Texas A&M Transportation Institute
Proving Ground

Test Report No. 0-7021-01-R1

DEVELOPING AN ENHANCED PROTECTION OF MEDIAN OPENINGS BETWEEN PARALLEL BRIDGE STRUCTURES

Sponsored by the
Texas Department of Transportation
and the
Federal Highway Administration

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16. Abstract

The objective of this project was to develop a method to prevent errant motorists from entering the median openings between parallel bridge structures. This project identified characteristics that could be used to target potential sites for implementation of a median opening protection system (MOPS). In this identification process, the research team completed a systematic approach analysis on the available crash data to determine these characteristics. Because of the risk associated with larger vehicles being involved with this type of crash, the research team was tasked with investigating both the crashes involving median opening areas and the crashes involving buses. Additionally, this project investigated readily available technologies for their application in a vehicle arresting system. This system would be implemented in median openings between parallel bridge structures and would arrest errant vehicles before they plunged into the hazard below the bridge. Last, the research team developed a MOPS using readily available technologies and evaluated the MOPS through full-scale crash testing.

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

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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

CHAPTER 1. INTRODUCTION

When a divided highway crosses over a lower roadway, river, or other obstacle, two separate but parallel bridge structures span over this obstacle. Typically, departments of transportation (DOTs) shield motorists from entering the median by installing a steel guardrail for the appropriate length of need. This creates a zone with two installations of guardrail that act as a funnel to the steep precipice over the obstacle that the bridges are spanning. While the guardrail typically protects motorists from entering this median opening, there have been instances where errant vehicles have traversed into the median and been funneled toward the precipice.

Vehicles that leave the roadway and travel through the median may enter this opening between parallel bridge structures. This causes the errant vehicles to drop below to the obstacle over which the bridge is spanning. This drop can be fatal to the vehicle occupants, and if the obstacle below is another roadway, the motorists driving on that roadway are also in danger. Furthermore, these vehicles are not limited to passenger cars but also include trucks and buses. In fact, the National Transportation Safety Board (NTSB) investigated a bus accident that involved this median opening scenario located in Alabama (NTSB Accident No. HWY18MH008). Because of the weight and height of a bus, this type of impact requires special attention in the design process of a safety treatment.

Proprietary solutions exist for bringing errant vehicles to a controlled and safe stop on flat and level terrain. However, this median opening situation has not been explored with the use of one of these proprietary devices. These devices may provide an optimum solution for protecting these median openings, but their crashworthiness with regard to the median openings and larger vehicles must be evaluated.

The objective of this project was to develop a method to prevent errant motorists from entering the median openings between parallel bridge structures. This project identified characteristics that could be used to target potential sites for implementation of a developed median opening protection system (MOPS). In this identification process, the research team completed a systematic approach analysis on the available crash data to determine these characteristics. Because of the risk associated with larger vehicles being involved with this type of crash, the research team was tasked with investigating both the crashes involving median opening areas and the crashes involving buses. Additionally, this project investigated readily available technologies for their application in a vehicle arresting system. This system would be implemented in median openings between parallel bridge structures and would arrest errant vehicles before they plunged into the hazard below the bridge. Last, the research team developed a MOPS using readily available technologies and evaluated the MOPS through full-scale crash testing according to the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*), Second Edition (*1*). This report documents this research effort.

CHAPTER 2. CRASH DATA ANALYSIS

2.1. IDENTIFYING CRASHES AT MEDIAN OPENINGS BETWEEN PARALLEL STRUCTURES

The research team analyzed the crash data from the Texas Department of Transportation's (TxDOT's) Crash Records Information System (CRIS). The data were accessed on August 21, 2019. These data include information related to "TxDOT reportable" crashes of all levels of injury severity that occurred from January 1, 2010, to August 21, 2019. A TxDOT reportable crash is one that occurs on a public roadway and results in a fatality, injury, or $1,000 or more in damage. The primary focus of this analysis was to identify characteristics related to crashes between parallel bridge structures. Within the CRIS dataset, the variable "bridge detail ID" is an interpreted field that is assigned during the crash report review process. This variable was used to identify crashes related to parallel bridge structures. A preliminary review of the crashes where BRIDGE_DETAIL_ID = 5 or "VEHICLE WENT BETWEEN PARALLEL STRUCTURES" found that there were no crashes in that time period involving buses and parallel bridge structures. Therefore, the data set also included crashes involving buses where the crash was identified as occurring off the roadway or in the median. This task was aimed at identifying relevant crash characteristics of buses that could be used in this project. Figure 2.1 lists the annual count of parallel structure crashes by crash type. This figure also shows the fatal and incapacitating injury parallel structure crashes. Figure 2.2 shows the location of the identified median opening crashes.

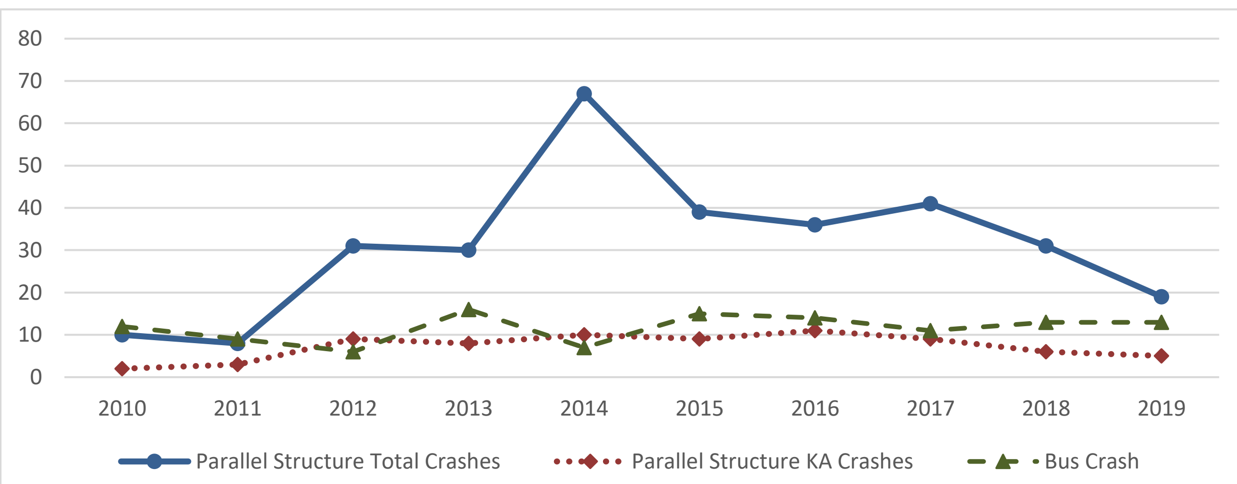


Figure 2.1. Annual Counts of Parallel Structure and Bus Crashes.

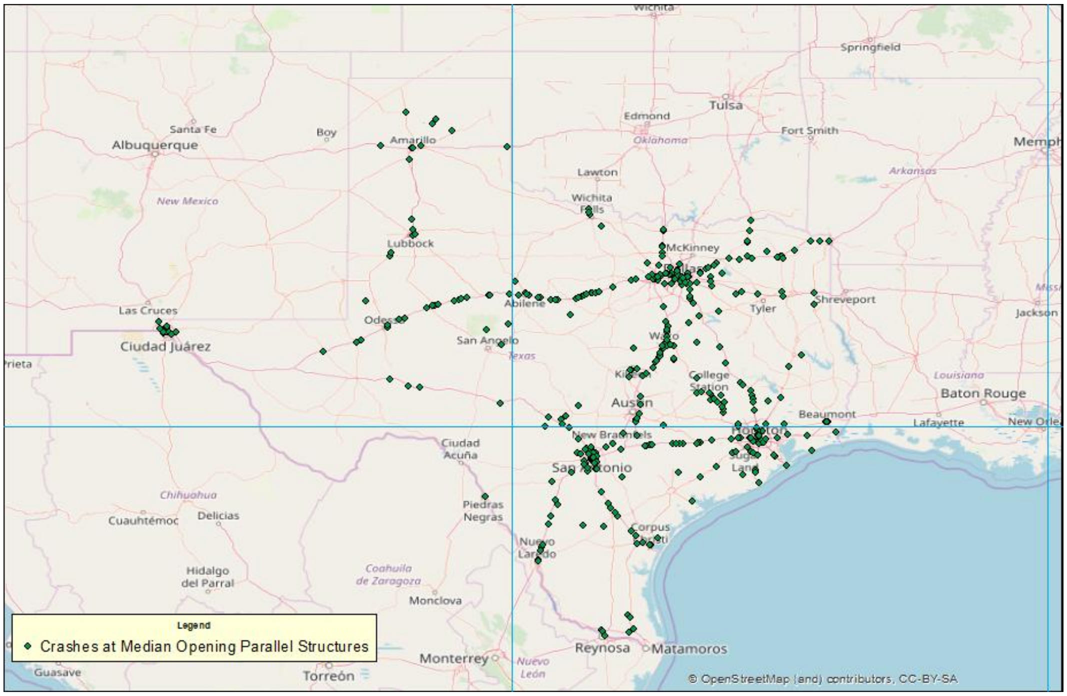


Figure 2.2. Median Opening Crash Locations.

Due to the minimal number of crashes involving parallel structures and a bus/motorcoach, the project team also considered the crashes involving buses using the CRIS variable “vehicle body style.” Figure 2.3 shows the location of the identified median opening crashes and the separate bus crashes.

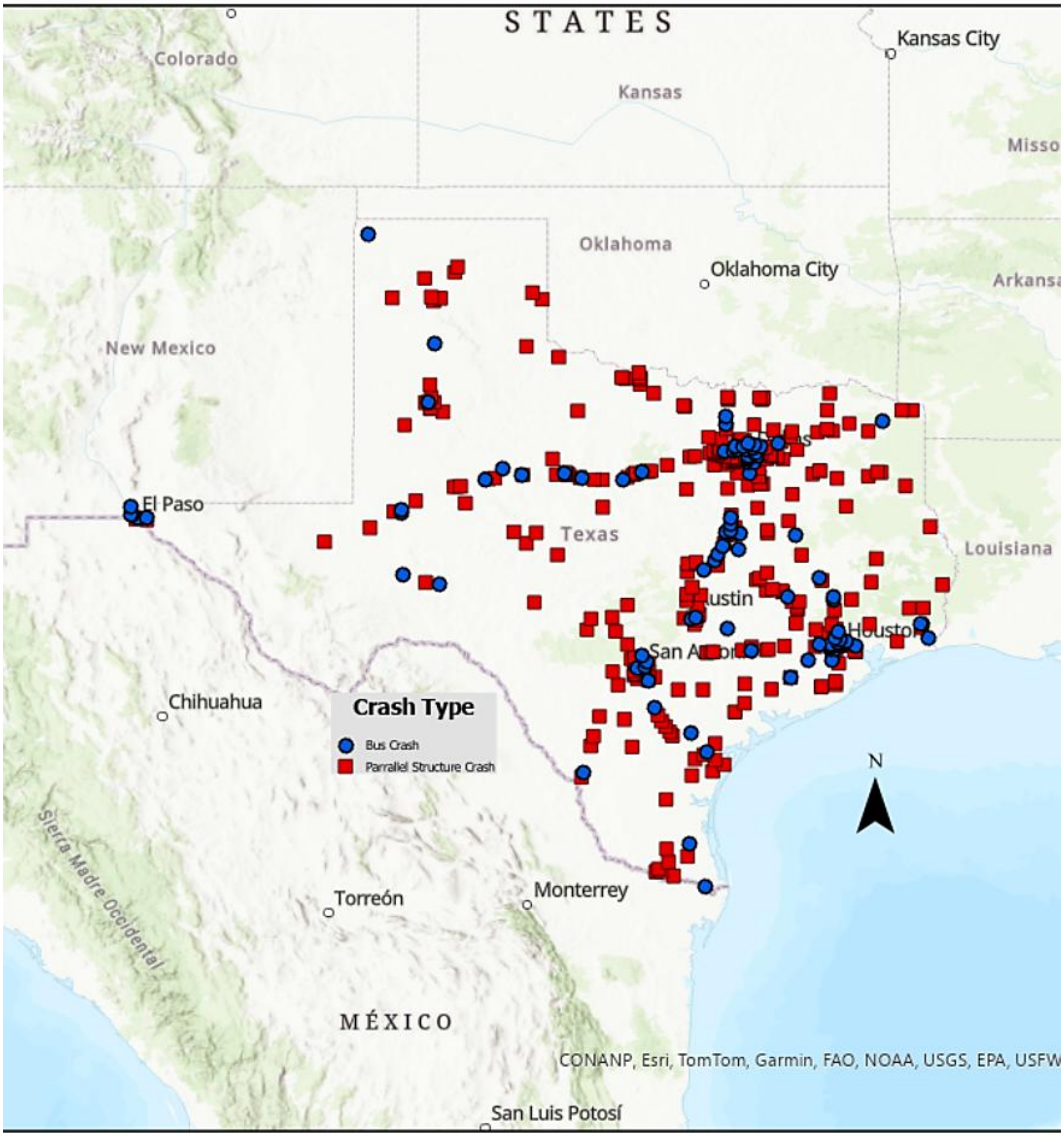


Figure 2.3. Parallel Structure and Bus Crash Locations.

2.2. PARALLEL STRUCTURE CRASH CHARACTERISTICS

From January 1, 2010, to July 16, 2019, 312 crashes involved a parallel structure, but none involved a bus. Of those, 58 percent were crashes on four-lane roads, and 41 percent of the crashes were on four-lane roadways with unprotected medians. Table 2.1 shows the crashes separated by lane count and median type.

Table 2.1. Parallel Structure Crash Counts and Percentages by Number of Lanes.

Number of Lanes	Curbed	No Data	No Median	Positive Barrier	Unprotected	Grand Total
2	0.0%	0.0%	9.6%	0.0%	0.0%	9.6%
4	1.3%	0.0%	3.8%	11.5%	41.0%	57.7%
5	0.0%	0.0%	0.0%	0.0%	0.3%	0.3%
6	0.0%	0.0%	0.0%	2.9%	2.6%	5.4%
7	0.0%	0.0%	0.0%	0.3%	0.0%	0.3%
8	0.0%	0.0%	0.0%	1.3%	1.0%	2.2%
13	0.0%	0.0%	0.0%	0.3%	0.0%	0.3%
No Data	0.0%	24.0%	0.0%	0.0%	0.0%	24.0%
Grand Total	**1.3%**	**24.0%**	**13.5%**	**16.3%**	**44.9%**	**100.0%**

Furthermore, 250 of the crashes were classified as occurring on an on-system roadway. Table 2.2 shows a breakdown of the crashes by functional system.

Table 2.2. Parallel Structure Crashes Counts and Percentages by Functional System Classification.

Functional System	Count of Crashes	Percentage of Crashes
Rural Interstate	55	22.0%
Urban Prin Arterial (IH)	45	18.0%
Rural Prin Arterial	43	17.2%
Urban Prin Arterial (Other Freeway)	31	12.4%
Urban Prin Arterial (Other)	26	10.4%
Rural Major Coll	14	5.6%
No Data	13	5.2%
Rural Minor Arterial	13	5.2%
Urban Minor Arterial	4	1.6%
Rural Minor Coll	4	1.6%
Urban Collector	2	0.8%
Grand Total	**250**	**100.0%**

Of the 312 crashes involving parallel structures, 71 percent occurred on roadways with a posted speed limit of 60 mi/h or higher (see Table 2.3).

Table 2.3. Parallel Structure Crashes Counts and Percentages by Speed Limit Group.

Speed Limit	Count of Crashes	Percentage of Crashes
35 mi/h or less	32	10.3%
40 mi/h to 55 mi/h	54	17.3%
60 mi/h or higher	221	70.8%
Unknown	5	1.6%
Grand Total	**312**	**100.0%**

Of the crashes occurring on four-lane roadways with unprotected medians, 95 percent (121 crashes) occurred on roadways with a posted speed limit of 60 mi/h or higher. Figure 2.4 shows parallel structure crashes with coordinates on four-lane roadways with unprotected medians and speed limits greater than or equal to 60 mi/h.

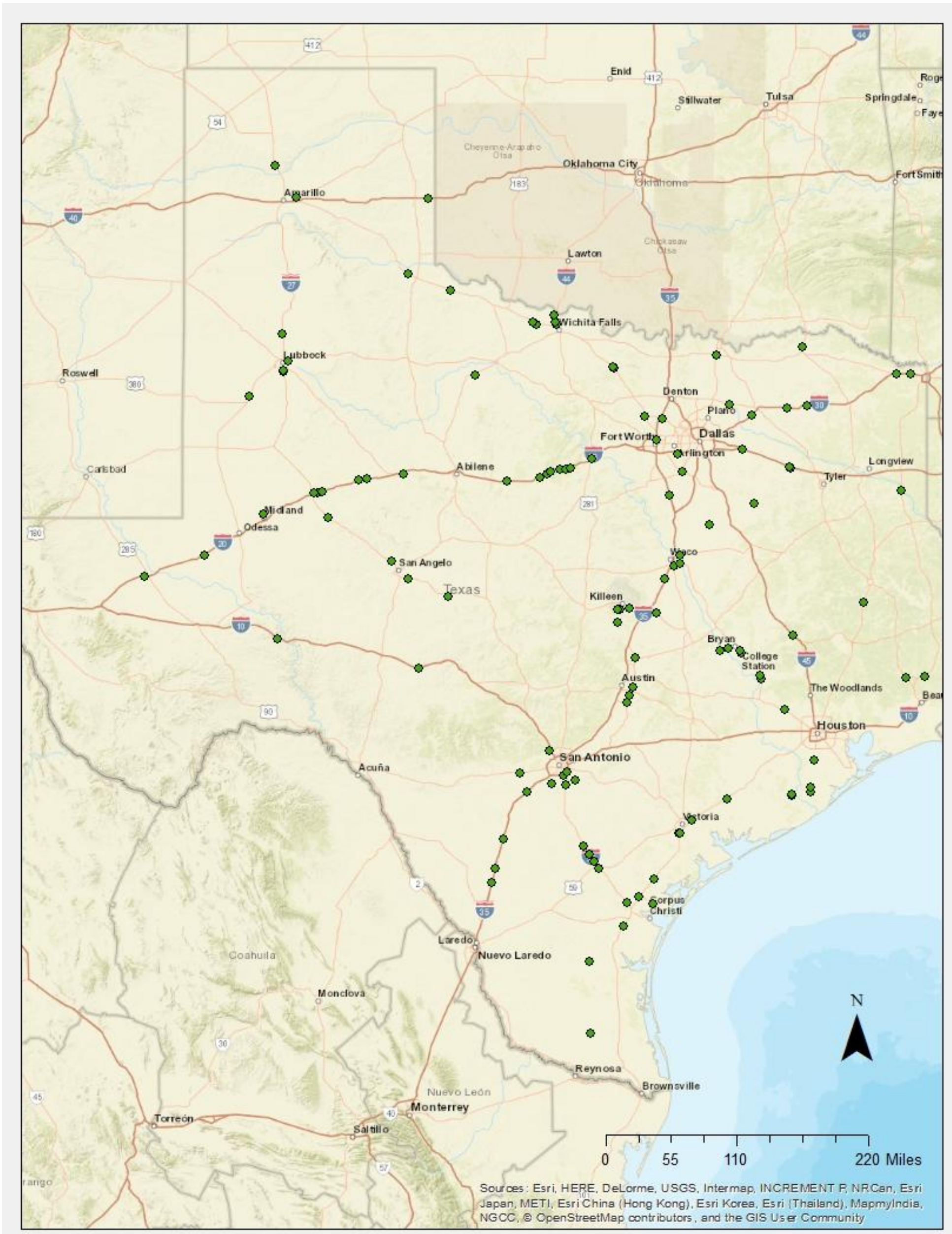


Figure 2.4. Parallel Structure Crashes Occurring on Four-Lane Roadways with a Posted Speed of 60 mi/h or Higher.

