Report No. 614091-01
Report Date: May 2021

A STUDY OF ACCEPTABLE SIDEWALK HEIGHTS AND WIDTHS

by

Sun Hee Park
Associate Transportation Researcher

A Rum Han
Engineering Graduate Student

Akram Y. Abu-Odeh
Research Scientist

Wanda L. Menges
Research Specialist

and

William Schroeder
Research Engineering Associate

Contract No.: T4541-DV
Test No.: 614091-01-1 and 614091-01-2
Test Date: 2021-01-27 and 2021-01-28

Sponsored by
Roadside Safety Pooled Fund Group

TEXAS A&M TRANSPORTATION INSTITUTE

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

DISCLAIMER

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
A STUDY OF ACCEPTABLE SIDEWALK HEIGHTS AND WIDTHS	October 2022
	6. Performing Organization Code
7. Author(s) Sun Hee Park, A Rum Han, Akram Y. Abu-Odeh , Wanda L. Menges, and William Schroeder	8. Performing Organization Report No. Report No. 614091-01
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. T4541-DV
12. Sponsoring Agency Name and Address Roadside Safety Pooled Fund Washington State Department of Transportation Transportation Building, MS: 47372 Olympia, Washington 98504-7372	13. Type of Report and Period Covered Technical Report: December 2019—June 2021 14. Sponsoring Agency Code

15. Supplementary Notes
Project Title: A Study of Acceptable Sidewalk Heights and Widths
Name of Contacting Representative: Taya Retterer, P.E., Texas Department of Transportation

16. Abstract

The objective of this research is to provide guidance for bridge parapet placement on sidewalks, considering a maximum traversable curb height. The study focused on Test Level 2 (TL 2) impact conditions, as defined in the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware, Second Edition* (*MASH).* Researchers performed tests on an 8-inch curb to determine the vehicular trajectory profiles under MASH TL-2 conditions. They then calibrated the finite element (FE) vehicle models using the trajectory testing results and Caltrans impact test report, calibrating the models to capture vehicular behavior reasonably. The research team performed parametric simulations with various parapet heights and locations incorporating different curb parameters. They developed placement guidelines for 8-inch-tall curbs under *MASH* TL-2 impact conditions.

17. Key Words	18. Distribution Statement
Sidewalk, curb, roadside safety, parapet placement, impact simulation, guideline	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	81	

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

ACKNOWLEDGEMENTS

This research project was performed under a pooled fund program between the following States and Agencies. The authors acknowledge and appreciate their guidance and assistance.

Roadside Safety Research Pooled Fund Committee
Revised May 2023

ALABAMA

Wade Henry, P.E.
Assistant State Design Engineer
Design Bureau, Final Design Division
Alabama Dept. of Transportation
1409 Coliseum Boulevard, T-205
Montgomery, AL 36110
(334) 242-6464
henryw@dot.state.al.us

Stanley (Stan) C. Biddick, P.E.
State Design Engineer
Design Bureau, Final Design Division
Alabama Dept. of Transportation
1409 Coliseum Boulevard, T-205
Montgomery, AL 36110
(334) 242-6833
biddicks@dot.state.al.us

ALASKA

Mary F. McRae
Design and Construction Standards Engineer
Alaska Depart. of Transportation & Public Facilities
3132 Channel Drive
P.O. Box 112500
Juneau, AK 99811-2500
(907) 465-1222
mary.mcrae@alaska.gov

Cole Carnahan
Design and Construction Standards Engineering Assistant
Alaska Depart. of Transportation & Public Facilities
3132 Channel Drive
P.O. Box 112500
Juneau, AK 99811-2500
(907) 465-6955
cole.carnahan@alaska.gov

CALIFORNIA

Bob Meline, P.E.
Caltrans
Office of Materials and Infrastructure
Division of Research and Innovation
5900 Folsom Blvd
Sacramento, CA 95819
(916) 227-7031
Bob.Meline@dot.ca.gov

John Jewell, P.E.
Senior Crash Testing Engineer
Office of Safety Innovation & Cooperative Research
(916) 227-5824
John_Jewell@dot.ca.gov

COLORADO

Andy Pott, P.E.
Senior Bridge Design and Construction Engineer
Division of Project Support, Staff Bridge Design and Construction Management
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-512-4020
andrew.pott@state.co.us

Shawn Yu, P.E.
Miscellaneous (M) Standards and Specifications Unit Manager
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-757-9474
shawn.yu@state.co.us

David Kosmiski, P.E.
Miscellaneous (M) Standards Engineer
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-757-9021
david.kosmiski@state.co.us

Amin Fakhimalizad
Assistant Miscellaneous (M) Standards Engineer
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
303-757-9229
amin.fakhimalizad@state.co.us

CONNECTICUT

David Kilpatrick
State of Connecticut Depart. of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546
(806) 594-3288
David.Kilpatrick@ct.gov

DELAWARE

Craig Blowers
Construction Resource Engineer
Construction Section
Delaware DOT
(302)760-2336
Craig.Blowers@delaware.gov

James Osborne
Traffic Safety Programs Manager
Traffic Operations
Delaware DOT
(302)659-4651
James.Osborne@delaware.gov

FLORIDA

Richard Stepp
Florida Department of Transportation
Richard.Stepp@dot.state.fl.us

Derwood C. Sheppard, Jr., P.E.
State Roadway Design Engineer
Florida Depart. of Transportation
Roadway Design Office
605 Suwannee Street, MS-32
Tallahassee, FL 32399-0450
(850) 414-4334
Derwood.Sheppard@dot.state.fl.us

IDAHO

Marc Danley, P.E.
Technical Engineer
(208) 334-8558
Marc.danley@itd.idaho.gov

Kevin Sablan
Design/Traffic Engineer
Idaho Transportation Department
(208) 334-8558
Kevin.sablan@itd.idaho.gov

ILLINOIS

Martha A. Brown, P.E.
Safety Design Bureau Chief
Bureau of Safety Programs and Engineering
Illinois Depart. of Transportation
2300 Dirksen Parkway, Room 005
Springfield, IL 62764
(217) 785-3034
Martha.A.Brown@illinois.gov

Edgar Galofre
Safety Design Engineer
(217) 558-9089
edgar.glofre@illinois.gov

IOWA

Daniel Harness
Office of Design – Methods
Iowa Department of Transportation
Daniel.Harness@iowadot.us

Chris Poole
State Traffic Engineer
Traffic and Safety Bureau
Iowa Department of Transportation
Chris.Poole@iowadot.us

LOUISIANA

Chris Guidry
Bridge Manager
Louisiana Transportation Center
Bridge & Structural Design Section
P.O. Box 94245
Baton Rouge, LA 79084-9245
(225) 379-1933
Chris.Guidry@la.gov

Carl Gaudry
Bridge Design Manager
Bridge & Structural Design Section
Louisiana Department of Transportation & Development
Carl.Gaudry@la.gov

MARYLAND

Matamba Kabengele
Traffic Engineer
Office of Traffic and Safety
Maryland State Highway Administration
MKabengele@mdot.maryland.gov

MASSACHUSETTS

Alex Bardow
Director of Bridges and Structure
Massachusetts Depart. of Transportation
10 Park Plaza, Room 6430
Boston, MA 02116
(517) 335-9430
Alexander.Bardow@state.ma.us

James Danila
State Traffic Engineer
(857) 368-9640
James.danilla@state.ma.us

MICHIGAN

Carlos Torres, P.E.
Crash Barrier Engineer
Geometric Design Unit, Design Division
Michigan Depart. of Transportation
P. O. Box 30050
Lansing, MI 48909
(517) 335-2852
TorresC@michigan.gov

MINNESOTA

Khamsai Yang
Design Standards Engineer
Office of Project Management and Technical Support
(651) 366-4622
Khamsai.Yang@state.mn.us

Brian Tang
Assistant Design Standards Engineer
Office of Project Management and Technical Support
Minnesota Department of Transportation
(651) 366-4684
brian.tang@state.mn.us

MISSOURI

Sarah Kleinschmit, P.E.
Policy and Innovations Engineer,
Missouri Department of Transportation
P.O. Box 270
Jefferson City, MO 65102
(573) 751-7412
sarah.kleinschmit@modot.mo.gov

Kaitlyn (Katy) Bower
Roadside Design Specialist
Missouri Department of Transportation
573-472-9028
kaitlyn.bower@modot.mo.gov

NEW MEXICO

Brad Julian
Traffic Technical Support Engineer
(505) 827-3263
Brad.Julian@state.nm.us

OHIO

Don P. Fisher, P.E.
Ohio Depart. of Transportation
1980 West Broad Street
Mail Stop 1230
Columbus, OH 43223
(614) 387-6214
Don.fisher@dot.ohio.gov

OREGON

Christopher Henson
Senior Roadside Design Engineer
Oregon Depart. of Transportation
Technical Service Branch
4040 Fairview Industrial Drive, SE
Salem, OR 97302-1142
(503) 986-3561
Christopher.S.Henson@odot.state.or.us

PENNSYLVANIA

James A. Borino, Jr., P.E.
Chief, Standards and Criteria Unit
Highway Design and Technology Division
Pennsylvania DOT
(717) 612-4791
jborino@pa.gov

Evan Pursel
Senior Civil Engineer
Highway Design and Technology Division
Pennsylvania DOT
(717) 705-8535
epursel@pa.gov

Nina Ertel
Project Development Engineer
Highway Design and Technology Division
Pennsylvania DOT
(717) 425-7679
nertel@pa.gov

TEXAS

Chris Lindsey
Transportation Engineer
Design Division
Texas Department of Transportation
125 East 11th Street
Austin, TX 78701-2483
(512) 416-2750
Christopher.Lindsey@txdot.gov

Taya Retterer
TxDOT Bridge Standards Engineer
Bridge Division
Texas Department of Transportation
(512) 416-2719
Taya.Retterer@txdot.gov

UTAH

Shawn Debenham
Traffic and Safety Division
Utah Depart. of Transportation
4501 South 2700 West
PO Box 143200
Salt Lake City UT 84114-3200
(801) 965-4590
sdebenham@utah.gov

WASHINGTON

Mustafa Mohamedali
Assistant Research Project Manager
P.O. Box 47372
Olympia, WA 98504-7372
(360) 704-6307
mohamem@wsdot.wa.gov

Tim Moeckel
Roadside Safety Engineer
Washington State Department of Transportation
Development Division
P.O. Box 47329
Olympia, WA 98504-7246
(360) 704-6377
moecket@wsdot.wa.gov

WEST VIRGINIA

Donna J. Hardy, P.E.
Safety Programs Engineer
West Virginia Depart. of Transportation – Traffic Engineering
Building 5, Room A-550
1900 Kanawha Blvd E.
Charleston, WV 25305-0430
(304) 558-9576
Donna.J.Hardy@wv.gov

Ted Whitmore
Traffic Services Engineer
Traffic Engineering
WV Division of Highways
(304)414-7373
Ted.J.Whitmore@wv.gov

WISCONSIN

Erik Emerson, P.E.
Standards Development Engineer – Roadside Design
Wisconsin Department of Transportation
Bureau of Project Development
4802 Sheboygan Avenue, Room 651
P. O. Box 7916
Madison, WI 53707-7916
(608) 266-2842
Erik.Emerson@wi.gov

CANADA – ONTARIO

Kenneth Shannon, P. Eng.
Senior Engineer, Highway Design (A)
Ontario Ministry of Transportation
301 St. Paul Street
St. Catharines, ON L2R 7R4
CANADA
(904) 704-3106
Kenneth.Shannon@ontario.ca

FEDERAL HIGHWAY ADMINISTRATION (FHWA)

WebSite: safety.fhwa.dot.gov

Richard B. (Dick) Albin, P.E.
Safety Engineer
FHWA Resource Center Safety & Design Technical Services Team
711 S. Capital
Olympia, WA 98501
(303) 550-8804
Dick.Albin@dot.gov

Eduardo Arispe
Research Highway Safety Specialist
U.S. Department of Transportation
Federal Highway Administration
Turner-Fairbank Highway Research Center
Mail Code: HRDS-10
6300 Georgetown Pike
McLean, VA 22101
(202) 493-3291
Eduardo.arispe@dot.gov

Christine Black
Highway Safety Engineer
Central Federal Lands Highway Division
12300 West Dakota Ave.
Lakewood, CO 80228
(720) 963-3662
Christine.black@dot.gov

Isbel Ramos-Reyes
Lead Safety and Transportation Operations Engineer
(703) 948-1442
isbel.ramos-reyes@dot.gov

Matt Hinshaw, M.S., P.E.
Highway Safety Engineer
Central Federal Lands Highway Division
(360)619-7677
matthew.hinshaw@dot.gov

TEXAS A&M TRANSPORTATION INSTITUTE (TTI)

WebSite: tti.tamu.edu
www.roadsidepooledfund.org

D. Lance Bullard, Jr., P.E.
Senior Research Engineer
Roadside Safety & Physical Security Div.
Texas A&M Transportation Institute
3135 TAMU
College Station, TX 77843-3135
(979) 317-2855
L-Bullard@tti.tamu.edu

Roger P. Bligh, Ph.D., P.E.
Senior Research Engineer
(979) 317-2703
R-Bligh@tti.tamu.edu

Nauman Sheikh
Research Scientist
Roadside Safety and Physical Security
Texas A&M Transportation Institute
n-sheikh@tti.tamu.edu

Ariel Sheil
Research Assistant
Roadside Safety and Physical Security
Texas A&M Transportation Institute
A-Sheil@tti.tamu.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page intentionally left blank.

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

Bridge parapets are used to protect errant vehicles from departing the bridge into a hazard. Some parapets are mounted directly to the deck or on a raised sidewalk. The placement location is important since it can affect the safety performance of the parapet. There have been many studies regarding the safety performance of bridge parapets. However, most of the studies were related to parapets mounted on the deck directly, and only a few have accounted for the presence of a curb and sidewalk. More research is needed since a curb is installed for functions such as drainage, right-of-way reduction, and sidewalk separation *[1]*.

To evaluate the safety performance of new roadside hardware, the American Association of State Highway and Transportation Officials (AASHTO) provides the *Manual for Assessing Safety Hardware* (*MASH*) as guidelines *[2]*. *MASH* includes test standard matrices which depend on test level conditions and safety requirements specified for each test level. In this study, Test Level 2 (TL-2) and to some degree Test Level 3 (TL-3) impact conditions on curbs are investigated. Table 1.1 illustrates the *MASH* recommendations for each condition. A passenger car and a pickup truck are designated as the 1100C and 2270P test vehicles, respectively.

Table 1.1. Test Matrices for *MASH* TL-2 and TL-3 for Longitudinal Barriers *[2]*

Test level	Test No.	Vehicle	Impact speed, mi/h (km/h)	Impact angle, θ, deg.	Evaluation criteria
2	2-10	1100C	44 (70.0)	25	A, D, F, H, I
	2-11	2270P	44 (70.0)	25	A, D, F, H, I
3	3-10	1100C	62 (100.0)	25	A, D, F, H, I
	3-11	2270P	62 (100.0)	25	A, D, F, H, I

A curbed sidewalk has two key design variables that make the curb profile: the curb height and the curb slope. The parapet heights and locations are studied for several curb profiles. Figure 1.1 shows the explanation of each variable. As shown in Table 1.2, 8-inch-tall curb profiles are studied with various slopes values. If the curb slope becomes shallower, the vehicle can traverse the curb in a smoother fashion. Curb designated as No.1, the 8-inch-tall and 2-inch offset curb profile, is first considered for investigation since it is a very common curb profile.

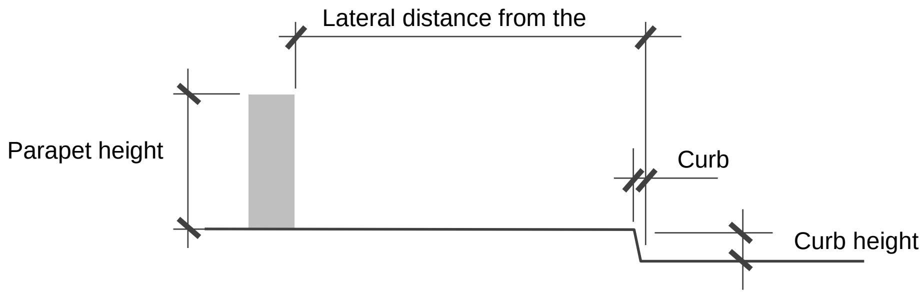


Figure 1.1. Design Variables for a Curbed Sidewalk

Table 1.2. Curb Profiles for Placement Guidelines

	Curb height (inches)	Curb offset (inches)	Impact conditions
No.1	8	2	TL-2 & TL-3
No.2	8	3	TL-2 & TL-3
No.3	8	1	TL-2 & TL-3

The placement guidelines are developed from the results of the parametric simulations. These guidelines will assist state agencies in choosing appropriate parapet systems.

1.2. RESEARCH METHODOLOGIES

This study utilizes full-scale trajectory testing and computer simulations to develop the placement guidance. Computer simulations using LS-DYNA are used for the parametric analyses and full-scale crash testing has been conducted to calibrate the models. The testing can capture the vehicular trajectories when the test vehicles travel across the sidewalk after impact with a curb as shown in Figure 1.2. To calibrate the finite element (FE) vehicle model, a previous study undertaken by the California Department of Transportation (Caltrans) was referenced *[3]*. This study includes crash testing the Type 732SW bridge rail system under *MASH* TL-3 and TL-2 conditions.

Figure 1.2. Vehicular Trajectories

The computer simulations were performed using the ANSYS LS-DYNA *[4]* explicit finite element code. The simulation model is compared with full-scale crash testing results so it can be calibrated to better represent the reasonable behavior of the phenomenon of interest.

Once the model is reasonably calibrated, parametric simulations are conducted to determine appropriate parapet heights and lateral distances from the curb edge. Figure 1.3 shows the overall flow chart of the research.

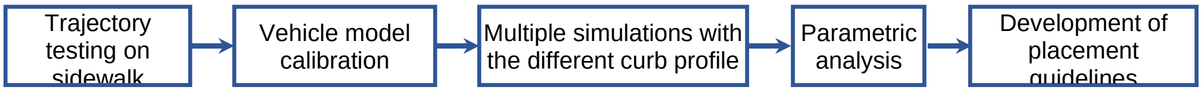


Figure 1.3. Flow Chart of Research

1.3. OBJECTIVES

The objective of this research is to propose placement guidelines for bridge parapets on sidewalks with curbs under *MASH* TL-2 conditions. The placement guidelines are to provide the range of parapet heights and locations for curbed sidewalks that do not present propensity for vehicular instability or high occupant risk metrics. Therefore, the guidelines are expected to be useful for practicing engineers and user agencies. These parapets are expected to be designed to withstand such the impact loading hence no strength calculation is performed and the model use a rigid behavior for the parapet.

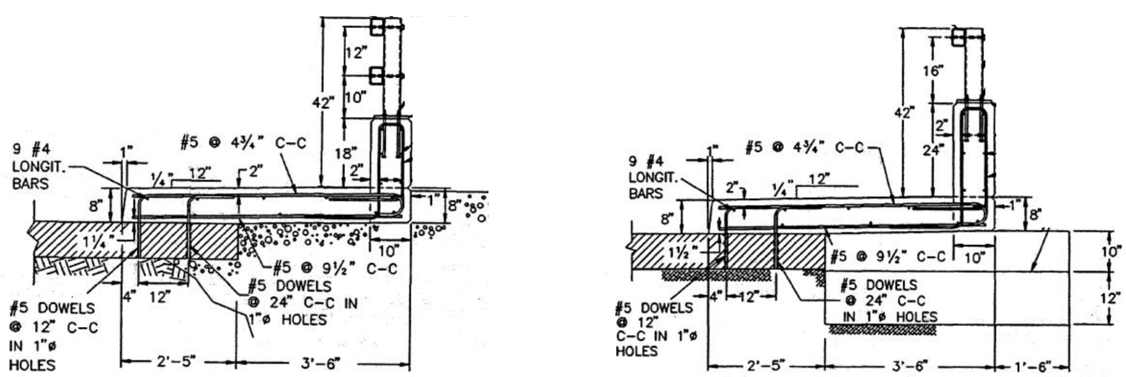
CHAPTER 2. LITERATURE REVIEW

2.1. INTRODUCTION

Key literature review is presented herewith. There are relevant full-scale crash testing literatures of bridge parapet systems on a sidewalk with a curb and available past studies on placement guidelines of curb and guardrail systems.

2.2. STUDY OF CURBED SIDEWALKS

There have been several past studies investigating bridge rail systems on a curbed sidewalk which include different levels of full-scale crash testing. Buth et al *[5]* conducted the performance evaluation of many different types of bridge rails and transitions. Among them, two bridge railing types, BR27D and BR27C, were tested on a sidewalk with a curb. They were also tested on a deck without a sidewalk and results were compared with the curbed sidewalk. As seen in Figure 2.1, the height of the curb was 8 inches, and the curb had a 1-inch offset. The testing was conducted using 1989 AASHTO's guide specifications *[6]*. The specifications had a total of three performance levels as shown in Table 2.1. BR27D and BR27C bridge railings were evaluated under Performance Level 1 and 2, respectively. While test results indicated minor damage to the railing systems, they nonetheless contained and redirected the test vehicles. Additionally, the same systems on a deck showed increased safety. Hence, both BR27D and BR27C bridge railings were considered acceptable per the AASHTO guide specifications.



(a) BR27D (b) BR27C

Figure 2.1. Cross Sections of BR27D and BR27C Bridge Railings on Sidewalk *[5]*

Table 2.1. Bridge Railing Performance Levels and Crash Test Criteria *[6]*

Performance Levels	Test Speeds – mi/h			
	Impact Angles			
	Small Automobile (θ = 20 deg.)	Pickup Truck (θ = 20 deg.)	Medium Single-Unit Truck (θ = 15 deg.)	Van-Type Tractor-Trailer (θ = 15 deg.)
PL-1	50	45		
PL-2	60	60	50	
PL-3	60	60		50

Caltrans conducted two studies to crash test two parapet systems, Type 80SW and Type 732SW *[3, 8]*. The studies followed NCHRP Report 350 [*9*] and *MASH* [*2*], respectively. The first study saw the evaluation of Type 80SW under Test Level 4 (TL-4) as seen in Table 2.2. TL-4 required three tests for each vehicle type; however, the 820C test did not fully meet the requirements. Thus, an additional 820C test was performed with the modified bridge rail design. Figure 2.2 shows the designed cross section and its actual construction. Out of a total of four tests, the 2000P test showed a snagging problem. Upon impact, the vehicle's hood hooked on the handrails, causing it to detach at the opposite end of the impacting location. Further, NCHRP Project 12-33 *[7]* and the 1989 AASHTO guide specifications *[6]* dictate that a pedestrian sidewalk should not be used for highways with a speed of 43.5 mi/h (70 km/h) or greater. For these two reasons, the Type 80SW bridge rail was finally recommended for roadways requiring TL-2 conditions.

Table 2.2. Test Matrices for Test Level 4 in NCHRP Report 350 *[9]*

Test Level	Test designation	Impact conditions			Evaluation criteria
		Vehicle	Nominal speed (km/h)	Nominal Angle (degree)	
4	4-10	820C	62.1	20	A,D,F,H,I(J),K,M
	4-11	2000P	62.1	25	A,D,F,K,L,M
	4-12	8000S	49.7	15	A,D,G,K,M

Figure 2.2. Cross Section and Installation of Type 80SW *[8]*

The second study undertaken by Caltrans was to crash test the Type 732SW under *MASH* TL-3 conditions *[3]*. Figure 2.3 shows the cross section and construction. An 1100C passenger car and a 2270P pickup truck were used for TL 3-10 and TL 3-11, respectively. TL 3-10 revealed that the bridge rail did not satisfy the limits required by *MASH*. For this reason, one supplementary test was executed under TL 2-10 conditions. TL 2-10 and TL 3-11 test results satisfied the requirements. Consequently, the Type 732SW bridge rail was recommended for use with pedestrian sidewalks under TL-2 conditions.

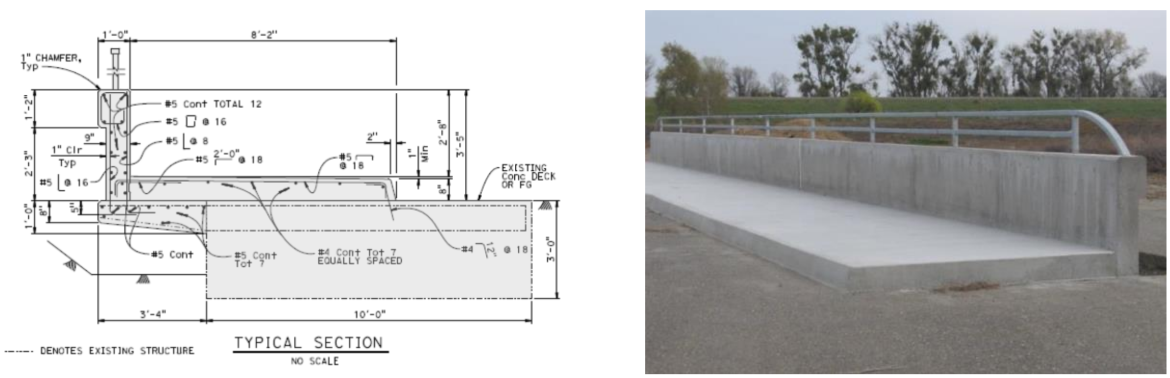


Figure 2.3. Cross Section and Installation of Type 732SW *[3]*

This study includes trajectory tests under TL-2 conditions; TL-3 tests are excluded. Thus, the crash test of the Type 732SW bridge rail is referenced throughout the course of this research.

2.3. PLACEMENT OF CURB AND GUARDRAIL SYSTEM

Researchers at the Midwest Roadside Safety Facility (MwRSF) conducted trajectory tests of a pickup truck and a passenger car impacting with a 6-inch curb *[10]*. The purpose of the study was to determine the lateral offset from the curb for the Midwest Guardrail System (MGS). A total of four trajectory tests were conducted: two 2270P pickup truck tests, an 1100C passenger car test, and a 2000P pickup truck test. The 2000P pickup truck was in accordance with NCHRP Report 350, and it was the only one vehicle model used for simulations. Others were in accordance with *MASH* and were not used for simulations. From the trajectory tests, the critical impact point (CIP) of each vehicle was determined and compared with MGS height. Safe ranges for the lateral offset of the guardrail were then determined so that the vehicles do not override the guardrail. Figure 2.4 shows the results of the pickup truck tests. Multiple simulations using a 2000P pickup truck were performed to validate the relationship therein. Simulation results generally correlated with testing results. However, there was one discrepancy in the vehicle model related to the impact between the rear tires and guardrail which caused a different trajectory than observed in a full-scale crash test after the vehicle model was redirected. The issue has remained throughout the research.

