: 02/05/21
Report Date: 02/12/21
Task: 690900-MCU17-20

Terracon
6198 Imperial Loop
College Station, TX 77845-5765
979-846-3767 Reg No: F-3272

Client

Texas Transportation Institute
Attn: Gary Gerke
TTI Business Office
3135 TAMU
College Station, TX 77843-3135

Project

Riverside Campus
Riverside Campus
Bryan, TX

Project Number: A1171057

Material Information

Specified Strength:

Specified Length:
Mix ID:
Nominal Maximum Size Aggregate:

Sample Information

Placement Date:
Date Tested: 02/04/21 **Time:** 0000
Sampled By:
Drill Directions: Vertical
Date Core Obtained: 02/04/21 **Time:** 0000
Date Ends Trimmed: 02/04/21 **Time:** 0000
Moisture Conditioning History: According to ASTM C-42

Laboratory Test Data

Core ID	Location	Cored Length (in)	Trim Length (in)	Capped Length (in)	Diam. (in)	Area (sq in)	Length / Diam. Ratio	Max Load (lbs)	Corr. Factor	Comp. Strength (psi)	Fracture Type	Density (pcf)	Tested By
1	Barrier 1	7.80	7.20	7.50	4.04	12.82	1.86	129260	1.000	10080	3		BJA
2	Barrier 2	10.55	10.00	7.10	4.04	12.82	1.76	116810	1.000	9110	3		BJA
3	Barrier 6	6.75	6.10	6.45	4.04	12.82	1.60	114210	0.968	8620	2		BJA
4	Barrier 7	9.90	9.25	6.65	4.04	12.82	1.65	69600	0.972	5280	1		BJA

Comments:

Services:
Terracon Rep.: Cullen Turney
Reported To:
Contractor:
Report Distribution:
(1) Texas Transportation Institute, Gary Gerke (1) Texas Transportation Institute, Bill Griffith

Start/Stop: 0800-1500

Reviewed By:
Alexander Dunigan
Project Manager

Test Methods:
The tests were performed in general accordance with applicable ASTM, AASHTO, or DOT test methods. This report is exclusively for the use of the client indicated above and shall not be reproduced except in full without the written consent of our company. Test results transmitted herein are only applicable to the actual samples tested at the location(s) referenced and are not necessarily indicative of the properties of other apparently similar or identical materials.

CR0004, 11-16-12, Rev.5

Page 1 of 1

APPENDIX C. *MASH* TEST 2-10 (CRASH TEST NO. 690905-UOF1)

C.1. VEHICLE PROPERTIES AND INFORMATION

Table C.1. Vehicle Properties for Test No. 690905-UOF1.

Date: 2021-02-03 Test No.: 690905-UOF1 VIN No.: 3N1CN7APXGL895953

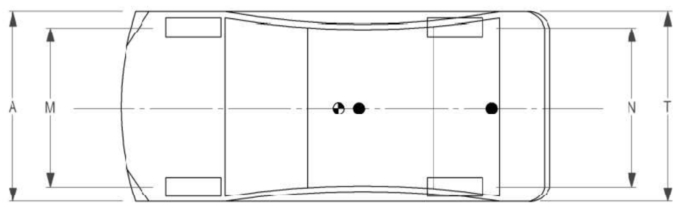
Year: 2016 Make: NISSAN Model: VERSA

Tire Inflation Pressure: 36 PSI Odometer: 91273 Tire Size: P185/65R15

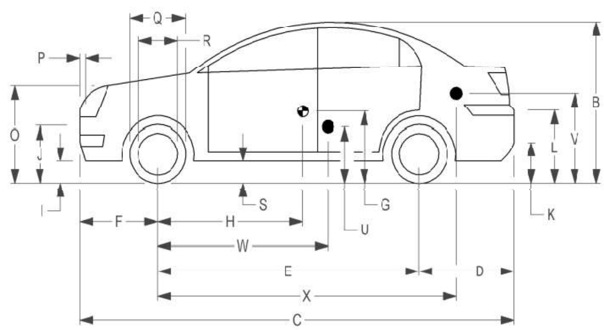
Describe any damage to the vehicle prior to test: None

● Denotes accelerometer location.

NOTES: None



Engine Type: 4 CYL
Engine CID: 1.6 L
Transmission Type:
☑ Auto or ☐ Manual
☑ FWD ☐ RWD ☐ 4WD
Optional Equipment:
None



Dummy Data:
Type: 50th Percentile Male
Mass: 165 lb
Seat Position: IMPACT SIDE

Geometry: inches

A	66.70	F	32.50	K	12.50	P	4.50	U	15.50
B	59.60	G		L	26.00	Q	24.00	V	21.25
C	175.40	H	40.92	M	58.30	R	16.25	W	40.90
D	40.50	I	7.00	N	58.50	S	7.50	X	79.75
E	102.40	J	22.25	O	30.50	T	64.50		

Wheel Center Ht Front 11.50 Wheel Center Ht Rear 11.50 W-H -0.02

RANGE LIMIT: A = 65 ±3 inches; C = 169 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; H = 39 ±4 inches; O (Top of Radiator Support) = 28 ±4 inches
(M+N)/2 = 59 ±2 inches; W-H < 2 inches or use MASH Paragraph A4.3.2

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	1750	M_{front}	1430	1442	1527
Back	1687	M_{rear}	964	960	1040
Total	3389	M_{Total}	2394	2402	2567

Allowable TIM = 2420 lb ±55 lb | Allowable GSM = 2585 lb ± 55 lb

Mass Distribution:
lb LF: 733 RF: 709 LR: 475 RR: 485

Table C.2. Exterior Crush Measurements for Test No. 690905-UOF1.

Date:	2021-2-3	Test No.:	690905-UOF1	VIN No.:	3N1CN7APXGL895953
Year:	2016	Make:	NISSAN	Model:	VERSA

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	**Side Damage**
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1	B2 X2
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2}$ = _______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width*** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bmp ht	16	3	24							-24
2	Side plane above bmp ht	16	3	40							56
	Measurements recorded										
	☑ **inches** or ☐ **mm**										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

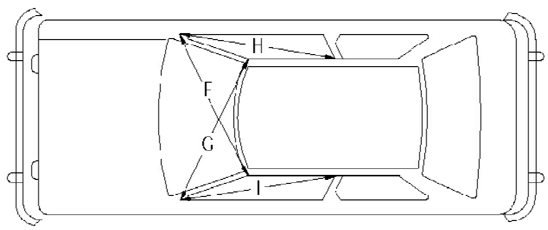
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

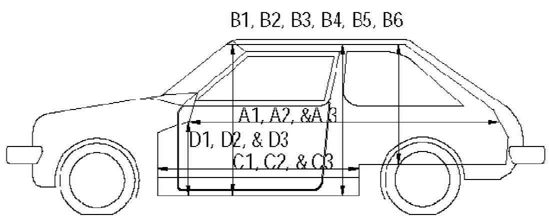
***Measure and document on the vehicle diagram the location of the maximum crush.