To better identify the location of the crashes, Table 2.4 lists the 131 parallel structure crashes on four-lane roadways with unprotected medians and speed limits of 60 mi/h or higher by roadway and county. Similarly, Table 2.5 lists the number of on-system parallel structure crashes by control section.

Table 2.4. Parallel Structure Crashes by Roadway and County (Grand Total 131).

Roadway	County	Count of Crash
IH0020	Eastland	6
	Howard	3
	Palo Pinto	2
	Van Zandt	2
	Mitchell	2
	Reeves	1
	Ward	1
	Kaufman	1
	Nolan	1
	Callahan	1
	Erath	1
SH0006	Brazos	3
	McLennan	3
	Grimes	2
IH0035	McLennan	2
	Lasalle	2
	Bexar	1
	Medina	1
	Frio	1
IH0037	Live Oak	5
	San Patricio	1
	Bexar	1
US0077	Victoria	3
	San Patricio	1
	Nueces	1
	Refugio	1
US0087	Tom Green	2
	Lubbock	2
	Glasscock	1
	Potter	1
US0287	Wichita	2
	Montague	1
	Childress	1
	Hardeman	1
IH0030	Bowie	2
	Hopkins	2
	Hunt	1
SH0130	Travis	3
	Williamson	1
US0059	Victoria	1
	Panola	1
	Angelina	1
	Jackson	1
IH0045	Ellis	2
	Walker	1
	Dallas	1
IH0044	Wichita	3
IH0410	Bexar	3
SH0288	Brazoria	3
IH0820	Tarrant	2
US0190	Bell	2
IH0035W	Tarrant	1
	Hill	1
SH0031	Navarro	2
US0062	Terry	1
	Lubbock	1
SH0035	Brazoria	2
US0082	Wichita	1
	Grayson	1
SH0114	Wise	1
SH0114	Denton	1
US0181	San Patricio	1
	Bexar	1
SH0195	Bell	2
US0281	Jim Wells	1
US0181	Hidalgo	1
IH0010	Sutton	1
	Pecos	1
SH0021	Brazos	2
US0277	Knox	1
US0096	Jasper	1
SH0360	Tarrant	1
SH0099	Harris	1
SL1604	Bexar	1
US0380	Collin	1
SH0016	Bexar	1
US0069	Hardin	1
US0090	Medina	1
SH0201	Bell	1
SL0250	Midland	1
US0081	Montague	1
US0271	Lamar	1
IH0027	Hale	1
IH0040	Wheeler	1
US0083	Concho	1
US0060	Potter	1
US0084	McLennan	1
US0067	Ellis	1

Table 2.5. Parallel Structure Crashes by Control Section (Grand Total 237).

Control Section	Count of Crash	Control Section	Count of Crash	Control Section	Count of Crash	Control Section	Count of Crash	Control Section	Count of Crash	Control Section	Count of Crash
0006-06	4	0222-01	1	0227-07	1	0194-02	1	0366-06	1	0781-01	1
0535-04	4	0018-01	1	0050-05	1	0088-05	1	0135-04	1	0176-03	1
0007-06	4	0314-05	1	0009-12	1	0200-10	1	0371-03	1	0006-03	1
0005-06	3	0018-02	1	0050-06	1	0089-05	1	0135-07	1	0179-02	1
0371-01	3	0400-02	1	0275-13	1	0204-09	1	0379-01	1	1017-04	1
0156-07	3	0018-05	1	0053-19	1	0090-09	1	0136-05	1	0179-03	1
0440-06	3	0535-08	1	0314-03	1	0211-09	1	0440-05	1	1356-02	1
0043-08	3	0024-06	1	0063-10	1	0092-02	1	0136-08	1	0180-10	1
0015-01	3	0864-01	1	0315-03	1	0224-03	1	0456-02	1	1451-01	1
0521-06	3	0030-09	1	0065-04	1	0092-04	1	0140-06	1	0185-05	1
0258-09	2	0204-08	1	0353-01	1	0231-03	1	0484-01	1	1939-02	1
0495-03	2	0035-04	1	0067-06	1	0092-05	1	0141-07	1	0189-05	1
0049-12	2	0255-02	1	0009-13	1	0255-07	1	0014-01	1	0193-02	1
0007-02	2	0041-05	1	0067-07	1	0092-14	1	0142-12	1	0157-11	1
0008-14	2	0291-01	1	0372-01	1	0260-02	1	0500-03	1	2373-02	1
0836-02	2	0042-12	1	0003-07	1	0093-05	1	0142-14	1	0162-01	1
0364-01	2	0328-07	1	0013-05	1	0271-02	1	0521-05	1	2374-05	1
0074-02	2	0043-02	1	0069-02	1	0095-02	1	0156-04	1	0162-03	1
0050-03	2	0010-02	1	0508-01	1	0290-03	1	0014-16	1	2479-01	1
0095-03	2	0006-05	1	0070-02	1	0006-01	1	0009-11	1	0163-02	1
0116-04	2	0480-04	1	0535-05	1	0314-02	1	0535-07	1	3429-01	1
0068-01	2	0045-01	1	0072-06	1	0095-04	1	2224-01	1	0169-02	1
0610-06	2	0014-08	1	0598-02	1	0314-04	1	0593-01	1	3510-05	1
0073-07	2	0045-18	1	0007-04	1	0095-13	1	2281-02	1	0172-09	1
0074-01	2	0598-04	1	0613-01	1	0314-07	1	0598-03	1	0001-04	1
2266-02	2	0045-19	1	0073-09	1	0100-02	1	2374-04	1	0172-12	1
0495-07	1	0756-05	1	0675-08	1	0327-07	1	0014-23	1		
0271-01	1	0049-01	1	0005-08	1	0101-04	1	2452-02	1		
0017-02	1	1420-02	1	0783-02	1	0346-06	1	0627-03	1		
0017-05	1	0004-04	1	0008-03	1	0102-02	1	2957-01	1		
0356-01	1	0196-02	1	1188-02	1	0353-02	1	0675-06	1		
0017-07	1	0050-02	1	0074-05	1	0009-09	1	3510-04	1		
0675-04	1	0206-03	1	1763-02	1	0363-01	1	0683-01	1		
0017-10	1	0006-07	1	0081-13	1	0131-01	1	3534-02	1		

2.3. BUS-INVOLVED CRASH CHARACTERISTICS

Although there were no crashes identified as involving parallel structures and buses, this project required information on bus crash characteristics. This section details the analysis of crash data related to bus crashes that occurred in the median. The team chose to analyze crashes that occurred in the median because that is where parallel bridge structures would be found.

The highest percentage, 33 percent, of the 116 bus crashes occurred on off-system roadways, which are not defined by functional system. The next two highest percentages aligned more closely with the parallel structure crashes in that a high percentage of bus median crashes occurred on urban principal arterials or rural interstates. Table 2.6 lists the crash counts and percentages by functional system classification.

Table 2.6. Median Bus Crashes by Functional System Classification.

Functional System	Count of Crashes	Percentage of Crashes
No Data	38	32.8%
Urban Prin Arterial (IH)	30	25.9%
Rural Interstate	22	19.0%
Rural Prin Arterial	9	7.8%
Urban Prin Arterial (Other Freeway)	7	6.0%
Urban Prin Arterial (Other)	7	6.0%
Rural Major Coll	1	0.9%
Urban Minor Arterial	1	0.9%
Rural Minor Arterial	1	0.9%
Grand Total	**116**	**100.0%**

Bus crashes that occurred on urban principal arterials and rural interstates had characteristics of the bus traveling in a forward non-turning manner, and the majority were traveling on a straight and level roadway, per the officers' reports. Table 2.7 lists the roadway alignment indicated by the reporting officer for median bus crashes on urban principal arterials and rural interstates.

Table 2.7. Roadway Alignment Related to Median Bus Crashes on Urban Principal Arterials and Rural Interstates.

Roadway Alignment	Count of Crashes	Percentage of Crashes
Straight, Level	36	69.2%
Straight, Grade	8	15.4%
Curve, Grade	3	5.8%
Straight, Hillcrest	2	3.8%
Curve, Level	2	3.8%
Other (Explain in Narrative)	1	1.9%
Grand Total	**52**	**100.0%**

2.3.1. Bus Type

A total of 1,005 buses were involved in median or off-roadway crashes. Using the National Highway Traffic Safety Administration batch VIN decoder (https://vpic.nhtsa.dot.gov/api/), the research team decoded 974 to learn more information about the buses' physical characteristics. The buses used in this process were not limited to the 116 crashes described in the previous section in order to have a better understanding of the types of buses involved in crashes and the possibility of having more data from the VIN decoding process. Table 2.8 lists the count of buses by gross vehicle weight rating (GVWR).

Table 2.8. Weight Classifications for Buses Involved in Median and Off-Roadway Crashes.

GVWR	Count of Buses	Percentage of Buses
Class 1C: 4,001–5,000 lb (1,814–2,268 kg)	2	0.2%
Class 1D: 5,001–6,000 lb (2,268–2,722 kg)	3	0.3%
Class 2: 6,001–10,000 lb (2,722–4,536 kg)	3	0.3%
Class 2E: 6,001–7,000 lb (2,722–3,175 kg)	2	0.2%
Class 2G: 8,001–9,000 lb (3,629–4,082 kg)	9	0.9%
Class 2H: 9,001–10,000 lb (4,082–4,536 kg)	41	4.2%
Class 3: 10,001–14,000 lb (4,536–6,350 kg)	47	4.8%
Class 4: 14,001–16,000 lb (6,350–7,258 kg)	93	9.5%
Class 5: 16,001–19,500 lb (7,258–8,845 kg)	22	2.3%
Class 6: 19,501–26,000 lb (8,845–11,794 kg)	39	4.0%
Class 7: 26,001–33,000 lb (11,794–14,969 kg)	188	19.3%
Class 8: 33,001 lb and above (14,969 kg and above)	267	27.4%
No Data	258	26.5%
Grand Total	**974**	**100.0%**

A review of the buses most often involved in median and run-off-the-road crashes in the Class 7 and 8 GVWR groups found that many of the buses were school and metro type buses. For this project, school buses and metro buses were not the primary bus types of interest since they are not commonly found on high-speed highways where median openings between parallel bridge structures are found. Table 2.9 shows the four motorcoach type buses, separated by make and model, that were involved in crashes.

Table 2.9. Motor Coach Type Bus Counts by Make and Model.

Bus Make	Model	Class 7: 26,001–33,000 lb	Class 8: 33,001 lb and above	Grand Total
Les Autobus MCI	102DL3 Intercity/D4500	0	21	21
	J4500 Intercity	0	8	8
	102GL3 Intercity/G4500	0	7	7
	102EL3 Intercity/E4500	0	3	3
	102D3 ISTV/D4000 ISTV	0	1	1
	MC-12 Intercity	0	1	1
Van Hool	Commuter Coach	27	2	29
	Tourist Coach	5	0	5
	Double Deck Coach	1	0	1
Prevost	H3 Passenger Coach	0	10	10
	H3 Coach	0	5	5
	XL2-45 Entertainer	0	4	4
	H3-45 V.I.P.	0	2	2
	XL-45 Entertainer	0	1	1
	X3 Incomplete Passenger Coach	0	1	1
Motor Coach Industries	102DL3 Intercity/D4500	0	3	3
	102GL3 Intercity/G4500	0	2	2
	J4500 Intercity	0	2	2
	102EL3 Intercity/E4500	0	2	2
	MC-9 Intercity	0	1	1
	MC-12 Intercity	0	1	1
	102D3 ISTV/D4000 ISTV	0	1	1
	102C3 Intercity	0	1	1
	Grand Total	**33**	**80**	**113**

The most common Class 8 vehicle was the MCI Intercity D4500. The year of the D4500 buses ranged from 1993 to 2018. Figure 2.5 shows an example of the Les Autobus MCI motorcoach. Table 2.10 shows the crash counts for each model year of the MCI Intercity D4500.

Figure 2.5. Example of an MCI D4500 (*2*).

Table 2.10. Model Year of MCI Intercity D4500 Buses Involved in Crashes.

D4500 Year Model	Crash Count
1993	1
1995	1
1996	1
1997	2
1998	4
1999	2
2001	1
2003	3
2005	1
2006	1
2008	1
2009	3
2014	1
2016	1
2018	1
Grand Total	**24**

The next most common motorcoach involved in the crashes was the Van Hool commuter coach bus, which is in Class 7. The bus year ranged from 2000 to 2015. Table 2.11 shows the crash counts for each model year of the Van Hool commuter coach bus.

Table 2.11. Model Year of Van Hool Commuter Coach Buses Involved in Crashes.

Commuter Coach Year Model	Crash Count
2000	3
2001	6
2002	3
2004	3
2006	2
2007	2
2009	3
2010	1
2013	3
2015	1
Grand Total	**27**

2.4. CRASH-CONTRIBUTING FACTORS

Crash-contributing factors include roadway design characteristics, roadside elements, environmental factors, and meteorological factors. In pursuit of this study's objectives, the research team conducted an exploratory analysis of the following crash-contributing factors:

- Operational factors:
  - Annual average daily traffic.
  - Posted speed limit.
- Temporal factors:
  - Crash time and date.
  - Weather conditions.
  - Lighting conditions.
  - Surface conditions.
- Roadway design characteristics:
  - Functional classification.
  - Roadbed width.
  - Median characteristics.
  - Lane characteristics.
  - Shoulder characteristics.
  - Roadway alignment.

2.4.1. Integrating Roadway and Crash Data

The research team integrated the crashes identified in this study and discussed earlier in this chapter with TxDOT's Roadway Highway Inventory Network Offload (RHiNO) data to conduct the crash data analyses. RHiNO is a roadway inventory database in a variety of common geographic information system (GIS) and tabular formats. Data include GIS linework and all roadway inventory attributes. TxDOT submits these data annually to the Federal Highway Administration (FHWA) as part of the Highway Performance Monitoring System program. The research team used ArcGIS tools to identify the roadway segments where the median opening crashes occurred and then integrated them.

2.4.2. Exploratory Data Analysis

2.4.2.1. Operational Factors: Posted Speed Limit and Annual Average Daily Traffic

Figure 2.6 shows the roadway posted speed limits where the median opening crashes occurred. As the figure shows, the highest number of crashes (147) occurred on roadways with 75 mi/h speed limits. Highways with 55 mi/h speed limits were the second type of roadways, with a high number (70) of median opening crashes. Figure 2.7 shows the annual average daily traffic (AADT) for all vehicles and for trucks for the roadways where median opening crashes occurred.

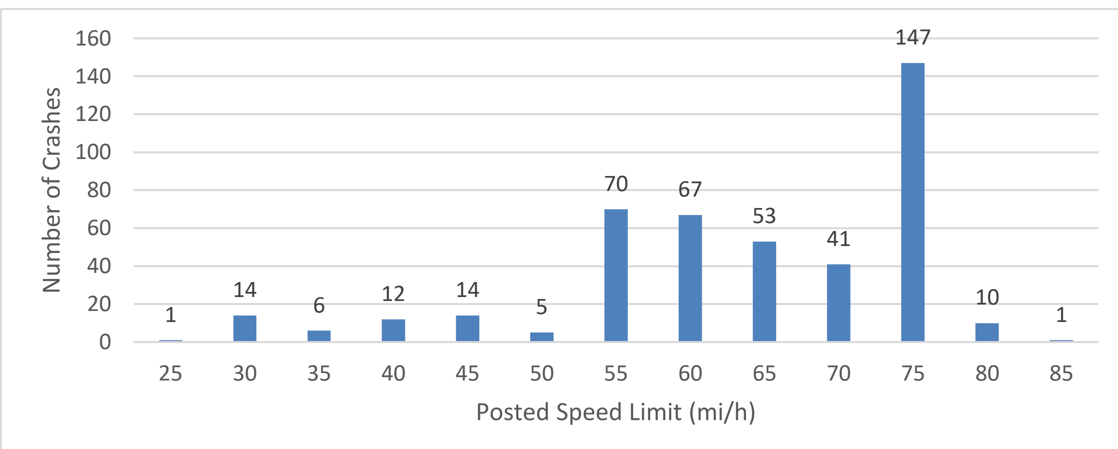
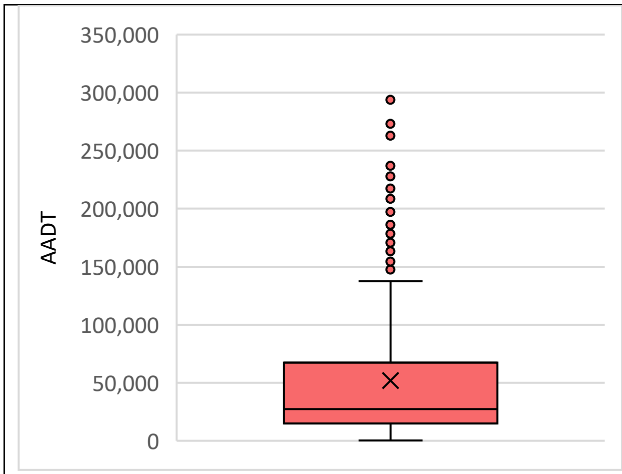
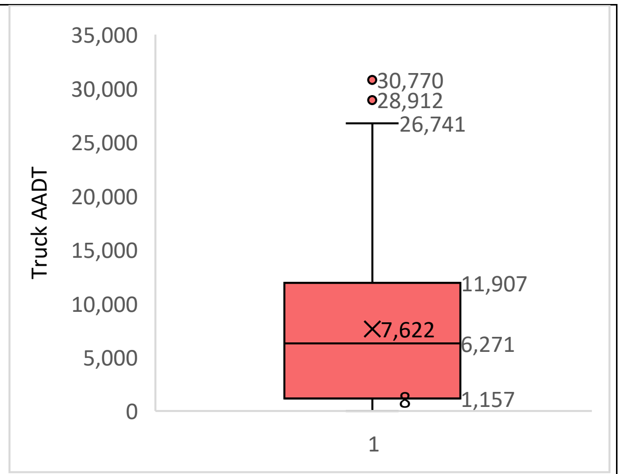


Figure 2.6. Posted Speed Limit of Roadways with Median Opening Crashes.



a) Total AADT



b) Truck AADT

Figure 2.7. AADT of Roadways with Median Opening Crashes.