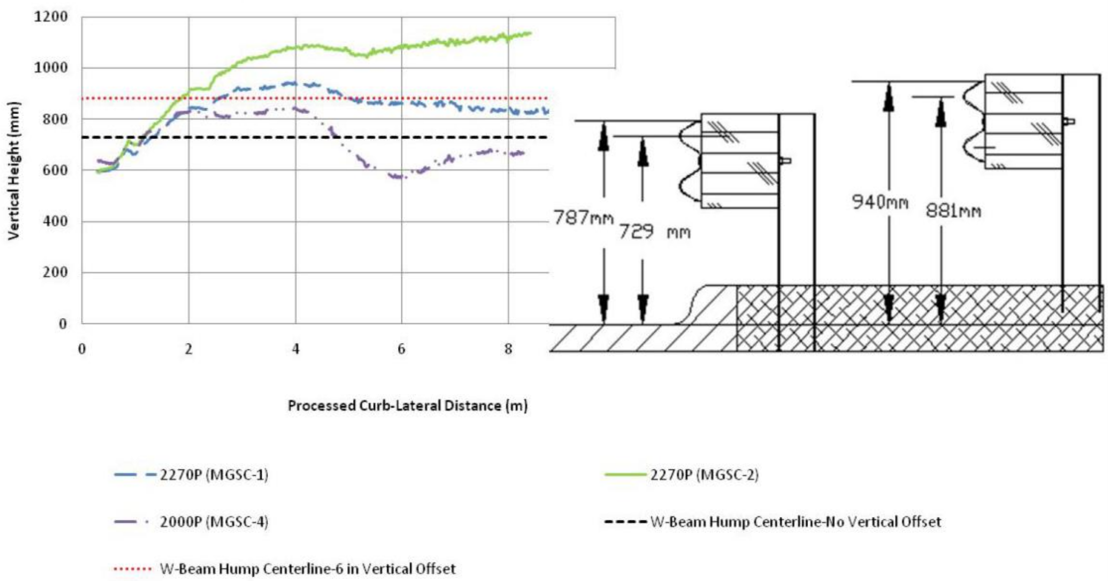


Figure 2.4. Relationship Between the Critical Impact Point and the Lateral Offset of MGS [*10*]

Plaxico *[11]* studied the placement guidelines for curbs and curb-guardrail combination systems in cases where vehicular speeds are 37.3 mi/h (60 km/h) or higher. This study and other previous literature covering both full-scale crash testing and simulation testing was extensively reviewed. Full-scale crash testing and simulation testing was also conducted. The relationships between vehicular speeds, curb heights, and lateral offset distances of guardrails were analyzed by drawing from both the literature and from testing results. Finally, placement guidelines are recommended as seen in Figure 2.5.

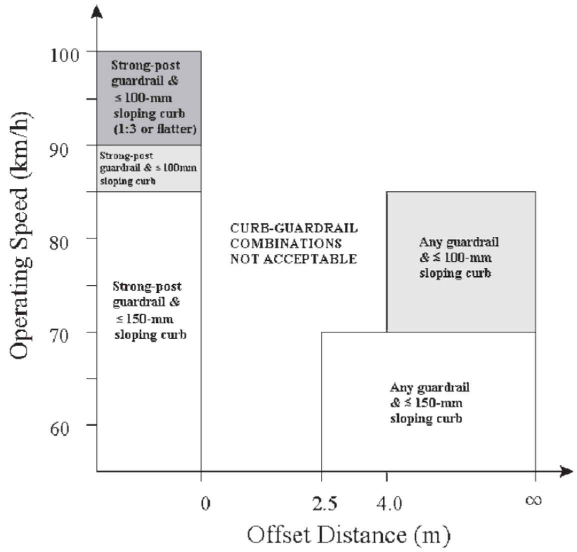


Figure 2.5. Guidelines for the Use of Curbs [11]

CHAPTER 3. FULL-SCALE TESTING

3.1. TEST INSTALLATION DETAILS

The test installation consisted of a reinforced concrete slab measuring 60 ft long × 29 ft wide × and 8 in thick, cast in-place on the existing concrete runway. The traffic face of the slab had a top edge radius of 3 inches and sloped outward 2 inches to the bottom of the slab.

The specified compressive strength of the concrete used in the sidewalk and curb was 4000 psi. On January 12, 2021, fifteen days before the first test, the average compressive strength of the concrete was 5565 psi.

Figure 3.1 provides photographs of the installation, and Figure 3.2 presents the overall information on the sidewalk. Drawings were provided by the Texas A&M Transportation Institute (TTI) Proving Ground, and construction was performed by TTI Proving Ground personnel.

Figure 3.1. Sidewalk Prior to Testing

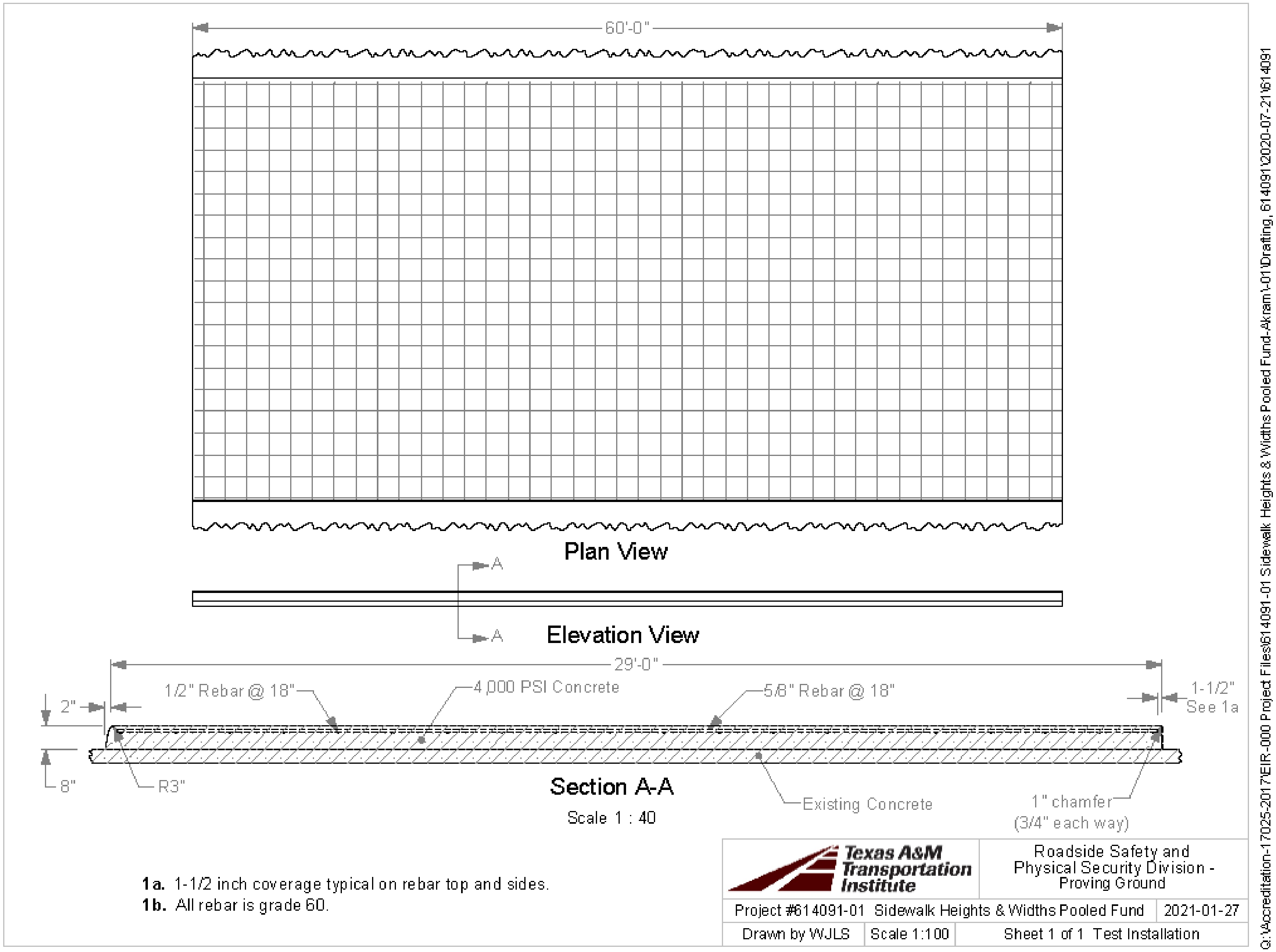


Figure 3.2. Sidewalk Details

3.2. TEST NO. 614091-01-1

3.2.1. Impact Conditions

Table 3.1 shows the target impact conditions for Test No. 614091-01-1 on the 8-inch sidewalk. Figure 3.3 depicts the target impact setup.

Table 3.1. Target Impact Conditions for Test No. 614091-01-1

Test Vehicle	1100C Small Car weighing 2420 lb ± 55 lb
Impact Speed	44 mi/h ± 2.5 mi/h
Impact Angle	25 degrees ± 1.5 degrees
Impact Point	240 inches ± 12 inches from left edge of the 8-inch-tall sidewalk

Figure 3.3. Sidewalk/Test Vehicle Geometrics for Test No. 614091-01-1

Table 3.2 shows the actual impact conditions for Test No. 614091-01-1 on the 8-inch sidewalk.

Table 3.2. Actual Impact Conditions for Test No. 614091-01-1

Test Vehicle	2014 Nissan Versa weighing 2446 lb
Impact Speed	44.2 mi/h
Impact Angle	25.3 degrees
Impact Point	237.9 inches from the downstream of the upstream edge of the sidewalk

3.2.2. Weather Conditions

The test was performed on the morning of January 27, 2021. Weather conditions at the time of testing were as follows: wind speed: 12 mi/h; wind direction: 306 degrees (vehicle was traveling at a heading of 170 degrees); temperature: 59°F; relative humidity: 56 percent.

3.2.3. Test Vehicle

Figure 3.4 shows the 2014 Nissan Versa used for the crash test. The vehicle's test inertia weight was 2446 lb, and its gross static weight was 2446 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 A.1 in Appendix A.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.

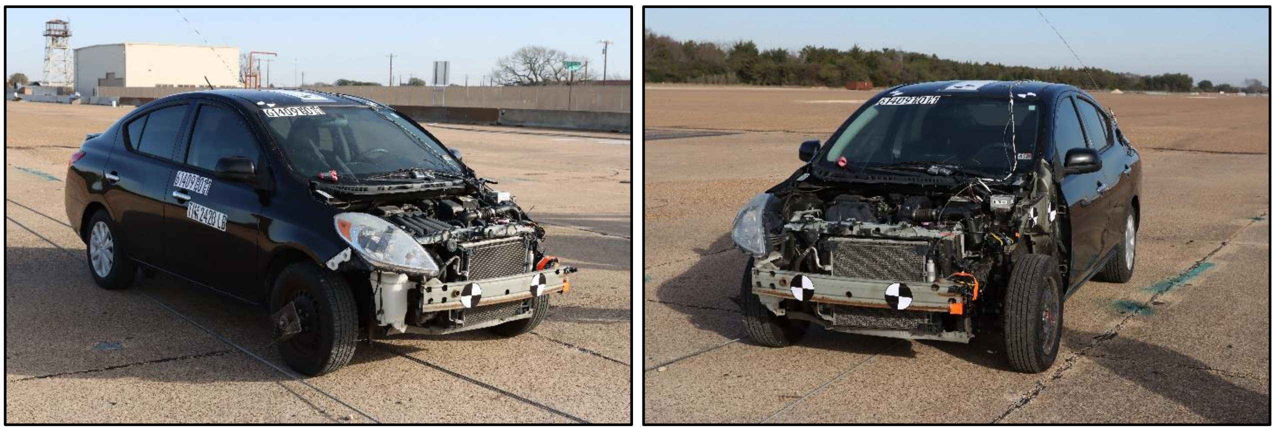


Figure 3.4. Test Vehicle Before Test No. 614091-01-1

3.2.4. Test Description

Figure A1 and Figure A2 in Appendix A show sequential photographs of Test No. 614091-01-1.

3.2.5. Damage to Sidewalk Installation

Figure 3.5 shows the damage to the sidewalk. There was some scuffing at impact and along the path of the vehicle. No cracking, spalling, or gouging was noted on the concrete slab. Working width* was 348.0 inches (the width of the slab), and height of working width was 8.0 inches.

3.2.6. Damage to Test Vehicle

Figure 3.6 shows the damage sustained by the vehicle. No fuel tank damage was observed.

* 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 3.5. Sidewalk After Test No. 614091-01-1

Figure 3.6. Test Vehicle After Test No. 614091-01-1

3.2.7. Occupant Risk Factors

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 3.3. Figure A.3 in Appendix A.3 shows the vehicle angular displacements, and Figures A.4 through A.6 in Appendix A.4 show acceleration versus time traces.

Table 3.3. Occupant Risk Factors for Test No. 614091-01-1

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV) Longitudinal Lateral	 3.0 ft/s 2.3 ft/s	 at 0.4754 s on left side of interior
Occupant Ride-down Accelerations Longitudinal Lateral	 1.8 g 2.3 g	 1.0725 - 1.0825 s 0.7759 - 0.7859 s
Theoretical Head Impact Velocity (THIV)	1.2 m/s	at 0.4626 s on left side of interior
Acceleration Severity Index (ASI)	0.2	0.0320 - 0.0820 s
Maximum 50-ms Moving Average Longitudinal Lateral Vertical	 −1.1 g 1.0 g −2.2 g	 0.1470 - 0.1970 s 0.1460 - 0.1960 s 0.0051 - 0.0551 s
Maximum Yaw, Pitch, and Roll Angles Roll Pitch Yaw	 10° 5° 4°	 0.2040 s 0.3463 s 0.6466

3.2.8. Summary of Results

This test is not compliance test for a given device but a measurement test for identifying needed signals to calibrate the finite element models presented in subsequent chapters. Therefore, no passing or failing outcome is required.

3.3. TEST NO. 614091-01-2

3.3.1. Impact Conditions

Table 3.4 shows the target impact conditions for Test No. 614091-01-2 on the 8-inch sidewalk. Figure 3.7 depicts the target impact setup.

Table 3.4. Target Impact Conditions for Test No. 614091-01-2

Test Vehicle	2270P Pickup Truck weighing 5000 lb ± 110 lb
Impact Speed	44 mi/h ± 2.5 mi/h
Impact Angle	25 degrees ± 1.5 degrees
Impact Point	240 inches ± 12 inches from left edge of the 8-inch-tall sidewalk

Figure 3.7. Sidewalk/Test Vehicle Geometrics for Test No. 614091-01-2

Table 3.5 shows the actual impact conditions for Test No. 614091-01-2 on the 8-inch sidewalk.

Table 3.5. Actual Impact Conditions for Test No. 614091-01-2

Test Vehicle	2014 RAM 1500 pickup truck weighing 5005 lb
Impact Speed	49.4 mi/h
Impact Angle	25.9 degrees
Impact Point	234.8 inches from the downstream of the upstream edge of the sidewalk

3.3.2. Weather Conditions

The test was performed on the morning of January 28, 2021. Weather conditions at the time of testing were as follows: wind speed: 4 mi/h; wind direction: 46 degrees (vehicle was traveling at a heading of 170 degrees); temperature: 46°F; relative humidity: 69 percent.

3.3.3. Test Vehicle

Figure 3.8 shows the 2014 RAM 1500 pickup truck used for the crash test. The vehicle's test inertia weight was 5005 lb, and its gross static weight was 5005 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 27.00 inches. The height to the vehicle's center of gravity was 28.75 inches. Tables B.1 and B.2 in Appendix B.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 3.8. Test Vehicle Before Test No. 614091-01-2

3.3.4. Test Description

Figure B1 and Figure B2 in Appendix B show sequential photographs of Test No. 614091-01-2.

3.3.5. Damage to Sidewalk Installation

Figure 3.9 shows the damage to the sidewalk. There was some scuffing at impact and along the path of the vehicle. No cracking, spalling, or gouging was noted on the concrete slab. Working width* was 348.0 inches, and height of working width was 8.0 inches.

3.3.6. Damage to Test Vehicle

Figure 3.10 shows the damage sustained by the vehicle. No fuel tank damage was observed.

* 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 3.9. Sidewalk After Test No. 614091-01-2
(White Paint Used to Obscure Tire Marks from Previous Test)

Figure 3.10. Test Vehicle After Test No. 614091-01-2

3.3.7. Occupant Risk Factors

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 3.6. Figure B.3 in Appendix B.3 shows the vehicle angular displacements, and Figures B.4 through B.6 in Appendix B.4 show acceleration versus time traces.

Table 3.6. Occupant Risk Factors for Test No. 614091-01-2

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	3.1 ft/s	at 0.7483 s on right side of interior
Lateral	5.2 ft/s	
Occupant Ride-down Accelerations		
Longitudinal	1.1 g	1.9489 - 1.9589 s
Lateral	2.3 g	0.7614 - 0.7714 s
Theoretical Head Impact Velocity (THIV)	1.9 m/s	at 0.7110 s on right side of interior
Acceleration Severity Index (ASI)	0.3	0.2246 - 0.2746 s
Maximum 50-ms Moving Average		
Longitudinal	−1.6 g	0.1529 - 0.2029 s
Lateral	−1.7 g	0.7348 - 0.7848 s
Vertical	−2.5 g	0.1955 - 0.2455 s
Maximum Yaw, Pitch, and Roll Angles		
Roll	8°	0.8146 s
Pitch	4°	0.8482 s
Yaw	15°	2.0000 s

3.3.8. Summary of Results

This test is not a compliance test for a given device but a measurement test for identifying needed signals to calibrate the finite element models presented in subsequent chapters. Hence, no passing or failing outcome is required.

CHAPTER 4. CALIBERATION OF VEHICLE DYNAMIC BEHAVIOR

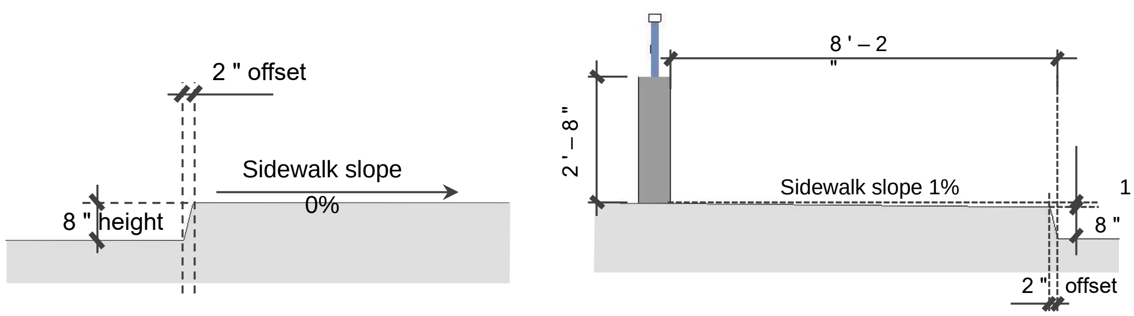
4.1. INTRODUCTION

In this chapter, finite element (FE) models for a vehicle and system are calibrated for the dynamic analyses using LS-DYNA. To calibrate the FE vehicle models using a full-scale crash test, the FE models were setup using the same conditions as the full-scale crash test. If simulation results do not correlate reasonably with the full-scale crash test results, certain vehicle parameters were changed to improve the correlation. Test results such as signal data or photos were used to evaluate the simulation results and enhance the FE model as needed.

4.2. FINITE ELEMENT MODELS

4.2.1. System Models

Figure 4.1 shows two different models that were developed in this project: (a) sidewalk with a curb for the TL-2 trajectory simulation and (b) the Caltrans Type 732SW bridge rail for the impact simulation. The sidewalk with a curb is the same system that underwent the trajectory testing conducted in Chapter 3. The Type 732SW bridge rail is the parapet system used in the Caltrans study *[3]*.



(a) Sidewalk System (TTI) *(b) Parapet System used by Caltrans [3]*

Figure 4.1. System Models used for FE Vehicle Model Validation

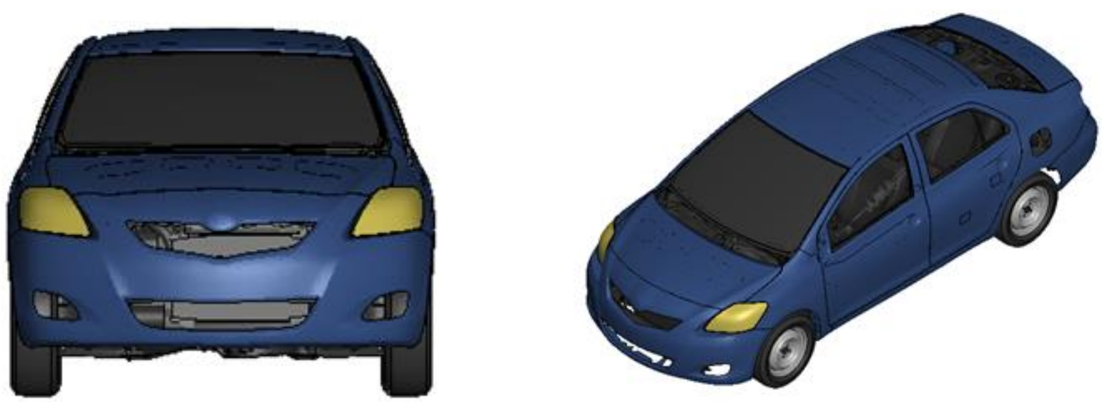
4.2.2. Vehicle Models

The 2018 Dodge Ram and the 2010 Toyota Yaris vehicle models were adopted as representative of the *MASH* 2270P pickup test vehicle and the *MASH* 1100C passenger test vehicle, respectively *[12, 13]*.

Figure 4.2 and Figure 4.3 show the Dodge Ram and the Toyota Yaris FE models, respectively. Both vehicle models were subjected to calibration and subsequently used in the simulations to develop placement guidelines.

(a) Front View *(b) Isometric View*

Figure 4.2. Dodge RAM Model Used for Simulation [13]



(a) Front View *(b) Isometric View*

Figure 4.3. Toyota Yaris Model Used for Simulation [12]

4.3. PICKUP TRUCK MODEL CALIBERATION

This section presents the process of the Dodge Ram model calibration. A simulation of the Dodge Ram model was first performed on a flat ground for initialization purpose. After the model was initialized under the steady-state conditions, it was calibrated through comparisons with the *MASH* TL-3 crash test and the *MASH* TL-2 trajectory test.

For the initialization step, two simulations were conducted. The first was performed in a stationary condition, and the second was performed under while the vehicle is moving.

During the stationary simulation, the entire vehicle model including the tires did not move but the vehicle was subjected to gravity. At the end of the simulation, the vertical force under each tire location was extracted, and the weight distribution of the tires was calculated based on the force data. Table 4.1 presents the comparison of weight for each tire location between the vehicle model and the actual vehicles. The TL-2 test vehicle refers to the vehicle used in the trajectory testing in this study, and the TL-3 test vehicle refers the vehicle used in the Caltrans study *[3]*. The differences indicate the correlation between the FE model and actual vehicle in terms of weight.

Table 4.1. Weight Comparison of Test Vehicles and Model in Stationary Condition

Location		Weight, lb (N)			% difference	
		Ram Model	TL-2 Test Vehicle	TL-3 Test Vehicle	TL-2	TL-3
A	**Left Front Tire**	1507 (6699)	1371 (6093)	1489 (6618)	9.9	1.2
B	**Left Rear Tire**	1111 (4939)	1153 (5124)	1062 (4720)	3.8	4.6
C	**Right Front Tire**	1476 (6559)	1372 (6098)	1397 (6209)	7.6	5.7
D	**Right Rear Tire**	1059 (4707)	1109 (4929)	1114 (4951)	4.7	5.2
Total Weight		5153 (22904)	5005 (22244)	5061 (22493)	3.0	1.8

The next simulation was set up under a moving condition. All conditions were identical to the first simulation except for the speed. The vehicle model was set to move forward at a speed of 49.4 mi/h at 0.7 seconds. Weight distribution of each tire was calculated using a force transducer after 0.7 seconds in order to analyze the values only during the moving condition.

Table 4.2 lists each tire weight from this simulation comparing to actual vehicle models used for full-scale tests. The FE vehicle model were calibrated to decrease the maximum difference in the total weights between the FE model and the full-scale test vehicles to be 2 percent.

Table 4.2. Weight Comparison of Test Vehicles and Model in Moving Condition

Location		Weight, lb (N)			% difference	
		Ram Model	TL-2 Test Vehicle	TL-3 Test Vehicle	TL-2	TL-3
A	**Left Front Tire**	1494 (6640)	1371 (6093)	1489 (6618)	9.0	0.3
B	**Left Rear Tire**	1103 (4904)	1153 (5124)	1062 (4720)	4.5	3.8
C	**Right Front Tire**	1466 (6517)	1372 (6098)	1397 (6209)	6.9	4.9
D	**Right Rear Tire**	1044 (4638)	1109 (4929)	1114 (4951)	6.2	8.9
Total Weight		5107 (22699)	5005 (22244)	5061 (22493)	2.0	0.9

The vehicle model was considered stable enough for subsequent impact analysis. Therefore, the Ram model was confirmed for use in the further calibration. For the model calibrations, the Caltrans report *[3]* and the trajectory testing results presenting in Chapter 3, which included sequential photos, occupant risk factors, and the contact phenomena between the vehicle and parapet, were used.

4.3.1. Calibration Using *MASH* TL 2-11 Trajectory Test

The initialized Ram model was setup under the conducted *MASH* TL-2 test conditions. Figure 4.4 shows the model setup at a speed of 49.4 mi/h and an angle of 25 degrees to represent the actual testing impact conditions. Simulation results were compared to the measured testing results described in Chapter 3.

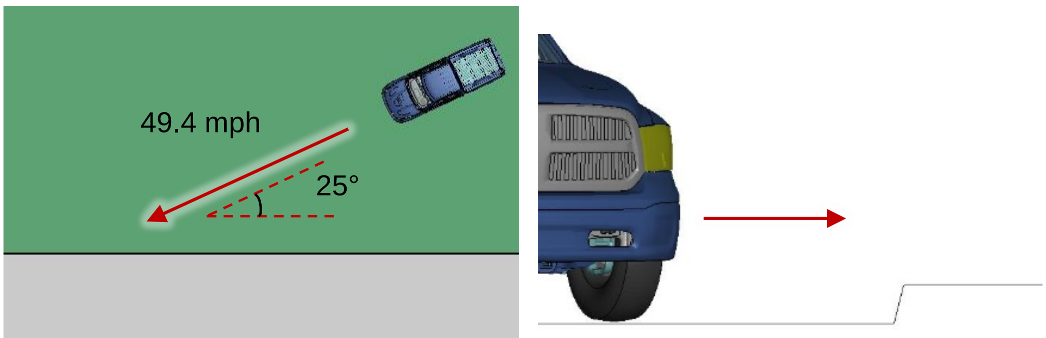
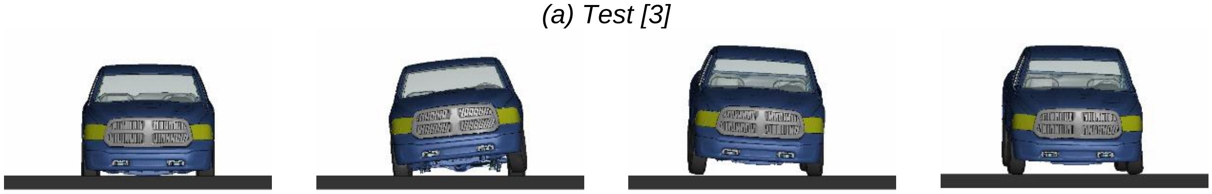


Figure 4.4. Simulation Set-Up Under TL-2 Conditions

Figure 4.5 shows the sequential head-on photos of the test and simulation. The Ram model was observed to behave similarly to the test vehicle. In the trajectory test, some targets were attached to the surface of the test vehicle for tracking purposes. Displacements profiles of the targets were compared to displacements profiles calculated by the simulation.