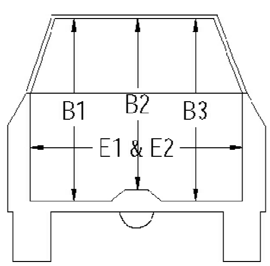
Note: Use as many lines/columns as necessary to describe each damage profile.

Table C.3. Occupant Compartment Measurements for Test No. 690905-UOF1.

Date:	2021-2-3	Test No.:	690905-UOF1	VIN No.:	3N1CN7APXGL895953
Year:	2016	Make:	NISSAN	Model:	VERSA







*Lateral area across the cab from driver's side kick panel to passenger's side kick panel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	75.00	75.00	0.00
A2	74.00	74.00	0.00
A3	74.00	74.00	0.00
B1	43.00	43.00	0.00
B2	37.00	37.00	0.00
B3	43.00	43.00	0.00
B4	46.50	46.50	0.00
B5	42.50	42.50	0.00
B6	46.50	46.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	26.00	0.00
D1	12.50	12.50	0.00
D2	0.00	0.00	0.00
D3	10.00	10.00	0.00
E1	45.00	45.00	0.00
E2	48.75	48.75	0.00
F	47.50	47.50	0.00
G	47.50	47.50	0.00
H	39.00	39.00	0.00
I	39.00	39.00	0.00
J*	48.50	48.50	0.00

C.2. SEQUENTIAL PHOTOGRAPHS

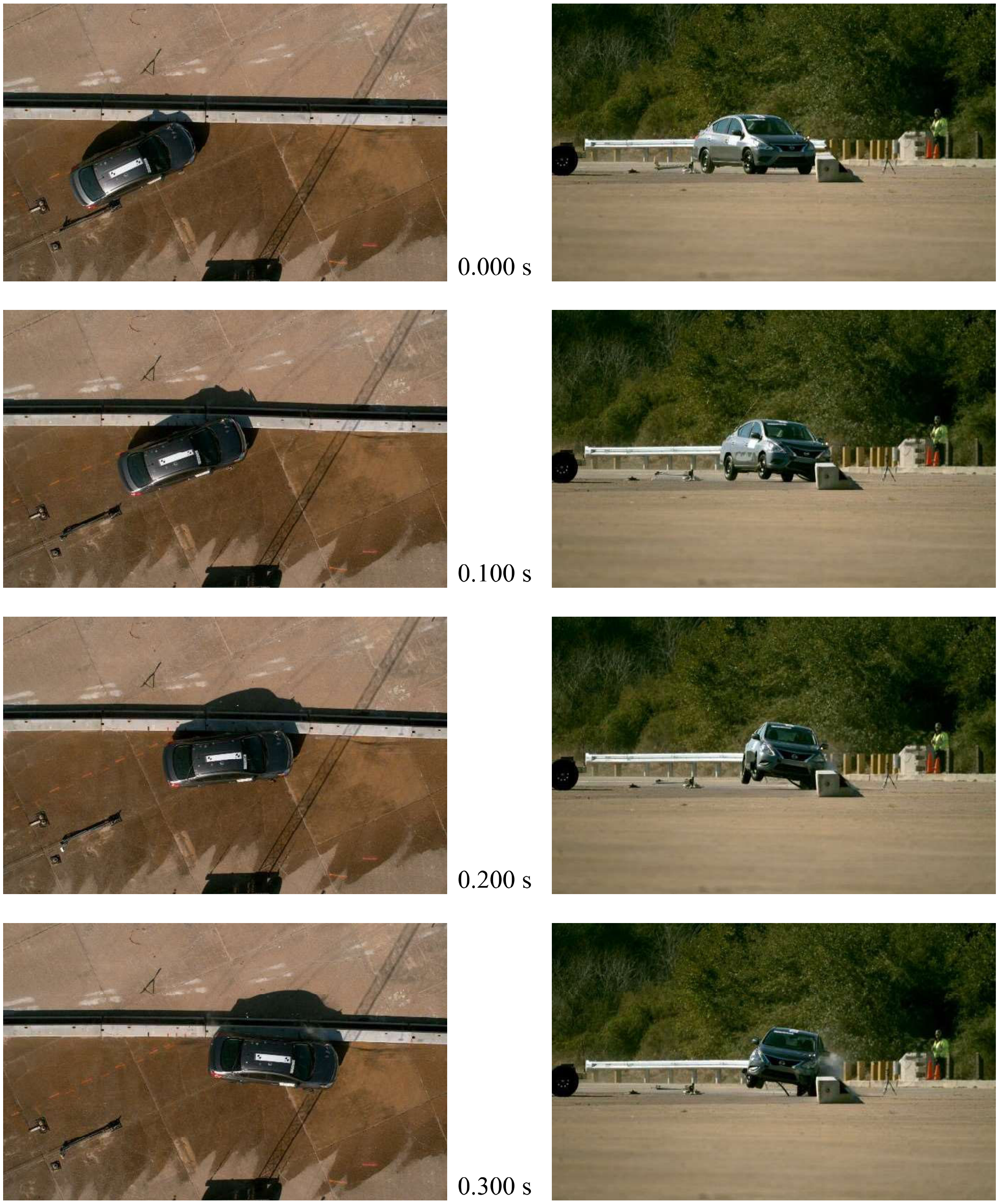


Figure C.1. Sequential Photographs for Test No. 690905-UOF1 (Overhead and Frontal Views).

0.400 s

0.500 s

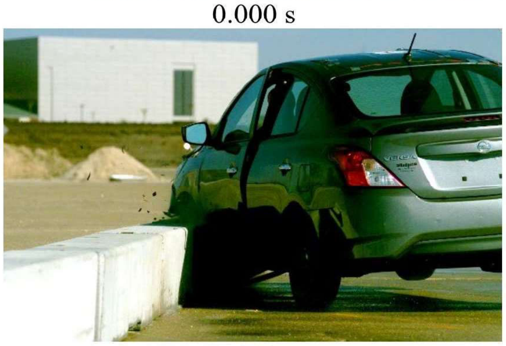
0.600 s

0.700 s

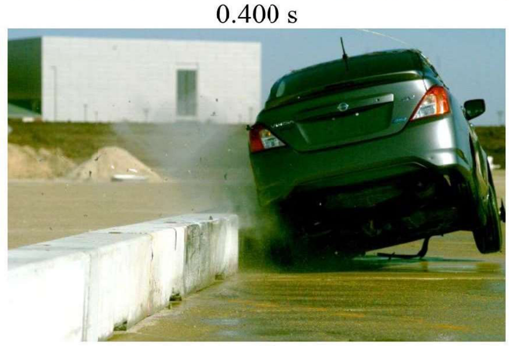
Figure C.1. Sequential Photographs for Test No. 690905-UOF1 (Overhead and Frontal Views) (Continued).