2.4.2.2. Temporal Factors: Crash Time

Figure 2.8 shows the number of crashes in median openings by year of occurrence. Between the years 2014 and 2017, the number of median opening crashes remained relatively constant. The year 2018 saw a drop in number of crashes, but 2019 saw a subsequent increase. Figure 2.9 shows the number of crashes in median openings by time of day. The number of crashes during peak hours (7 a.m.–10 a.m. and 3 p.m.–6 p.m.) are somewhat higher than the rest of the day.

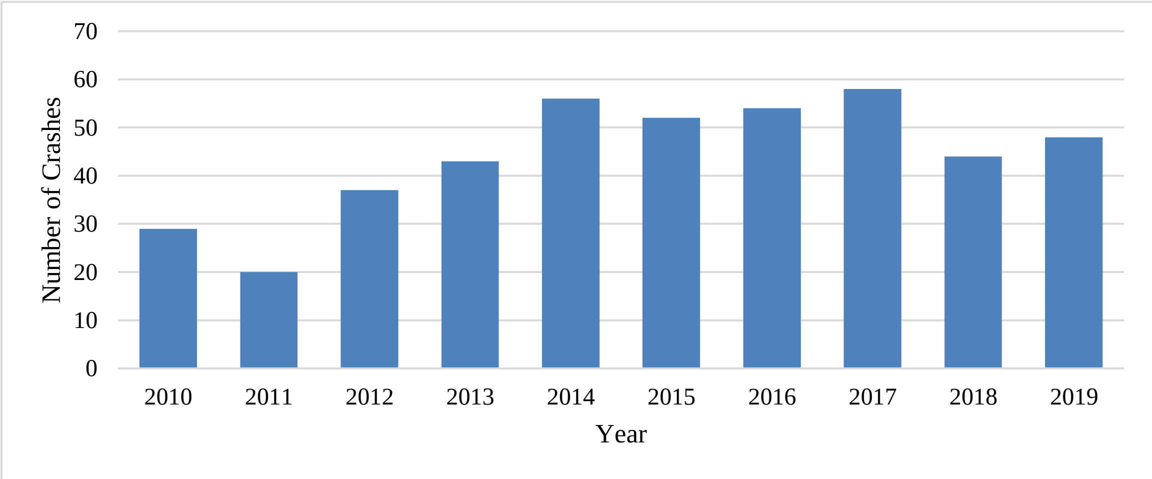


Figure 2.8. Crashes in Median Openings by Year.

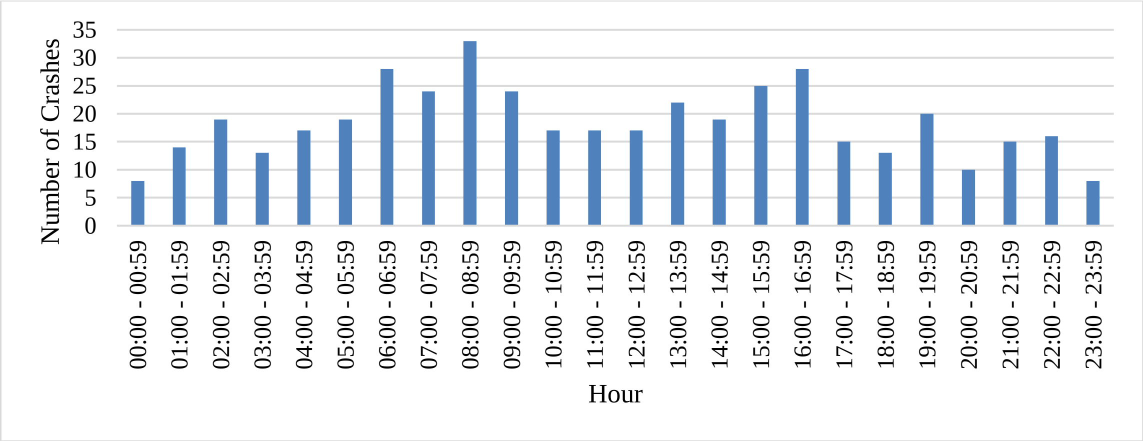


Figure 2.9. Crashes in Median Openings by Time of Day.

2.4.2.3. Lighting Conditions

Figure 2.10 shows the lighting conditions under which the median opening crashes tended to occur. Most of the crashes (247) were observed to take place during daylight. However, a significant number of crashes (110, or approximately 20 percent) were observed to take place in dark, not lighted conditions.

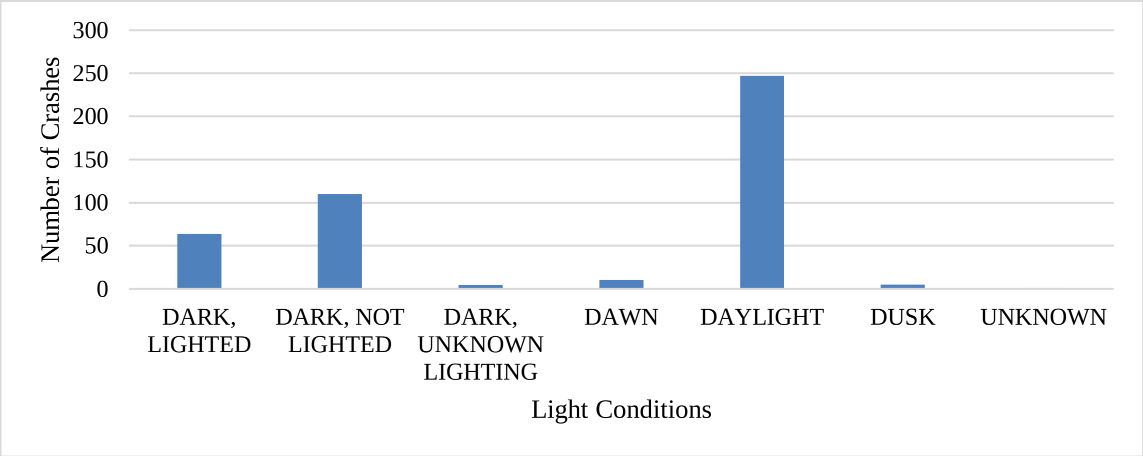


Figure 2.10. Lighting Conditions.

2.4.2.4. Surface and Weather Conditions

Figure 2.11 and Figure 2.12 show the surface and weather conditions when the median opening crashes occurred. Although most of the crashes seemed to occur during normal (dry and clear) conditions, wet and icy roads during cloudy and rainy weather also seemed to affect crash occurrence.

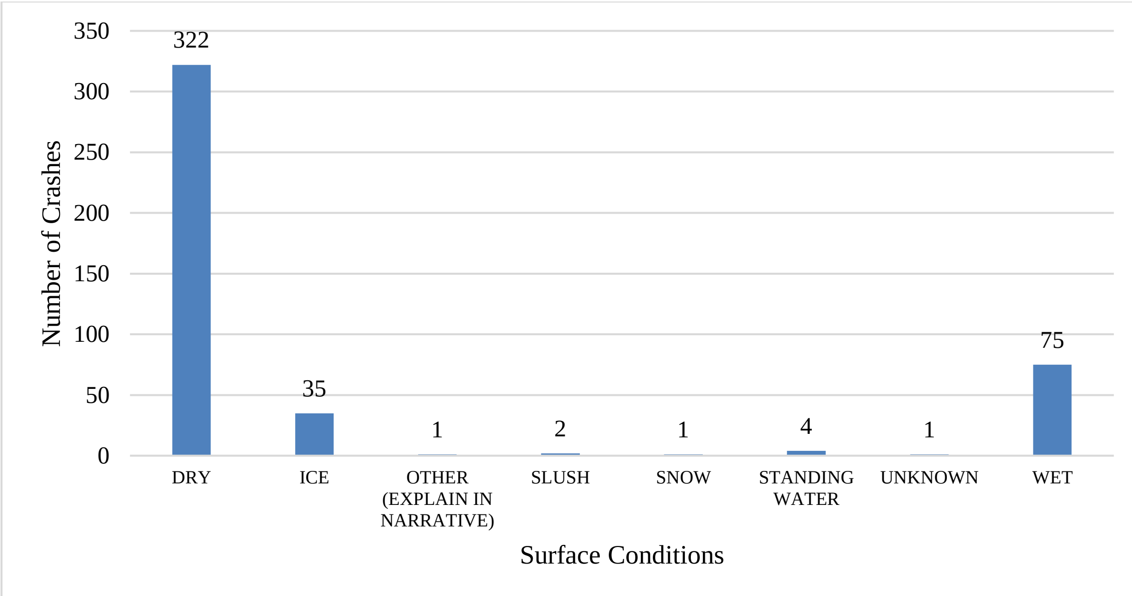


Figure 2.11. Surface Conditions.

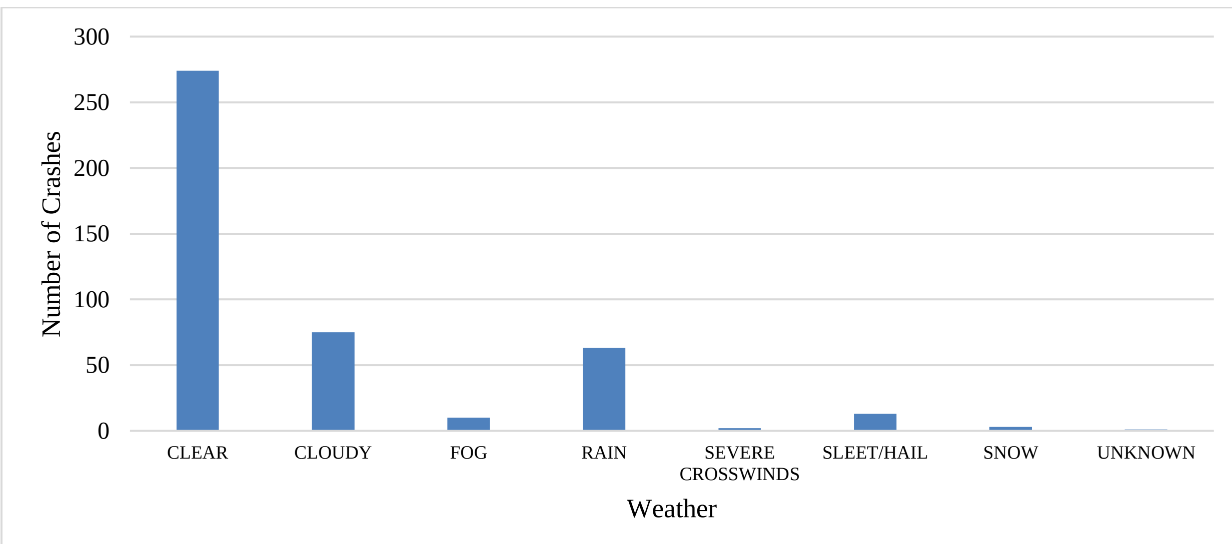


Figure 2.12. Weather Conditions.

2.4.3. Roadway Design Characteristics

2.4.3.1. Functional Classification

Functional classification of roadway is determined based on the operational, design, and access characteristics of roadways and is divided into the following classes:

- Rural:
  - R1—Rural Interstate.
  - R2—Rural Other Freeway.
  - R3—Rural Principal Arterial.
  - R4—Rural Minor Arterial.
  - R5—Rural Major Collector.
- Urban:
  - U1—Urban Interstate
  - U2—Urban Other Freeway
  - U3—Urban Principal Arterial
  - U4—Urban Minor Arterial
  - U5—Urban Major Collector.

Figure 2.13 shows a breakdown of the median opening crashes by functional classification.

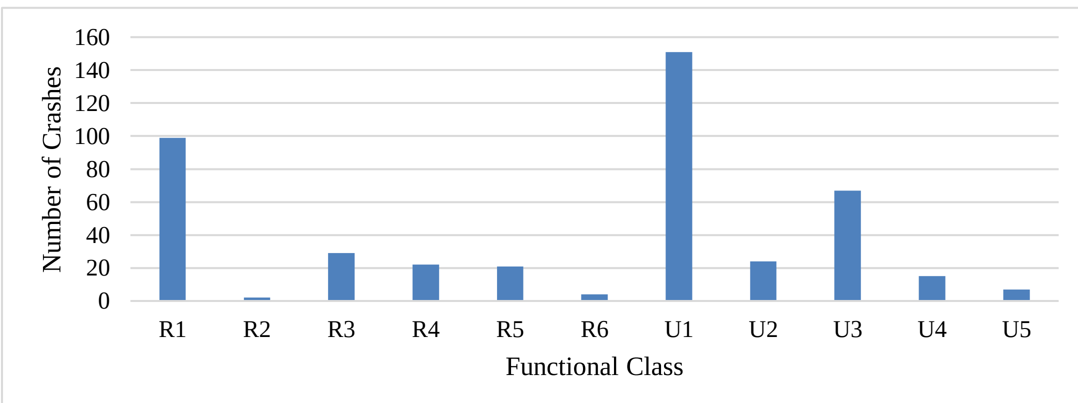


Figure 2.13. Median Opening Crashes by Functional Classification.

2.4.3.2. Highway System

Table 2.12 presents the highway systems (as defined by TxDOT) with median opening crashes.

Table 2.12. Highway Systems with Median Opening Crashes and their Abbreviations

Highway System	Abbreviation
Business IH Highways	BI
Business State Highways	BS
Business US Highways	BU
Business Farm to Market Roads	BF
Interstate Highway	IH
Ranch to Market Road	RM
State Highway	SH
State Highway Loop	SL
State Highway Spur	SS
U. S. Highway Alternate roadway	UA
U. S. Highway Spur	UP
United States Highway	US

Figure 2.14 shows the highway system of roadways where median opening crashes occurred. As can be observed, most of the crashes took place on interstate highways (IH), state highways (SH), farm-to-market (FM) roads, and US highways (US).

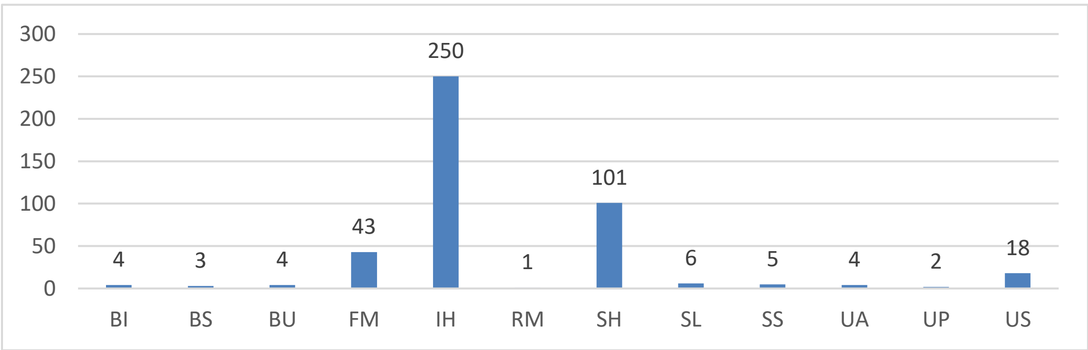


Figure 2.14. Median Opening Crashes by Highway System.

2.4.3.3. Roadbed Width

Figure 2.15 shows the descriptive statistics of roadbed width. As the figure shows, most of the crashes occurred on roadways with at least a 72-ft-wide roadbed width.

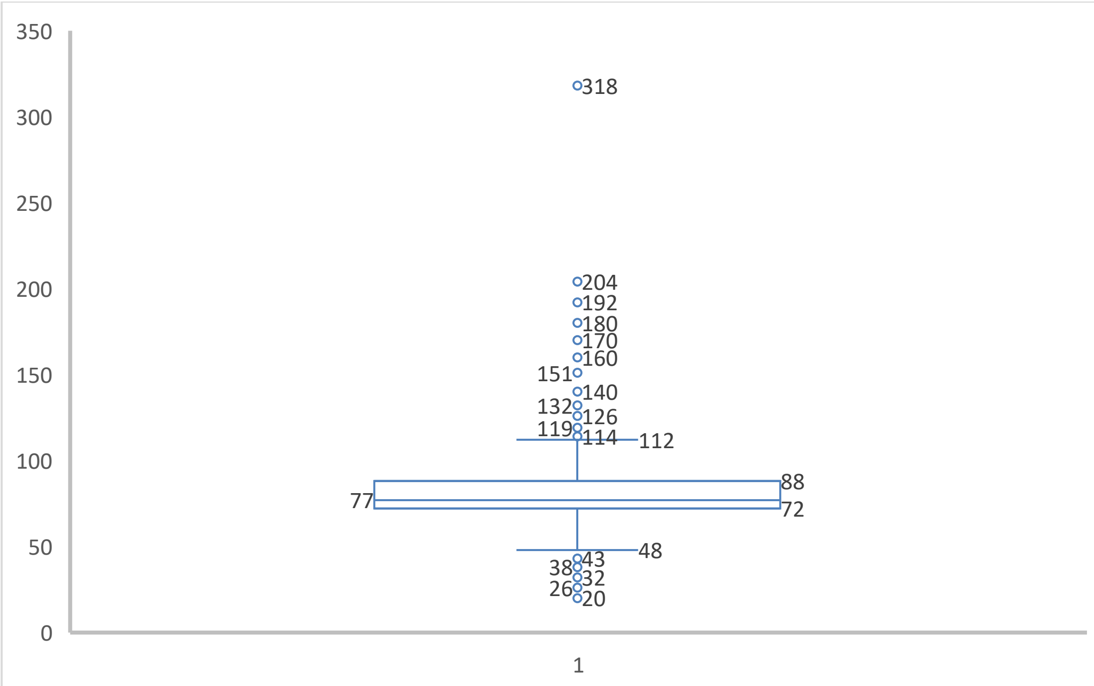


Figure 2.15. Median Opening Crashes by Roadbed Width.

2.4.3.4. Median Type and Width

Figure 2.16 and Figure 2.17 show the median type and width where crashes occurred. As shown, most of the crashes took place on highways with either unprotected medians or positive barriers, such as guardrails. This finding corresponds to the initial issue investigated in this project: the thought that guardrails and sloped medians funnel errant vehicles to the opening between parallel structures. Last, the median width of locations with median opening crashes was 28 ft on average, while the range was between 2 ft to 65 ft.