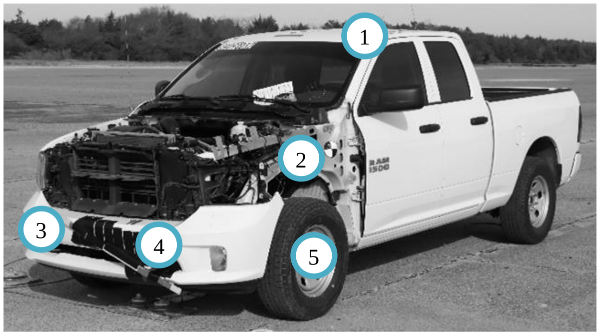
(a) Test [3]



(b) Simulation

Figure 4.5. Sequential Photos of Pickup Truck Under TL-2 Conditions

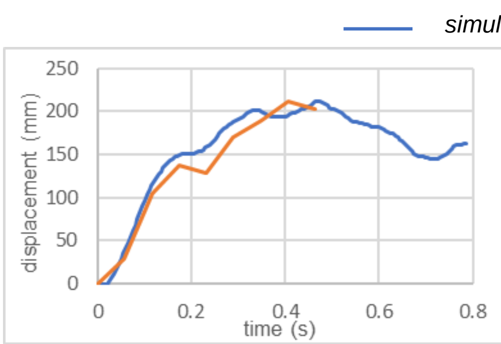
Figure 4.6 presents the locations where the data were compared: Location No. 1 through Location No. 4 are targets markers on the vehicle body, Location No. 5 is a target marker at the center of the wheel, and Location No. 6 is the displacement of the linear potentiometer. The displacement comparison for each location is shown in Figure 4.7. The displacement magnitude was slightly different, yet less than 2 inches. Overall displacements of the simulation reasonably followed the trend of the test.



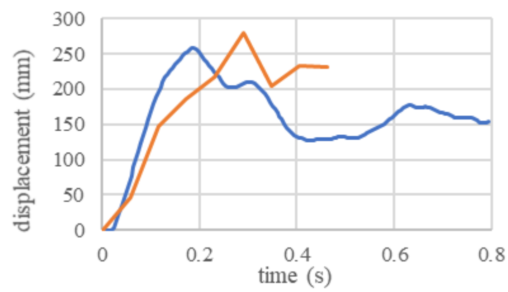
(a) Target Location

(b) Linear Potentiometer

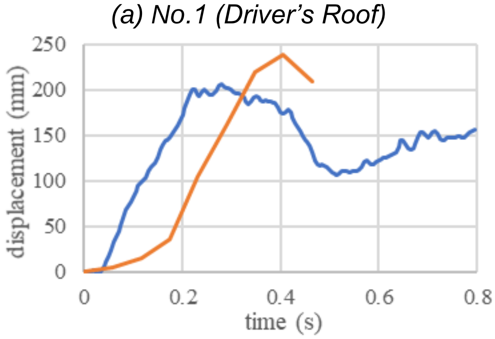
Figure 4.6. Location Information for the Data Comparison



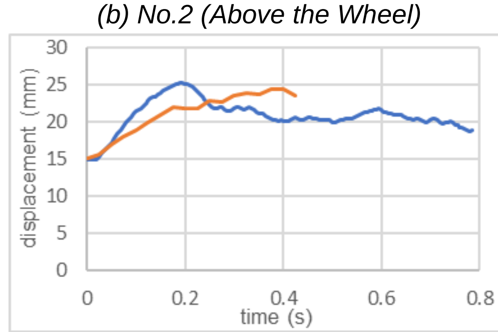
(a) No.1 (Driver's Roof)



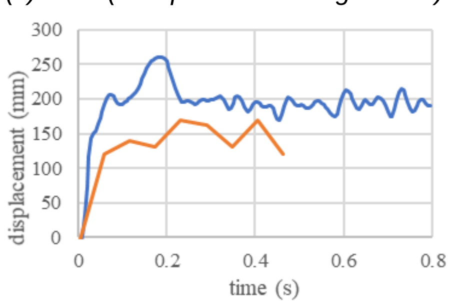
(b) No.2 (Above the Wheel)



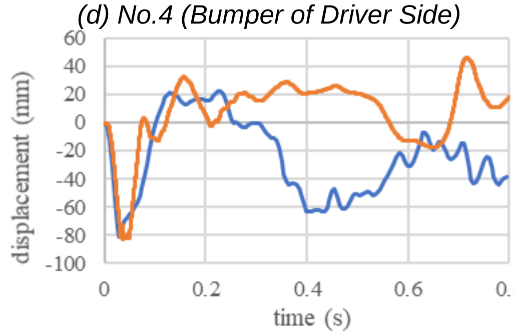
(c) No.3 (Bumper of Passenger Side)



(d) No.4 (Bumper of Driver Side)



(e) No.5 (Center of Wheel)



(f) No.6 (Linear Potentiometer)

Figure 4.7. Displacement Comparison

Finally, signals received from both testing and simulation were compared using the Roadside Safety Verification Validation Program (RSVVP) *[14]*. Since there were two accelerometers at the center of gravity (C.G.) and near the left front tire in the trajectory testing, the signals from both locations were analyzed. All data from the simulation and test are filtered at CFC 180 and then used. The results are tabulated in Table 4.3 and Table 4.4. For the C.G. location, the X acceleration and roll rate channels are important compared to other channels. In the same manner, for the front location, the X acceleration and pitch rate channels are the most important. Some values are above the MPC limits while ANOVA metrics of both C.G. and front locations successfully satisfy the criteria. It needs to be noted that the limit is basically set for a guardrail system without a curb. Therefore, it is not required to meet MPC and ANOVA limits with a curb system but the limits were used for a reference.

Table 4.3. RSVVP Results for Vehicle C.G. Signal

Channel	Weighting Factor	Sprague-Geers Metrics		ANOVA Metrics	
		M≤40	P≤40	Mean Residual (≤5%)	Std. Deviation (≤35%)
X acceleration	0.439	*44.9*	*45.5*	0.26	25.29
Y acceleration	0.002	*40.6*	*46.2*	-3.11	25.62
Z acceleration	0.060	*72.9*	*50.3*	0.56	27.53
Roll rate	0.320	*44.2*	*41.6*	2.71	17.66
Pitch rate	0.086	*80.3*	*48.1*	-0.89	27.58
Yaw rate	0.092	36.7	26.6	*-16.57*	29.2
Multi-channel	1.000	*47.1*	39.7	-5	26.2

Table 4.4. RSVVP Results of Vehicle Frontal Signal

Channel	Weighting Factor	Sprague-Geers Metrics		ANOVA Metrics	
		M≤40	P≤40	Mean Residual (≤5%)	Std. Deviation (≤35%)
X acceleration	0.346	16.2	*50*	-2.86	27.19
Y acceleration	0.131	39.6	*44.9*	-0.45	20.2
Z acceleration	0.023	*59.1*	*47.2*	0.28	11.27
Roll Rate	0.135	*71.9*	*46.7*	1.09	6.17
Pitch Rate	0.356	*47.1*	*46.5*	-1.72	11.58
Yaw Rate	0.009	*42.8*	39.6	-7.14	32.18
Multi-Channel	1.000	*44*	*46.6*	-1.6	18.9

4.3.2. Calibration Using CALTRANS *MASH* TL 3-11 Tests

Using the initialized Ram model, the simulation under *MASH* TL-3 conditions was first set up with the bridge parapet system. The bridge parapet system tested by Caltrans were adopted for *MASH* TL-3 simulation test. According to the Caltrans test report *[3]*, the actual speed and angle were 62.7 mi/h and 24.8 degrees as shown in Figure 4.8. The test inertial mass of the test vehicle was 5062 lb, which was approximately 99 percent similar to the Ram model at 5107 lb.

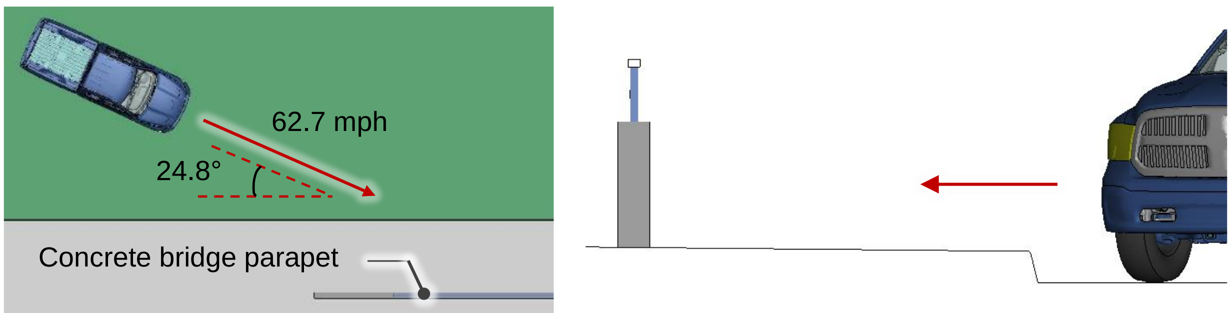


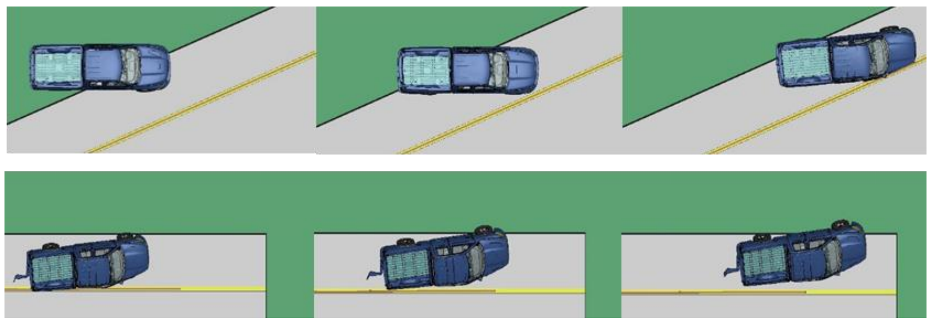
Figure 4.8. Simulation Setup Under TL-3 Conditions

From the first simulation under *MASH* TL-3 conditions, the Ram model showed different performance to the actual testing in terms of the contact duration between the vehicle and parapet. According to the Caltrans report *[3]*, it took approximately 0.36 seconds until the vehicle completely lost contact with the parapet after the front bumper of the vehicle impacted the parapet. During this time, the vehicle engaged with the parapet for around 16 feet (4.9 m). However, in the simulation, the vehicle rebounded after the front bumper initially impacted the parapet. Therefore, the vehicle lost contact for a while, before the rear of the vehicle impacted the parapet again. To correct this rebounding issue, the friction coefficients and properties of the vehicle were adjusted for in the next calibration. Additionally, during the Caltrans test *[3],* the suspension components were affected by the impact while joint failures of the suspension did not; however, in the simulation, the opposite phenomena was observed. Therefore, the performance of the suspension and joint failures became the consideration for the next calibration as well.

For the next simulation, the friction coefficients of the vehicle body and tires were lowered. Also, the element formulations of some parts were changed to lead the vehicle to be softer. These calibrations were performed to reduce the rebounding issue between the vehicle and parapet. In addition, to reflect the effect on the suspension and joints, failure forces were considered so that the joints should be failed in only the TL-3 simulation.

After several iterations were run to increase vehicular stability, including the gradual application of gravity and the calibration of the total suspension spring forces, a suitable Ram model was achieved. Using this Ram model, *MASH* TL-3 simulation results were compared with the data from the Caltrans test report *[3]*. Figure 4.9 shows the overhead sequential photos of the simulation and test.

(a) Test [3]



(b) Simulation

Figure 4.9. Sequential Overhead Photos of Pickup Truck Under TL-3 Conditions

In the simulation, the rear bumper was partially detached after the impact; however, this was a minor issue which did not affect vehicular movement. Except for the partial detachment of the rear bumper, overall trajectories of the simulation and the test were observed to be similar.

Table 4.5 and

Table 4.6 present the vehicle descriptions for each timestep, the contact phenomena comparison, and the occupant risk factors of the simulation and test. The occupant risk factors were calculated and obtained by using Test Risk Assessment Program (TRAP) version 2.5.2 [*15*].

The Ram model stayed in contact with the parapet for less time than the test did. It also had a higher yaw angle compared to the test value. These discrepancies exist as a result of the rebounding issue which affected vehicular behavior. Generally, in light of the vehicle descriptions and other results, the simulation was observed to follow the test closely.

Table 4.5. Descriptive Comparison for Timestep

Vehicle Description for Each Timestep			
Description		Test	Simulation
Right Front Tire Impact to Curb		0.000 s	0.000 s
Left Front Tire Impact to Curb		0.110 s	0.135 s
Front Side Impact to Parapet		0.180 s	0.210 s
Rear Side Impact to Parapet		0.370 s	0.415 s
Lost Contact with Parapet		0.540 s	0.520 s
Contact Phenomena			
Stayed-in-contact	**Time**	0.180 s – 0.540 s	0.210 s – 0.520 s
	Duration	0.36 s	0.31 s
	Distance	16 ft (4.9 m)	10.5 ft (3.2 m)

Table 4.6. Comparisons of the Occupant Risk Factors

Occupant Risk Factors		Test	Simulation
OIV (m/s)	**X**	5.4	5.7
	Y	8.5	7.6
Ride-down Acceleration (g)	**X**	9.2	-4.8
	Y	-8.1	-10.9
Max. Angle (degrees)	**Roll**	27.9	24.8
	Pitch	4.9	-4.8
	Yaw	-20.6	-33.7

As a result of the TL-2 and TL-3 simulations, the Ram model was reasonably correlated with the actual tests. Even though there was a mild rebounding issue which led to some differences between the simulation and test, the data generally indicate good agreement. The sequential vehicular trajectories were comparable. The displacements of the Ram model closely matched the test data under *MASH* TL-2 conditions, and the contact phenomena under *MASH* TL-3 conditions also followed test results. Based on these results, the model was reasonably accurate and valid for the development of placement guidelines.

4.4. PASSENGER CAR MODEL DEVELOPMENT

This section presents the process of the passenger car model calibration. The Toyota Yaris model was calibrated through comparisons to a *MASH* TL-2 trajectory test and two impact tests (*MASH* TL 2-10 and TL 3-10).

For the model calibrations, the Caltrans test report *[3]* and the trajectory testing results presented in Chapter 3, which included sequential photos, occupant risk factors, and the contact phenomena between the vehicle and parapet, were used.

4.4.1. Calibration Using *MASH* TL 2-10 Trajectory Test

The *MASH* TL-2 simulation was set up with an 8-inch sidewalk and a 2-inch offset curb – the same system used for the trajectory testing. According to the trajectory test data, the actual speed was 43.32 mi/h and the actual angle was 25.25 degrees. Figure 4.10 shows the TL-2 sidewalk trajectory simulation test set-up.

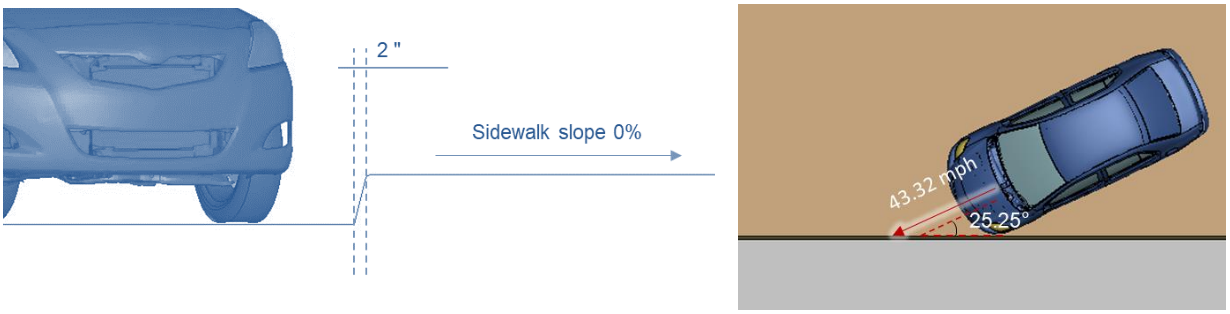
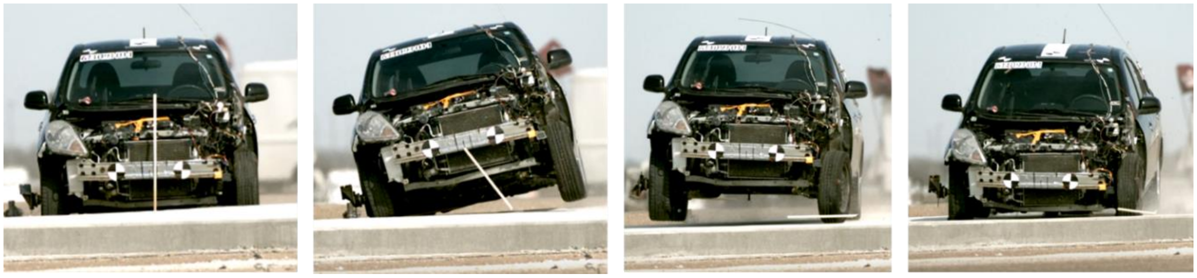


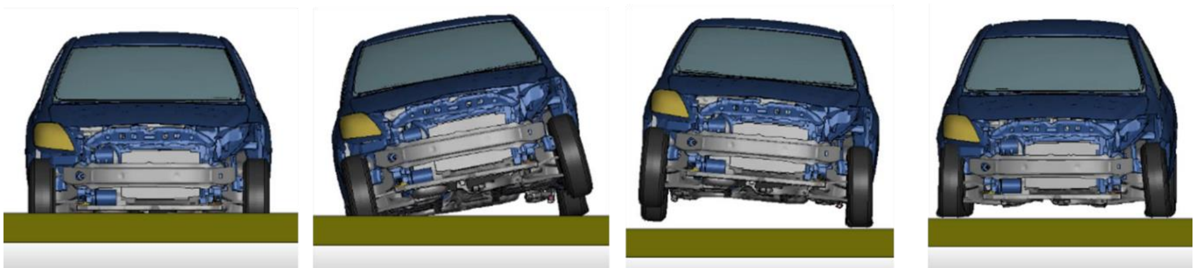
Figure 4.10. Trajectory Simulation Set-Up Under TL-2 Conditions

Using the initial Yaris model, the trajectory simulation with an 8-inch curbed sidewalk was performed under *MASH* TL-2 conditions. When the simulation results were compared to the testing results described in Chapter 3, there were two significant phenomenon that needed to be accommodated for by calibrating the model: (1) the simulation model did not fly as much as the actual test vehicle; and (2) the yaw angle disparity between the simulation and full-scale test was too large. Several iterations were calibrated by modifying spring stiffness, and the behavior trend of the final simulation model followed that of the actual test vehicle.

Figure 4.11 shows the sequential overhead photos of the test and simulation. The modified Yaris model shows similar performance compared to the trajectory test results.



(a) Test

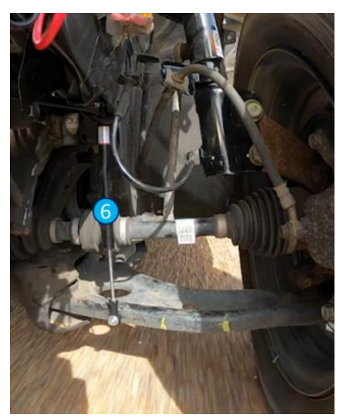


(b) Simulation

Figure 4.11. Sequential Overhead Photos of Passenger Car Under TL-2 Conditions.

In the trajectory test, targets were attached to the surface of the test vehicle. The displacements of the targets were compared to similar displacements in the simulation. Figure 4.12 presents the locations where the data were compared: No. 1 through No. 4 are targets on the vehicle surface, No. 5 is the center of the wheel, and No. 6 is the displacement of the linear potentiometer. The displacement comparison for each location is shown in Figure 4.13. The displacement magnitude was slightly different, but less than 3 inches. Overall displacements of the simulation reasonably followed the trend of the test.

(a) Target Location



(b) Linear Potentiometer

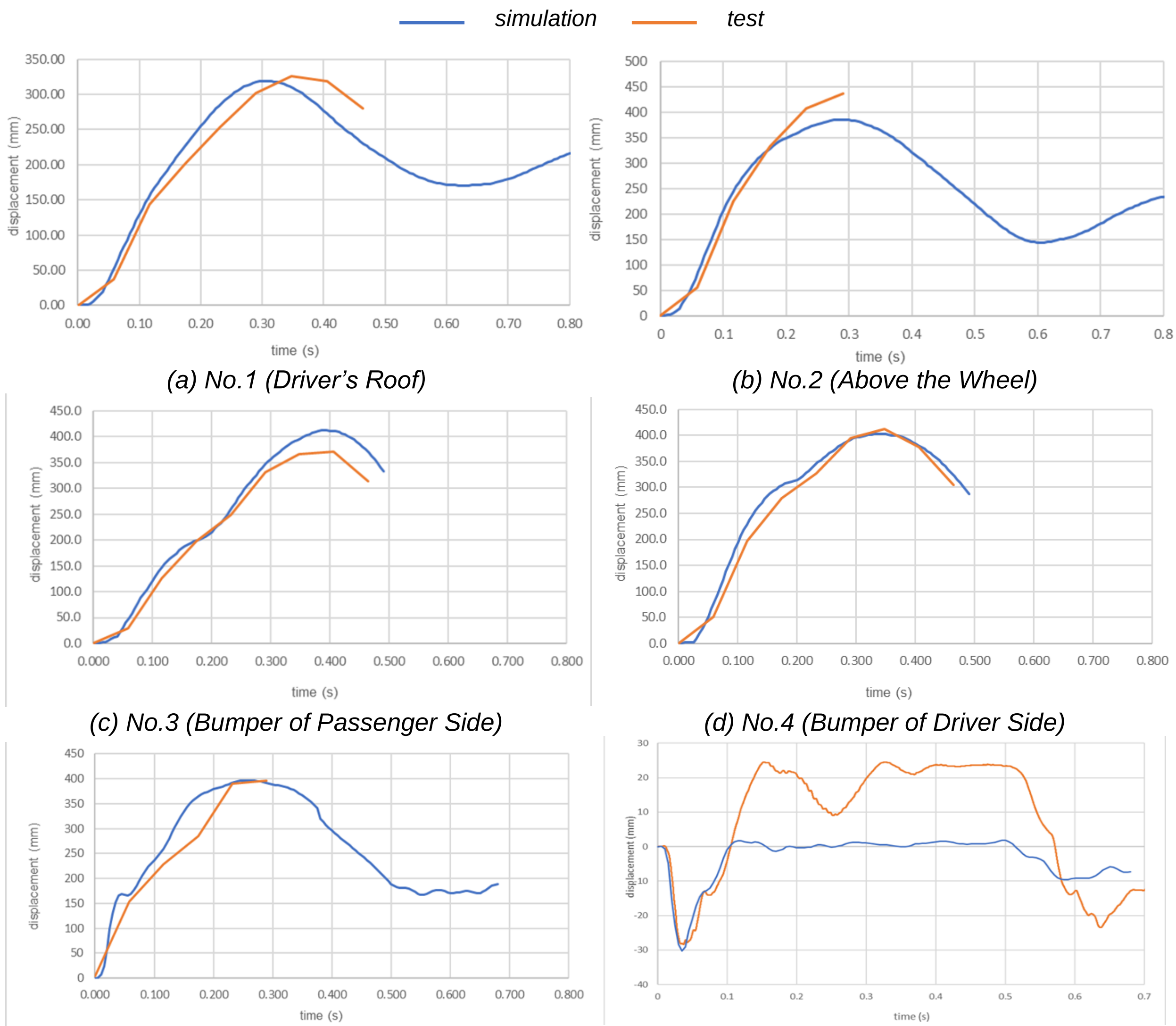
Figure 4.12. Location Information for the Data Comparison

The test and simulation signals were compared using RSVVP *[14]*. Multi-channel analysis using signals from C.G. was conducted with a time window of 0.6 seconds after impact. All data from the simulation and test were filtered at CFC 180. Table 4.7 list the comparative analysis results.

Table 4.7. Multi-Channel RSVVP Results of the Signals from C.G. Location

Channel	Weighting Factor	Sprague-Geers Metrics		ANOVA Metrics	
		M≤40	P≤40	Mean Residual (≤5%)	Std. Deviation (≤35%)
X acceleration	0.223	*40.2*	*44.9*	1.25	18.69
Y acceleration	0.150	25.7	*49.1*	-1.17	24.11
Z acceleration	0.128	*48.6*	*48.0*	-0.33	16.63
Roll rate	0.188	1.00	29.3	0.93	21.81
Pitch rate	0.132	30.2	35.6	-0.92	18.11
Yaw rate	0.180	22.5	32.4	-5.84	28.27
Multi-channel	1.000	28.8	39.8	-1.10	21.30

Since the X acceleration and roll rate channels are important compared to other channels, they have higher weighting factors. The overall value (multi-channel result) satisfies both MPC and ANOVA criteria. Although the Sprague-Geers values for the accelerations are slightly over MPC limits, other values prove the test and the simulation shows agreement. As aforementioned, the limits are only for a reference, but not required for a curb test since the limits are set for a guardrail system without a curb. Therefore, it can be said that the FE model is reasonably accurate and valid for further investigation.



(a) No.1 (Driver's Roof) (b) No.2 (Above the Wheel)

(c) No.3 (Bumper of Passenger Side) (d) No.4 (Bumper of Driver Side)

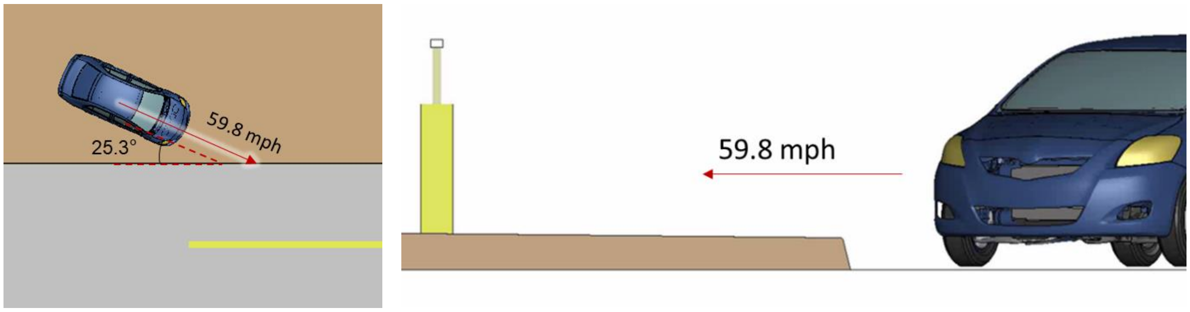
(e) No.5 (Center of Wheel) (f) No.6 (Linear Potentiometer)

Figure 4.13. Passenger Car Trajectory Displacement Comparison

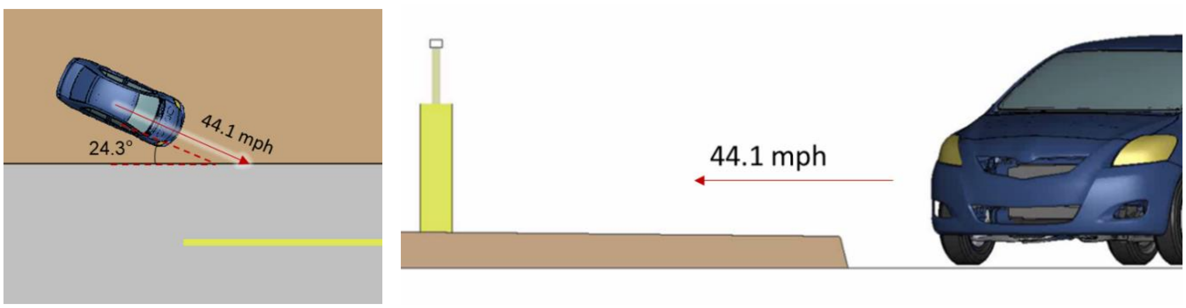
4.4.2. Calibrations Using Caltrans Bridge Parapet and Railing on Sidewalk Tests

As a result of the TL-2 simulations, the Yaris model was reasonably correlated with the actual tests. Even though there was a slight discrepancy in the front tire damping which led to differences in the linear potentiometer displacement, the data generally indicated good agreement.