0.000 s

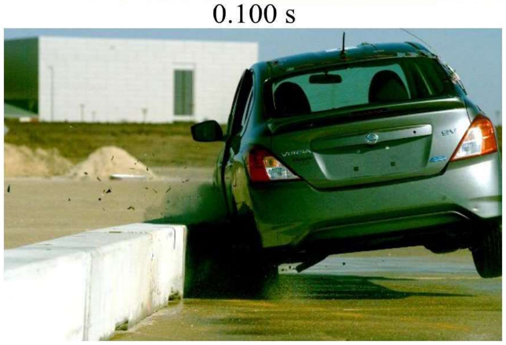
0.400 s



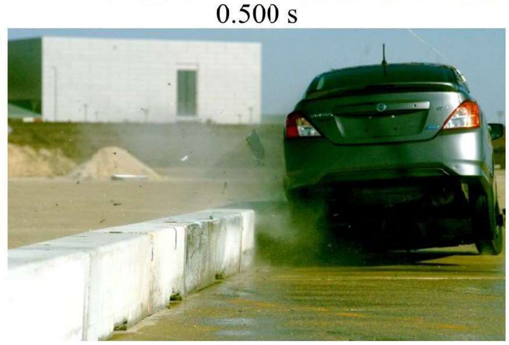
0.100 s



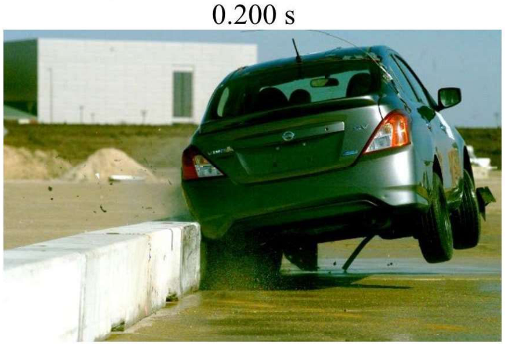
0.500 s



0.200 s



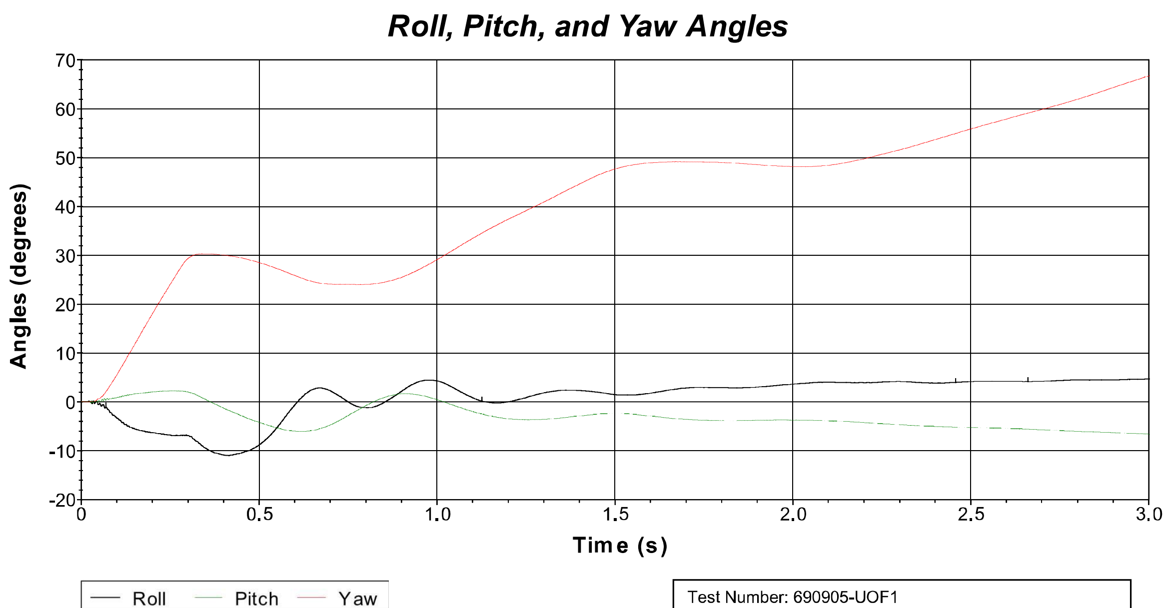
0.600 s



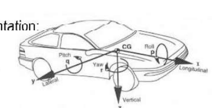
0.300 s

0.700 s

Figure C.2. Sequential Photographs for Test No. 690905-UOF1 (Rear View).

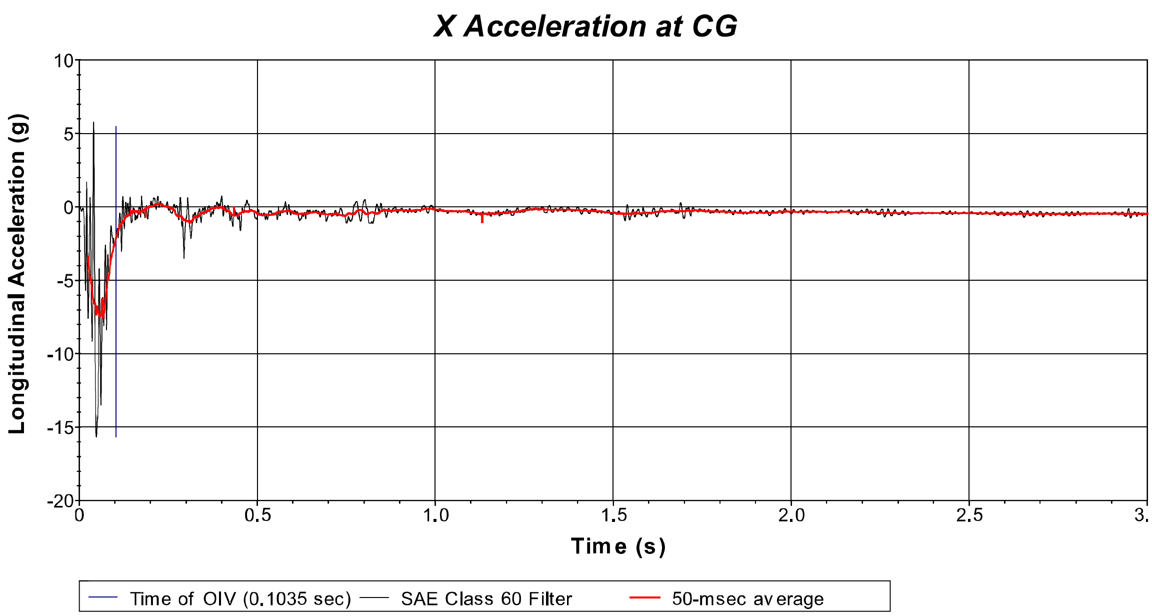


Axes are vehicle-fixed.
Sequence for determining orientation:
1. Yaw.
2. Pitch.
3. Roll.



Test Number: 690905-UOF1
Test Standard Test Number: *MASH* Test 2-10
Test Article: Portable Concrete Construction Zone Barrier
Test Vehicle: 2016 Nissan Versa
Inertial Mass: 2402 lb
Gross Mass: 2567 lb
Impact Speed: 44.4 mi/h
Impact Angle: 25.6 degrees

Figure C.3. Vehicle Angular Displacements for Test No. 690905-UOF1.