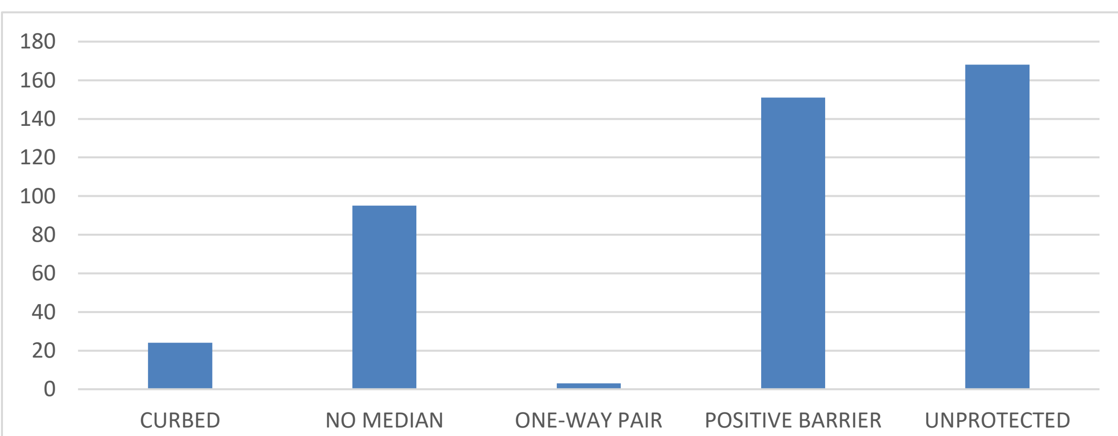


Figure 2.16. Median Opening Crashes by Median Type.

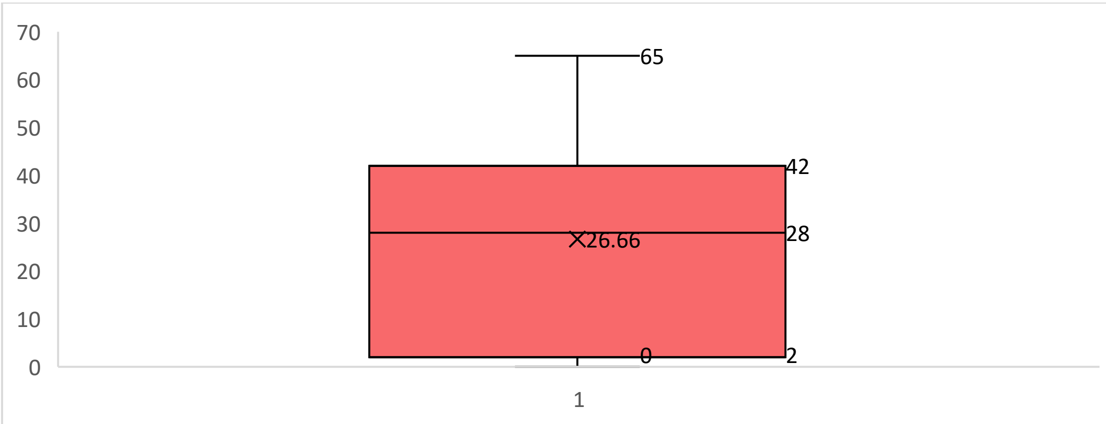
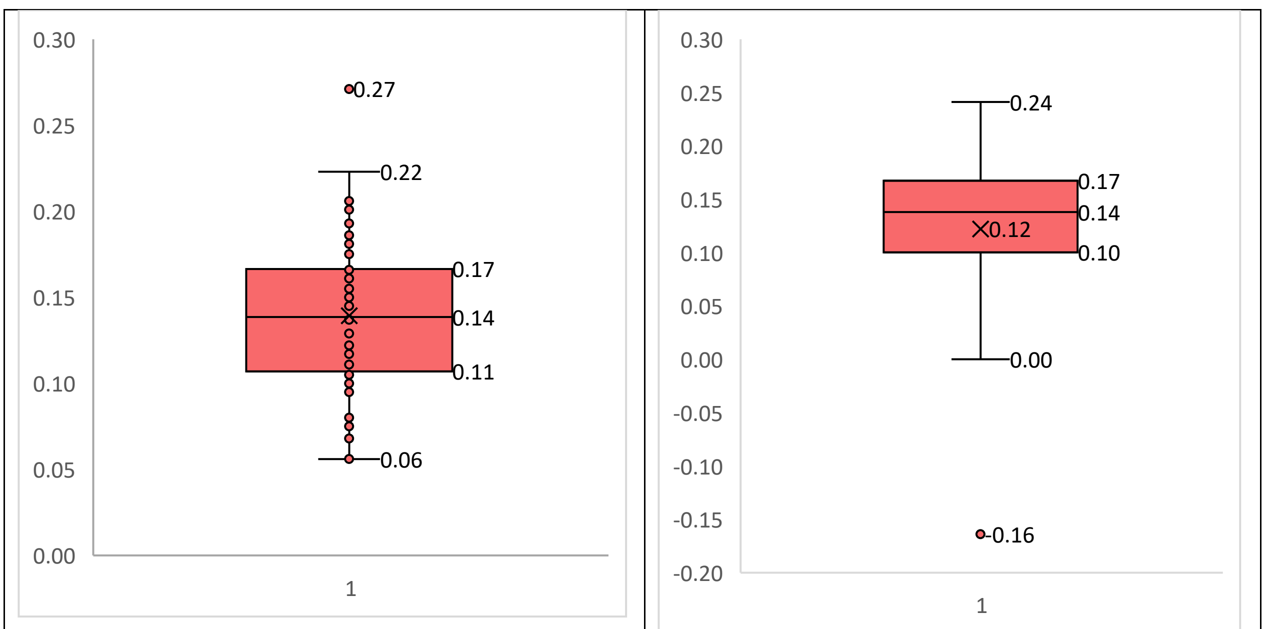


Figure 2.17. Median Opening Crashes by Median Width.

2.4.3.5. Median Slope

All of the parallel structure crash locations were reviewed using Google Earth in order to calculate the slope of the median involved in the crash. Of the 312 crashes investigated, 98 were determined to have occurred in locations where the slope was considered non-negligible. The slopes of the medians for the 98 locations were obtained through a slope/image analysis process that was able to calculate the slope of the medians from Google Earth photos. The research team inspected both the fore and back slope in this analysis. The results indicated that the average slope of the median where these crashes occurred was 0.14 percent. Figure 2.18 shows the results of the analysis.



a) Fore Slope	b) Back Slope

Figure 2.18. Median Opening Crashes by Box Plot of Slope Degree.

2.4.3.6. Lane Number and Width

Figure 2.19 and Figure 2.20 show the number of lanes and lane width of roadways with median opening crashes. As shown, most of the crashes took place on four-lane highways (257).

The average lane width of crash locations was 12 ft, although the lane width was observed to range between 9 ft to 14 ft.

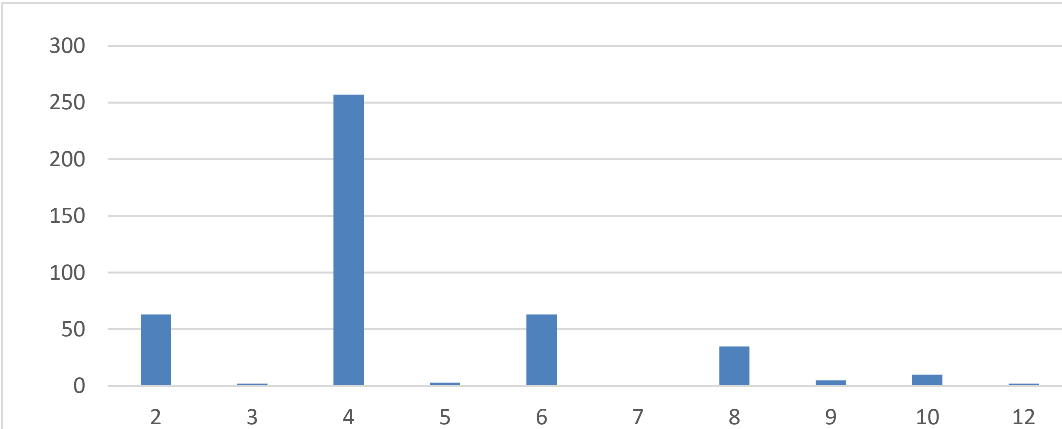


Figure 2.19. Median Opening Crashes by Number of Lanes.

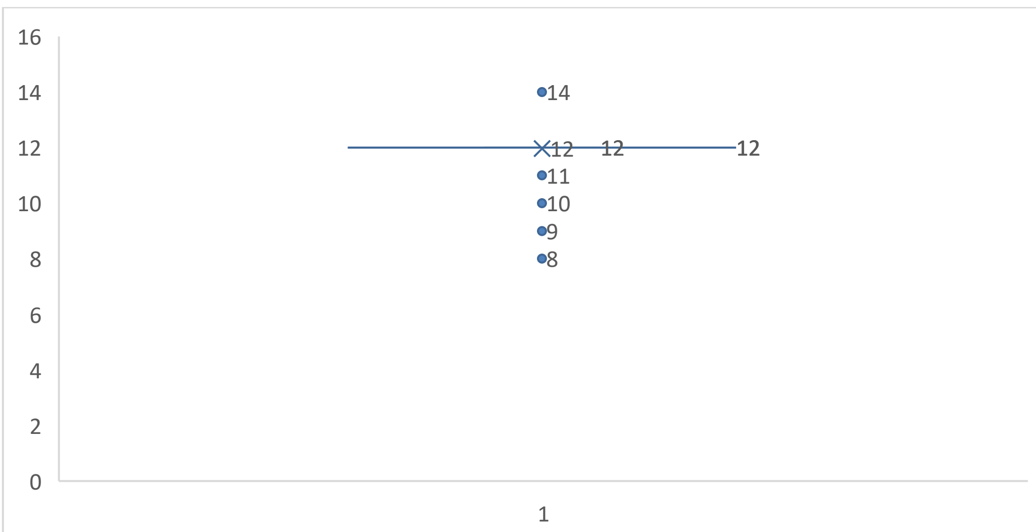


Figure 2.20. Median Opening Crashes by Box Plot of Lane Width.

2.4.3.7. Shoulder Type and Width

Figure 2.21 and Figure 2.22 show the type and width of roadway shoulders where the median opening crashes occurred. As the figures show, median opening crashes occurred on highways with surfaced shoulders. The widths of the inside and outside shoulders of roadways with median opening crashes were 8 ft and 10 ft, respectively.

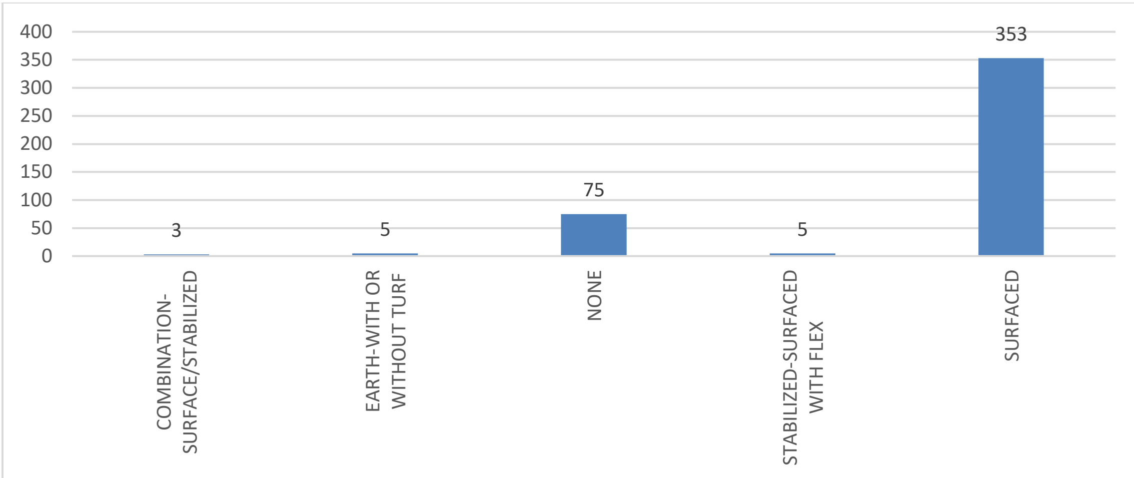
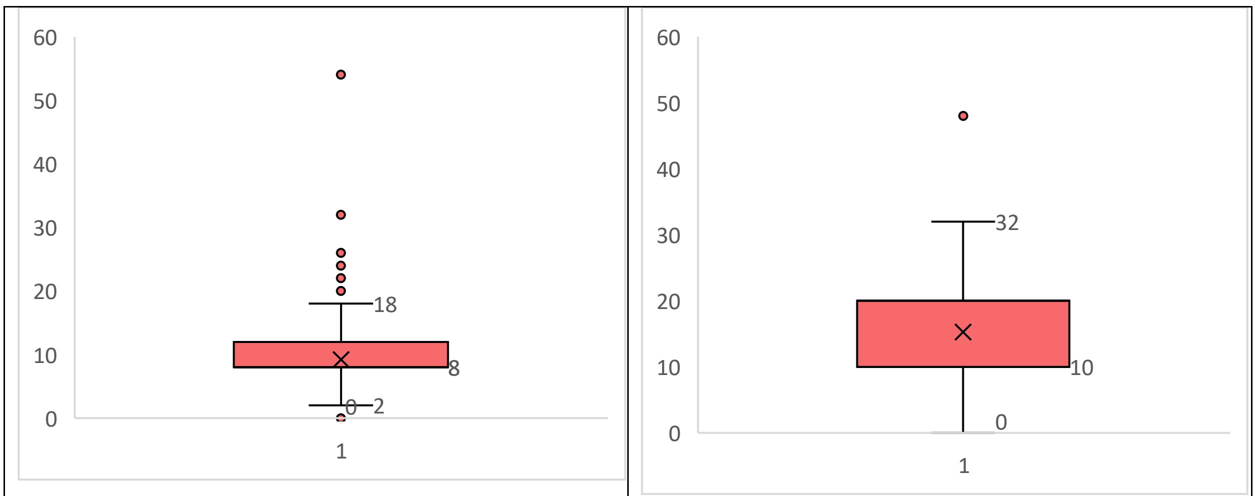


Figure 2.21. Median Opening Crashes by Shoulder Type.



a) Inside shoulder width

b) Outside shoulder width

Figure 2.22. Median Opening Crashes by Shoulder Width.

2.4.3.8. Roadway Alignment

Figure 2.23 shows the roadway alignment (horizontal and vertical curve) of roadways with median opening crashes. Most of the crashes occurred on straight and level highways, indicating that horizontal and vertical curves may not be contributing factors in the occurrence of this crash type.

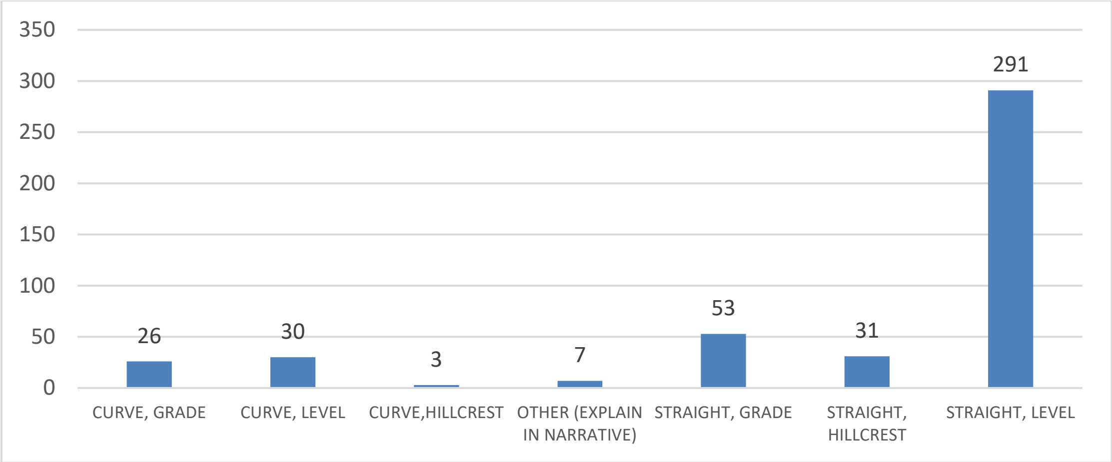


Figure 2.23. Median Opening Crashes by Roadway Alignment.

2.5. DATA ANALYSIS CONCLUSIONS

The research team completed a systematic approach analysis of the crash data and roadway characteristics to evaluate characteristics associated with crashes within the median opening between parallel bridge structures. This information aided the research team in developing test parameters and also in identifying characteristics that could be utilized for identifying sites that might benefit from MOPS implementation.

CHAPTER 3. DEVELOPMENT OF A MEDIAN OPENING PROTECTION SYSTEM

3.1. CURRENTLY AVAILABLE VEHICLE ARRESTING SYSTEMS

3.1.1. Net Vehicle Arresting Systems

The Dragnet vehicle arresting barrier (*3*) system uses a mesh net to span between two end posts. This mesh is connected to a set of steel tapes that unspool during a vehicular impact. The pull out of this steel tape dissipates the impact energy and safely brings the vehicle to a stop. The two end posts are bolted to concrete piers that are embedded 4 ft below grade. The span distance of the net can vary depending on the installation, and the top of the net rests at approximately 48 inches above grade. Because the net is anchored at the two ends, additional measures must be taken to maintain proper height above grade when installed in a sloped median. Figure 3.1 shows a photo of this system.

Figure 3.1. Vehicle Arresting Net (*3*).

The Dragnet can safely stop a 20,000-lb truck traveling 52 mi/h in 200 ft. The Dragnet can stop a lighter passenger vehicle in a much shorter distance, depending on the impacting speed. The Dragnet also has modifications available to arrest much larger vehicles traveling at faster speeds. Maintenance is relatively simple after an impact, with the replacement of only the steel tapes and mesh net. Standard groundskeeping or median maintenance is also relatively simple. While the net prevents large equipment from mowing in that specific area, the equipment can easily drive around the system and resume mowing. Groundskeeping teams can then mow closely around the system with smaller equipment.

The chain link fence vehicle arresting system (*4*) is the ancestor of many current net-based arresting systems. It was developed at the Texas Transportation Institute (now known as the Texas A&M Transportation Institute [TTI]). It incorporates many of the same details as the Dragnet. This net system is comprised of a chain link fence attached with cables to energy absorbers (metal benders) at each end. The metal benders consist of coiled metal tapes that bend around a series of steel pins and are mounted on top of wooden guardrail posts embedded 48 inches deep in 12-inch-diameter concrete footings. When the system is engaged, the tapes are pulled through the series of pins, which exert a stopping force dependent on the size of the tape. The chain link fence spans 47 ft and reaches a nominal height of 48 inches. The test installation was evaluated and approved for implementation on a median with a 12:1 side-slope ratio. Figure 3.2 shows a drawing of this system.