Figure 4.14 shows the model set-up for impact simulation tests under *MASH* TL 2-10 and TL 3-10 conditions. The actual measured impact speeds and angles were used in accordance with the test report *[3]*: for TL 2-10, measured speed was 44.1 mi/h and impact angle was 24.3 degrees; for TL 3-10, measured speed was 59.8 mi/h and impact angle was 25.3 degrees.



(a) TL 3 - 10



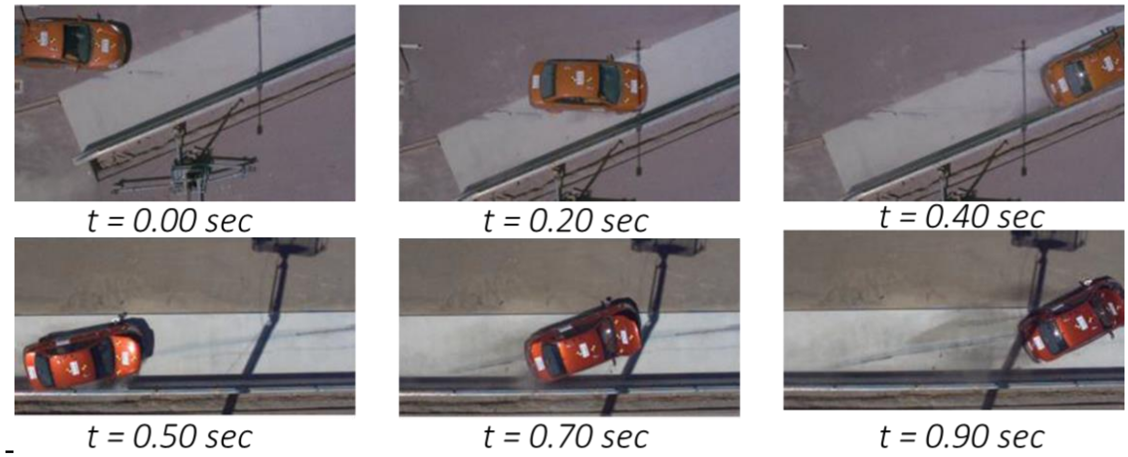
(b) TL 2 -10

Figure 4.14. Passenger Car Impact Simulation Set-Up with Caltrans Bridge Parapet with Rails on Sidewalk System

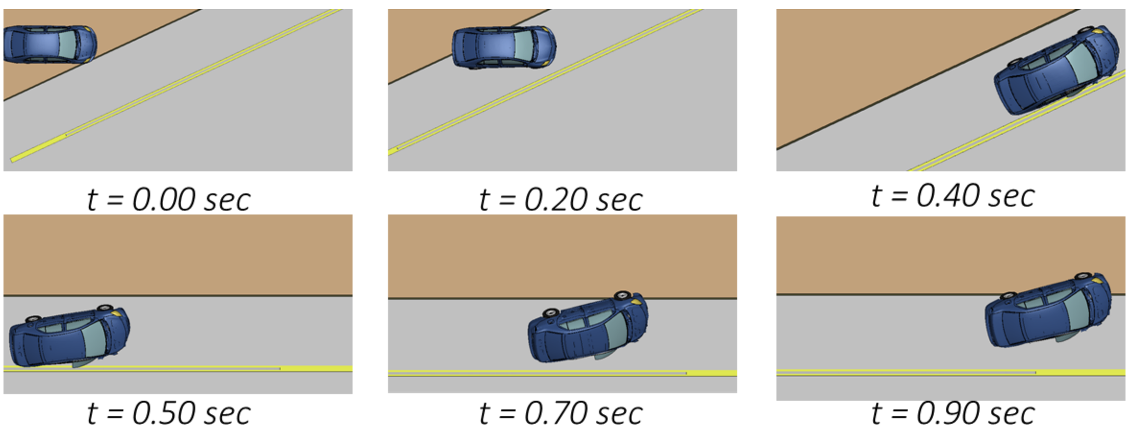
4.4.2.1. Calibration using Caltrans TL 3-10 Test

The results of the simulation under *MASH* TL-3 conditions were compared with the data from the Caltrans report. The Caltrans TL 3-10 test could not meet the *MASH* TL-3 evaluation criteria because of the high ride-down acceleration value *[3]*. By calibrating the simulation model, the failed test results were adjusted to validate the model. Figure 4.15 shows the overhead sequential photos of the test and the simulation. During the full-scale test, the hood opened after impacting the parapet, while the hood in the simulation model was not designed to open. Except for the hood opening, the overall vehicular behavior of the test and the simulation followed a similar trend.

Table 4.8 and Table 4.9 present the passenger car behavior descriptions for each timestep, the contact phenomena comparison, and the occupant risk factor for the simulation and test. The simulation model stayed in contact with the parapet for 0.11 seconds less than the test did. It also had a higher roll angle compared to the test value. However, these differences are not significant under *MASH* evaluation criteria. Moreover, it should be noted that the simulation model adopted a different vehicle model (Toyota Yaris) from the full-scale tested vehicle model (Kia Rio), which may have caused minor differences when comparing the simulation results to the test results. With consideration to the model difference, the overall vehicular behavior and high ride-down acceleration values, which exceeded *MASH* evaluation criteria, are similar between the two tests.



(a) Test [3]



(b) Simulation

Figure 4.15. Sequential Photos of Passenger Car Under TL 3-10 Conditions

Table 4.8. Descriptive Comparison for Timestep

Vehicle Description for Each Timestep			
Description		Test	Simulation
Right Front Tire Impact to Curb		0.000	0.000
Right Rear Tire Impact to Curb		0.100	0.100
Front Side Impact to Parapet		0.240	0.235
Rear Side Impact to Parapet		0.380	0.410
Lost Contact with Parapet		0.620	0.495
Contact Phenomena			
Stayed-in-Contact	**Time**	0.24-0.62	0.235-0.495
	Duration	0.38	0.26
	Distance	8.3 ft (2.5 m)	7.7 ft (2.35 m)

Table 4.9. Comparisons of the Occupant Risk Factors

Category		Test	Simulation
OIV (m/s)	**X**	3.6	4.6
	Y	6.1	5.7
Ride-down Acceleration (g)	**X**	-9.5	-16.5
	Y	-23.8	-24.5
Max. Angle (degrees)	**Roll**	-16.2	-32.1
	Pitch	-10.2	-16.1
	Yaw	-51.0	-31.4

4.4.2.2. Calibration using Caltrans TL 2-10 test

Caltrans conducted a TL 2-10 test which passed after it was discovered that the TL 3-10 test could not meet *MASH* evaluation criteria *[2]*. Figure 4.16 shows the sequential shots for both the simulation and the full-scale test.

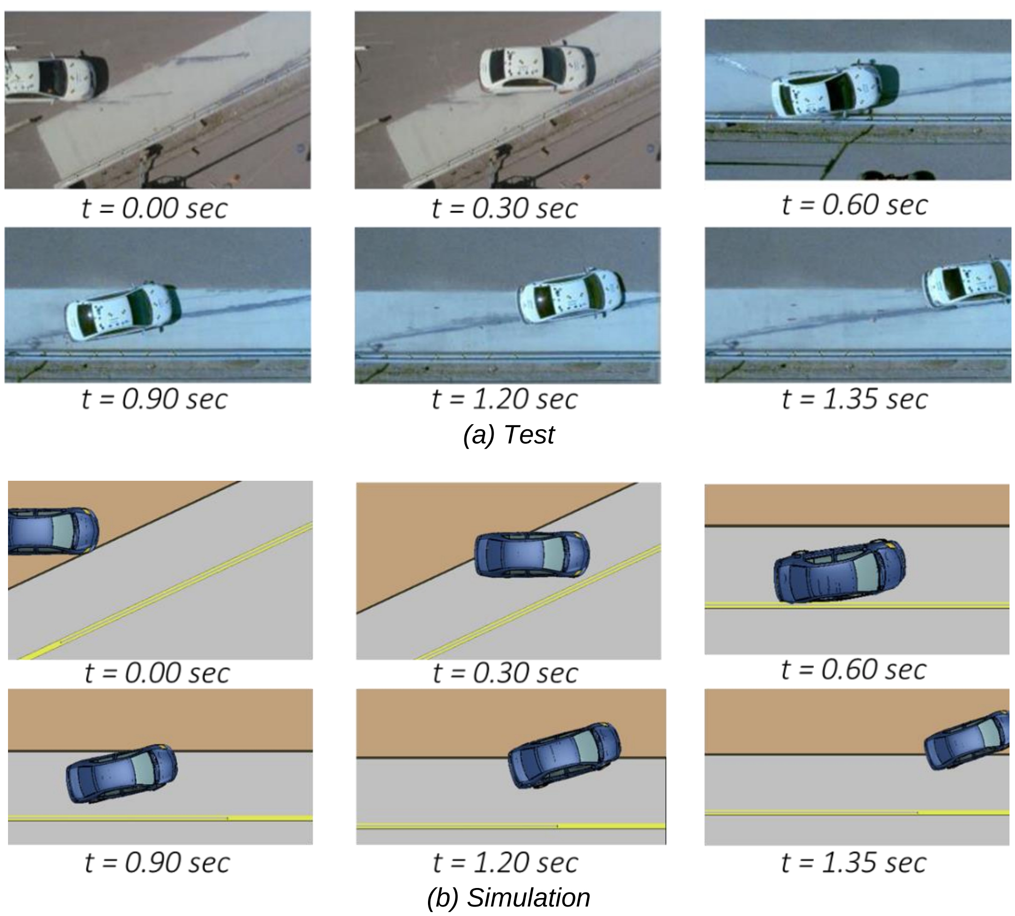


Figure 4.16. Sequential Photos of Passenger Car Under TL 2-10 Conditions.

Table 4.10 and Table 4.11 list the test and simulation results. When comparing the stayed-in-contact values, the simulation model was in contact with the parapet for 0.01 second longer than the full-scale vehicle, but for 4.9 feet less distance, which did not result in a significant difference between the two tests. There may be several reasons for this phenomenon; regardless, the simulation tends to follow the test closely. When comparing occupant risk factors, the ride-down acceleration values from the simulation are higher than from the full-scale test, but still meet *MASH* TL-2 evaluation criteria. The higher occupant risk factors from the simulation mean that the simulation provides conservative predictive results compared to the full-scale test.

Overall, the trajectory profiles and displacements of the Yaris model closely matched the test data, and the contact phenomena under *MASH* TL-3 and TL-2 conditions also followed full-scale test results. Based on these results, the FE model was considered as a reasonably accurate and valid model to develop a sidewalk placement guideline.

Table 4.10. Descriptive Comparison for Timestep

Vehicle Description for Each Timestep			
Description		Test	Simulation
Right Front Tire Impact to Curb		0.000	0.000
Right Rear Tire Impact to Curb		0.130	0.135
Front Side Impact to Parapet		0.330	0.330
Rear Side Impact to Parapet		0.520	0.565
Lost Contact with Parapet		0.640	0.650
Contact Phenomena			
Stayed-in-Contact	**Time**	0.33-0.64	0.330-0.650
	Duration	0.310	0.320
	Distance	14.3 ft (4.32 m)	9.38 ft (2.52 m)

Table 4.11. Comparisons of the Occupant Risk Factors

Category		Test	Simulation
OIV (m/s)	**X**	3.4	3.9
	Y	5.9	4.4
Ride-down Acceleration (g)	**X**	-3.9	-9.3
	Y	-3.8	-16.1
Max. Angle (Degrees)	**Roll**	17	13.6
	Pitch	-12	-13.6
	Yaw	-33.9	-39.2

CHAPTER 5. PARAPET PLACEMENT GUIDELINES

5.1. PARAMETRIC SIMULATIONS

In this chapter, the parapet heights and lateral distances from the curb were investigated using the vehicular trajectory profiles. As shown in Figure 5.1, the lateral distance is defined as the distance from the bottom of the curb to the traffic face of the parapet, and the parapet height is defined as the distance from the base of the parapet on the sidewalk to the top of the parapet. For each curb profile, the ranges of the recommendable parapet heights and lateral distance were analyzed through iterative simulations under TL-2 and TL-3 conditions.

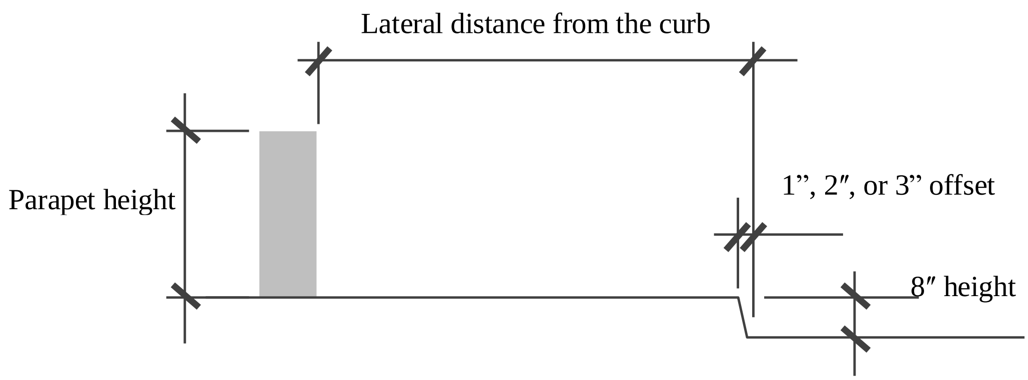


Figure 5.1. Parameters for Placement Guidelines

The vehicle performance was evaluated based on *MASH* evaluation criteria [2], which including vehicular behavior and occupant risk factors. The parametric simulations were achieved via iteration and evaluation. If the parameters met the evaluation criteria, the parapet height would be lowered for the next iteration. If parameters could not meet the criteria, there would be two solutions: i) to increase the parapet height, and ii) to move the location of the parapet, meaning that the lateral distance from the edge is increased or decreased. In this study, the parapet height and lateral distance were differentiated by 6 inches and 2 feet (24 inches), respectively. For example, if simulation results are acceptable, the parapet height for the next simulation decreases from 32 inches to 26 inches. Using this concept, several iterations of parametric simulations were performed.

All the vehicular behaviors including signal data are evaluated from when the vehicle impacts the curb.

5.2. 2270P PICKUP TRUCK

5.2.1. Pickup Truck Trajectory Profiles

To obtain a vehicle bumper corner profile with a curb shape, the trajectory simulations on different curb profiles were conducted using the calibrated vehicle models. Generally, the front bumper corner impacts the barrier system first due to its leading position. Therefore, one of the nodes in the bumper corner area was selected as a reference point, and the node was traced to obtain a trajectory profile. The trajectory profiles from the simulations were analyzed to find the maximum elevations. The parapet height and lateral distance from curb to parapet was investigated using these elevations.

Trajectory profiles for the pickup truck was investigated with three different curb profiles as shown in Figure 5.1 under MASH TL-2 and TL-3 conditions, respectively. Figure 5.2 shows the reference node of the pickup truck. In a stationary condition, the height of the reference node is about 24.4 inches above the ground. A total of six trajectory simulations with different curb profiles were performed. Figure 5.3 shows the trajectories of the reference nodes with regard to lateral distance from the curb. For the 8-inch-tall curb profiles, the maximum elevations of the reference nodes were reached when the lateral distance from the curb was 54 inches under TL-2 conditions and 65 inches under TL-3 conditions.

Additionally, in this section, a trajectory for the pickup truck was investigated under *MASH* TL-2 conditions for the 10-inch-tall curb with 2.5-inch offset for a future reference. As shown in Figure 5.4, the reference node reached the maximum elevation when the lateral distance of the parapet was about 58 inches from the curb. The maximum elevation was measured above the sidewalk. While curb slope did not have a significant impact on the trajectories of the reference nodes, curb height did.

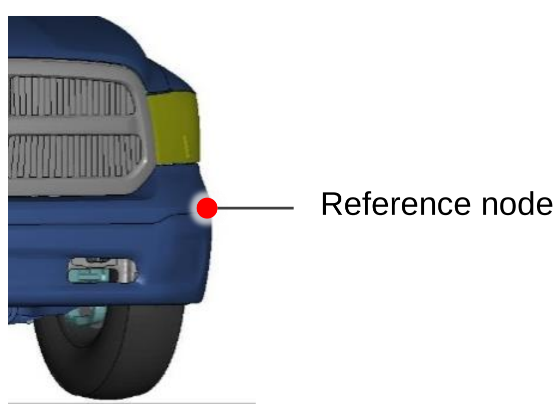
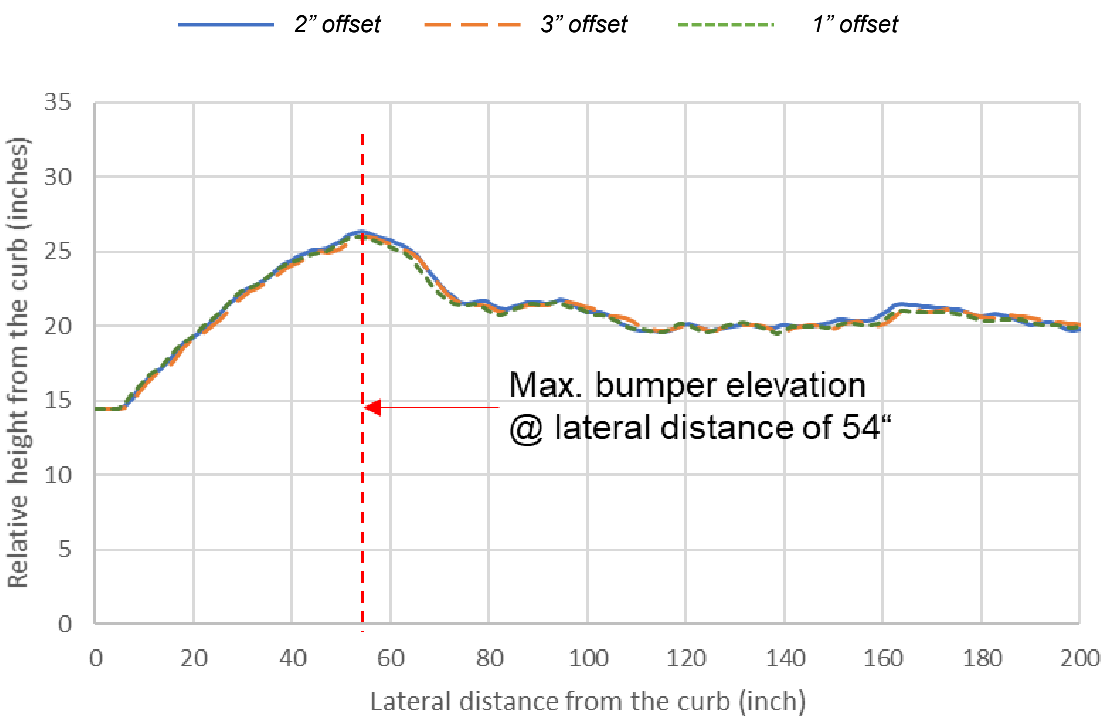
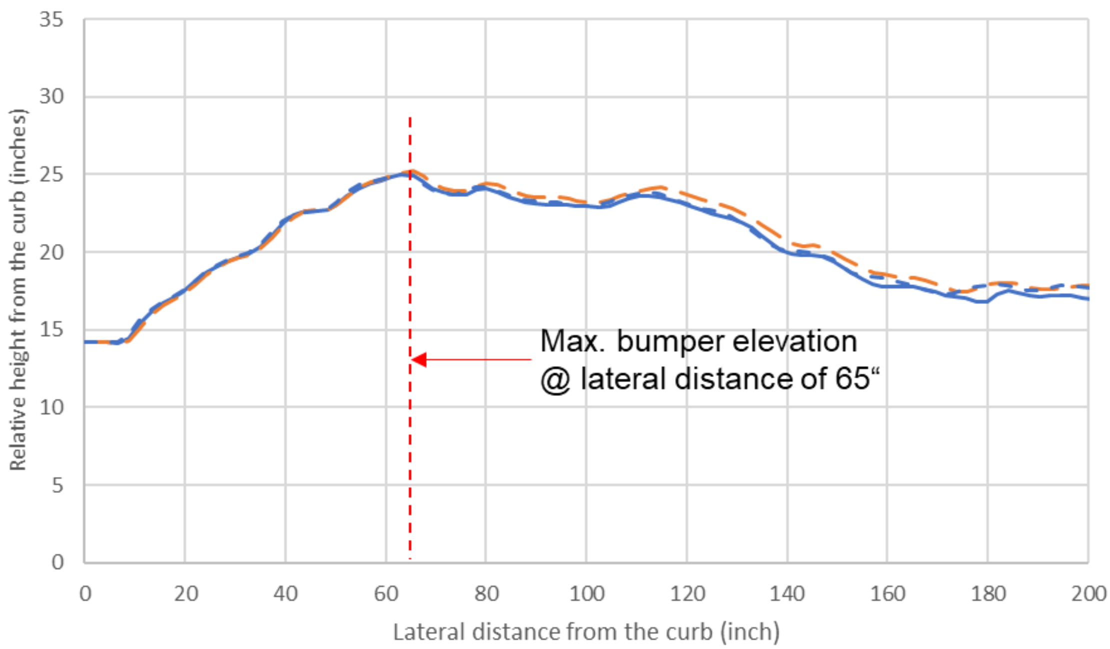


Figure 5.2. Reference Node of the Pickup Truck



(a) TL-2 Simulations



(b) TL-3 Simulations

Figure 5.3. Pickup Truck Trajectories of the Reference Nodes for the 8-inch-tall Curb

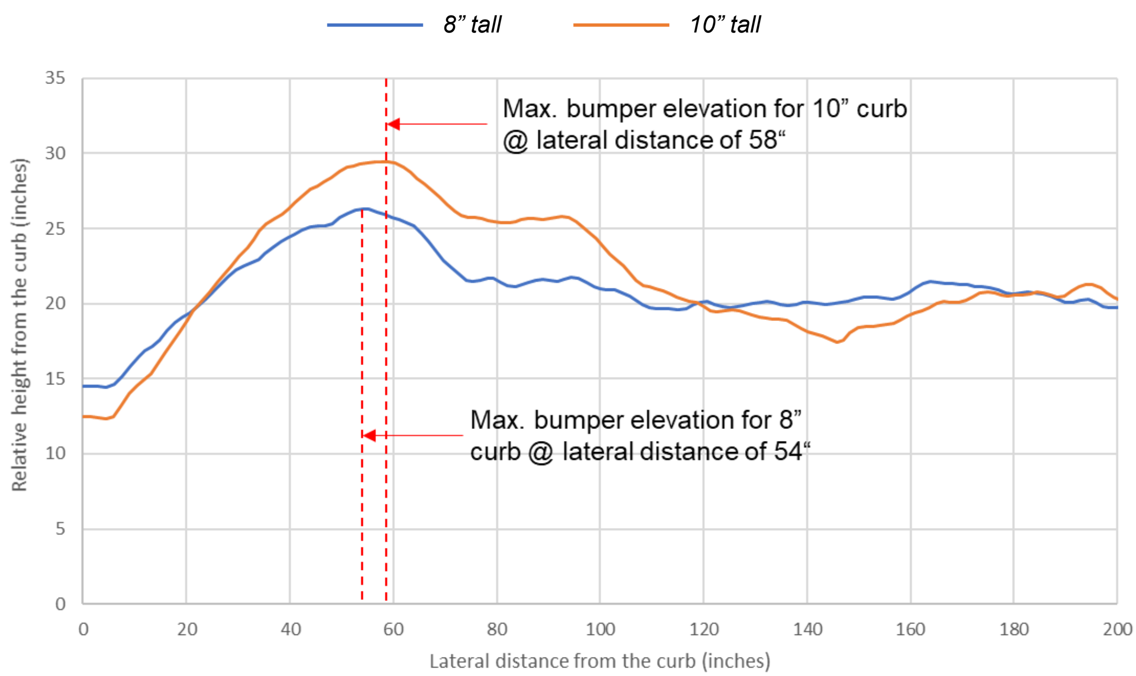


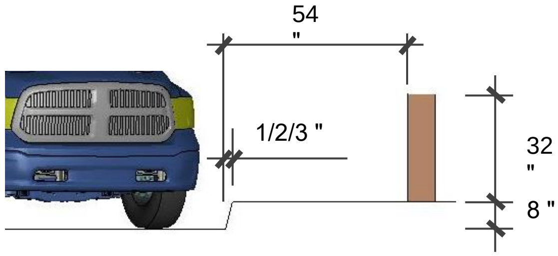
Figure 5.4. Pickup Truck Trajectory Comparison of the Reference Nodes for 8-inch-tall and 10-inch-tall Curb Under *MASH* TL-2 Conditions

5.2.2. Pickup Truck Simulations

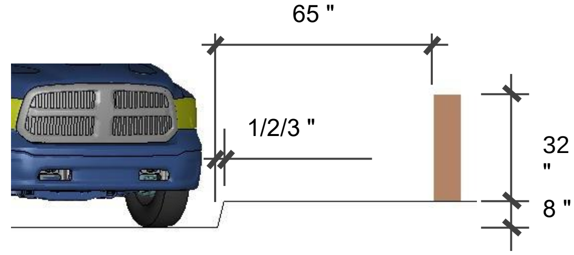
For the pickup truck parametric simulations, the vehicular behavior was mainly considered to evaluate the parapet placement parameters. It is because the pickup truck showed less critical behavior than the passenger car when impacting the parapet *[3]*, and occupant impact velocities and ridedown acceleration values were significantly lower than the values for the small car. Therefore, if the vehicle was safely redirected and remained upright after impacting the parapet, the associated placement parameters were assessed as ‘*Preferred*.’ On the contrary, if the vehicle rolled over or overrode the parapet, the associated placement parameters were assessed as ‘*Not-preferred*.’