Test Number: 690905-UOF1
Test Standard Test Number: *MASH* Test 2-10
Test Article: Portable Concrete Construction Zone Barrier
Test Vehicle: 2016 Nissan Versa
Inertial Mass: 2402 lb
Gross Mass: 2567 lb
Impact Speed: 44.4 mi/h
Impact Angle: 25.6 degrees

Figure C.4. Vehicle Longitudinal Accelerometer Trace for Test No. 690905-UOF1 (Accelerometer Located at Center of Gravity).

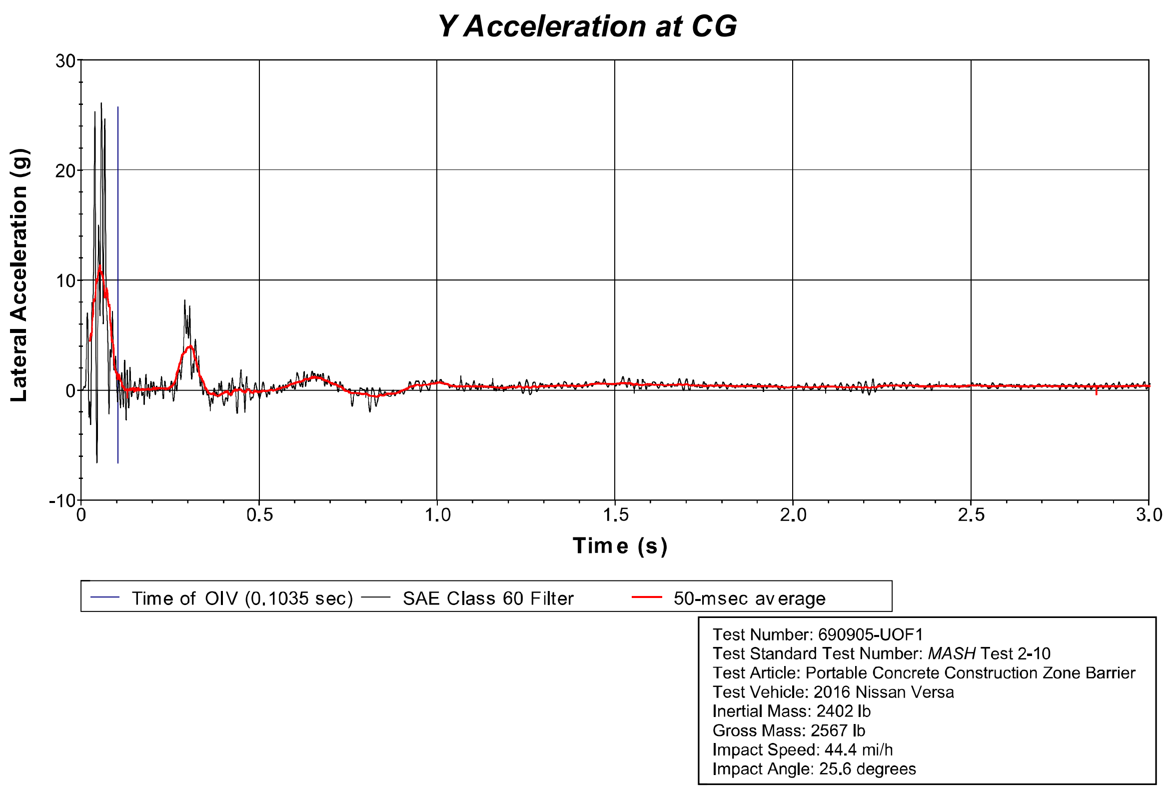


Figure C.5. Vehicle Lateral Accelerometer Trace for Test No. 690905-UOF1 (Accelerometer Located at Center of Gravity).

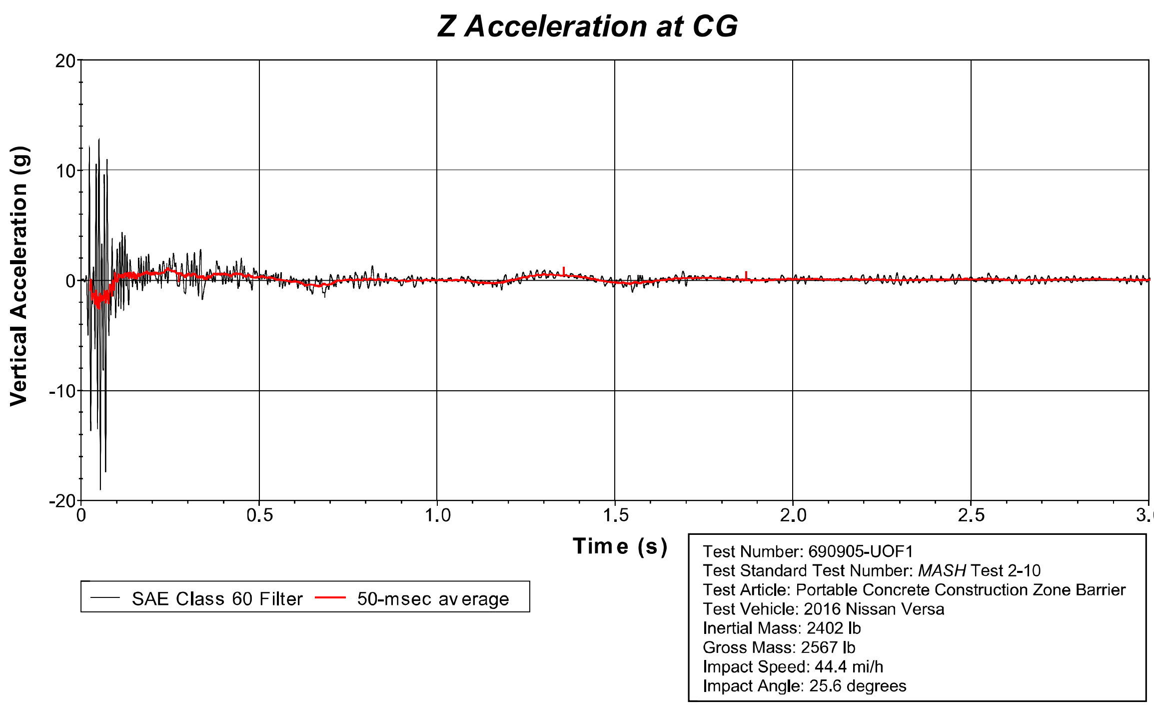


Figure C.6. Vehicle Vertical Accelerometer Trace for Test No. 690905-UOF1 (Accelerometer Located at Center of Gravity).

APPENDIX D. *MASH* TEST 2-11 (CRASH TEST NO. 690905-UOF2)

D.1. VEHICLE PROPERTIES AND INFORMATION

Table D.1. Vehicle Properties for Test No. 690905-UOF2.