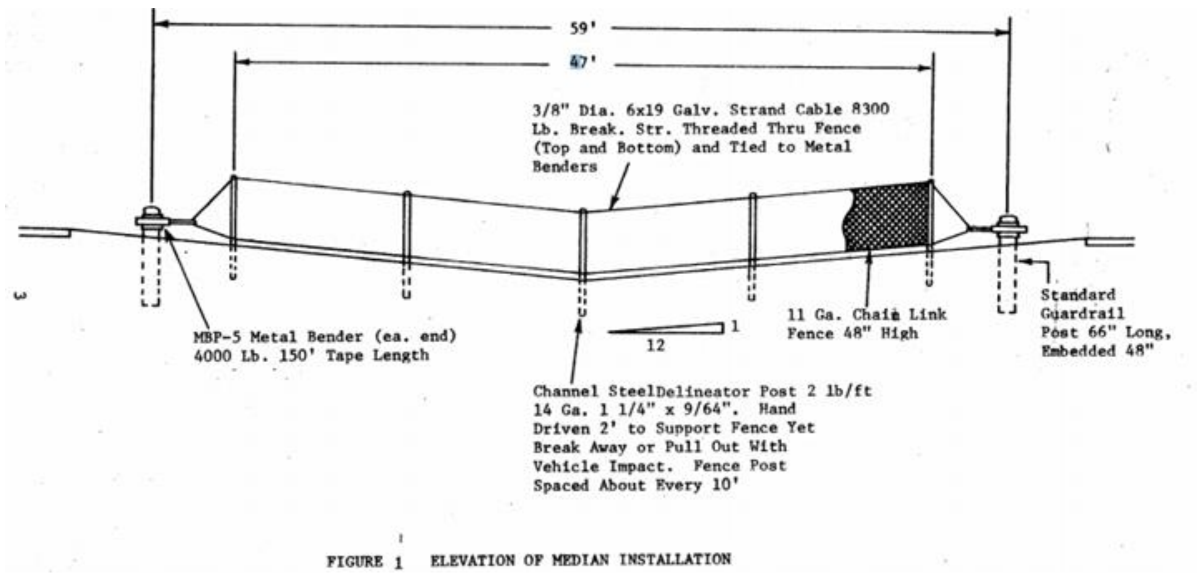


Figure 3.2. Chain Link Fence Vehicle Arresting System Installation Drawing (*4*).

This system successfully stopped a 4000-lb car moving 57 mi/h within 60 ft (*4*). The system was additionally tested with an impact angle of 30 degrees and successfully stopped a 4000-lb car moving 60.1 mi/h in 70 ft. Repair to the system after an impact requires the replacement of tapes within the metal benders. Additional replacement of the breakaway delineator posts is required to fix the chain link fence in place. Groundskeeping around this system can be completed using smaller mowing equipment, but the system provides challenges to larger mowing and maintenance equipment.

Table 3.1 lists advantages and disadvantages of net vehicle arresting systems.

Table 3.1. Advantages and Disadvantages of the Net Vehicle Arresting Systems.

Advantages	Disadvantages
Low occupant deceleration	Long stopping distances
Minimal footprint allows water flow	Concrete footings required
Minimal disruption to standard groundskeeping	—
Adapted to a median slope	—

3.1.2. Low-Density Engineered Materials

3.1.2.1. Engineered Material Arresting System

An engineered material arresting system (EMAS) (*5*) is a cellular cement arresting bed. The material is a set mixture of portland cement, an air entraining foaming agent, and water. Each cement brick is 4 ft wide by 8 ft long with varying thicknesses. A 1-inch topcoat of cement slurry is applied on top of the test bed. The installation is 40 ft wide by 376 ft wide, with a taper to 25 inches deep. While the specific application described in (*5*) used a flat installation surface, the system can be modified for sloped conditions. When impacted, the system deforms and applies a drag force that safely and predictably decelerates the test vehicle. Figure 3.3 shows a photo of this system arresting an airplane.

Figure 3.3. EMAS Airplane Test (*5*).

This system was evaluated using a B-727 aircraft weighing 131,600 lb (*5*). The B-727 was traveling at 55 knots (approximately 63.3 mi/h) and was successfully brought to rest with a stopping distance of 278 ft. Maintenance to the system after impact only involves replacing damaged cement bricks. The unaffected bricks may be left in place. Because this system will be placed at grade level, groundskeeping will not be required in this area. Despite this system being designed for aircraft use, a modified cement brick composition could be developed for roadway vehicles. Table 3.2 lists advantages and disadvantages of the EMAS.

Table 3.2. Advantages and Disadvantages of the EMAS.

Advantages	Disadvantages
Low occupant deceleration	Long stopping distances
Below grade, which allows water flow	Development process required for proper brick composition
No groundskeeping required	More costly than other options

3.1.2.2. EMAS Alternative to Runaway Truck Ramp

The EMAS alternative to runaway truck ramp system (*6*) is an arresting bed intended as an alternative to traditional gravel or gravity-based runaway truck ramps. This design consists of a variable number of deformable cement blocks similar to the airport EMAS. The cementitious block units are 110 cm in length and 70 cm in width, and they range from 15 cm to 60 cm in thickness. The total length of the system is 38.5 m long and 5.5 m wide. The design was implemented on flat ground; however, the system's units can be modified to allow for median slope applications. Figure 3.4 shows a photo of this system arresting a truck.

Figure 3.4. Vehicle Evaluation of Arresting Bed (*6*).

This system was evaluated using a 88,000-lb truck traveling at 35 mi/h (*6*). The system successfully brought the vehicle to rest in 83.3 ft. Maintenance to the system after impact only involves replacing damaged cement bricks. The unaffected bricks may be left in place. Groundskeeping will not be required in this area because the cement blocks prevent vegetation from growing. Table 3.3 lists advantages and disadvantages of this system.

Table 3.3. Advantages and Disadvantages of the EMAS Alternative to Runaway Truck Ramp.

Advantages	Disadvantages
Low occupant deceleration	Long stopping distances
Below grade which allows water flow	More costly than other options
No groundskeeping required	—

3.1.3. Bullnose System

The bullnose system (*7–9*) is a guardrail installation developed by researchers at the Midwest Roadside Safety Facility (MwRSF) for the purpose of protecting large gore areas. It is composed of a thrie-beam rail mounted to 22 wood posts (11 posts on each side). A steel cable is installed behind the first thrie-beam section to prevent rail rupture. The thrie beam has a radius of 1580 mm, and the barrier is a nominal height of 804 mm. The system is 4500 mm wide and 20,144 mm long. This bullnose system was designed and tested on flat ground. Because of the complexity of the system, a large development effort would be required to modify it for sloped medians. Figure 3.5 shows a photo of the bullnose system.

Figure 3.5. MwRSF Bullnose System (*7*).

The system was successfully evaluated head on with an 886-kg small car impacting the system at 103.3 km/h (*7–9*). The test vehicle came to rest 6.55 m downstream. Furthermore, this bullnose system successfully brought a 2010-kg pickup truck impacting at 103.5 km/h to a stop in 16.33 m. After the test, much of the system requires costly replacement. Because of the design of the bullnose, groundskeeping crews will not be able to use large equipment to maintain the protected area. Therefore, smaller equipment will be required for upkeep. Table 3.4 lists advantages and disadvantages of the bullnose system.

Table 3.4. Advantages and Disadvantages of the Bullnose System.

Advantages	Disadvantages
Large amount of previous testing and research	Restrictive to groundskeeping equipment
Short stopping distance	Complete barrier replacement after impact
—	Higher occupant decelerations
—	Significant development effort to account for sloped median

3.1.4. Sand Barrels:

Several sand barrel systems exist in the current market, and each varies slightly from manufacturer to manufacturer. Sand barrel systems arrest vehicles by displacing large volumes of sand. The sand barrels typically consist of three main parts: the plastic barrel, the sand filling, and the plastic lid. The sand barrels range widely in weight, from 200 to over 2000 lb when filled. The barrels are arranged in consecutive rows, but the overall system configuration varies per speed application. These systems were designed for installation on a flat surface, so it would need to be modified for a sloped median. Figure 3.6 shows a photo of a sand barrel array. These systems obstruct groundskeeping equipment, so groundskeeping will require manual effort with little help from larger equipment. Table 3.5 lists advantages and disadvantages of sand barrel systems.

Figure 3.6. Sand Barrel Application (*10*).

Table 3.5. Advantages and Disadvantages of Sand Barrel Systems.

Advantages	Disadvantages
Low cost	Higher occupant decelerations
Short stopping distance	Restrictive to mowing equipment
Low-cost repair and replacement	Has not been developed for larger vehicles

3.1.5. Wire Rope Barrier Systems

Several wire rope barrier systems were investigated in this project. These systems can be separated into two broad categories: safety and security systems. The safety systems are the typical wire rope barriers that can be seen in roadway medians across the country. These systems are designed to take oblique impacts from errant motorists. These systems safely redirect the impacting vehicle while minimizing the risk of harm to the occupants.

Conversely, the security systems are meant to arrest vehicles from head-on impacts. However, these systems typically significantly damage the impacting vehicle, which could cause serious injury to the occupants. While these systems could potentially be modified to minimize occupant risk, they would then essentially behave similar to the net-based arresting systems described previously. Therefore, the research team decided to remove the wire rope systems from further investigation or evaluation.

3.1.6. Runaway Truck Ramps

State DOTs have varying research and guidelines regarding runaway truck ramps (also known as truck escape ramps) (*11*, *12*). These guidelines describe the physical geometry of the runaway truck ramp required for the design vehicle size and speed. Figure 3.7 shows a photo of a runaway truck ramp. The AASHTO's *A Policy on Geometric Design of Highways and Streets* (Green Book) (*13*) provides several common recommendations:

- Ramp must be long enough to counteract the kinetic energy of the vehicle.
- Ramp must be wide enough to fit multiple vehicles (allow emergency vehicle access).
- Surface material must be clean, with a high rolling resistance. It must also be a rounded aggregate with proper drainage capabilities.
- Ramp must have a minimum depth of 36 inches, with a recommended depth of 42 inches.
- Ramp entry must be considered safe for vehicles traveling at high speeds.
- Signs indicating the ramp must be provided with enough distance to allow for ample driver reaction.

Figure 3.7. Truck Escape Ramp in Colorado (*12*).

Truck escape ramps use gravity and/or frictional resistance to safely arrest vehicles. Most use a gravel-like material that slowly decelerates the impacting vehicle. The frictional resistance of this material is a key element that needs to be carefully considered when designing a truck escape ramp. To aid the frictional material in slowing the vehicle, engineers often design truck escape ramps with an upward grade to force the impacting vehicle to fight against gravity when traveling forward. After a truck escape ramp is used, repair crews would regrade the ramp to smooth any tracks that were made by the impacting vehicle. While the repair effort may be minimal, the groundskeeping effort could be large. The gravel-like material would prevent large equipment from accessing the area but would allow vegetation to grow through the depth of the ramp. Therefore, manual groundskeeping would be required for the filled area. Table 3.6 lists advantages and disadvantages of truck escape ramps.

Table 3.6. Advantages and Disadvantages of Truck Escape Ramps

Advantages	Disadvantages
Minimal repair required	Long stopping distance
Low occupant decelerations	Prevents use of large groundskeeping equipment
—	Requires maintenance due to vegetation growth through friction material
—	Could prevent water flow in median

3.1.7. Technology Review Conclusions

The research team investigated readily available technologies for their possible implementation in a MOPS. During this investigation, each technology was analyzed with respect to the following characteristics:

- Arresting length for different vehicle types and speeds.
- Installation site requirements and conditions.

- Impact vehicle weight and speed capacity.
- Accessibility to median beyond arresting system for groundskeeping and maintenance.
- Cost of installation, maintenance, and repair/replacement.
- Anchorage requirements.
- Capture height of arresting system and how it could be adapted to sloped terrain.

Based upon this review, the research team adapted one of these technologies to develop the MOPS, as described in the next section.

3.2. MEDIAN OPENING PROTECTION SYSTEM

The research team developed a MOPS based upon the readily available technologies investigated and the analytical crash data reviewed. After the technology investigation, TxDOT and the research team chose to pursue the use of net-based vehicle arresting technology. Consequently, the research team worked with Impact Absorption, a roadside safety company, to adapt its net arrestor product to the median opening condition. This system uses a mesh net that spans between two end anchors. This mesh is connected to a set of steel tapes that unspool after the net wraps around the front of a vehicle during an impact. The unspooling of this steel tape dissipates the impact energy and helps to safely bring the vehicle to a stop. The two end anchors are attached to concrete piers. The net is anchored at the midspan of the median ditch section to hold the net at the appropriate catch height. This configuration will minimize the risk of underriding the net during an impact. More details regarding the specific energy absorbers and the net configuration are included in the final installation drawings. Figure 3.8 shows a photo of this system.

Figure 3.8. Vehicle Arresting Net (*3*).

The net arrestor system has been installed in Texas to provide hazard protection similar to the median opening scenario. In Wise County, the net arrestor was installed on FM 1658 to protect the roadside ditch area adjacent to the bridge ends (4).

Figure 3.9 shows the installation. This is a similar condition to the median opening, as it shows the net anchored at the center of the ditch.

Figure 3.9. Net Arrestor Installed in Wise County (photo courtesy of A. Cruz).

The next chapter presents the proposed test installation for the recommended MOPS design, with the MOPS constructed in a 6:1 V-ditch median. The crash data discussed previously showed that the median slope of the median openings involved in crashes with passenger vehicles was 14 degrees. This approximately equates to a slope of 7:1. The research team selected a 6:1 slope because it is slightly steeper than common median slopes and would increase the chance of the vehicle underriding the net. The width of the median was chosen to be 28 ft, which was the median width found in the crash data analysis.

The MOPS is intended to be one component in a redundant roadside safety system designed to mitigate the severity of median opening crashes. The first line of defense is provided by the metal beam guard fence (MBGF), which protects errant motorists from impacting the bridge ends and, to some extent, the median opening. Vehicles leaving the roadway in close proximity to the bridge end would be redirected by the MBGF. Vehicles leaving the roadway upstream of the MBGF would encounter the MOPS before encountering the hazard in the opening between the parallel bridge structures.

The proposed MOPS includes two sets of nets spaced 50 ft apart. The first net is designed to arrest passenger vehicles before they contact the second net, which is designed for heavier vehicles like motorcoaches. Because the vast majority of the median opening crashes occur with passenger vehicles, most of the impacts and repairs on the MOPS will be limited to the first net. This will help minimize repair and replacement costs.

The two nets are installed on a mostly standard TxDOT mowstrip. This minimizes the need for hand mowing/trimming by maintenance crews. The differences between the standard TxDOT mowstrip and the MOPS slab design are the concrete strength and the inclusion of drilled shaft anchors. The nets require a 4-ft-deep drilled shaft at each end. These drilled shafts can be poured continuously with the mowstrip; thus, it is convenient to make the compressive strength of the mowstrip slab the same as the drilled shafts. The drilled shafts require a 4000 psi concrete mix; consequently, the mowstrip is recommended to have this same compressive strength.

The following chapters discuss the system details and the full-scale crash testing and evaluation of MOPS.

CHAPTER 4. SYSTEM DETAILS

4.1. TEST ARTICLE AND INSTALLATION DETAILS

The MOPS installation consisted of two impact attenuating nets, each anchored into a concrete mowstrip and pier system. The MOPS was installed in the center of a 28-ft-wide 6:1 V-shape ditch. The two nets were separated by 50 ft along the length of the ditch. Each net was anchored with energy absorbers, which arrest impacting vehicles through the deforming of a steel tape around a series of pins or bearings. The lower cable of the first net was located 10 inches above grade. The second lowest cable on the second net was located 20 inches above grade.

Figure 4.1 presents the overall information on the MOPS, Figure 4.2 presents the overall information for the first net, and Figure 4.3 through Figure 4.8 provide photographs of the installation. Appendix A provides further details on the MOPS. Drawings were provided by TTI Proving Ground, and construction was performed by TTI Proving Ground personnel and Impact Absorption installers. TTI Proving Ground personnel supervised installation efforts.

4.2. DESIGN MODIFICATIONS DURING TESTS

In Crash Test 440210-01-2, the test vehicle impacted the second net, causing the swivel mount for the second net's energy absorber to release the energy absorber. This was not intended in the design and was undesirable for future testing. Therefore, a new swivel mount was designed and utilized for all subsequent testing, including a retest of Test 440210-01-2 (440210-01-4). Test 3-40 (440210-01-1) was not repeated because the test vehicle did not contact the second net, and therefore the swivel mount design had no effect on the test results. Figure 4.9 presents the overall information for the second net after modifications, and Figure 4.10 through Figure 4.13 provide photographs of the installation.