As seen in Figure 5.3, the reference nodes of the 8-inch-tall curb profiles reached maximum elevation when the lateral distance from the curb was about 54 inches under *MASH* TL-2 conditions and 65 inches under *MASH* TL-3 conditions. In the same manner, the reference nodes of the 10-inch-tall curb profile under the TL-2 simulations reached maximum elevation when the lateral distance was about 58 inches (see Figure 5.4). Each value should be the most critical case for each condition. Thus, it was decided that these values would be the concrete parapet locations for the initial simulations. A parapet height of 32 inches was used for the initial simulations. The concrete system was applied for the parapet, and it was reflected as a rigid material in the simulation since structural integrity of the parapet is outside the scope of this study.

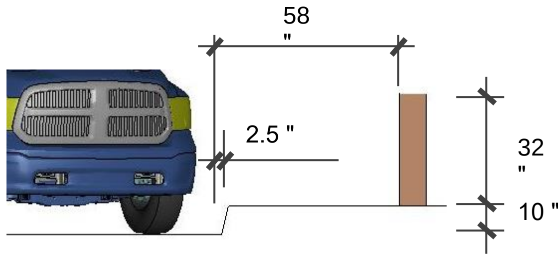
Figure 5.5 shows the initial simulation setups. As results of the initial TL-2 simulations for both the 8-inch and 10-inch-tall curbs show, the vehicle was successfully redirected and remained stable. Accordingly, the parapet height was lowered from 32 inches to 30 inches. Unlike the TL-2 simulations, in the initial TL-3 simulation, the vehicle lost stability after impacting with the parapet. The vehicle was not redirected and ultimately rolled over. For this reason, three different simulations were developed. The first was an increase in the parapet height from 32 inches to 34 inches while keeping the sidewalk width fixed. The second was the increase of the sidewalk width from 65 inches to 89 inches. The third one was a decrease in the sidewalk from 65 inches to 41 inches. For the last two models, the parapet height was maintained at 32 inches. In this way, iterative simulations were conducted, and the results are listed in Table 5.1 through Table 5.3.



(a) TL-2 with the 8-inch-tall Curb



(b) TL-3 with the 8-inch-tall Curb



(c) TL-2 with the 10-inch-tall Curb

Figure 5.5. Initial Simulation Setup

Table 5.1. Pickup Truck Simulation Results of TL-2 Simulations for 8-inch-tall Curb

Iteration No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result
1	32	54	Preferred
2	26	54	Preferred
3	22	54	Preferred
4	20	54	Preferred
5	18	102	Preferred
6	18	78	Preferred
7	18	54	Not-preferred
8	18	30	Not-preferred
9	18	6	Preferred
10	16	150	Preferred
11	16	126	Not-preferred

Table 5.2. Pickup Truck Simulation Results of TL-3 Simulations for 8-inch-tall Curb

Iteration No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result
1	36	65	Preferred
2	34	137	Preferred
3	34	113	Not-preferred
4	34	89	Not-preferred
5	34	65	Not-preferred
6	32	161	Preferred
7	32	137	Not-preferred
8	32	113	Not-preferred
9	32	89	Not-preferred
10	32	65	Not-preferred
11	32	41	Preferred
12	30	161	Preferred
13	30	41	Preferred
14	28	185	Preferred
15	28	161	Not-preferred
16	28	41	Preferred
17	26	41	Preferred
18	24	185	Preferred
19	24	41	Preferred
20	22	185	Not-preferred
21	22	41	Preferred
22	20	41	Not-preferred
23	18	41	Not-preferred
24	18	17	Preferred
25	16	17	Not-preferred

Table 5.3. Pickup Truck Simulation Results of TL-2 Simulations for 10-inch-tall Curb

Iteration No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result
1	32	58	Preferred
2	30	58	Preferred
3	28	58	Preferred
4	26	58	Preferred
5	24	58	Not-preferred
6	24	34	Preferred
7	24	82	Preferred
8	22	34	Preferred
9	22	82	Preferred
10	20	34	Preferred
11	20	82	Preferred
12	18	34	Preferred
13	18	82	Preferred
14	16	34	Not-preferred
15	16	82	Not-preferred
16	16	106	Preferred

5.2.3. Simulation Summary

Based upon results derived from the iterative parametric simulations, summary tables were developed for each condition. These tables consider parapet heights and lateral distances from the curb by presenting the preferred combinations of parapet height and location for each curb parameter and impact condition as shown in Table 5.4 through Table 5.6. For example, regarding the 8-inch tall curbs under *MASH* TL-2 conditions, if the parapet height is a minimum of 20 inches, the parapet can be located anywhere as seen in Table 5.4. In this case, the vehicle can be redirected and remain in a stable condition after impact with the parapet. If the parapet is shorter than 20 inches, the combinations in the pink area are not recommended since the vehicle can be rolled over or override the parapet. Likewise, the combinations in the blue are recommended for the 8-inch-tall and 10-inch-tall curb profiles as well.

Table 5.4. Summary of Parametric Simulation for Pickup Truck Under *MASH* TL-2 Conditions for the 8-inch-tall Curb

Unit: inches

Lateral distance / Parapet height	6 (0.5 ft)	30 (2.5 ft)	54 (4.5 ft)	78 (6.5 ft)	102 (8.5 ft)	126 (10.5 ft)	150 (12.5 ft)	174 (14.5 ft)
32	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
26	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
20	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
18	preferred	not-preferred	not-preferred	preferred	preferred	preferred	preferred	preferred
16	preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred	preferred	preferred

: preferred   : not-preferred

Table 5.5. Summary of Parametric Simulation for Pickup Truck Under *MASH* TL-3 Conditions for the 8-inch-tall Curb

Unit: inches

Parapet height \ Lateral distance	17 (1.4 ft)	41 (3.4 ft)	65 (5.4 ft)	89 (7.4 ft)	113 (9.4 ft)	137 (11.4 ft)	161 (13.4 ft)	185 (15.4 ft)
36	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
34	preferred	preferred	not-preferred	not-preferred	not-preferred	preferred	preferred	preferred
32	preferred	preferred	not-preferred	not-preferred	not-preferred	not-preferred	preferred	preferred
28	preferred	preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred	preferred
22	preferred	preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred
20	preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred	not-preferred

: preferred   : not-preferred

Table 5.6. Summary of Parametric Simulation for Pickup Truck Under *MASH* TL-2 Conditions for the 10-inch-tall Curb

Unit: inches

Parapet height \ Lateral distance	10 (0.8 ft)	34 (2.8 ft)	58 (4.8 ft)	82 (6.8 ft)	106 (8.8 ft)	130 (10.8 ft)	154 (12.8 ft)	178 (14.8 ft)
32	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
26	preferred	preferred	preferred	preferred	preferred	preferred	preferred	preferred
24	preferred	preferred	not-preferred	preferred	preferred	preferred	preferred	preferred
20	preferred	preferred	not-preferred	preferred	preferred	preferred	preferred	preferred

: preferred   : not-preferred

5.3. 1100C PASSENGER CAR

5.3.1. Passenger Car Trajectory Profiles

Figure 5.6 shows the reference node of the passenger car. In a stationary condition, the height of the reference node is about 21 inches above the flat ground.

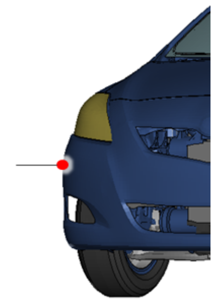


Figure 5.6. Reference Node of the Passenger Car

Figure 5.7 and Figure 5.8 show the trajectories of the reference nodes regarding lateral distance from the curb under *MASH* TL-2 and TL-3 conditions, respectively. For TL-2, because the pickup truck trajectory simulation results showed that there is no considerable difference in trajectories with different curb offsets, passenger car trajectory profiles with only 2-inch and 3-inch offsets for the 8-inch-tall curb were investigated. The maximum height of the reference node was reached when lateral distance from the curb was 82 inches (6.75 feet) under *MASH* TL-2 conditions.

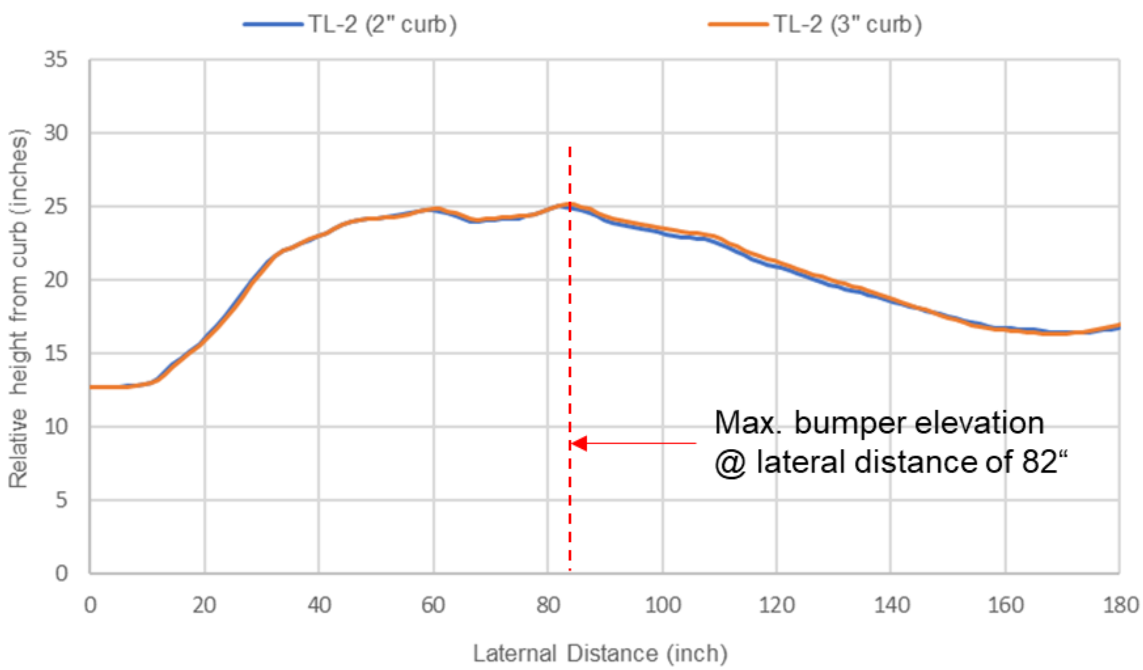


Figure 5.7. Passenger Car Trajectories of the Reference Nodes for the 8-inch-tall Curb under MASH TL-2 Conditions

For *MASH* TL-3, the peak height was observed at lateral distance of 101 inches and 107 inches for 2-inch offsets and 3-inch offsets, respectively. Unlike the pickup truck model, the passenger car trajectory under TL-3 conditions shows different profiles for 2-inch offsets and 3-inch offsets. This results indicated that under MASH TL-3 condition, the suspension behavior of the small car involved and the overall vehicular behavior depend more on, which means better understanding of suspension behavior should be followed to provide accurate guidelines.

Figure 5.9 shows bumper corner trajectory profiles for both the 8-inch curb with a 2-inch offset and the 10-inch curb with a 2.5-inch offset. The lateral distance where the maximum elevations were observed showed a 1-inch difference, while the maximum elevation showed a difference of approximately 7 inches.

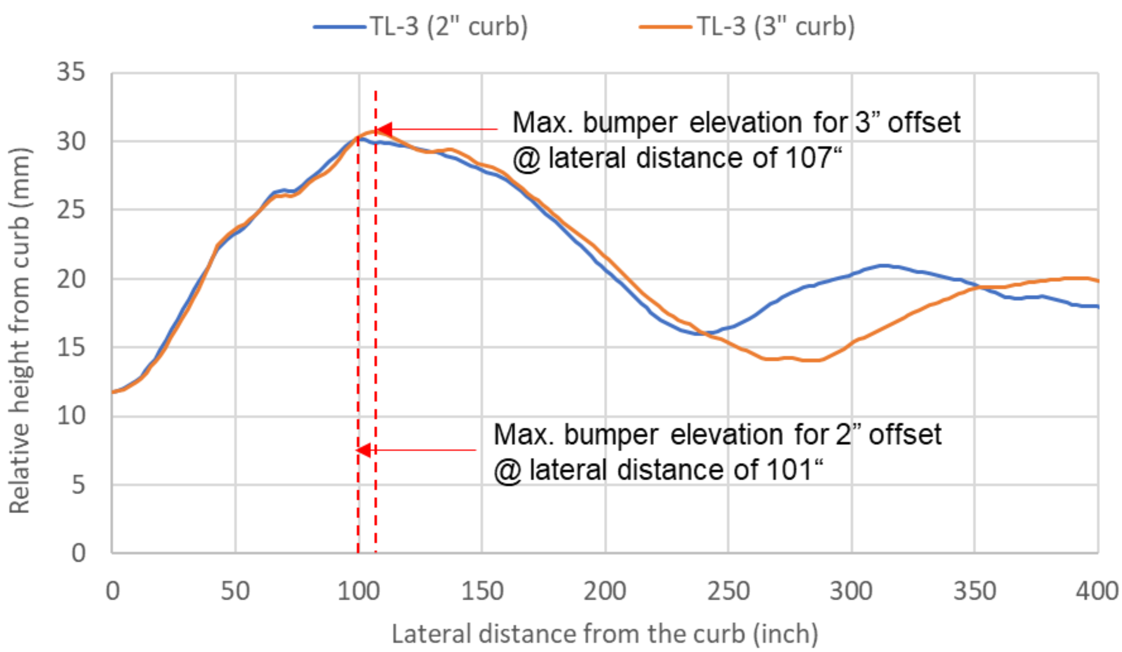


Figure 5.8. Passenger Car Trajectories of the Reference Nodes for the 8-inch-tall Curb under MASH TL-3 Conditions

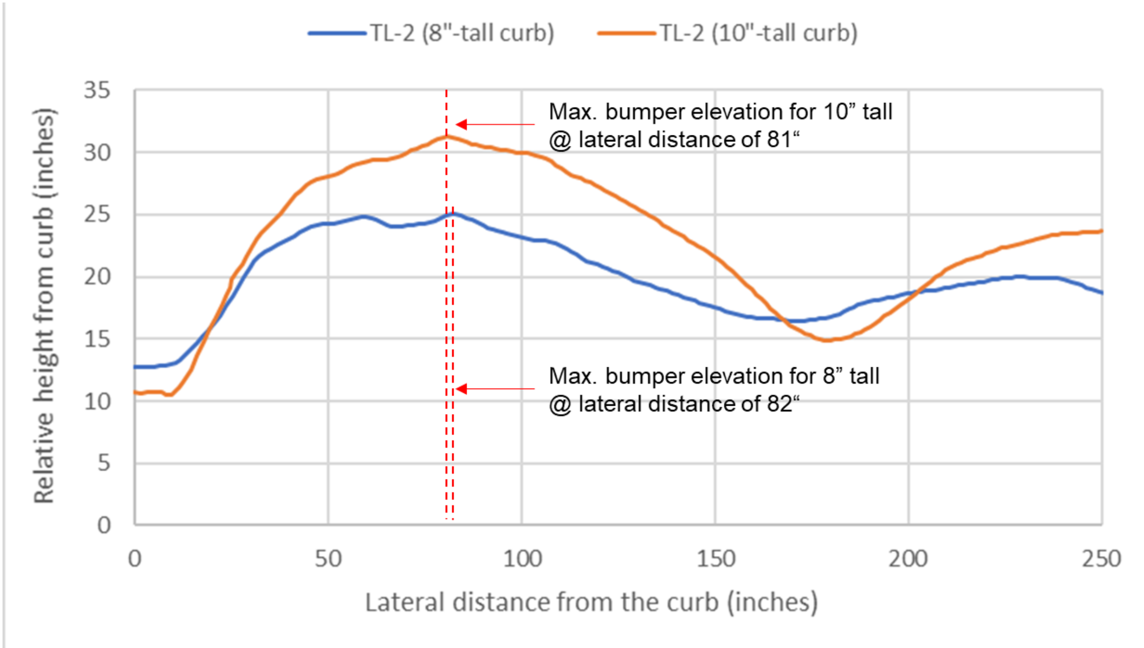


Figure 5.9. Trajectory Comparison of the Reference Nodes for 8-inch and 10-inch-tall Curb Under *MASH* TL 2-10

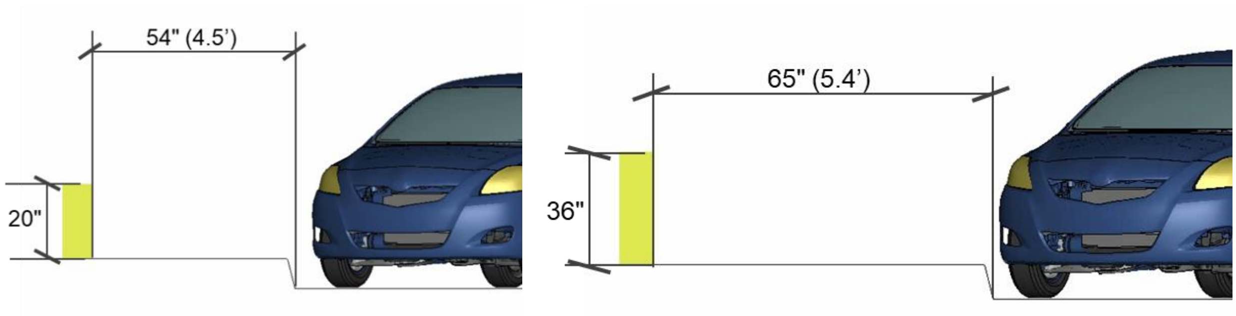
5.3.2. Passenger Car Simulations

Figure 5.10 shows the initial simulation parameters for both *MASH* TL 2-10 and TL 3-10 simulation iterations. To conduct the parametric simulations, the most critical case was assumed when maximum elevation was reached; maximum elevation height and longitudinal distance values were used to decide concrete parapet parameters (height and distance from the curb) to minimize the number of simulations run. The initial parameters for the simulation were determined based on the pickup truck simulation results. Whatever was 'not-preferred' for the truck was not considered for the passenger car simulation. In addition, a lateral distance of less than 4.5 feet is not considered for a passenger car iteration although the pickup truck simulation results showed as 'preferred,' since the minimum sidewalk width is 5 feet in accordance with the Americans with Disabilities Act (ADA) standards *[16]*.

For the 8-inch-tall curb, as shown in Figure 5.7, the reference nodes reached maximum elevation when the lateral distance from the curb was about 82 inches under *MASH* TL-2 conditions. In this case, because the curb offset did not produce considerable differences in trajectory results, the more commonly used curb, the 8-inch-tall curb with 2-inch offset, was used for further investigation in this section.

A parapet height of 20 inches with a lateral distance of 54 inches from the curb was adopted for the initial simulation as shown in Figure 5.10(a), considering that the acceptable minimum parapet height for a pickup truck is 20 inches at a lateral distance of 4.5 feet or greater.

For the *MASH* TL-3 iteration, the 8-inch-tall curb with a 3-inch offset was adopted as the most critical case due to higher maximum elevation and lower minimum elevation; any case with a lateral distance of under 65 inches was not considered in this study. Because the pickup truck results show the minimum height of the parapet with a lateral distance of 65 inches to be 36 inches under *MASH* TL-3 conditions, the initial simulation parameters were set to 36 inches and 65 inches for parapet height and lateral distance, respectively.



(a) TL 2-10 *(b) TL 3-10*

Figure 5.10. Initial Simulation Parameters for Passenger Car with 8-inch-tall Curb

Table 5.7 lists the parametric TL-2 simulation results. The simulation results considered vehicle stability and occupant risk factors obtained by TRAP [15], and the placement was decided as "preferred," "not-preferred" or "not-recommended." The initial analysis was conducted by setting up "time zero" as when the vehicle impacting the curb. The evidence of the preferences is shown in Table C.1.

Table 5.7. Passenger Car Simulation Results for 8-inch-tall under TL-2 Condition

Simulation No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result
1	20	54	Preferred
2	26	54	Preferred
3	20	78	Not-recommended
4	26	78	Preferred
5	20	102	Not-recommended
6	26	102	Not-preferred
7	32	54	Preferred
8	32	78	Preferred
9	20	150	Not-preferred
10	20	126	Not-preferred
11	26	150	Not-preferred
12	26	126	Not-preferred
13	20	174	Not-preferred
14	26	174	Not-preferred
15	32	102	Not-preferred
16	32	126	Not-recommended
17	32	174	Not-preferred
18	36	102	Not-preferred
19	36	126	Not-recommended
20	36	174	Not-preferred

Table 5.8 lists the result of TL-3 simulation results. Under high-speed condition, the small car is expected to experience a severe suspension failure that can potentially remove the wheel assembly and have the vehicle slides on its undercarriage. However, there is no such fully understood and developed wheel assembly and suspension failure FE model to capture this extreme failure phenomenon adopt in this study. Therefore, further investigations on the small car suspension model are required to develop full guidelines.

Table 5.8. Passenger Car Simulation Results for 8-inch Curb under TL-3 Condition

Simulation No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result
1	36	65	Preferred
2	36	89	Preferred
3	36	113	Not-preferred
4	42	113	Not-preferred
5	36	180	Not-preferred
6	42	180	Not-preferred

For a 10-inch curb system, vehicle trajectories for two different FE passenger car models with and without simple suspension failure are presented because it is expected to involve a severe suspension failure for the cases with the higher curb height like the cases under high-speed conditions. Figure 5.11 shows bumper corner trajectory profiles for both FE passenger car models traveling on a 10-inch curb. The model without suspension failure reached higher peak elevation than the FE model with a simple suspension failure. Based on the result, to investigate a vehicle behavior for a 10-inch curb system, a FE model with detailed wheel assembly and suspension failure should be developed to verify its validity with a depth knowledge. This figure shows the range of the dynamic response of the vehicle for just using a simple suspension failure model. The full understand of the vehicle response requires component testing of the wheel assembly and the suspension system.

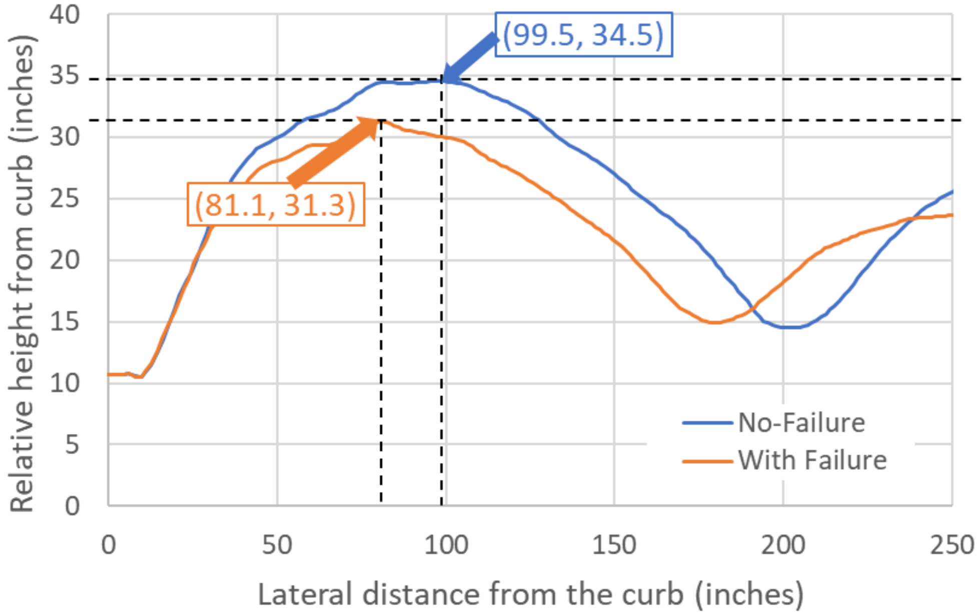


Figure 5.11. Difference of Trajectory Profiles of Passenger Car with and without Suspension Failure for 10-curb

5.3.3. Placement Guidelines

Table 5.9 shows the distribution of preferred parameters under *MASH* TL-2 conditions. Greens indicate the simulation met *MASH* TL-2 evaluation criteria and is preferred. Oranges indicate simulation values are below the maximum but above the recommended *MASH* TL-2 evaluation criteria values, and therefore, they are not-preferred for placement. Reds indicate simulation results could not meet *MASH* TL-2 evaluation criteria and are not-recommended.

A parapet with a height of 20 inches or higher is not-preferred to place at the lateral distance of 102 inches (8.5 feet) or over due to either high ride-down acceleration values or high roll angles.

Table 5.9 Summary of Parametric Simulation for Passenger Car for the 8-inch-tall Curb Under *MASH* TL-2 Conditions

Unit: inches

Lateral distance / Parapet height	6 (0.5 ft)	30 (2.5 ft)	54 (4.5 ft)	78 (6.5 ft)	102 (8.5 ft)	126 (10.5 ft)	150 (12.5 ft)	174 (14.5 ft)
36	Not considered							
32								
26								
20								

: preferred : not-preferred

Table 5.10 shows the distribution of preferred parameters under *MASH* TL 3-10 conditions. A parapet with a height of 36 inches is not preferred to place at the lateral distance of over 113 inches (9.4 feet) because of the high ride-down acceleration values.

Table 5.10. Summary of Parametric Simulation for Passenger Car for the 8-inch-tall Curb Under *MASH* TL-3 Conditions

Unit: inches

Lateral distance / Parapet height	17 (1.4 ft)	41 (3.4 ft)	65 (5.4 ft)	89 (7.4 ft)	113 (9.4 ft)	137 (11.4 ft)	161 (13.4 ft)	180 (15 ft)
42	Not considered							
36								

: preferred : not-preferred

CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1. SUMMARY

This study developed placement guidelines for a bridge parapet system on a sidewalk with a curb under *MASH* TL-2 condition. Three 8-inch-tall curb profiles and one 10-inch-tall curb profile were investigated. Trajectory testing was conducted to capture the vehicular trajectories after the vehicle impacts the curb and travels across the sidewalk then validation and parametric simulations were conducted using LS-DYNA [4]. The target impact speed and angle complied with *MASH* TL-2 conditions. *MASH* TL-2 conditions incorporate both a passenger car and a pickup truck, hence both types of vehicles were tested. The testing data were then used to validate the simulation results.

In this study, the vehicle model was validated under both *MASH* TL-2 and TL-3 conditions. Data from the *MASH* TL-2 trajectory tests and data from the *MASH* TL-3 crash tests undertaken by Caltrans were used to calibrate and enhance the vehicle models. One the calibration exercises are concluded; the vehicle models reasonably followed the behavior of the test vehicles. Although some differences between the tests and simulations were still observed, the trajectories of the vehicle models had an overall good correlation with the trajectories of the test vehicles.

Subsequently, the calibrated vehicle models were set up with the respective curb profiles and impact conditions. The researchers measured the trajectories of a defined reference node for each case, the lateral distance from the curb edge to the corresponding peak height of the reference node was determined. This distance is defined as the critical location for the parapet placements. This critical distance location was used first for the simulation cases involving the pickup truck model. This was done to isolate the failed cases due to vehicular stability. The simulations for the passenger car were determined using the dynamically stable pickup truck results. Depending on the simulation results, the parameters for the following simulations were determined. If the vehicle was safely redirected and meet *MASH* evaluation criteria, the parapet height would be decreased. On the other hand, if the vehicle model rolled over or overrode the parapet, either the parapet height would be increased, or the parapet would be moved to change its lateral distance from the curb. In this way, multiple iterations of the parametric simulations were performed. Finally, placement guidelines were developed for various parapet heights.