Date: 2021-2-1　Test No.: 690905-UOF2　VIN No.: 1C6RR6GT7GS311771

Year: 2016　Make: RAM　Model: 1500

Tire Size: 265/70 R 17　Tire Inflation Pressure: 35 psi

Tread Type: Highway　Odometer: 216536

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

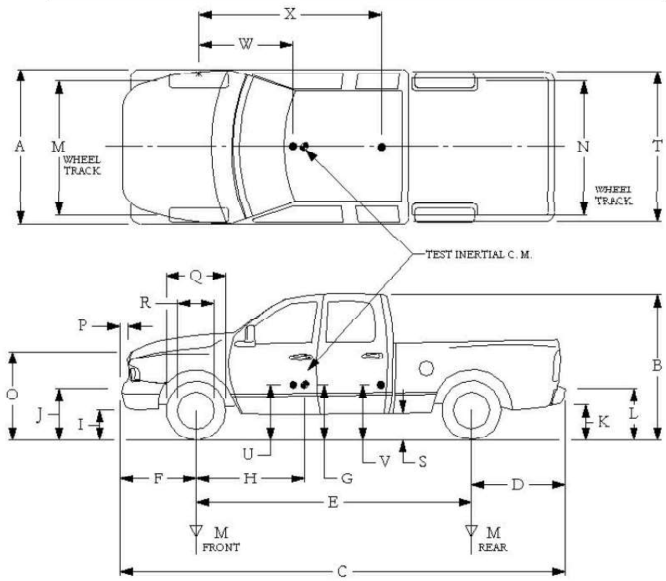
NOTES: None

Engine Type: V-8
Engine CID: 5.7

Transmission Type:
☑ Auto or ☐ Manual
☐ FWD ☑ RWD ☐ 4WD

Optional Equipment:
None

Dummy Data:
Type: NONE
Mass: 0 lb
Seat Position:



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	26.75
B	74.00	G	28.37	L	30.00	Q	30.50	V	30.25
C	227.50	H	59.83	M	68.50	R	18.00	W	59.8
D	44.00	I	11.75	N	68.00	S	13.00	X	79
E	140.50	J	27.00	O	46.00	T	77.00		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	6.00	Bottom Frame Height - Front	12.50
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	9.25	Bottom Frame Height - Rear	22.50

RANGE LIMIT: A=78 ±2 inches; C=237 ±13 inches; E=148 ±12 inches; F=39 ±3 inches; G = > 28 inches; H = 63 ±4 inches; O=43 ±4 inches; (M+N)/2=67 ±1.5 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2975	2880	2880
Back	3900	M_{rear}	2180	2136	2136
Total	6700	M_{Total}	5155	5016	5016

(Allowable Range for TIM and GSM = 5000 lb ±110 lb)

Mass Distribution:
lb　LF: 1438　RF: 1442　LR: 1102　RR: 1034

Table D.2. Measurements of Vehicle Vertical Center of Gravity for Test No. 690905-UOF2.

Date: 2021-2-1 Test No.: 690905-UOF2 VIN: 1C6RR6GT7GS311771

Year: 2016 Make: RAM Model: 1500

Body Style: Quad Cab Mileage: 216536

Engine: 5.7 V-8 Transmission: Automatic

Fuel Level: Empty Ballast: 80 (440 lb max)

Tire Pressure: Front: 35 psi Rear: 35 psi Size: 265/70 R 17

Measured Vehicle Weights: (lb)							
LF:	1438		RF:	1442		Front Axle:	2880
LR:	1102		RR:	1034		Rear Axle:	2136
Left:	2540		Right:	2476		Total:	5016
							5000 ±110 lb allowed
Wheel Base:	140.50	inches	Track: F:	68.50	inches	R:	68.00 inches
	148 ±12 inches allowed			Track = (F+R)/2 = 67 ±1.5 inches allowed			
Center of Gravity, SAE J874 Suspension Method							
X:	59.83	inches	Rear of Front Axle	(63 ±4 inches allowed)			
Y:	-0.44	inches	Left - Right +	of Vehicle Centerline			
Z:	28.37	inches	Above Ground	(minumum 28.0 inches allowed)			

Hood Height: 46.00 inches (43 ±4 inches allowed) Front Bumper Height: 27.00 inches

Front Overhang: 40.00 inches (39 ±3 inches allowed) Rear Bumper Height: 30.00 inches

Overall Length: 227.50 inches (237 ±13 inches allowed)

Table D.3. Exterior Crush Measurements for Test No. 690905-UOF2.

Date:	2021-2-1	Test No.:	690905-UOF2	VIN No.:	1C6RR6GT7GS311771
Year:	2016	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2} = $ ______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage: Width** (CDC)	Direct Damage: Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bmp ht	14	10	40							-26
2	Side plane at bmp ht	14	10	60							76
	Measurements recorded										
	☑ inches or ☐ mm										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

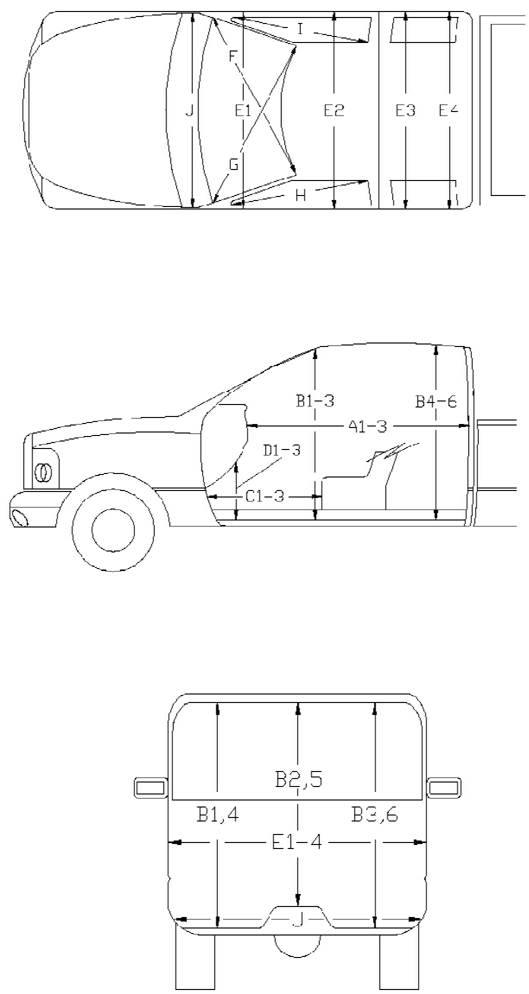
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

***Measure and document on the vehicle diagram the location of the maximum crush.

Note: Use as many lines/columns as necessary to describe each damage profile.

Table D.4. Occupant Compartment Measurements for Test No. 690905-UOF2.