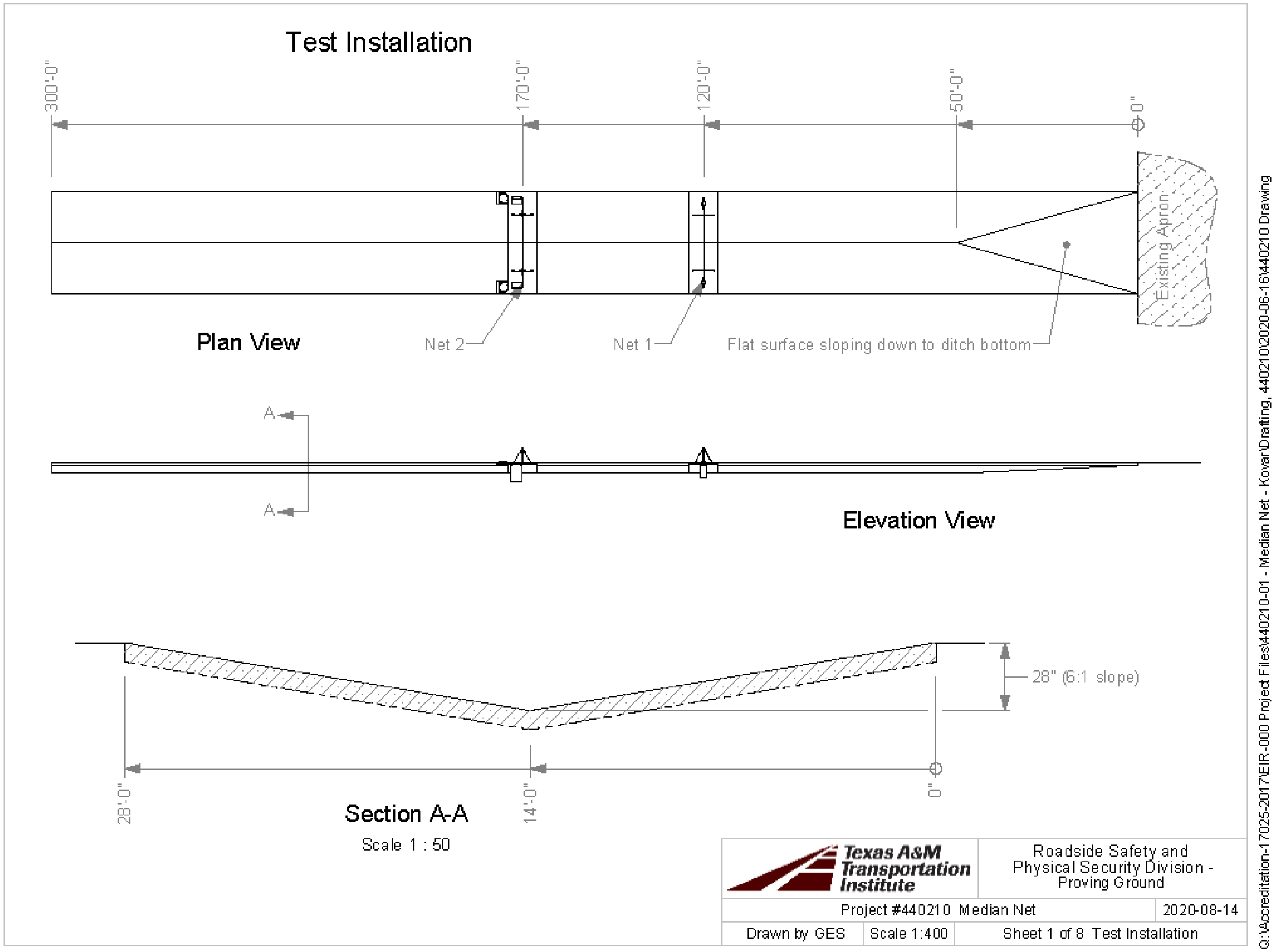


Figure 4.1. Details of Median Opening Protection System for Crash Tests 440210-01-1&2.

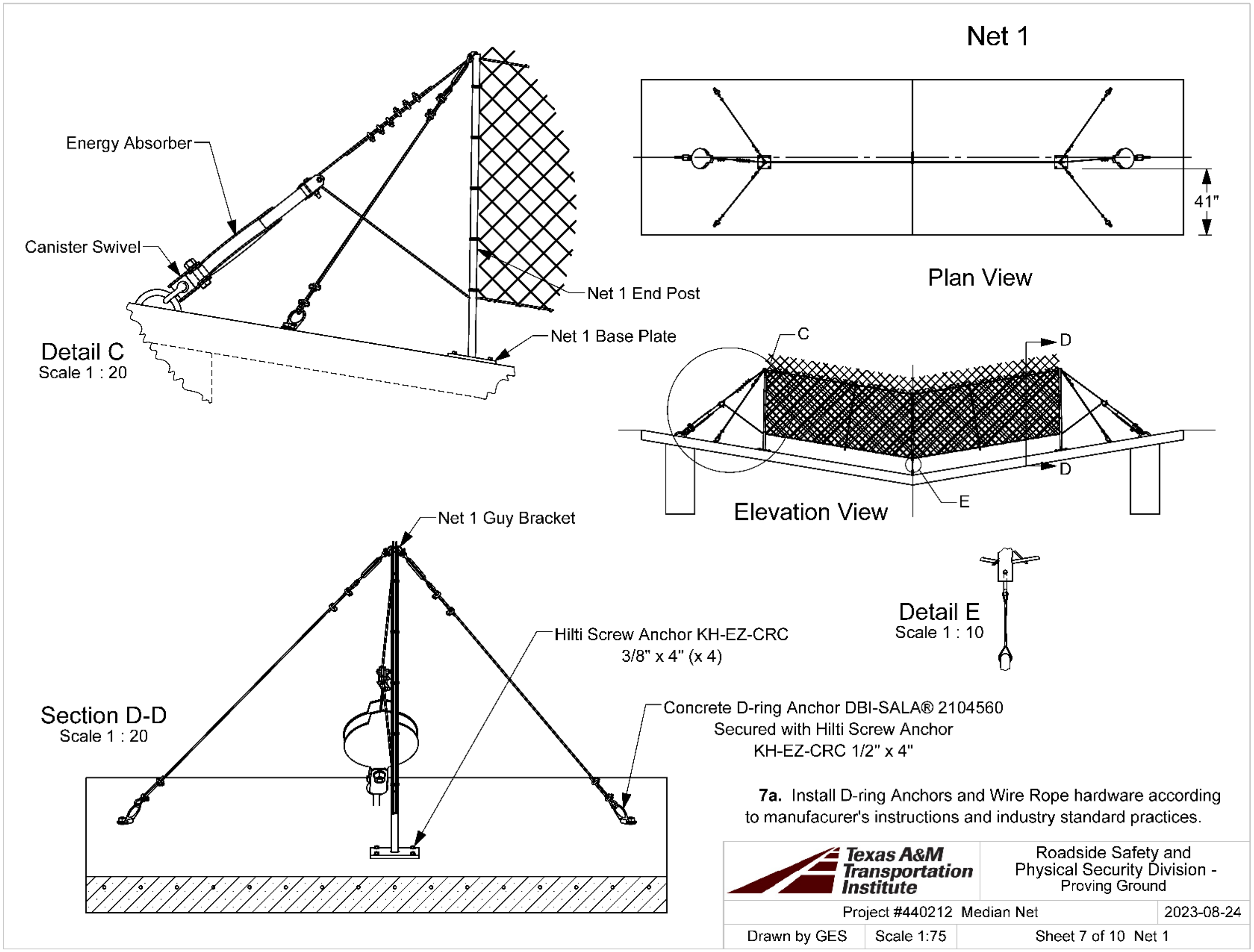


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Figure 4.2. Details of the First Median Opening Protection System for Crash Tests 440210-01-1&2.

Figure 4.3. Upstream In-Line View of the Median Opening Protection System prior to Crash Tests 440210-01-1&2.

Figure 4.4. Oblique View of the Median Opening Protection System prior to Crash Tests 440210-01-1&2.

Figure 4.5. First Median Opening Protection System prior to Crash Tests 440210-01-1&2.

Figure 4.6. Anchor Hardware for the First Median Opening Protection System prior to Crash Tests 440210-01-1&2.

Figure 4.7. Second Median Opening Protection System Net prior to Crash Tests 440210-01-1&2.

Figure 4.8. Anchor Hardware for the Second Median Opening Protection System Net prior to Crash Tests 440210-01-1&2.

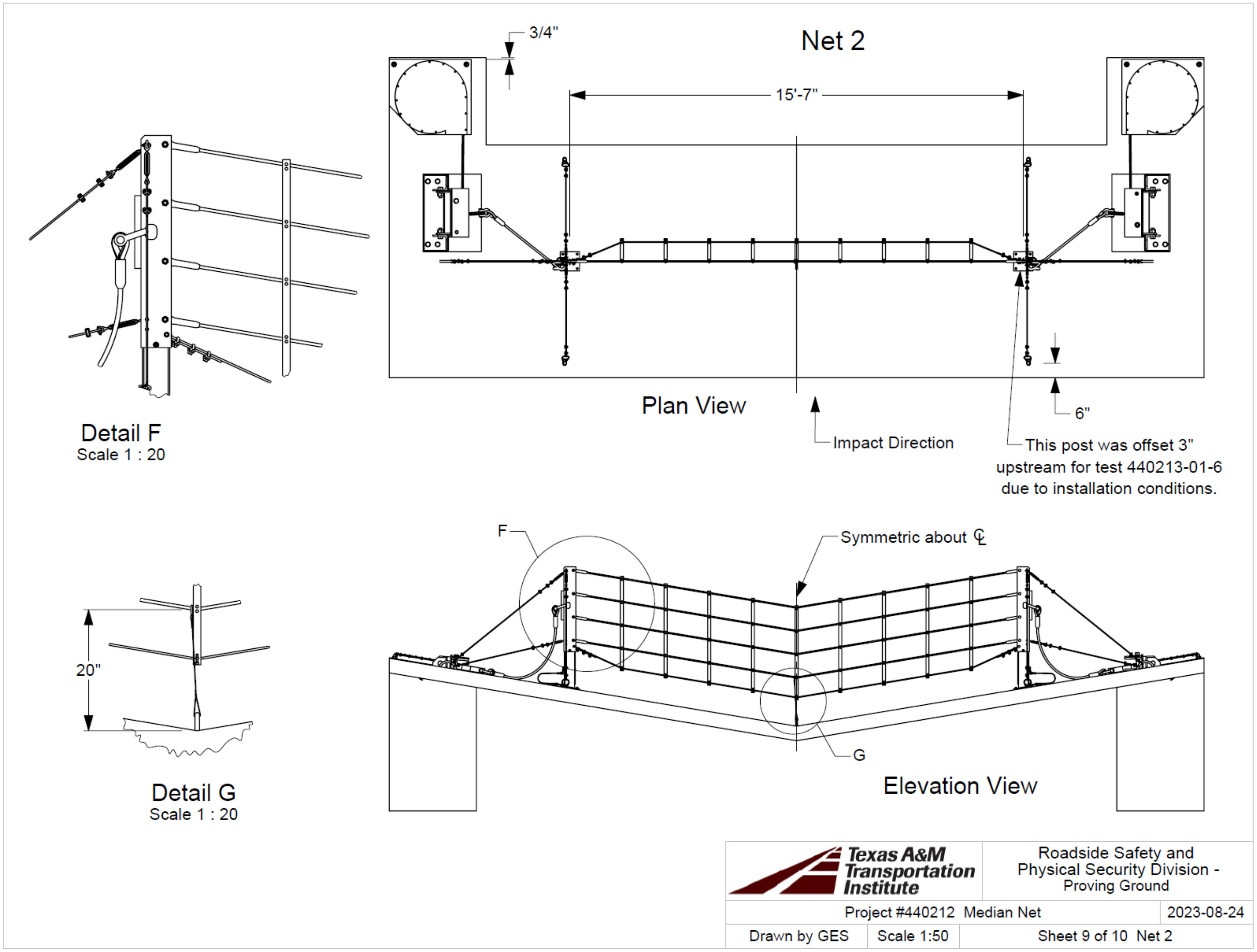

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Figure 4.9. Details of the Second Median Opening Protection System Net for Crash Tests 440210-01-4, 440211-01-3, 440211-01-5, and 440213-01-6.

Figure 4.10. Second Median Opening Protection System Net prior to Crash Tests 440210-01-4, 440211-01-3, 440211-01-5, and 440213-01-6.

Figure 4.11. Anchor Hardware for the Second Median Opening Protection System Net prior to Crash Tests 440210-01-4, 440211-01-3, 440211-01-5, and 440213-01-6.

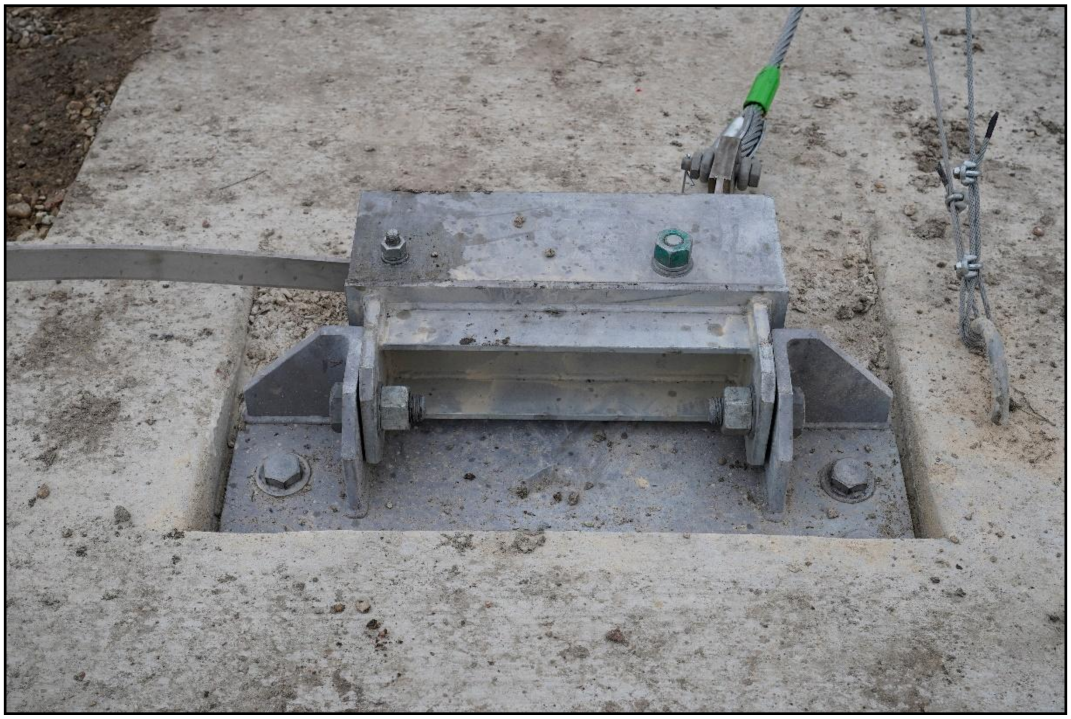

Figure 4.12. Swivel Mound System for the Second Median Opening Protection System Net prior to Crash Tests 440210-01-4, 440211-01-3, 440211-01-5, and 440213-01-6.

Figure 4.13. Swivel Mound System and Cannister for the Second Net prior to Crash Tests 440210-01-4, 440211-01-3, 440211-01-5, and 440213-01-6.

4.3. MATERIAL SPECIFICATIONS

Material certification documents for the materials used to install/construct the MOPS are on file with TTI. Table 4.1 shows the average compressive strengths of the concrete on the day of the test, August 20, 2020.

Table 4.1. Concrete Strength.

Location	Design Strength (psi)	Avg. Strength (psi)	Age (days)	Detailed Location
Footer	3600	2960	11	Footer for 4 posts
Deck	3600	2960	10	Front and back V-shape concrete deck

CHAPTER 5. TEST REQUIREMENTS AND EVALUATION CRITERIA

5.1. CRASH TEST PERFORMED/MATRIX

The TTI research team recommended performing three full-scale crash tests to evaluate the crashworthiness of the MOPS. The first two tests were *MASH* Tests 3-40 and 3-41. The third test was a non-standard test utilizing a passenger bus test involving a motorcoach. Below is a discussion on the determination of testing parameters.

The small car and the pickup truck are both standard *MASH* vehicles. While *MASH* does not currently provide a matrix for a net arrestor system, the TTI research team based this recommendation on treating the net as a resistance gate. Both a resistance gate and a net arrestor provide non-redirective protection against vehicles penetrating beyond the system. *MASH* recommends testing the resistance gates to Tests 3-40 and 3-41, which are 62 mi/h and 0-degree impacts with the *MASH* small car and the pickup truck, respectively. These two *MASH* tests are taken from the non-redirective crash cushion matrix, but *MASH* does not recommend performing the other non-redirective crash cushion tests.

MASH does not recommend testing the systems with angled impacts because the majority of impacts will be close to 0 degrees. Most locations where resistance gates are deployed direct vehicles in a 0-degree direction to the resistance gate, so most impacts will follow this direction. Furthermore, *MASH* explains that reducing the impact angle between 0 and 15 degrees would not increase the likelihood of test failure. In the MOPS application, the same logic would apply; the shape of the V-ditch median directs vehicles to a near 0-degree impact angle. *MASH* also explains that the resistance gates cannot be impacted on their sides (as a non-redirective crash cushion could) and therefore does not recommend testing resistance gates with those tests.

Last, *MASH* recommends testing resistance gates with an impact location at the quarter-point of the gate system. This is meant to evaluate asymmetrical loading on the system. The sloped median in which the MOPS is deployed minimizes the risk of vehicles impacting at locations other than the center of the system. As discussed earlier, the V-shape of the median directs vehicles to the center of the V-shape and the MOPS. Furthermore, a centerline hit would promote the potential for the small car to underride the nets and penetrate beyond the barrier. Consequently, the TTI research team recommended impacting the MOPS at the centerline of the system.

The last test in the recommended matrix involves a motorcoach or bus. The crash data analysis identified a target GVWR of 50,000 lb. *MASH* recommends an impact speed of 56 mi/h for the 22,000-lb single unit truck for TL-4 and 50 mi/h for the heavier 80,000-lb tractor-van trailer for TL-5. Since a motorcoach would need to traverse into and along the median prior to engaging the MOPS, its speed would likely be reduced in the process. Therefore, the 50 mi/h test speed was chosen.

Table 5.1 shows the test conditions and evaluation criteria for *MASH* TL-3 for non-redirective crash cushions. The target critical impact points (CIPs) for each test were determined using the information provided in *MASH* Section 2.2.1 and 2.3.2. Figure 5.1 shows the target CIP for *MASH* TL-3 tests on the MOPS.

Table 5.1. Test Conditions and Evaluation Criteria Specified for *MASH* TL-3 Non-Redirective Crash Cushions.

Test Designation	Test Vehicle	Impact Speed	Impact Angle	Evaluation Criteria
3-40	1100C	62 mi/h	0º	C, D, F, H, I, N
3-41	2270P	62 mi/h	0º	C, D, F, H, I, N
Non-Standard	Bus	50 mi/h	0º	C, D, G, H, I, N

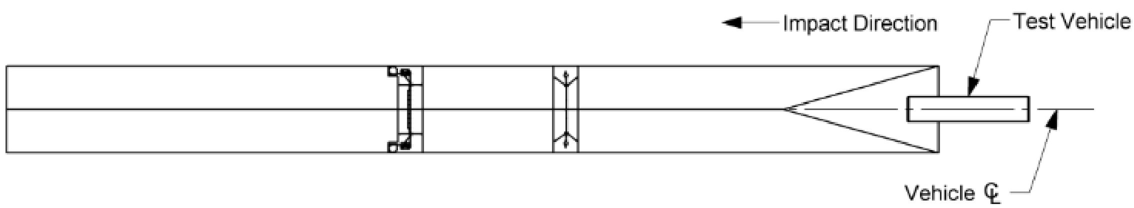

Figure 5.1. Target CIP for *MASH* TL-3 Tests on MOPS.

The crash tests and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 6 presents brief descriptions of these procedures.

5.2. EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2.2 and 5.1 of *MASH* were used to evaluate the crash tests reported herein. Table 5.1 lists the test conditions and evaluation criteria required for *MASH* TL-3, and Table 5.2 provides detailed information on the evaluation criteria.

Table 5.2. Evaluation Criteria Required for *MASH* Testing.