6.2. CONCLUSIONS

Since the ADA standards *[16]* limits the minimum sidewalk width as 5 feet and AASHTO LRFD *[17]* limits at 4 feet, placement guidelines derived through this study are intended for parapet locations from 4.5 feet to 15 feet from the curb bottom edge. Additionally, parapet height is recommended to be a minimum of 20 inches for TL-2 conditions. It is because if the parapet is lower than 20-inches, there is a high possibility of truck override. Therefore, further study is recommended for a parapet located beyond 15 feet from the curb bottom edge or a parapet height shorter than 20 inches.

As aforementioned, the simulations with a different set of parameters were evaluated based on the data from when the vehicle impacts the curb. However, *MASH* Section 5.3 *[2]* addresses that *"if a test with a geometric feature such as a ditch or curb involves three-dimensional vehicular motion, and the longitudinal or lateral acceleration exceeds 2 g during any average 50-ms period but the vehicle remains upright and did not exceed the maximum roll and pitch angle of 75 degrees, the occupant impact velocity (OIV) and RA values need to be reevaluated based on the data from the beginning of the period over which the average acceleration was computed."* In Appendix C, examples of acceleration curves for small car cases to show longitudinal and lateral acceleration with average 50-ms period acceleration. For 'not-preferred' small car cases, the acceleration did not exceed 2 g after the curb impact using the 50-ms average signals. Therefore, the OIV and RA values for the cases that were reevaluated based on the data from when the vehicle impacted the parapet. Since the pickup truck cases were only evaluated by the stability, only the signals of small car cases were reevaluated based on impacting the parapet as the initial impact point (time zero). Table 6.1**Error! Reference source not found.** lists the reevaluated OIV and RA values. After reevaluating the OIV and RA values, 'not-preferred' cases were determined to be 'pass.'

Table 6.1. Critical Risk Factors Analysis for The Passenger Car Parametric Simulations

Simulation No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result	
			OIV[1] (ft/s) (Lateral / Longitudinal)	RA[2] (g) (Lateral / Longitudinal)
1	20	54	15.4 / 21.3	2.5 / 7.3
2	26	54	15.5 / 22.4	2.2 / 6.1
3*	20	78	14.6/19.1	4.7 / 6.0
4	26	78	14.0 / 18.3	8.2 / 8.6
5*	20	102	10.4 / 10.7	8.9 / 15.1
6	26	102	14.6 / 17.6	2.0 / 9.7
7	32	54	15.6 / 22.2	2.4 / 5.8
8	32	78	13.9 / 19.8	6.3 / 6.8
9	20	150	14.8 / 20.5	2.7 / 8.7
10	20	126	14.8 / 19.6	2.4 / 8.7
11	26	150	Occupant does not impact vehicle interior	Occupant does not impact vehicle interior
12	26	126	Occupant does not impact vehicle interior	Occupant does not impact vehicle interior
13	20	174	4.3 / 1.1	0.3 / 1.2
14	26	174	4.1 / 1.9	0.4 / 0.9
15	32	102	14.9 / 17.0	1.4 / 7.8
16	32	126	14.0 / 19.0	2.2 / 13.3
17	32	174	Occupant does not impact vehicle interior	Occupant does not impact vehicle interior
18	36	102	13.9 / 17.6	1.4 / 11.0
19	36	126	13.8 / 18.8	1.7 / 15.1
20	36	174	3.8 / 2.1	0.4 / 0.8

NA = Not available
** Vehicle roll angles are higher than 75 degrees (MASH Limit)*
1. MASH OIV Preferred 30.0 ft/s / Maximum 40.0 ft/s
2. MASH RA Preferred 15.0 g / Maximum 20.49 g

Figure 6.1 illustrates an example of the 8-inch curb placement guideline for *MASH* TL-2 conditions. As aforementioned, the sidewalk width smaller than 4.5 feet is not considered in this study per ADA standards *[16]* and AASHTO LRFD *[17]*. In addition, parapets shorter than 20 inches are not considered since there are high potential for the vehicle to override the parapet. No guidance is developed for TL-3 conditions or 10-inch or higher curbs since the vehicle behavior is dependent on capturing an extreme failure of the wheel assembly and suspension once impacting a curb under TL-3 condition or impacting a 10-inch or higher curb under either condition. There are very limited test data to verify and fully calibrate vehicle suspension model for such an extreme failure phenomenon. Further investigation involving deeper curb and *MASH* TL-3 conditions is recommended as future research.

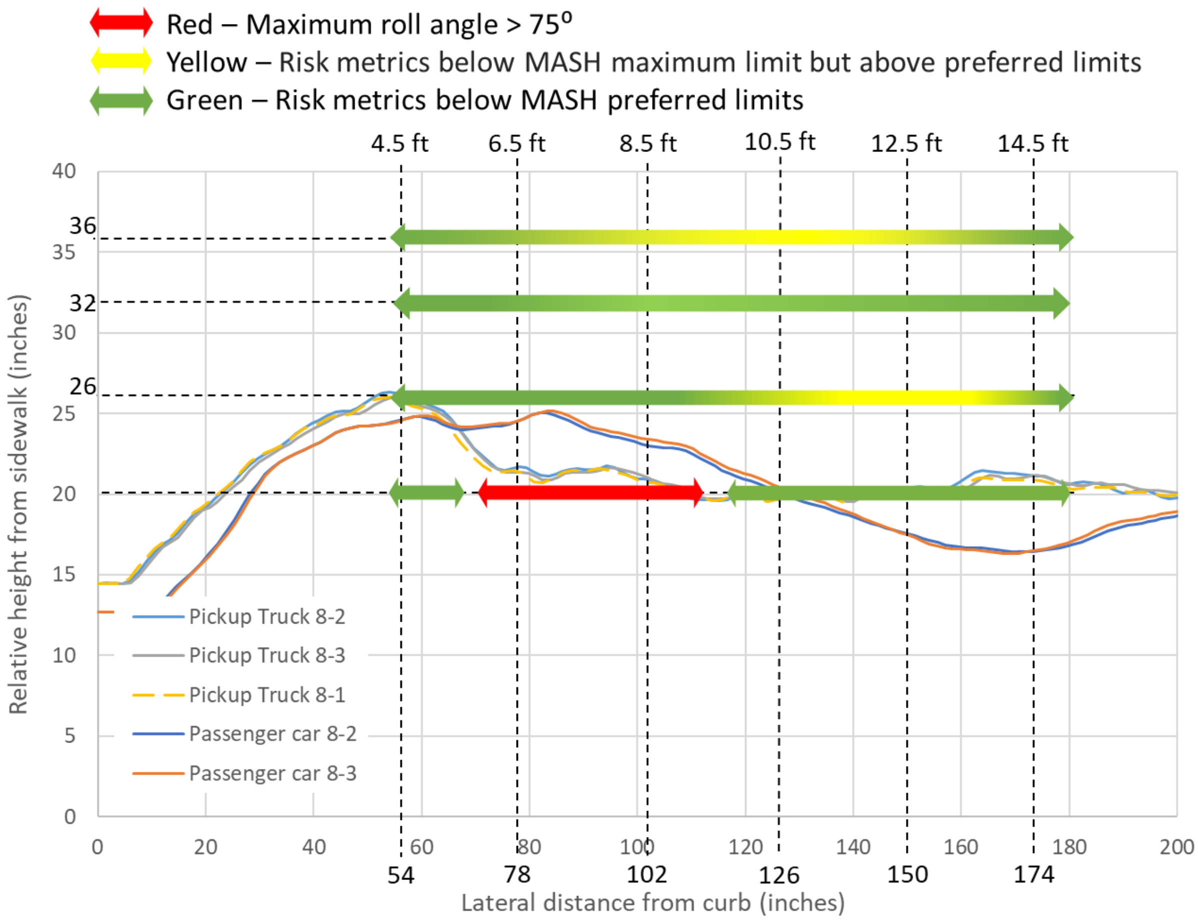


Figure 6.1. Placement Guidelines for 8-inch-tall Curb Under *MASH* TL-2 Conditions (Impact Speed = 44 mph, Impact Angle = 25 degrees)

In Figure 6.1 the red distance range indicates parapet placement is “not-recommended” over the range at that given parapet height, the yellow range indicates parapet placement is “not-preferred” over the yellow range given the parapet height. Green indicates a recommended placement over the green range and the given height. The curves showing in background are the trajectory profiles of both the pickup truck and the passenger car from the FE simulations. In the legend, the number after the vehicle types indicated the curb height and offset. For instance, the curve named ‘Pickup Truck 8-2’ presents the trajectory profile for the pickup truck model with 8-inch-tall and 2-inch-offset curb.

As an example, from the placement guideline shown in Figure 6.1**,** a parapet with the height of 26 inches or more can be placed anywhere between 4.5 ft and 14.5 ft from the curb edge.

REFERENCES

1. Hancock, M. W. and B. Wright. "*A policy on geometric design of highways and streets*." American Association of State Highway and Transportation Officials: Washington, D.C., USA, 2013.
2. AASHTO. *Manual for Assessing Roadside Safety Hardware, Second Edition.* American Association of State Highway and Transportation Officials: Washington, DC, 2016.
3. Whitesel, David, et al. *Compliance Crash Testing of the Type 732SW Bridge Rail*. Sacramento, California: California Department of Transportation, Division of Research, Innovation, and System Information, 2016.
4. LS-DYNA KEYWORD USER'S MANUAL, Livermore Software Technology (LST), AN ANSYS COMPANY, Livermore, California, 2021.
5. Buth, Eugene, T. J. Hirsch, and Wanda L. Menges. Testing of New Bridge Rail and Transition Designs: BR27D Bridge Railing. Volume III, Appendix B. McLean, VA: Federal Highway Administration, 1997.
6. AASHTO (1989). "Guide Specifications For Bridge Railings."
7. TRB (1993). Development of a Comprehensive Bridge Specification and Commentary. National Cooperative Highway Research Program Project 12-33.
8. Meline, R., et al. (1999). Vehicle Crash Tests of the Aesthetic, See-through Concrete Bridge Rail with Sidewalk, Type 80SW, Materials Engineering and Testing Services, California Department of Transportation: 81.
9. Ross Jr, H., et al. (1993). Recommended Procedures for the Safety Performance Evaluation Highway Appurtenances. National Cooperative Highway Research Program Report No.350. Washington, D.C, Transportation Research Board.
10. Zhu, L., et al. (2009). Performance Limits for 152-mm (6-in) High Curbs Placed in Advance of the MGS Using *MASH*-08 Vehicles. Part Ⅰ: Vehicle-Curb Testing and LS_DYNA Analysis. Lincoln, Nebraska, Midwest Roadside Safety Facility (MwRSF): 127.
11. Plaxico, C. A. (2005). Recommended guidelines for curb and curb-barrier installations, Transportation Research Board.
12. Center for Collision Safety and Analysis (CCSA). 2010 Toyota Yaris Finite Element Model Validation Detailed Mesh, Presentation | doi:10.13021/G8CC7G. George Mason University. 2016.
13. Center for Collision Safety and Analysis (CCSA). 2018 Dodge Ram 1500 FE Detailed Mesh Model v3 – Validation, Presentation | doi:10.13021/g8je-0t34. George Mason University, 2022.

14. Mongiardin, M. and M. Ray. “Roadside Safety Verification and Validation Program User’s Manual.” Worcester Polytechnic Institute, Worcester, MA, 2009.

15. CAPSHER Technology, Inc. *Test Risk Assessment Program Version 2.5.2*. Texas A&M Transportation Institute, 2022.

16. Department of Justice. *Guidance on the 2010 ADA Standards for Accessible Design*, Americans with Disabilities Act (ADA), 2010.

17. AASHTO. AASHTO LRFD Bridge Design Specifications. Washington, DC: American Association of State Highway and Transportation Officials, 2020.

APPENDIX A. TEST NO. 614091-01-1

A.1. VEHICLE PROPERTIES AND INFORMATION

Table A.1. Vehicle Properties for Test No. 614091-01-1

Date: 2021-01-27 Test No.: 614091-01-1 VIN No.: ____

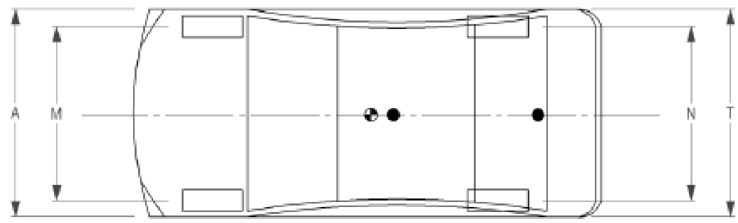
Year: 2014 Make: NISSAN Model: VERSA

Tire Inflation Pressure: 36 PSI Odometer: 93365 Tire Size: P185/65R15

Describe any damage to the vehicle prior to test: None

● Denotes accelerometer location.

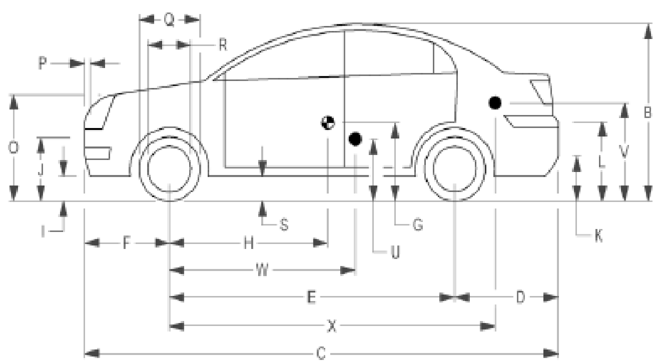
NOTES: REAR ACC IS 23" TO LT OF CL
2.5 ' FORWARD OF FRONT AXLE
34" ABOVE GROUND



Engine Type: 4 CYL
Engine CID: 1.6 L

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

Optional Equipment:
None



Dummy Data:
Type: NONE
Mass: ____
Seat Position: ____

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	34.00
C	175.40	H	42.91	M	58.30	R	16.25	W	42.90
D	40.50	I	7.00	N	58.50	S	7.50	X	-2.50
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 -0.01

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}	1472	1421	1421
Back	1687	M_{rear}	974	1025	1025
Total	3389	M_{Total}	2446	2446	2446

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

Mass Distribution:
lb LF: 727 RF: 694 LR: 523 RR: 502

A.2. SEQUENTIAL PHOTOGRAPHS

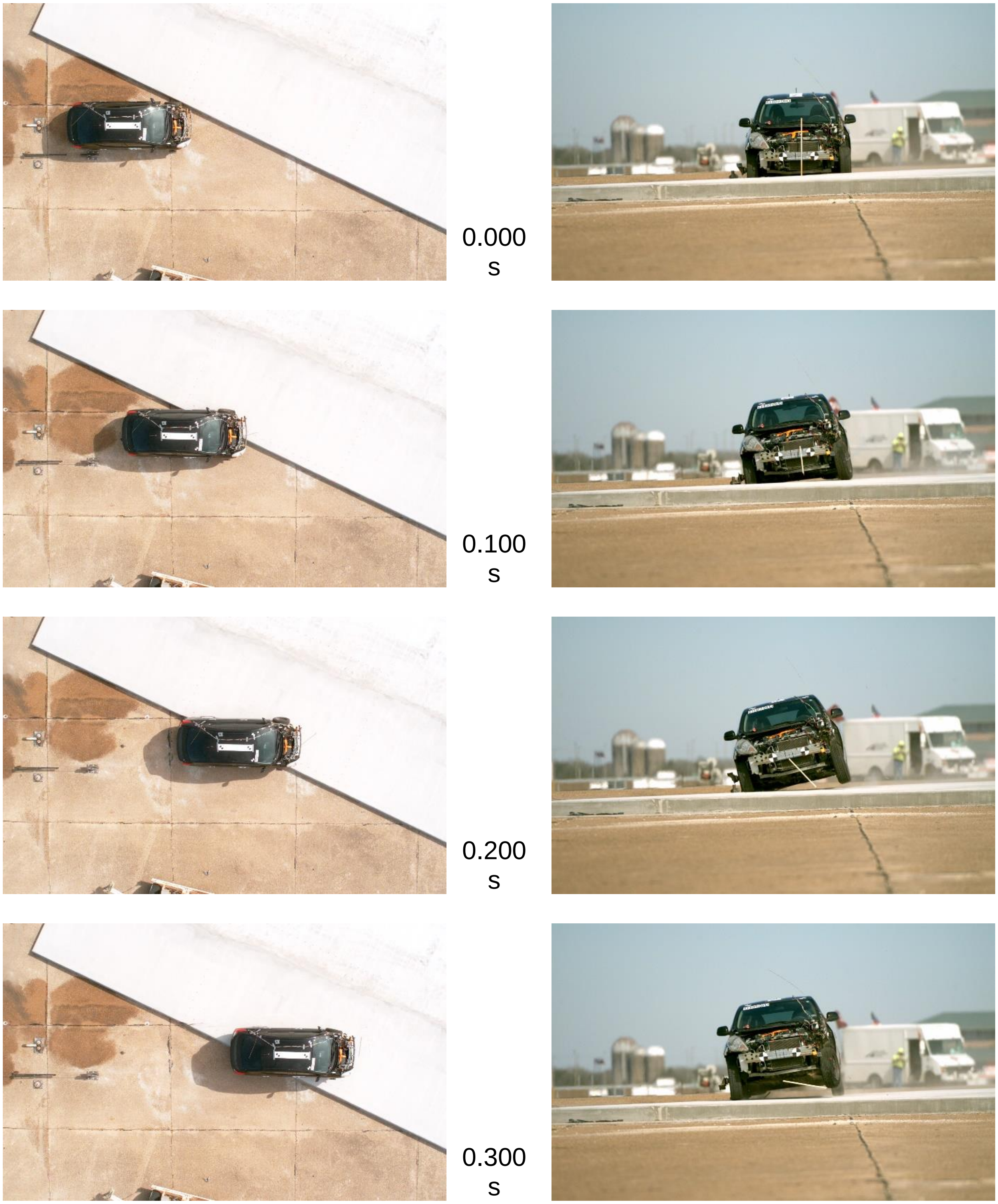
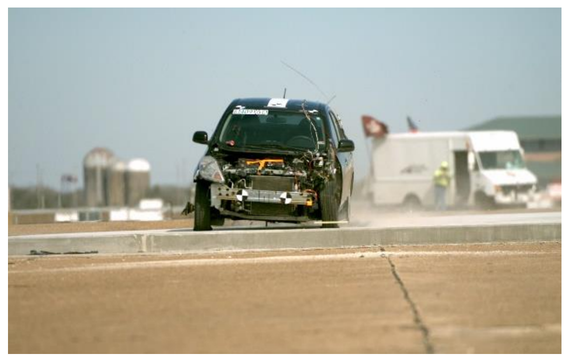


Figure A.1. Sequential Photographs for Test No. 614091-01-1 (Overhead and Frontal Views)

0.400 s

0.500 s

0.600 s



0.700 s

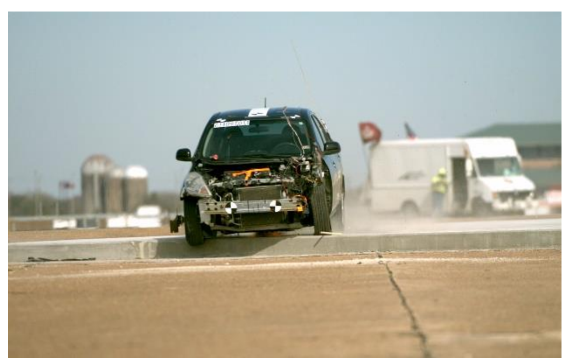
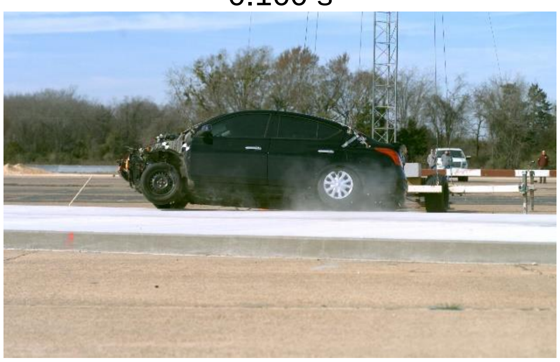


Figure A.1. Sequential Photographs for Test No. 614091-01-1 (Overhead and Frontal Views) (Continued)

0.000 s

0.100 s

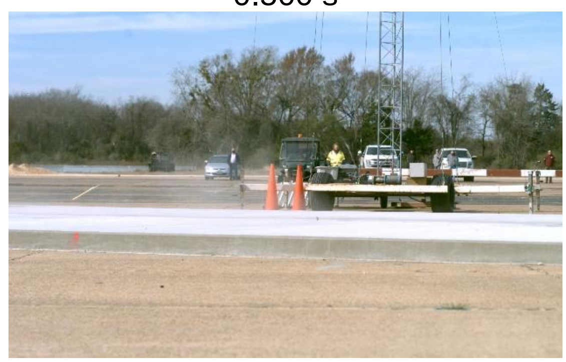


0.200 s

0.300 s

0.400 s

0.500 s



0.600 s

0.700 s

Figure A.2. Sequential Photographs for Test No. 614091-01-1 (Perpendicular View)