Date:	2021-2-1	Test No.:	690905-UOF2	VIN No.:	1C6RR6GT7GS311771
Year:	2016	Make:	RAM	Model:	1500

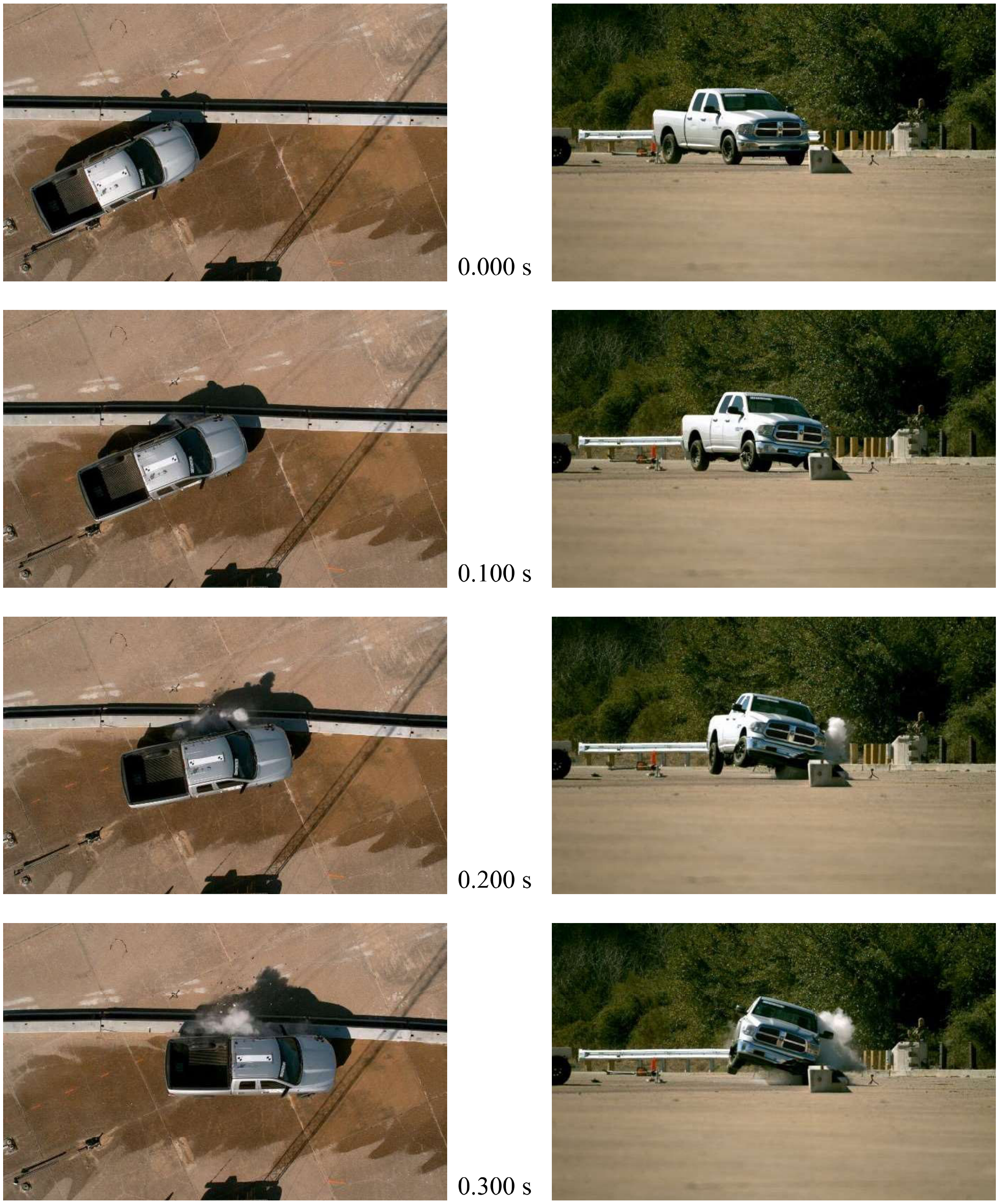


*Lateral area across the cab from driver's side kickpanel to passenger's side kickpanel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	65.00	65.00	0.00
A2	63.00	63.00	0.00
A3	65.50	65.50	0.00
B1	45.00	45.00	0.00
B2	38.00	38.00	0.00
B3	45.00	45.00	0.00
B4	39.50	39.50	0.00
B5	43.00	43.00	0.00
B6	39.50	39.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	26.00	0.00
D1	11.00	11.00	0.00
D2	0.00	0.00	0.00
D3	11.50	11.50	0.00
E1	58.50	58.50	0.00
E2	63.50	63.50	0.00
E3	63.50	63.50	0.00
E4	63.50	63.50	0.00
F	59.00	59.00	0.00
G	59.00	59.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	25.00	25.00	0.00

D.2. SEQUENTIAL PHOTOGRAPHS



0.000 s

0.100 s

0.200 s

0.300 s

Figure D.1. Sequential Photographs for Test No. 690905-UOF2 (Overhead and Frontal Views).