Evaluation Factors	Evaluation Criteria
C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.
D.	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of *MASH*.
F.	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
G.	It is preferable, although not essential, that the vehicle remain upright during and after the collision.
H.	Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.
I.	The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.
N.	Vehicle trajectory behind the test article is acceptable.

CHAPTER 6. TEST CONDITIONS

6.1. TEST FACILITY

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

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

6.2. VEHICLE TOW AND GUIDANCE SYSTEM

For the testing utilizing the 1100C and 2270P vehicles, each was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point and through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2:1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released and ran unrestrained. A system was employed that ejected the remaining coupling mechanism for guidance so as not to cause interference with the installation. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site.

In the bus crash tests, a remote control system drove the test vehicle into the test article. The remote control system included a redundant-brush electrical motor and cogged belt drive arrangement offset from the steering wheel shaft. The pedals were controlled via pneumatic cylinders for both the accelerator and brake. An engine stop system was also employed in the case of remote signal loss or manual activation by the operator of the remote control system.

6.3. DATA ACQUISITION SYSTEMS

6.3.1. Vehicle Instrumentation and Data Processing

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

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

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

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

Placement of the electronic instrumentation packages in the passenger bus vehicles is described in Table 6.1 and Table 6.2.

Table 6.1. Instrumentation Package Location for Tests 440211-01-3 and 440211-01-5.

Instrument Package	Distance from Vehicle Centerline	Height from Ground	Distance from Front Axle Centerline
Center of Vehicle	0.0 inches	53.5 inches	223.2 inches
Rear Axle	0.0 inches	53.5 inches	235.2 inches

Table 6.2. Instrumentation Package Location for Test 440213-01-6.

Instrument Package	Distance from Vehicle Centerline	Height from Ground	Distance from Front Axle Centerline
Center of Vehicle	0.0 inches	53.5 inches	208.4 inches
Rear Axle	0.0 inches	53.5 inches	214 inches

6.3.2. Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the front seat on the impact side of impact of the 1100C vehicle. The dummy was not instrumented. Additionally, two dummies were placed in the passenger seats during the bus crash tests.

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

6.3.3. Photographic Instrumentation Data Processing

Photographic coverage of each test included a combination of digital high-speed cameras placed in some of the following locations:

- One placed overhead with a field of view perpendicular to the ground and directly over the first net (OH-1).
- One placed overhead with a field of view perpendicular to the ground and directly over the midspan of the two nets (OH-1&2).
- One placed overhead with a field of view perpendicular to the ground and directly over the second net (OH-2).
- One placed with a field of view parallel to and aligned with the impact path at the downstream end (G).
- One placed with a field of view perpendicular to the impact path just downstream from the first net (RA-1).

- One placed with a field of view perpendicular to the impact path just downstream from the second net (RA-2).
- One placed with a field of view perpendicular to the impact path near the estimated stopping distance downstream from the second net (RA-D).
- One placed downstream and at an angle to the impact path, with a view of the first net (OB-1).
- One placed downstream and at an angle to the impact path, with a view of both nets (OB-1&2).
- One placed downstream and at an angle to the impact path, with a view of the second net (OB-2).

Table 6.3 shows the camera angles used for each test.

Table 6.3. High-Speed Camera Locations per Test.

Test	OH-1	OH-1&2	OH-2	G	RA-1	RA-2	RA-D	OB-1	OB-1&2	OB-2
-1	X	—	—	X	X	—	—	X	—	—
-2	—	X	—	X	—	X	—	—	X	—
-3	—	X	—	X	—	—	X	—	X	—
-4	—	—	X	X	—	X	—	—	—	—
-5	—	—	X	X	—	—	—	—	—	X
-6	—	—	X	X	—	—	X	—	—	—

Note: X indicates the camera angle in that column was used for the test in that row. — indicates that the camera angle was not used for that test.

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

CHAPTER 7. *MASH* TEST 3-40 (CRASH TEST 440210-01-1)

7.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

See Table 7.1 for the *MASH* impact conditions and Table 7.2 for the exit parameters for Test 440210-01-1. Figure 7.1 and Figure 7.2 depict the target impact setup.

Table 7.1. Impact Conditions for *MASH* Test 3-40, Crash Test 440210-01-1.

Test Parameter	Specification	Tolerance	Measured
Impact Speed (mi/h)	62	±2.5 mi/h	62.0
Impact Angle (deg)	0	±1.5°	0.0
Kinetic Energy (kip-ft)	288	≥288 kip-ft	311.0
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	±6 inches	Centerline of the vehicle aligned 2.7 inches to the left of the centerline of the MOPS

Table 7.2. Exit Parameters for *MASH* Test 3-40, Crash Test 440210-01-1.

Exit Parameter	Measured
Speed (mi/h)	Vehicle did not exit the installation
Brakes applied post impact (s)	0.8[a]
Vehicle at rest position	45 ft downstream of impact point 5 ft to the left side 45° left
Comments:	Vehicle remained upright and stable

[a] Brakes were unintentionally applied to the vehicle; however, the application occurred after the vehicle had ceased forward motion and therefore did not affect the results of the test.

Figure 7.1. MOPS/Test Vehicle Geometrics for Test 440210-01-1.

Figure 7.2. MOPS/Test Vehicle Impact Location for Test 440210-01-1.

7.2. WEATHER CONDITIONS

Table 7.3 provides the weather conditions for Test 440210-01-1.

Table 7.3. Weather Conditions for Test 440210-01-1.

Date of Test	2020-08-20
Wind Speed (mi/h)	5
Wind Direction (deg)	45
Temperature (°F)	91
Relative Humidity (%)	44
Vehicle Traveling (deg)	130

7.3. TEST VEHICLE

Figure 7.3 and Figure 7.4 show the 2016 Nissan Versa used for the crash test. Table 7.4 shows the vehicle measurements. Figure B.1 in Appendix B.1 gives additional dimensions and information on the vehicle.

Figure 7.3. Front of Test Vehicle before Test 440210-01-1.

Figure 7.4. Back of Test Vehicle before Test 440210-01-1.

Table 7.4. Vehicle Measurements for Test 440210-01-1.

Test Parameter	Specification	Tolerance	Measured
Dummy (if applicable)[a] (lb)	165	N/A	165
Inertial Weight (lb)	2420	±55	2420
Gross Static[a] (lb)	2585	±55	2585
Wheelbase (inches)	98	±5	102.4
Front Overhang (inches)	35	±4	32.5
Overall Length (inches)	169	±8	175.4
Overall Width (inches)	65	±3	66.7
Hood Height (inches)	28	±4	30.5
Track Width[b] (inches)	59	±2	58.4
CG aft of Front Axle[c] (inches)	39	±4	40.6
CG above Ground[c,d] (inches)	N/A	N/A	N/A

Note: N/A = not applicable; CG = center of gravity.
[a] If a dummy is used, the gross static vehicle mass should be increased by the mass of the dummy.
[b] Average of front and rear axles.
[c] For test inertial mass.
[d] 2270P vehicle must meet minimum CG height requirement.

7.4. TEST DESCRIPTION

Table 7.5 lists events that occurred during Test 440210-01-1. Figures B.4, B.5, B.6, and B.7 in Appendix B.2 present sequential photographs during the test.

Table 7.5. Events during Test 440210-01-1.

Time (s)	Events
0.0000	Car contacted the first net
0.0430	Energy absorbers from first net began to rotate
0.0760	Strap began to spool out from energy absorbers
0.9140	Vehicle came to a stop

7.5. DAMAGE TO TEST INSTALLATION

There was no movement or cracking noted on the foundation of the first net. The right and left post baseplates and the concrete immediately downstream of them had some scuffing, and the four oblique support cables all released from the net but remained attached to the concrete foundation. When facing the installation from upstream, the left tape pulled out from the canister 31 ft 11 inches, and the right tape pulled out 36 ft 7 inches. The fence remained attached to the tape and wrapped around the front and sides of the car. The left intermediate post fractured, and a section of it landed 46 ft downstream and 3 ft to the left of impact. Both the leftmost and rightmost posts deformed and sheared from the bottom cable. The test vehicle did not contact the second net (most downstream net) in the installation.

Table 7.6 describes the deflection and working width of the MOPS. Figure 7.5 and Figure 7.6 show the damage to the MOPS.

Table 7.6. Deflection and Working Width of the MOPS for Test 440210-01-1.

Test Parameter	Measured
Permanent Deflection/Location	45 ft toward field side
Dynamic Deflection	45 ft toward field side

Figure 7.5. MOPS after Test 440210-01-1.

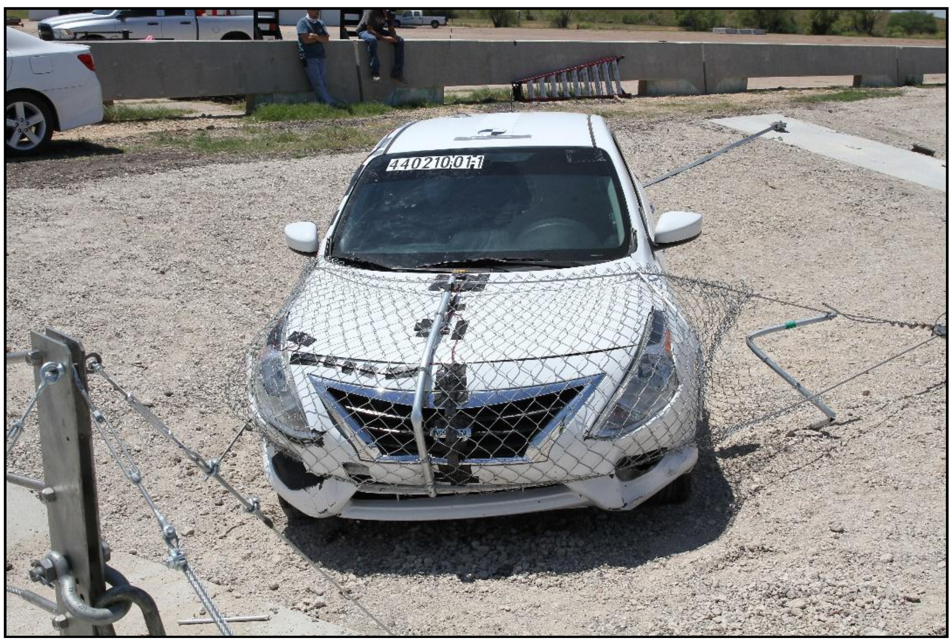

Figure 7.6. Maximum Penetration of the MOPS after Test 440210-01-1.

7.6. DAMAGE TO TEST VEHICLE

Figure 7.7 and Figure 7.8 show the damage sustained by the vehicle. Figure 7.9 and Figure 7.10 show the interior of the test vehicle. Table 7.7 and Table 7.8 provide details on the occupant compartment deformation and exterior vehicle damage. Figures B.2 and B.3 in Appendix B.1 provide exterior crush and occupant compartment measurements.

Figure 7.7. Test Vehicle after Test 440210-01-1.

Figure 7.8. Front End of Test Vehicle after Test 440210-01-1.

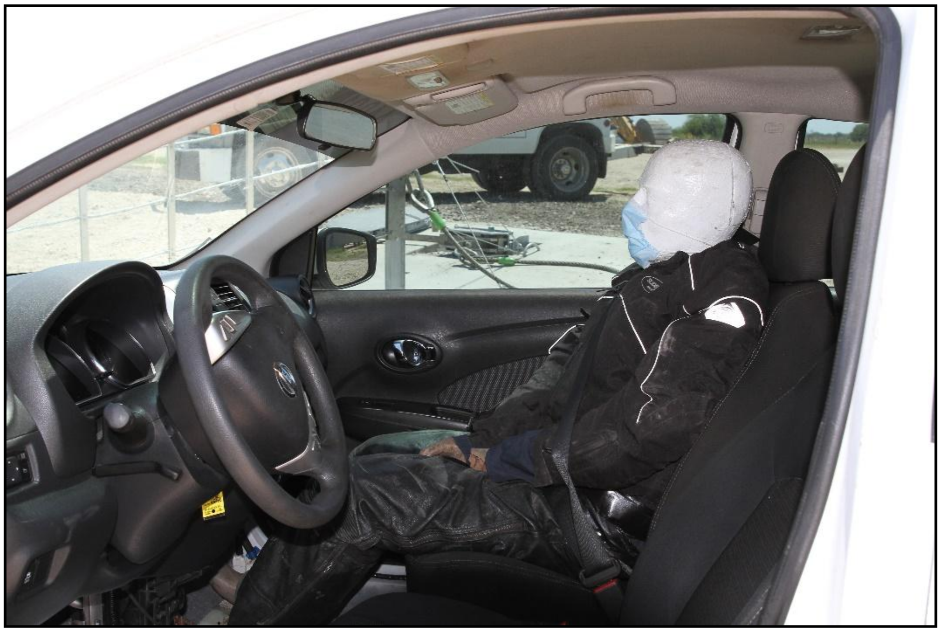

Figure 7.9. Overall Interior of Test Vehicle after Test 440210-01-1.

Figure 7.10. Interior of Test Vehicle after Test 440210-01-1.

Table 7.7. Occupant Compartment Deformation for Test 440210-01-1.

Test Parameter	Specification (inches)	Measured (inches)
Roof	≤4.0	0.0
Windshield	≤3.0	0.0
A and B Pillars	≤5.0 overall/≤3.0 lateral	0.0
Foot Well/Toe Pan	≤9.0	0.0
Floor Pan/Transmission Tunnel	≤12.0	0.0
Side Front Panel	≤12.0	0.0
Front Door (above Seat)	≤9.0	0.0
Front Door (below Seat)	≤12.0	0.0

Table 7.8. Exterior Vehicle Damage for Test 440210-01-1.

Side Windows	The side windows remained intact
Maximum Exterior Deformation	1 inch in the front plane at bumper height
VDS	12FC1
CDC	12FCEN1
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, hood, grill, right and left front fenders, right and left headlights, and lower radiator support were damaged.

7.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 7.9. Figure B.8 in Appendix B.3 shows the vehicle angular displacements, and Figures B.9 through B.11 in Appendix B.4 show acceleration versus time traces.

Table 7.9. Occupant Risk Factors for Test 440210-01-1.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	17.9	0.2693 seconds on front of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	0.7	0.2693 seconds on front of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	3.9	0.4977–0.5077 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	1.9	0.8988–0.9088 seconds
Theoretical Head Impact Velocity (THIV) (m/s)	N/A	5.5	0.2692 seconds on front of interior
Acceleration Severity Index (ASI)	N/A	0.3	0.7846–0.8346 seconds
50-ms Moving Avg. Accelerations (MA) Longitudinal (g)	N/A	−3.5	0.4316–0.4816 seconds
50-ms MA Lateral (g)	N/A	−1.6	0.7764–0.8264 seconds
50-ms MA Vertical (g)	N/A	1.3	0.1142–0.1642 seconds
Roll (deg)	≤75	6.3	1.3201 seconds
Pitch (deg)	≤75	8.8	0.8241 seconds
Yaw (deg)	N/A	35	0.9414 seconds

[a] Values in italics are the preferred *MASH* values.

7.8. TEST SUMMARY

Figure 7.11 summarizes the results of *MASH* Test 440210-01-1.

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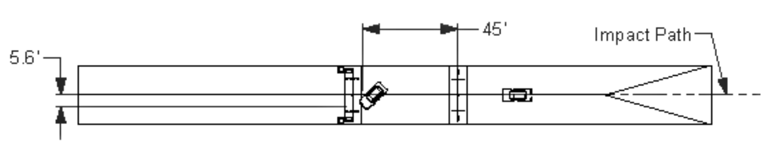
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	*MASH* 2016, Test 3-40
TTI Project No.	440210-01-1
Test Date	2020-08-20
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	1100C
Year, Make and Model	2016 Nissan Versa
Inertial Weight (lb)	2420
Dummy (lb)	165
Gross Static (lb)	2585
IMPACT CONDITIONS	
Impact Speed (mi/h)	62.0
Impact Angle (deg)	0.0
Impact Location	Centerline of the vehicle aligned 2.7 inches to the left of the centerline of the MOPS
Kinetic Energy (kip-ft)	311
EXIT CONDITIONS	
Exit Speed (mi/h)	Vehicle did not exit the installation
Stopping Distance	45 ft downstream 5 ft to the left side
TEST ARTICLE DEFLECTIONS	
Dynamic (ft)	45
Permanent (ft)	45
VEHICLE DAMAGE	
VDS	12FC1
CDC	12FCEN1
Max. Ext. Deformation (inches)	1
Max Occupant Compartment Deformation	No occupant compartment deformation

OCCUPANT RISK VALUES							
Long. OIV (ft/s)	17.9	Long. Ridedown (g)	3.9	Max 50-ms Long. (g)	−3.5	Max Roll (deg)	6.3
Lat. OIV (ft/s)	0.7	Lat. Ridedown (g)	1.9	Max 50-ms Lat. (g)	−1.6	Max Pitch (deg)	8.8
THIV (m/s)	5.5	ASI	0.3	Max 50-ms Vert. (g)	1.3	Max Yaw (deg)	35



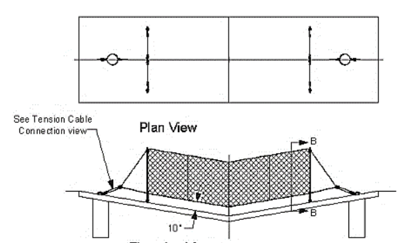


Figure 7.11. Summary of Results for *MASH* Test 3-40 on MOPS.

CHAPTER 8. *MASH* TEST 3-41 (CRASH TEST 440210-01-2)

8.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

See Table 8.1 for the *MASH* impact conditions and Table 8.2 for the exit parameters for Test 440210-01-2. Figure 8.1 and Figure 8.2 depict the target impact setup.

Table 8.1. Impact Conditions for *MASH* Test 3-41, Crash Test 440210-01-2.

Test Parameter	Specification	Tolerance	Measured
Impact Speed (mi/h)	62	±2.5 mi/h	62.1
Impact Angle (deg)	0	±1.5°	0.3
Kinetic Energy (kip-ft)	594	≥594 kip-ft	647.2
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	±6 inches	Centerline of the vehicle aligned 4.8 inches to the left of the centerline of the MOPS

Table 8.2. Exit Parameters for *MASH* Test 3-41, Crash Test 440210-01-2.