A.3. VEHICLE ANGULAR DISPLACEMENTS

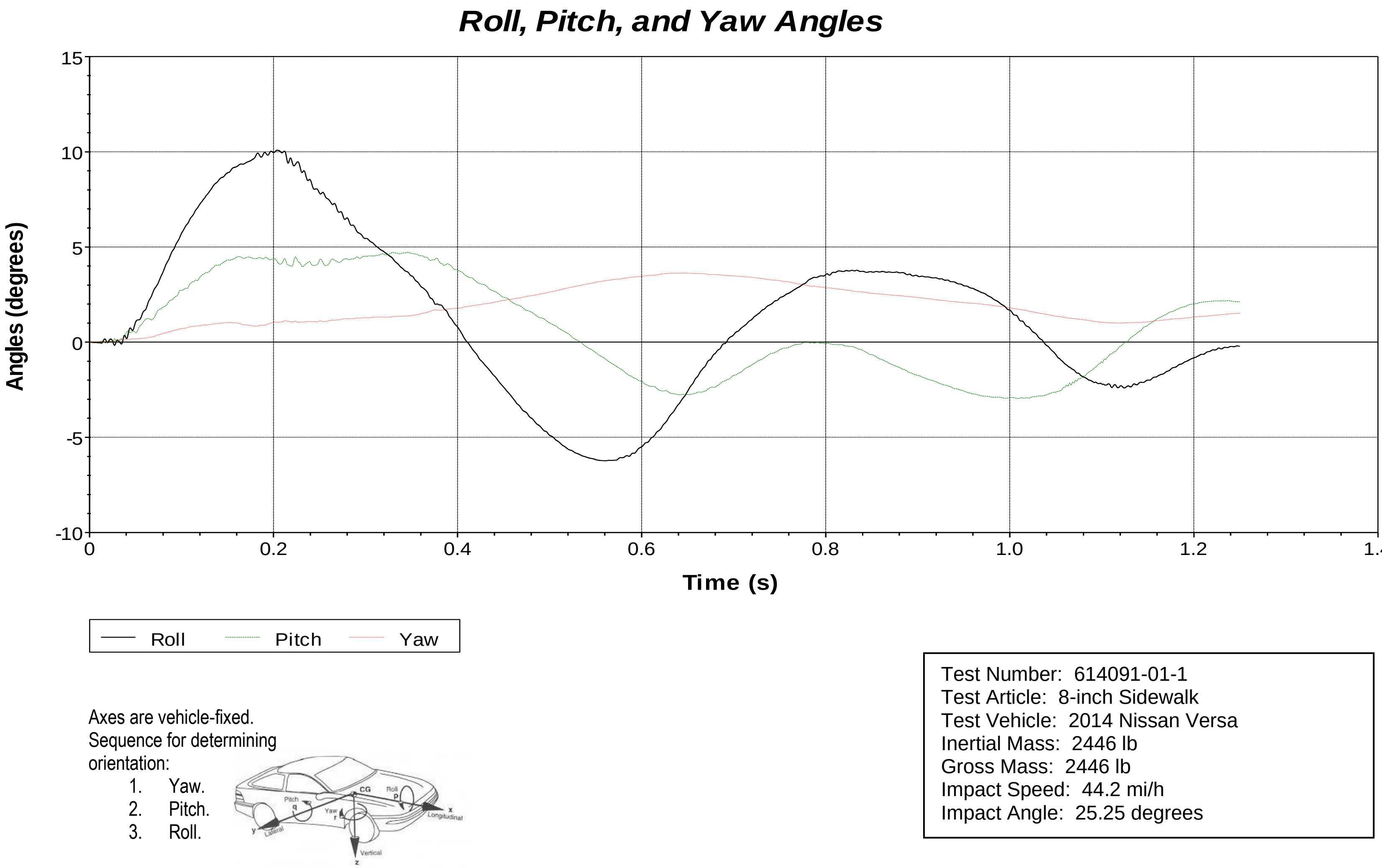


Figure A.3. Vehicle Angular Displacements for Test No. 614091-01-1

A.4. VEHICLE ACCELERATIONS

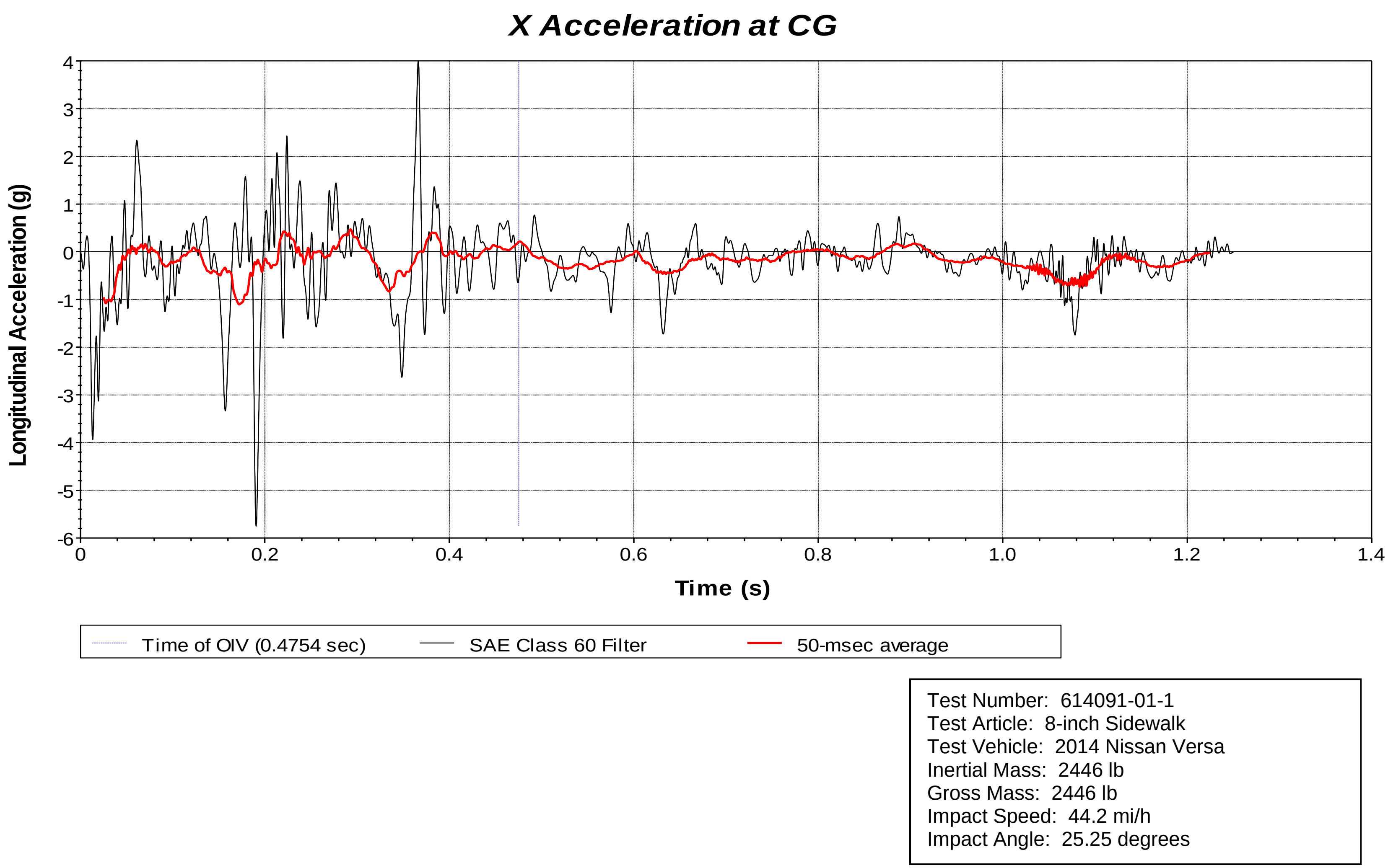
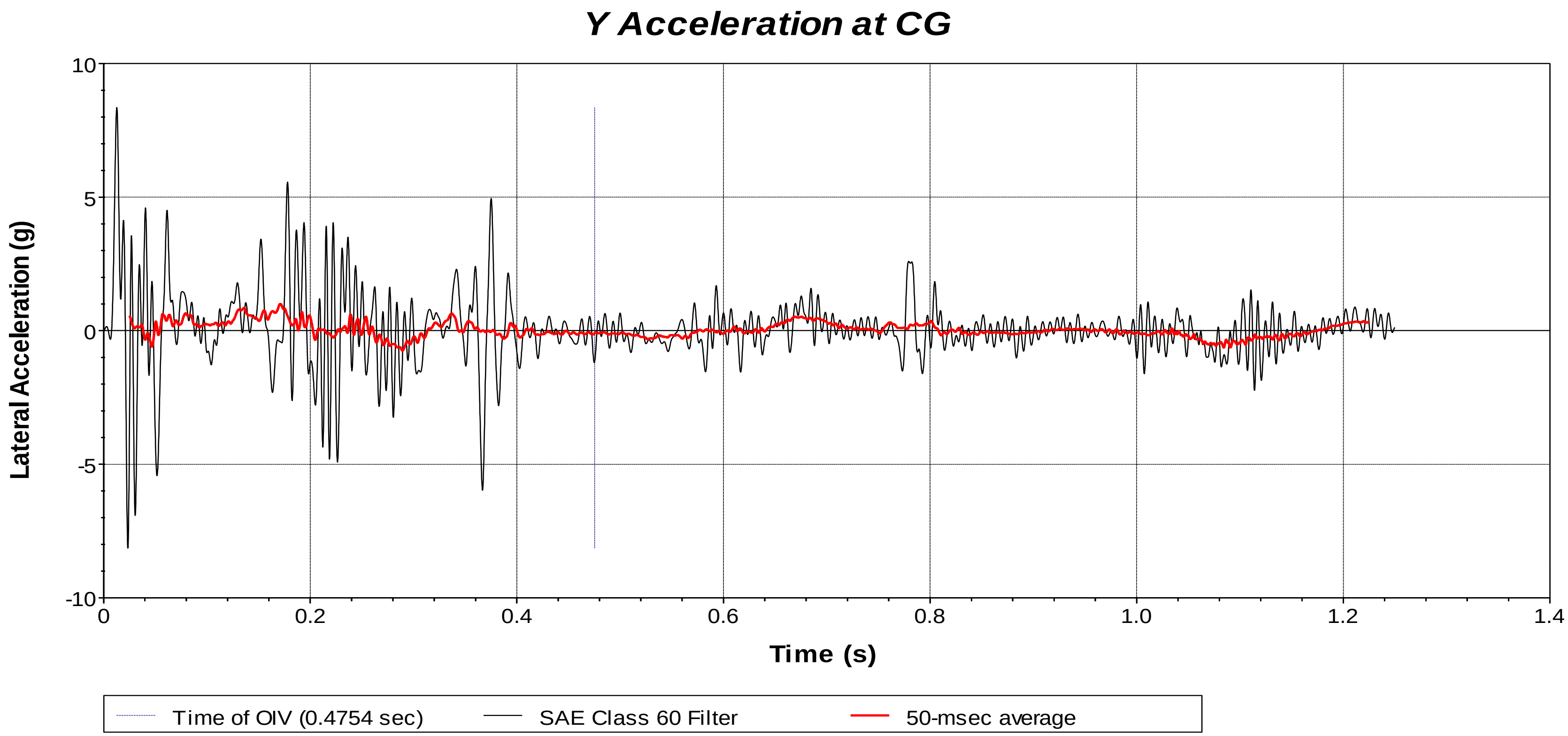


Figure A.4. Vehicle Longitudinal Accelerometer Trace for Test No. 614091-01-1 (Accelerometer Located at Center of Gravity)



Test Number: 614091-01-1
Test Article: 8-inch Sidewalk
Test Vehicle: 2014 Nissan Versa
Inertial Mass: 2446 lb
Gross Mass: 2446 lb
Impact Speed: 44.2 mi/h
Impact Angle: 25.25 degrees

Figure A.5. Vehicle Lateral Accelerometer Trace for Test No. 614091-01-1 (Accelerometer Located at Center of Gravity)

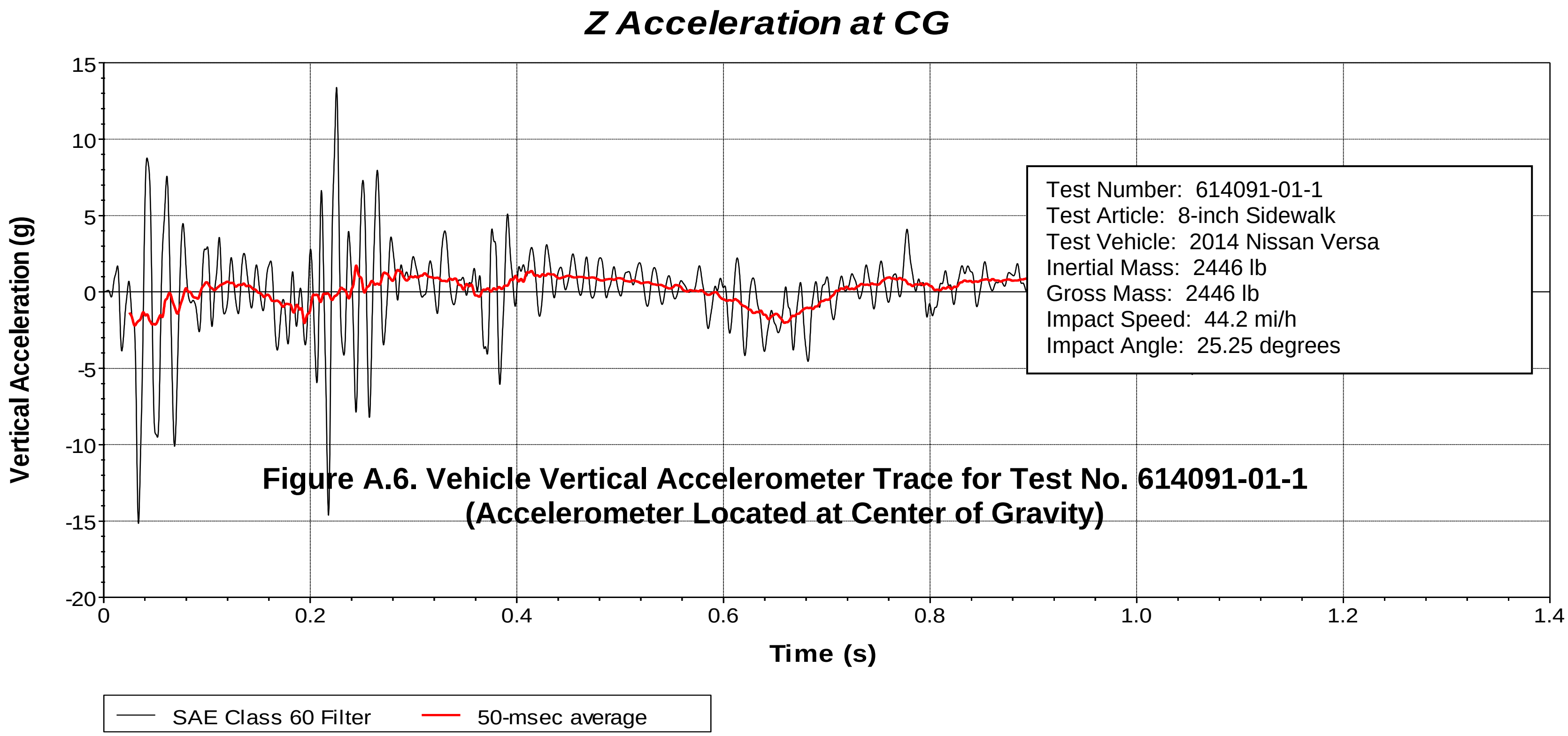


Figure A.6. Vehicle Vertical Accelerometer Trace for Test No. 614091-01-1 (Accelerometer Located at Center of Gravity)

APPENDIX B. TEST NO. 614091-01-2

B.1. VEHICLE PROPERTIES AND INFORMATION

Table B.1. Vehicle Properties for Test No. 614091-01-2.

Date: 2021-1-28 Test No.: 614091-01-2 VIN No.: 1C6RR6FT9ES243178

Year: 2014 Make: RAM Model: 1500

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

Tread Type: Highway Odometer: 131688

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

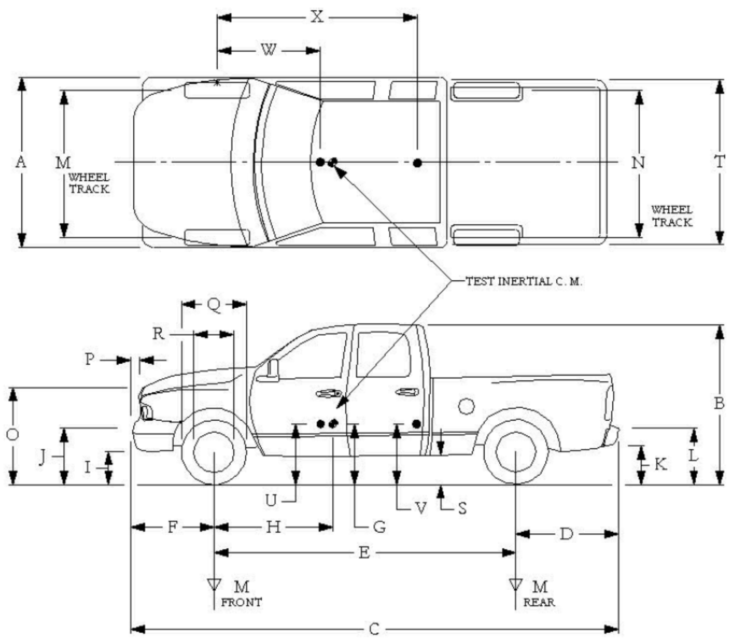
NOTES: REAR ACC IS 19.5" TO LT OF
AT FRONT AXLE 26" ABOVE GROUND

Engine Type: V-8
Engine CID: 5.7L

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	28.75	L	30.00	Q	30.50	V	26.00
C	227.50	H	63.49	M	68.50	R	18.00	W	63.5
D	44.00	I	11.75	N	68.00	S	13.00	X	0.00
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}	2903	2743	2743
Back	3900	M_{rear}	2130	2262	2262
Total	6700	M_{Total}	5033	5005	5005

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

Mass Distribution:
lb LF: 1371 RF: 1372 LR: 1153 RR: 1109

Table B.2. Measurements of Vehicle Vertical Center of Gravity for Test No. 614091-01-2

Date: 2021-1-28 Test No.: 614091-01-2 VIN: 1C6RR6FT9ES243178

Year: 2014 Make: RAM Model: 1500

Body Style: Quad Cab Mileage: 131688

Engine: 5.7L V-8 Transmission: Automatic

Fuel Level: Empty Ballast: (440 lb max)

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

Measured Vehicle Weights: (lb)								
LF:	1371		RF:	1372		Front Axle:	2743	
LR:	1153		RR:	1109		Rear Axle:	2262	
Left:	2524		Right:	2481		Total:	5005	
							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:	63.50	inches	Rear of Front Axle	(63 ±4 inches allowed)				
Y:	-0.29	inches	Left -	Right +	of Vehicle Centerline			
Z:	28.75	inches	Above Ground	(minumum 28.0 inches allowed)				

Hood Height: 46.00 inches Front Bumper Height: 27.00 inches

43 ±4 inches allowed

Front Overhang: 40.00 inches Rear Bumper Height: 30.00 inches

39 ±3 inches allowed

Overall Length: 227.50 inches

237 ±13 inches allowed

B.2. SEQUENTIAL PHOTOGRAPHS

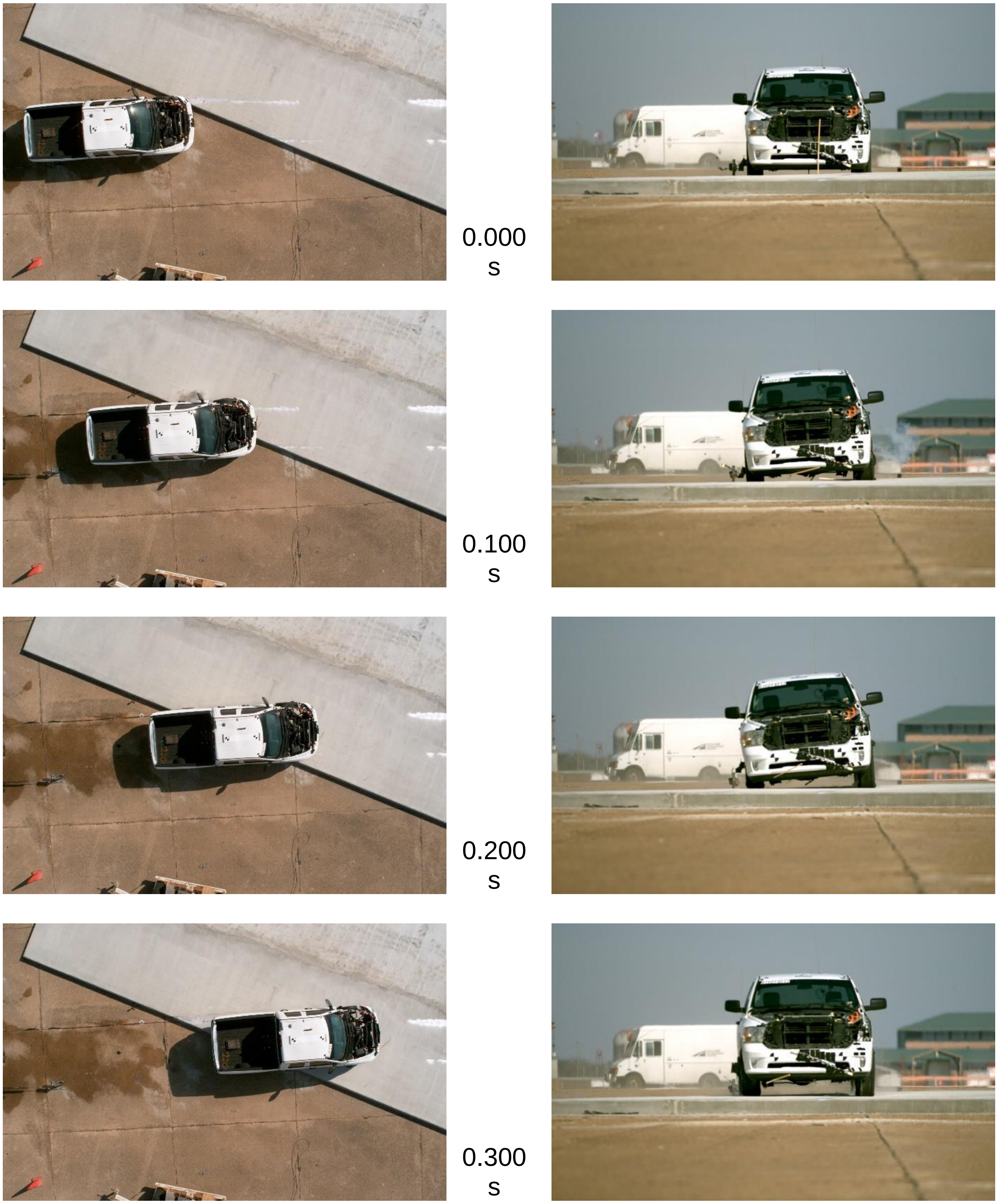


Figure B.1. Sequential Photographs for Test No. 614091-01-2 (Overhead and Frontal Views)

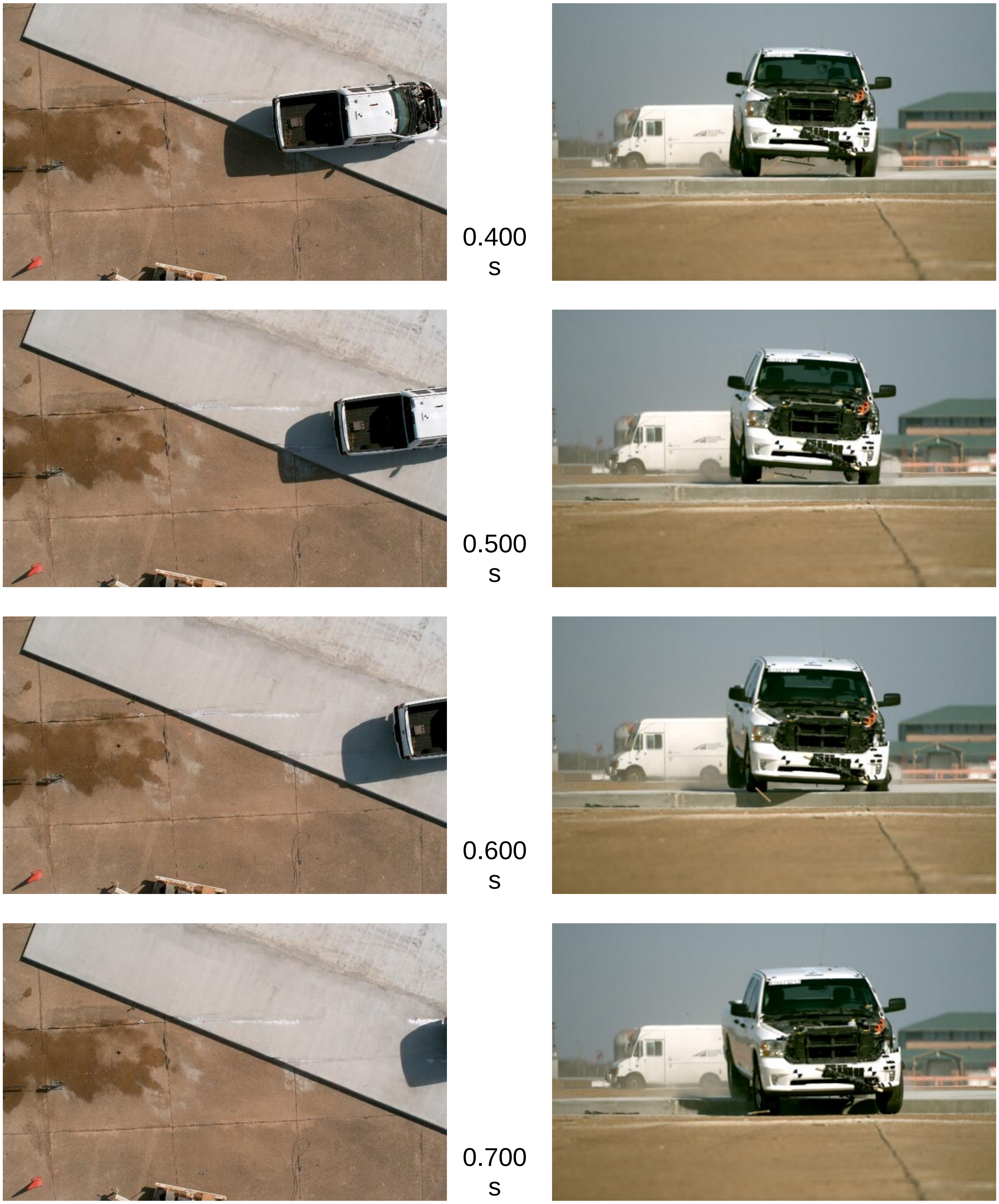


Figure B.1. Sequential Photographs for Test No. 614091-01-2 (Overhead and Frontal Views) (Continued)

0.000 s

0.100 s

0.200 s

0.300 s

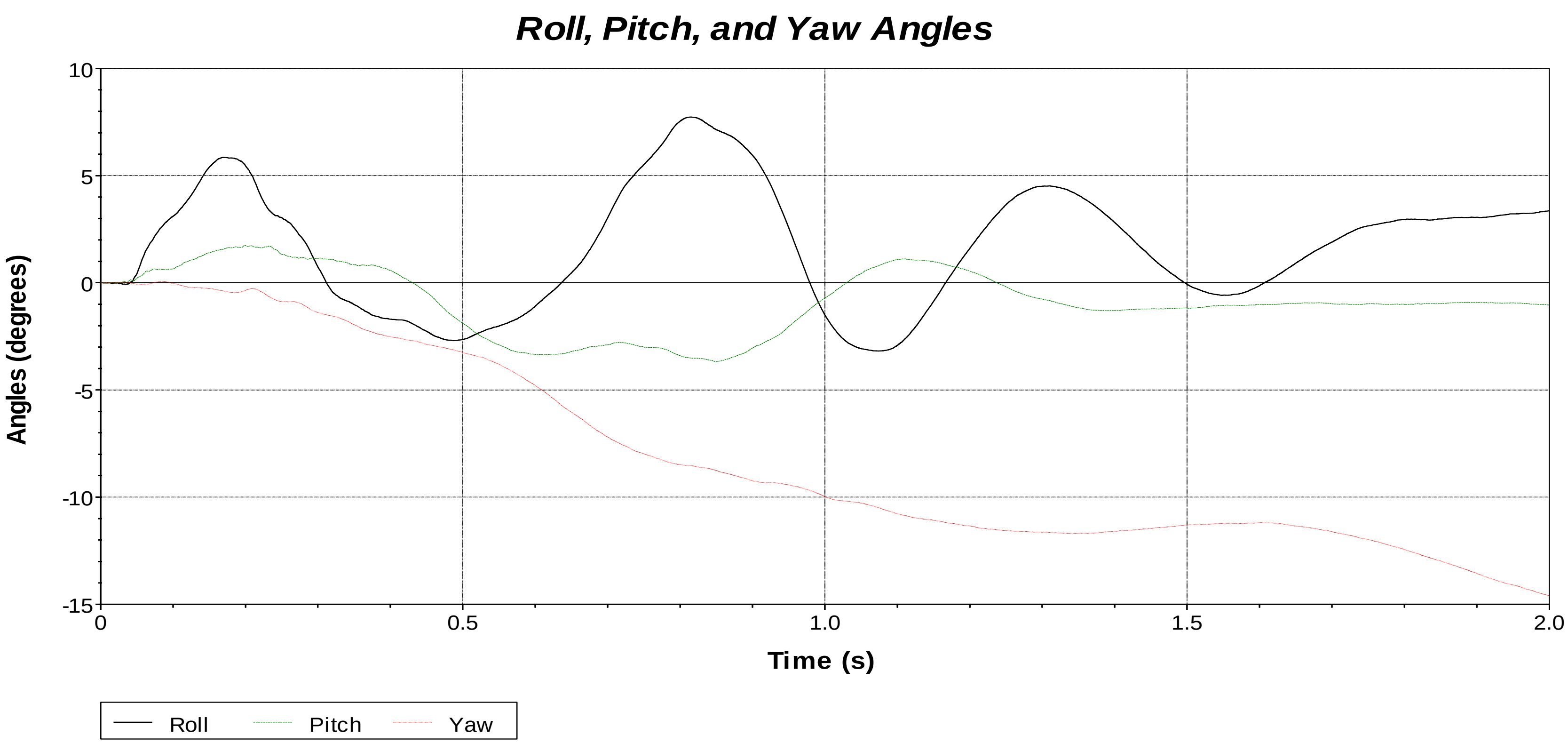
0.400 s

0.500 s

0.600 s

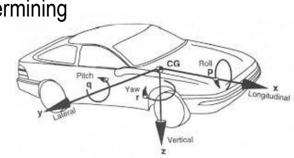
0.700 s

Figure B.2. Sequential Photographs for Test No. 614091-01-2 (Perpendicular View)



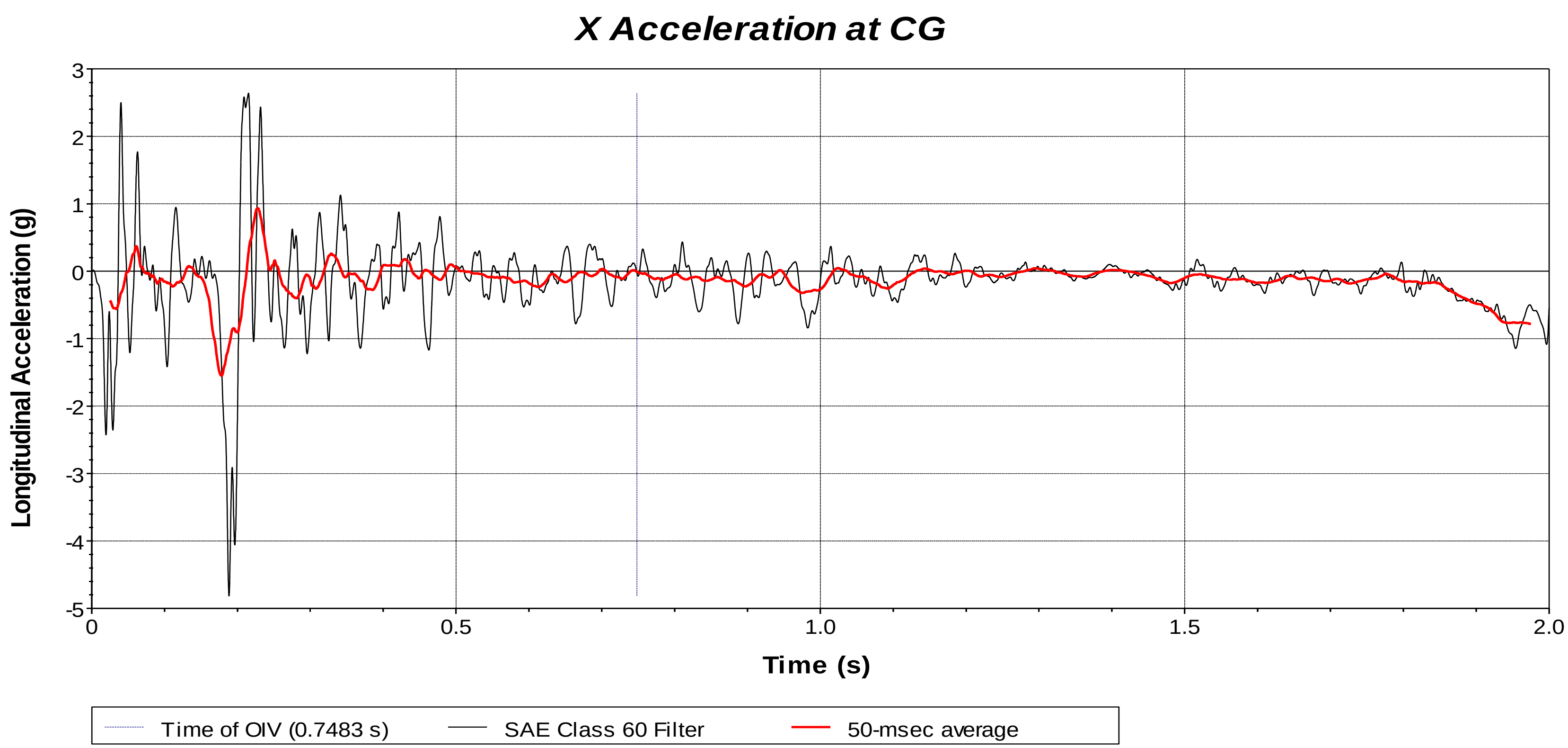
Axes are vehicle-fixed.
Sequence for determining orientation:

1. Yaw.
2. Pitch.
3. Roll.



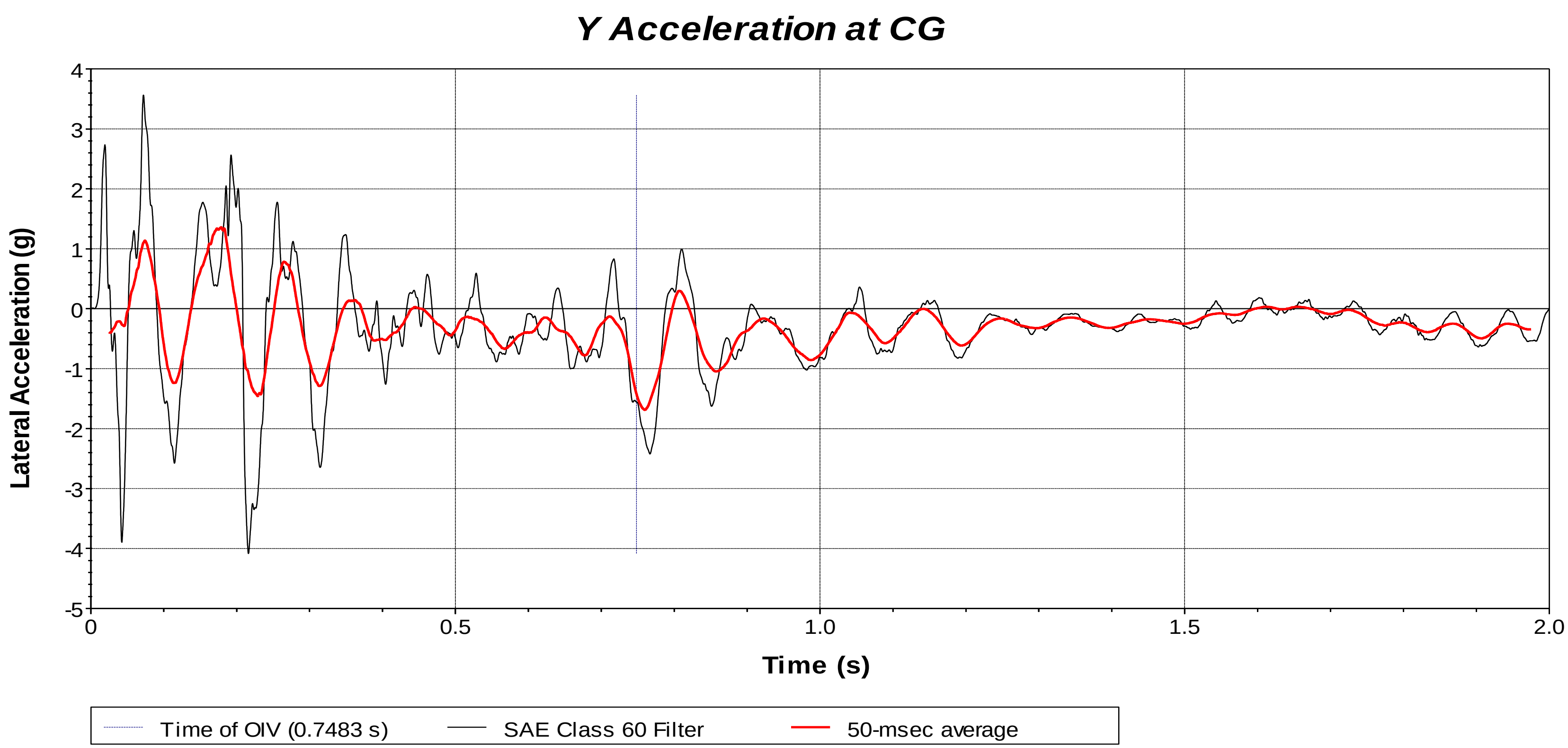
Test Number: 614091-01-2
Test Article: 8-inch Sidewalk
Test Vehicle: 2014 RAM 1500 Pickup
Inertial Mass: 5005 lb
Gross Mass: 5005 lb
Impact Speed: 49.4 mi/h
Impact Angle: 25.9 degrees

Figure B.3. Vehicle Angular Displacements for Test No. 614091-01-2



Test Number: 614091-01-2
Test Article: 8-inch Sidewalk
Test Vehicle: 2014 RAM 1500 Pickup
Inertial Mass: 5005 lb
Gross Mass: 5005 lb
Impact Speed: 49.4 mi/h
Impact Angle: 25.9 degrees

Figure B.4. Vehicle Longitudinal Accelerometer Trace for Test No. 614091-01-2 (Accelerometer Located at Center of Gravity)



Test Number: 614091-01-2
Test Article: 8-inch Sidewalk
Test Vehicle: 2014 RAM 1500 Pickup
Inertial Mass: 5005 lb
Gross Mass: 5005 lb
Impact Speed: 49.4 mi/h
Impact Angle: 25.9 degrees

Figure B.5. Vehicle Lateral Accelerometer Trace for Test No. 614091-01-2 (Accelerometer Located at Center of Gravity)

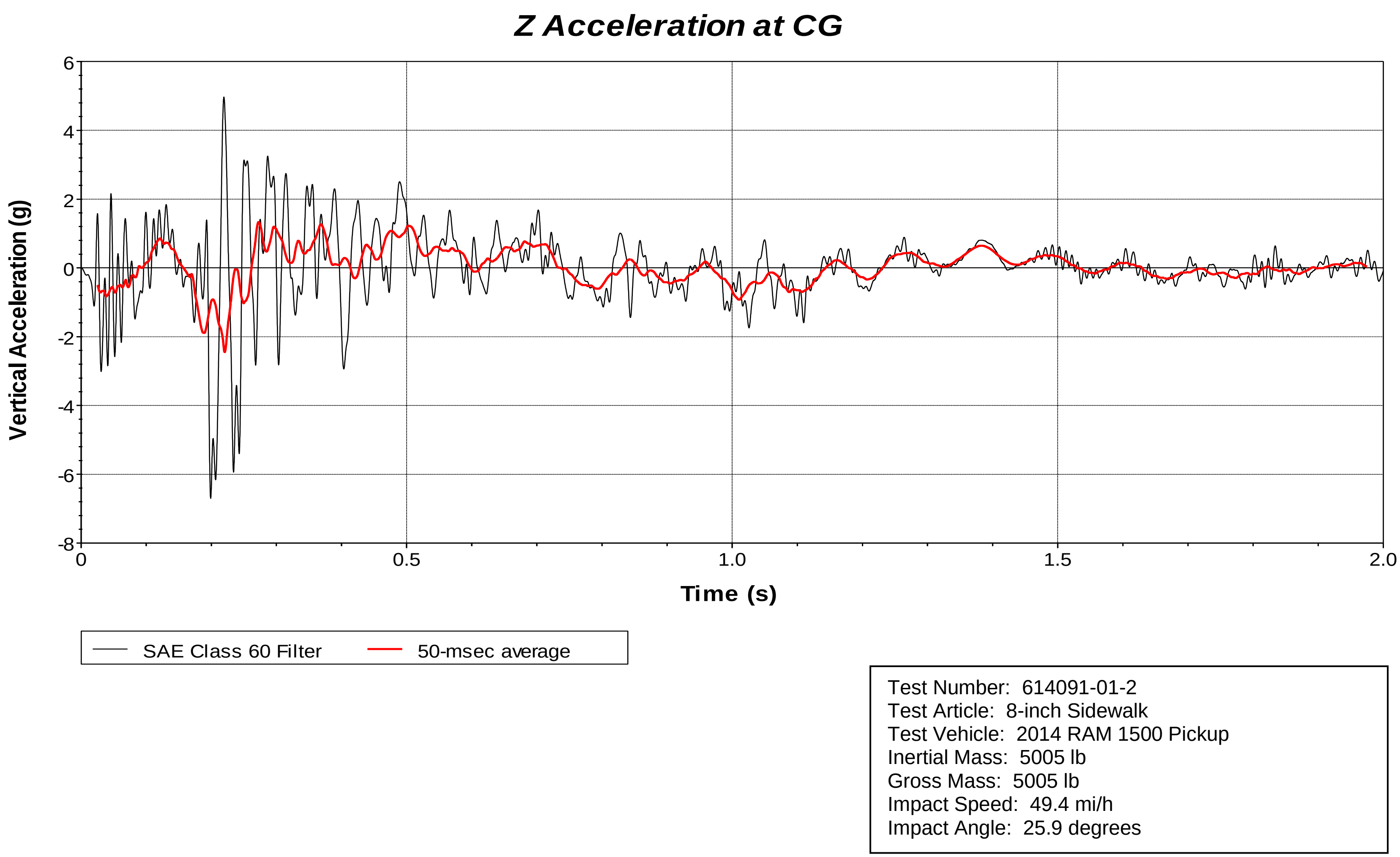


Figure B.6. Vehicle Vertical Accelerometer Trace for Test No. 614091-01-2 (Accelerometer Located at Center of Gravity)

APPENDIX C. PARAMETRIC ANALYSIS RESULTS

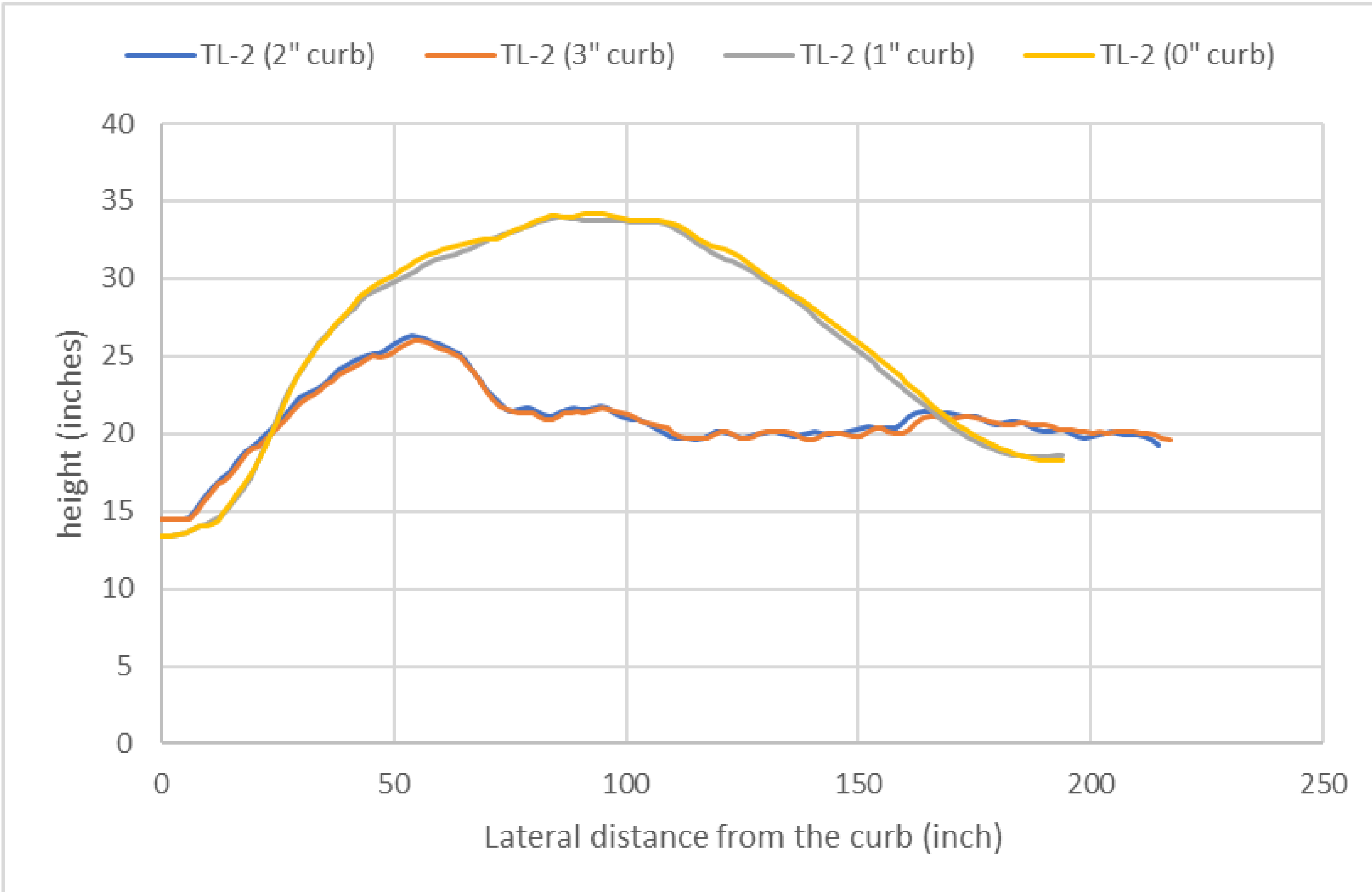


Figure C.1 Trajectory Profiles on 8-inch Height Curb with Different Offsets for Passenger Car with Suspension Failure (2-inch and 3-inch offsets) and without (1-inch and 0-inch offsets)

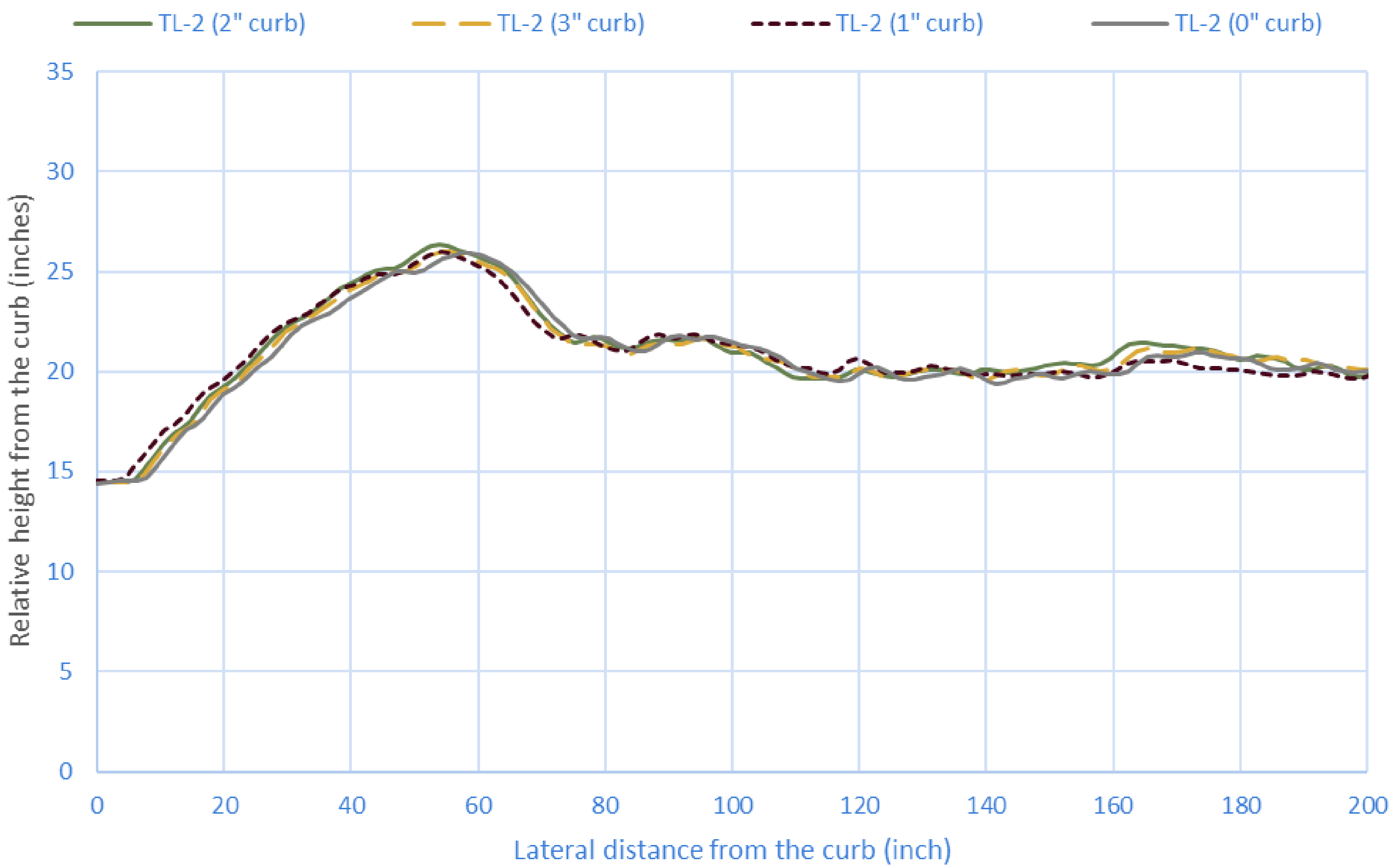
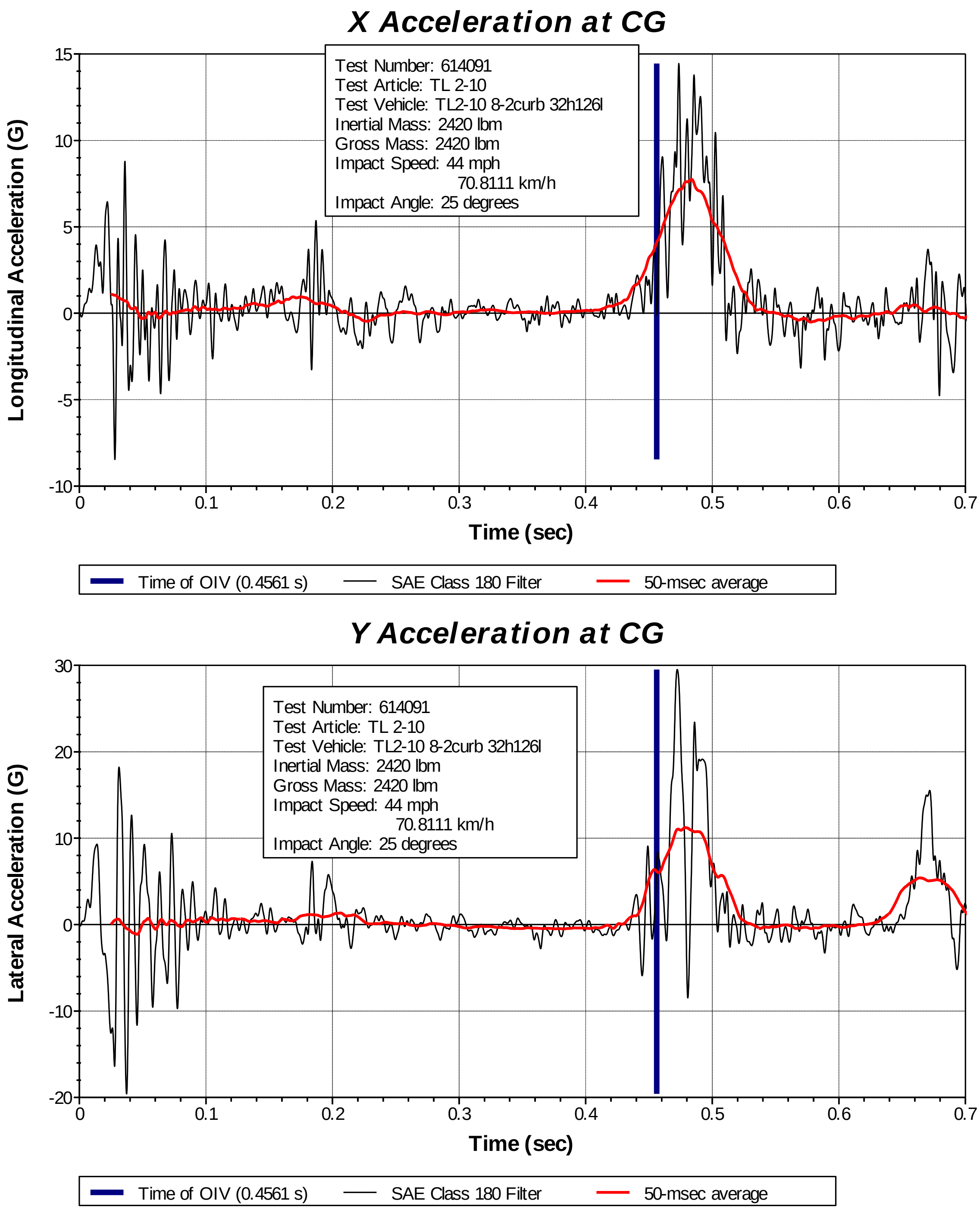


Figure C.2 Trajectory Profiles on 8-inch Height Curb with Different Offsets for Truck with Suspension Failure (2-inch and 3-inch offsets) and without (1-inch and 0-inch offsets)

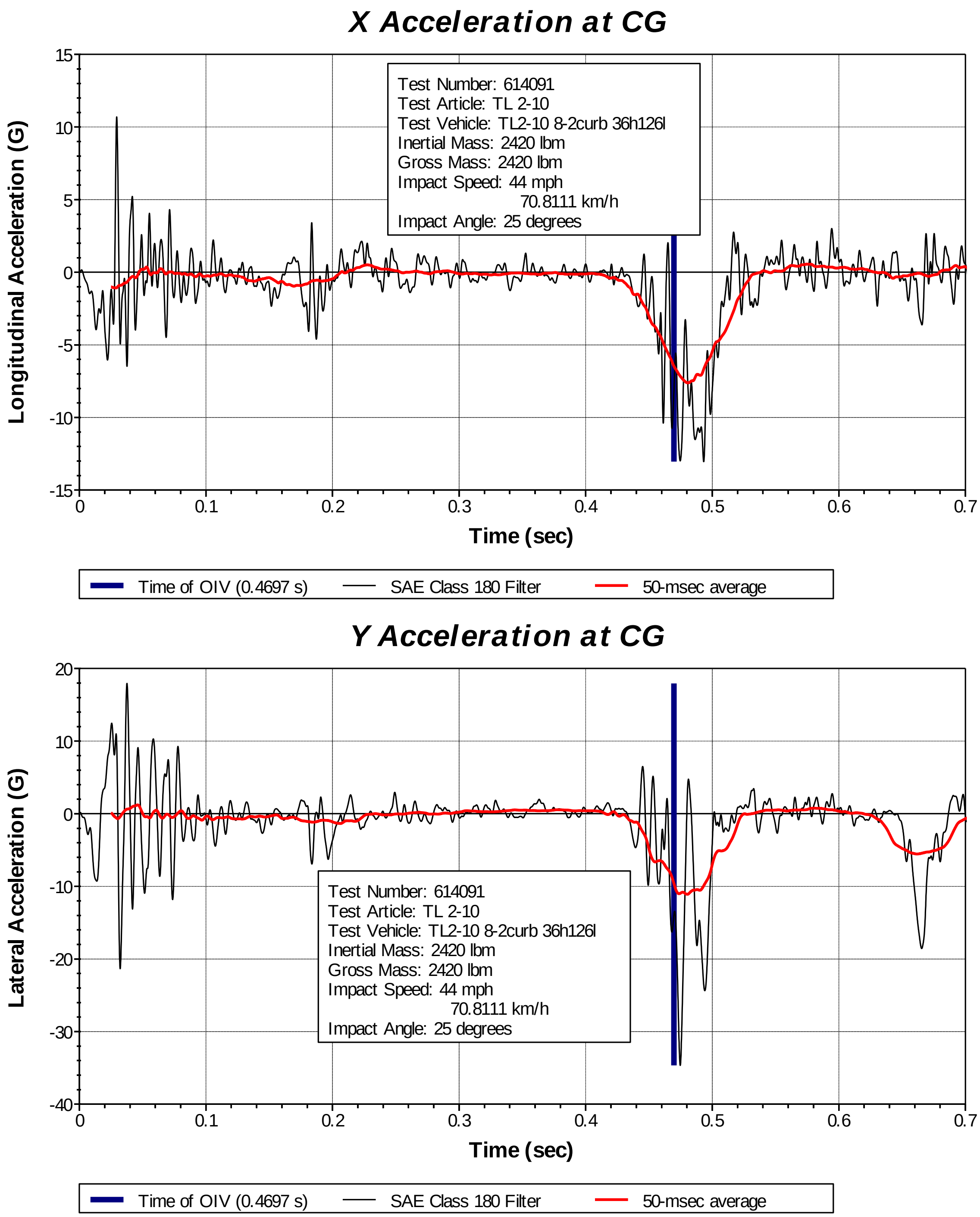
Table C.1. Initial Small Car Simulation Result and Reason of the Result (Time Zero at Curb)

Simulation No.	Parapet Height (inches)	Sidewalk Width (inches)	Simulation Result Reason of “not-preferred” (MASH RA max = 20.49 g / prefer = 15.0 g)	
			Time Zero at Curb	
1	20	54	Pass	NA
2	26	54	Pass	NA
3	20	78	Fail	High roll angle
4	26	78	Pass	NA
5	20	102	Fail	High roll angle
6	26	102	Not Preferred	RA (15.2 g)
7	32	54	Pass	NA
8	32	78	Pass	NA
9	20	150	Not Preferred	RA (18.1 g)
10	20	126	Not Preferred	RA (18.5 g)
11	26	150	Not Preferred	RA (20.3 g)
12	26	126	Not Preferred	RA (19.2 g)
13	20	174	Not Preferred	RA (14.9 g)
14	26	174	Not Preferred	RA (17.3 g)
15	32	102	Not Preferred	RA (16.0 g)
16	32	126	Fail	RA (22.1 g)
17	32	174	Not Preferred	RA (16.2 g)
18	36	102	Not Preferred	RA (15.1 g)
19	36	126	Fail	RA (20.7 g)
20	36	174	Not Preferred	RA (16.8 g)

NA = Not available



(a) Simulation No. 16– 32-inch parapet height at 126-inch offset



(b) Simulation No. 19 – 36-inch parapet height at 126-inch offset

Figure C.3. Longitudinal and Lateral Acceleration with 50-ms Average Acceleration.