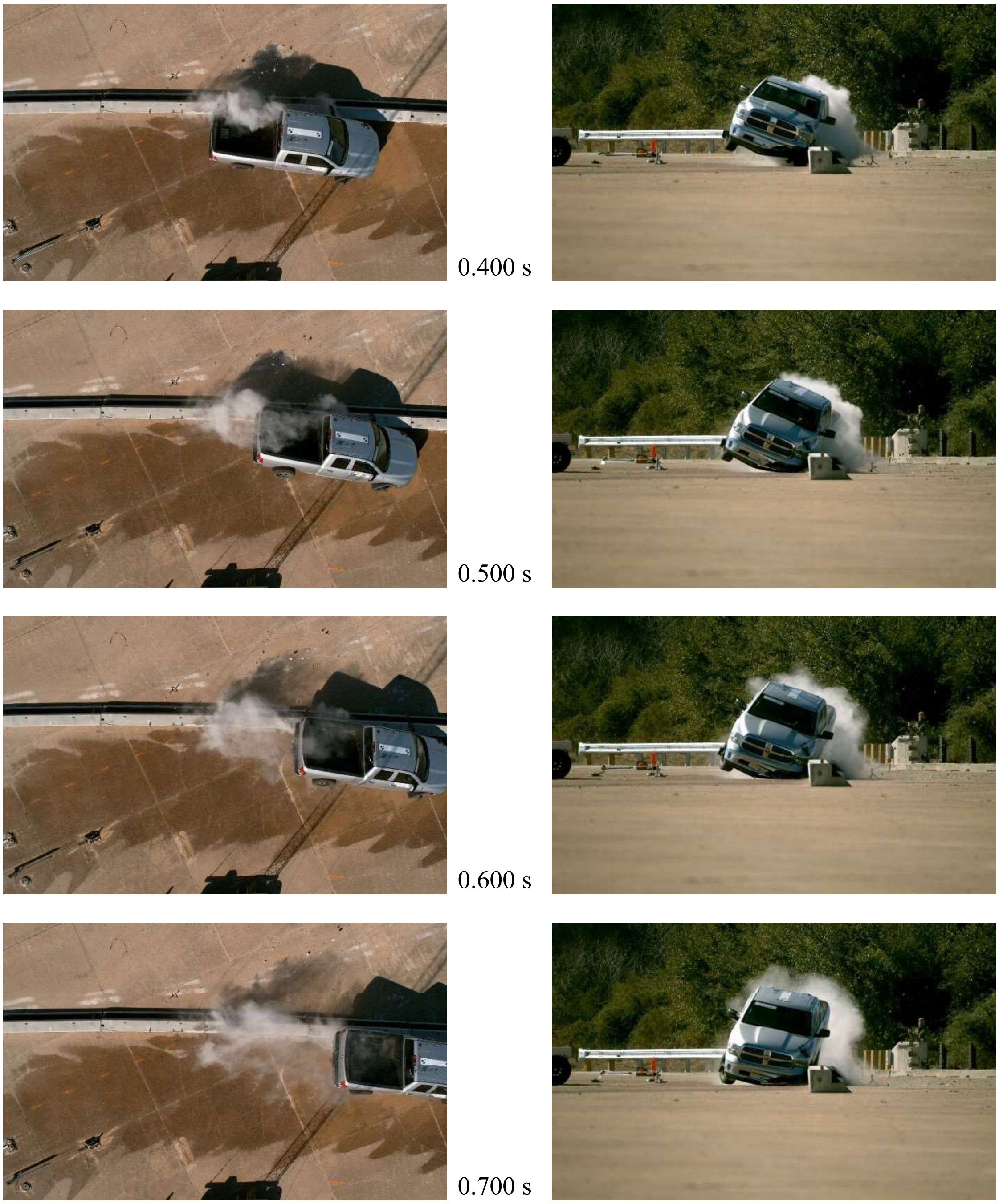


Figure D.1. Sequential Photographs for Test No. 690905-UOF2 (Overhead and Frontal Views) (Continued).

0.000 s

0.100 s

0.200 s

0.300 s

0.400 s

0.500 s

0.600 s

0.700 s

Figure D.2. Sequential Photographs for Test No. 690905-UOF2 (Rear View).

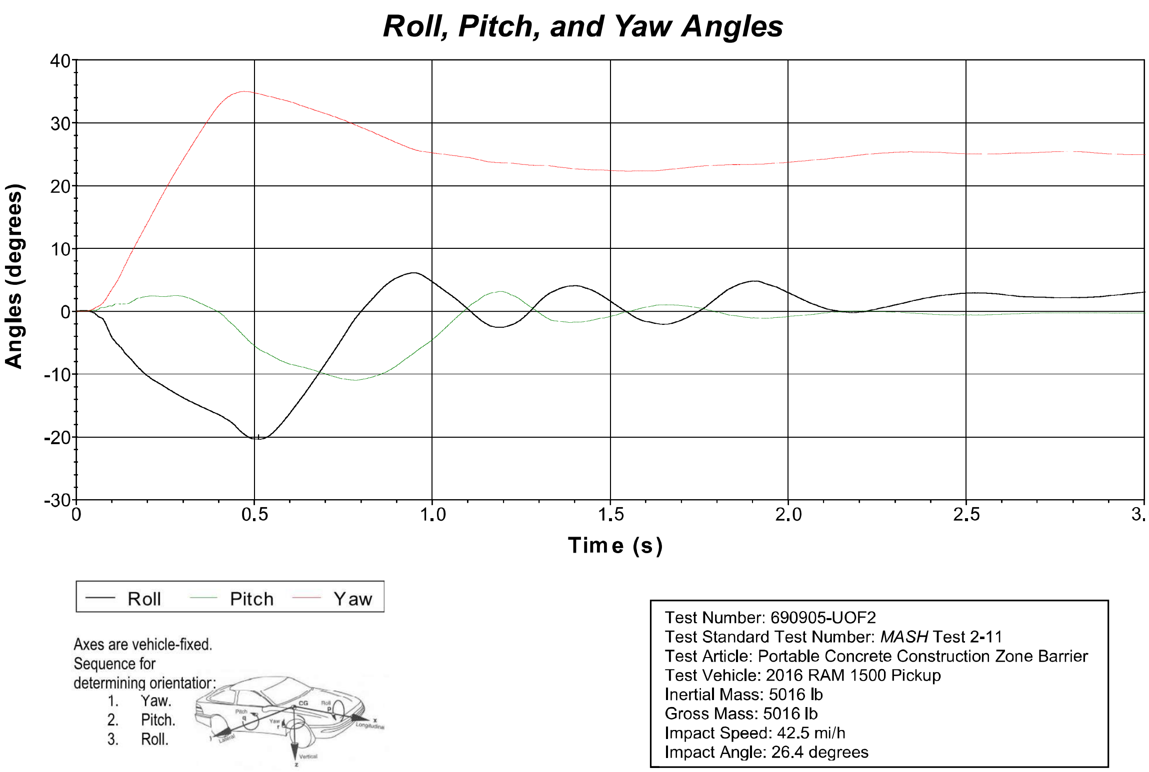


Figure D.3. Vehicle Angular Displacements for Test No. 690905-UOF2.

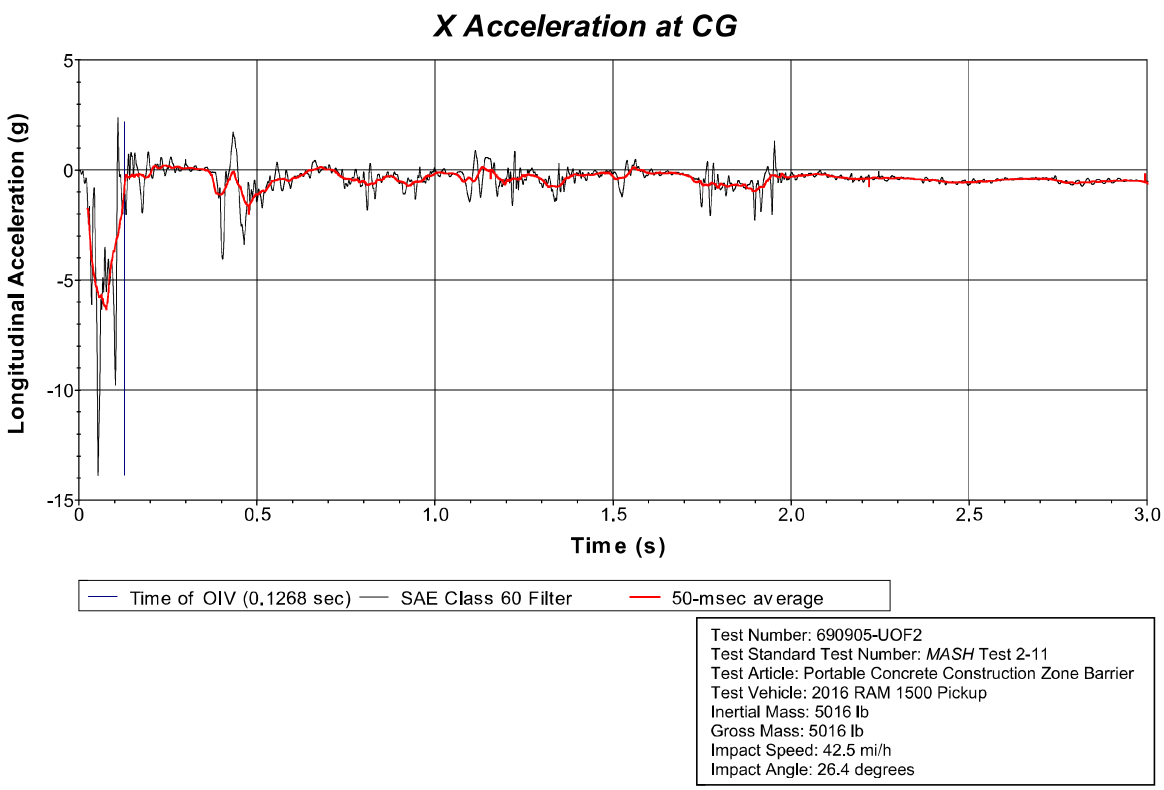


Figure D.4. Vehicle Longitudinal Accelerometer Trace for Test No. 690905-UOF2 (Accelerometer Located at Center of Gravity).

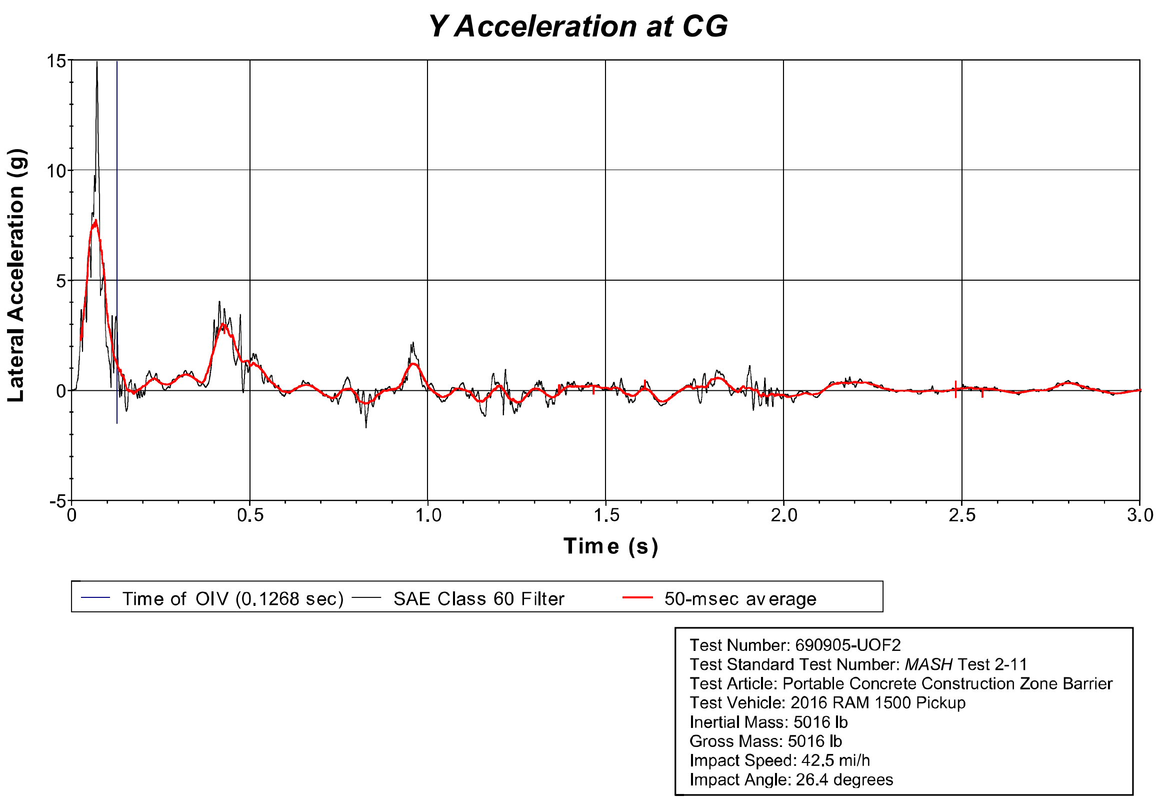


Figure D.5. Vehicle Lateral Accelerometer Trace for Test No. 690905-UOF2 (Accelerometer Located at Center of Gravity).

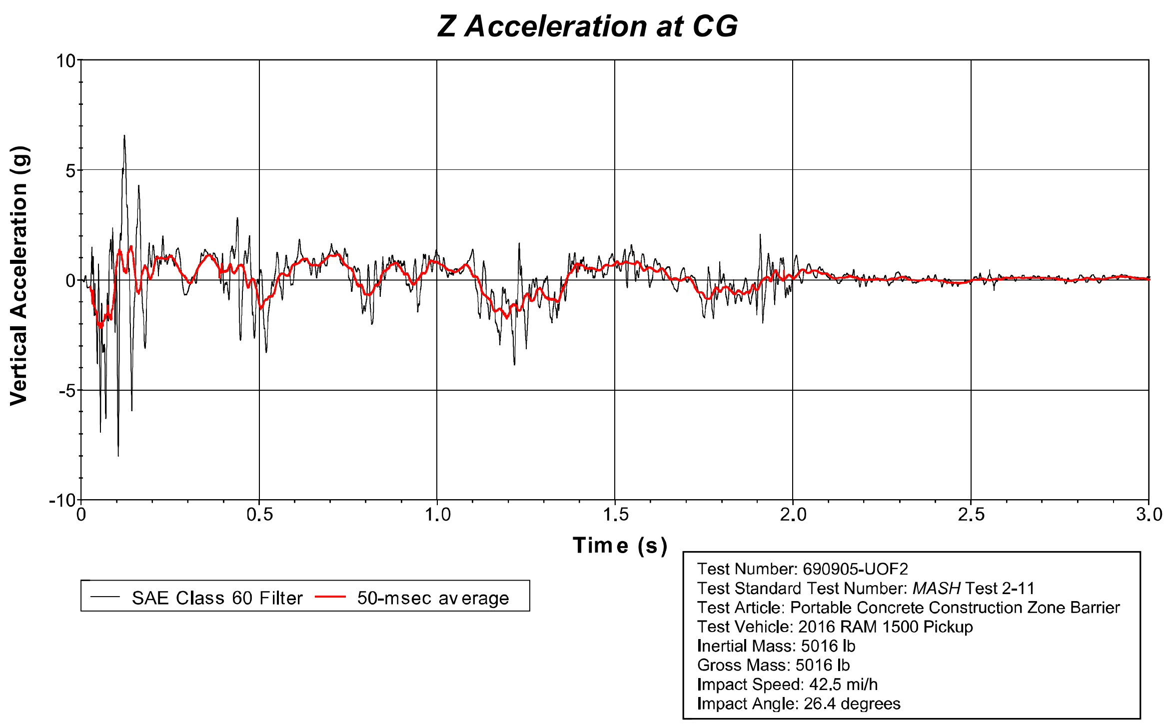


Figure D.6. Vehicle Vertical Accelerometer Trace for Test No. 690905-UOF2 (Accelerometer Located at Center of Gravity).