Exit Parameter	Measured
Speed (mi/h)	Vehicle did not exit the installation
Brakes applied post impact (s)	Brakes were not applied
Vehicle at rest position	67 ft downstream of impact point 4 ft to the left side 15° left
Comments:	Vehicle remained upright and stable

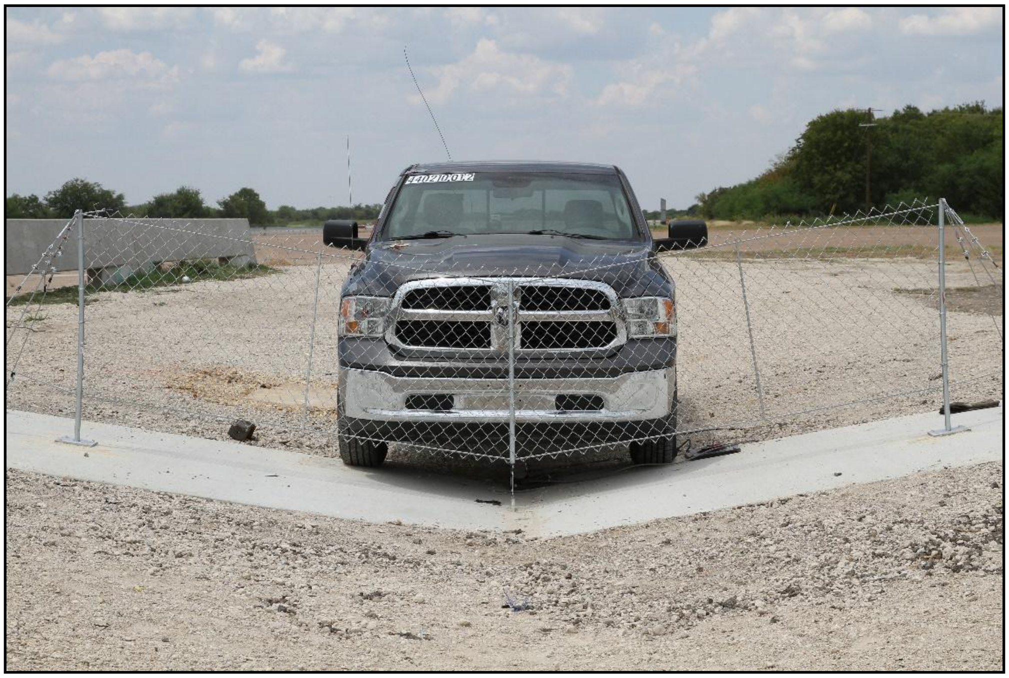


Figure 8.1. MOPS/Test Vehicle Geometrics for Test 440210-01-2.

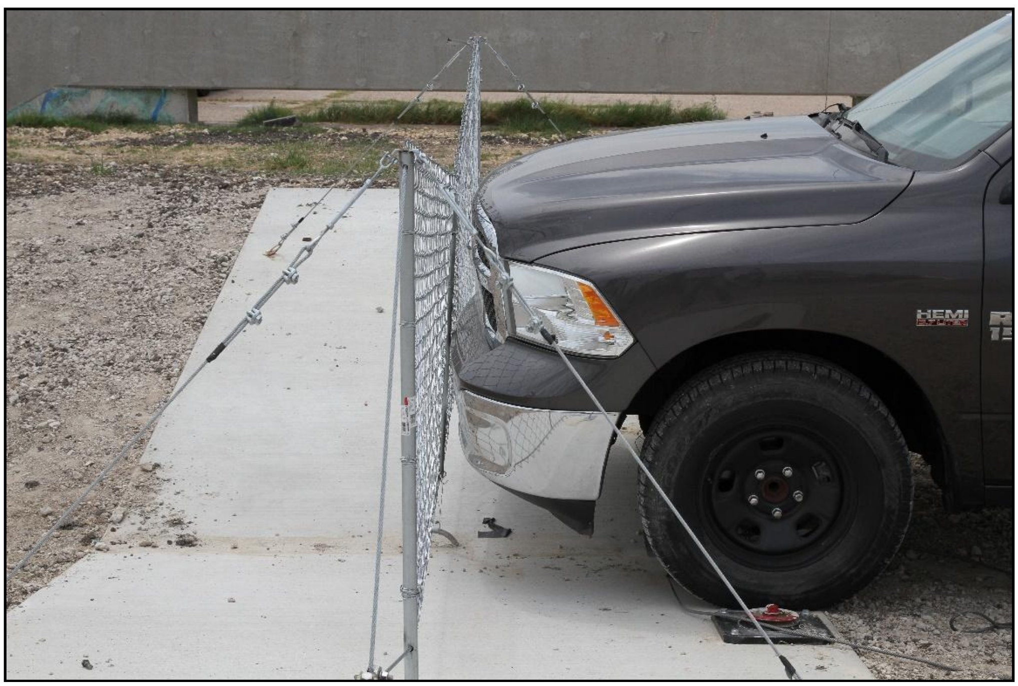


Figure 8.2. MOPS/Test Vehicle Impact Location for Test 440210-01-2.

8.2. WEATHER CONDITIONS

Table 8.3 provides the weather conditions for Test 440210-01-2.

Table 8.3. Weather Conditions for Test 440210-01-2.

Date of Test	2020-08-24
Wind Speed (mi/h)	7
Wind Direction (deg)	53
Temperature (°F)	96
Relative Humidity (%)	41
Vehicle Traveling (deg)	130

8.3. TEST VEHICLE

Figure 8.3 and Figure 8.4 show the 2015 RAM 1500 used for the crash test. Table 8.4 shows the vehicle measurements. Figure C.1 in Appendix C.1 gives additional dimensions and information on the vehicle.

Figure 8.3. Front of Test Vehicle before Test 440210-01-2.

Figure 8.4. Back of Test Vehicle before Test 440210-01-2.

Table 8.4. Vehicle Measurements for Test 440210-01-2.

Test Parameter	Specification	Tolerance	Measured
Dummy (if applicable)[a] (lb)	165	N/A	N/A
Inertial Weight (lb)	5000	±110	5020
Gross Static[a] (lb)	5000	±110	5020
Wheelbase (inches)	148	±12	140.5
Front Overhang (inches)	39	±3	40
Overall Length (inches)	237	±13	227.5
Overall Width (inches)	78	±2	78.5
Hood Height (inches)	43	±4	46
Track Width[b] (inches)	67	±1.5	68.3
CG aft of Front Axle[c] (inches)	63	±4	60.8
CG above Ground[c,d] (inches)	28	≥28	28.8

Note: N/A = not applicable; CG = center of gravity.
[a] If a dummy is used, the gross static vehicle mass should be increased by the mass of the dummy.
[b] Average of front and rear axles.
[c] For test inertial mass.
[d] 2270P vehicle must meet minimum CG height requirement.

8.4. TEST DESCRIPTION

Table 8.5 lists events that occurred during Test 440210-01-2. Figures C.4, C.5, C.6, and C.7 in Appendix C.2 present sequential photographs during the test.

Table 8.5. Events during Test 440210-01-2.

Time (s)	Events
0.0000	Vehicle contacted first net
0.0460	Energy absorbers began to rotate
0.0610	Straps began to spool out from energy absorbers
0.6550	Vehicle impacted the second net
1.0580	Absorber block on passenger's side of the second net began to release
1.0690	Absorber block on driver's side of the second net began to release
1.4840	Forward momentum of vehicle was stopped
1.4940	Vehicle began to roll backward
2.3850	Vehicle had rolled back 32.0 inches from its maximum intrusion and was in a state of backward motion when the video ended

8.5. DAMAGE TO TEST INSTALLATION

There was no movement or cracking noted on either foundation. All anchor cables released from net support posts for both nets. When facing the installation from upstream, the left tape of the first net pulled out 61 ft, the right tape of the first net pulled out 60 ft, and the tape for the second net did not pull out at all, but the absorber blocks released from the anchorage angles. The first fence wrapped around the bumper and sides of the truck and was also tangled with the lug nuts of the driver's side wheel. The second fence was wrapped around the top of the hood and front side panel of the truck, and the left bracket was deformed.

Table 8.6 describes the deflection and working width of the MOPS. Figure 8.5 and Figure 8.6 show the damage to the MOPS.

Table 8.6. Deflection and Working Width of the MOPS for Test 440210-01-2.

Test Parameter	Measured
Permanent Deflection/Location	67 ft toward field side
Dynamic Deflection	67 ft toward field side

Figure 8.5. MOPSs after Test 440210-01-2.

Figure 8.6. Second Net Swivel Anchor and Energy Absorbers after Test 440210-01-2.

8.6. DAMAGE TO TEST VEHICLE

Figure 8.7 and Figure 8.8 show the damage sustained by the vehicle. Figure 8.9 and Figure 8.10 show the interior of the test vehicle. Table 8.7 and Table 8.8 provide details on the occupant compartment deformation and exterior vehicle damage. Figures C.2 and C.3 in Appendix C.1 provide exterior crush and occupant compartment measurements.

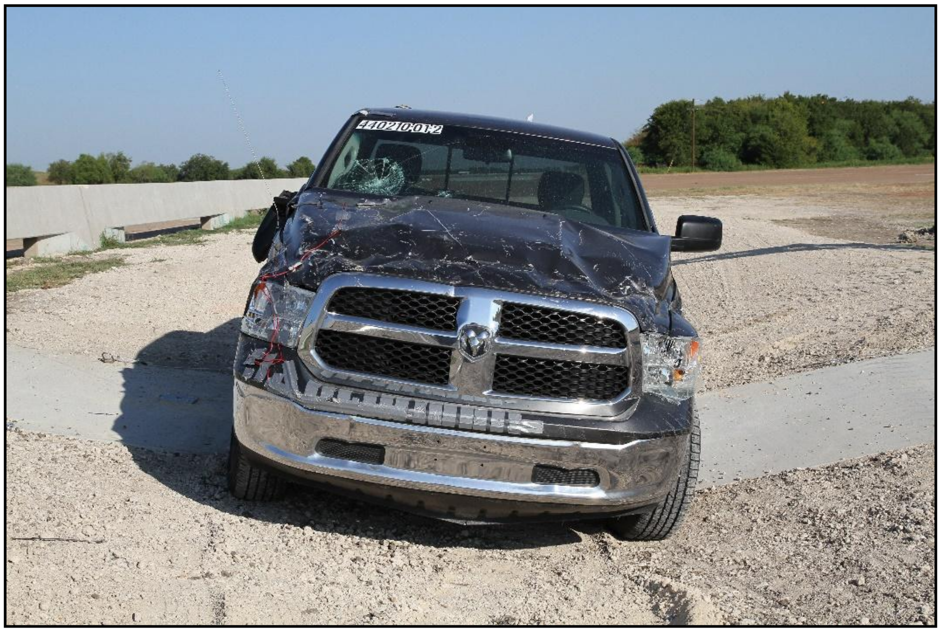


Figure 8.7. Front of Test Vehicle after Test 440210-01-2.

Figure 8.8. Windshield of Test Vehicle after Test 440210-01-2.

Figure 8.9. Overall Interior of Test Vehicle after Test 440210-01-2.

Figure 8.10. Upper Interior of Test Vehicle after Test 440210-01-2.

Table 8.7. Occupant Compartment Deformation for Test 440210-01-2.

Test Parameter	Specification	Measured
Roof	≤4.0 inches	0 inches
Windshield	≤3.0 inches	1.5 inches
A and B Pillars	≤5.0 overall/≤3.0 inches lateral	0 inches
Foot Well/Toe Pan	≤9.0 inches	0 inches
Floor Pan/Transmission Tunnel	≤12.0 inches	0 inches
Side Front Panel	≤12.0 inches	0 inches
Front Door (above Seat)	≤9.0 inches	0 inches
Front Door (below Seat)	≤12.0 inches	0 inches

Table 8.8. Exterior Vehicle Damage for Test 440210-01-2.

Side Windows	The side windows remained intact
Maximum Exterior Deformation	1.5 inches in the right-side plane above bumper height and in the front plane in the windshield
VDS	12FC3
CDC	12CEN2
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, hood, grill, right and left headlights, radiator and support, right and left fender, and right door were damaged. The right back panel had a 3-inch-long and 1-inch-wide cut on the lower front corner.

8.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 8.9. Figure C.8 in Appendix C.3 shows the vehicle angular displacements, and Figures C.9 through C.11 in Appendix C.4 show acceleration versus time traces.

Table 8.9. Occupant Risk Factors for Test 440210-01-2.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	13.4	0.3352 seconds on front of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	3.1	0.3352 seconds on front of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	7.6	1.0402–1.0502 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	2.1	1.0151–1.0251 seconds
THIV (m/s)	N/A	4.2	0.3340 seconds on front of interior
ASI	N/A	0.5	1.0488–1.0988 seconds
50-ms MA Longitudinal (g)	N/A	−5.7	1.0341–1.0841 seconds
50-ms MA Lateral (g)	N/A	−1.6	1.0149–1.0649 seconds
50-ms MA Vertical (g)	N/A	−2.1	1.0764–1.1264 seconds
Roll (deg)	≤75	6.8	0.8975 seconds
Pitch (deg)	≤75	6.1	1.1361 seconds
Yaw (deg)	N/A	25.7	1.4676 seconds

[a] Values in italics are the preferred *MASH* values.

8.8. TEST SUMMARY

Figure 8.11 summarizes the results of *MASH* Test 440210-01-2. In Test 440210-01-2, the test vehicle impacted the second net, causing the swivel mount for the second net's energy absorber to release the energy absorber. This was not intended in the design and was undesirable for future testing. Therefore, a new swivel mount was designed and utilized for all subsequent testing, including a retest of 440210-01-2 (440210-01-4).

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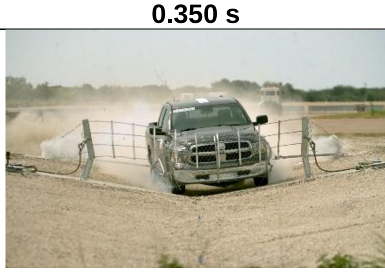

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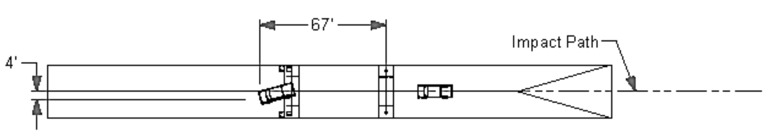
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	*MASH* 2016, Test 3-41
TTI Project No.	440210-01-2
Test Date	2020-08-24
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	2270P
Year, Make and Model	2015 RAM 1500
Inertial Weight (lb)	5020
Dummy (lb)	N/A
Gross Static (lb)	5020
IMPACT CONDITIONS	
Impact Speed (mi/h)	62.1
Impact Angle (deg)	0.3
Impact Location	Centerline of the vehicle aligned 4.8 inches to the left of the centerline of the MOPS
Kinetic Energy (kip-ft)	647.2
EXIT CONDITIONS	
Exit Speed (mi/h)	N/A
Stopping Distance	67 ft downstream 4 ft to the left side
TEST ARTICLE DEFLECTIONS	
Dynamic (ft)	67
Permanent (ft)	67
VEHICLE DAMAGE	
VDS	12FC3
CDC	12CEN2
Max. Ext. Deformation (inches)	1.5
Max Occupant Compartment Deformation	1.5 inches in the windshield and right rear fender

OCCUPANT RISK VALUES							
Long. OIV (ft/s)	13.4	Long. Ridedown (g)	7.6	Max 50-ms Long. (g)	−5.7	Max Roll (deg)	6.8
Lat. OIV (ft/s)	3.1	Lat. Ridedown (g)	2.1	Max 50-ms Lat. (g)	−1.6	Max Pitch (deg)	6.1
THIV (m/s)	4.2	ASI	0.5	Max 50-ms Vert. (g)	−2.1	Max Yaw (deg)	25.7



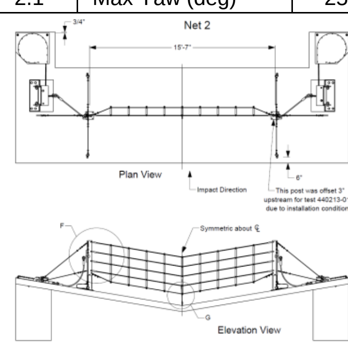


Figure 8.11. Summary of Results for *MASH* Test 3-41 on MOPS.

CHAPTER 9. *MASH* TEST 3-41 (CRASH TEST 440210-01-4)

9.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS*

See Table 9.1 for the *MASH* impact conditions and Table 9.2 for the exit parameters for Test 440210-01-4. Figure 9.1 and Figure 9.2 depict the target impact setup.

Table 9.1. Impact Conditions for *MASH* Test 3-41, Crash Test 440210-01-4.

Test Parameter	Specification	Tolerance	Measured
Impact Speed (mi/h)	62	±2.5 mi/h	62.8
Impact Angle (deg)	0	±1.5°	0.0
Kinetic Energy (kip-ft)	594	≥594 kip-ft	668.3
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	±6 inches	Centerline of the vehicle aligned 7.3 inches to the right of the centerline of the MOPS

Table 9.2. Exit Parameters for *MASH* Test 3-41, Crash Test 440210-01-4.

Exit Parameter	Measured
Speed (mi/h)	Vehicle did not exit the installation
Brakes applied post impact (s)	Brakes not applied
Vehicle at rest position	52.7 ft downstream of impact point In line with the impact path
Comments:	Vehicle remained upright and stable

MASH specifies a ±6-inch tolerance for the impact location in Test 3-41. The test vehicle impacted the first net 7.3 inches away from the target centerline of the net, which is slightly outside of the allowable tolerance. This 6-inch tolerance is typically utilized for test articles when installed on flat and level terrain. In this test, the first net was installed 120 ft within a V-ditch. With this configuration, it is significantly more difficult to release a vehicle and impact a narrow target compared to flat and level terrain. Additionally, the energy absorbers on the net system are allowed to pivot around the anchorage bars, which allows the net system to self-align during an impact. The energy absorbers are also designed for the strap material to be pulled out of the canister at a specific force. Therefore, the strap material will be pulled out of the canister before any additional force can be applied to the energy absorber due to the slightly misaligned impact. Consequently, the research team chose to not rerun Test 3-41 and proceeded with the subsequent tests, detailed in later chapters.

* The opinions/interpretations identified/expressed in this section of the report are outside the scope of TTI Proving Ground's A2LA Accreditation.

Figure 9.1. MOPS/Test Vehicle Geometrics for Test 440210-01-4.

Figure 9.2. MOPS/Test Vehicle Impact Location for Test 440210-01-4.

9.2. WEATHER CONDITIONS

Table 9.3 provides the weather conditions for Test 440210-01-4.

Table 9.3. Weather Conditions for Test 440210-01-4.

Date of Test	2021-01-20
Wind Speed (mi/h)	3
Wind Direction (deg)	39
Temperature (°F)	52
Relative Humidity (%)	99
Vehicle Traveling (deg)	100

9.3. TEST VEHICLE

Figure 9.3 and Figure 9.4 show the 2016 RAM 1500 used for the crash test. Table 9.4 shows the vehicle measurements. Figure D.1 in Appendix D.1 gives additional dimensions and information on the vehicle.

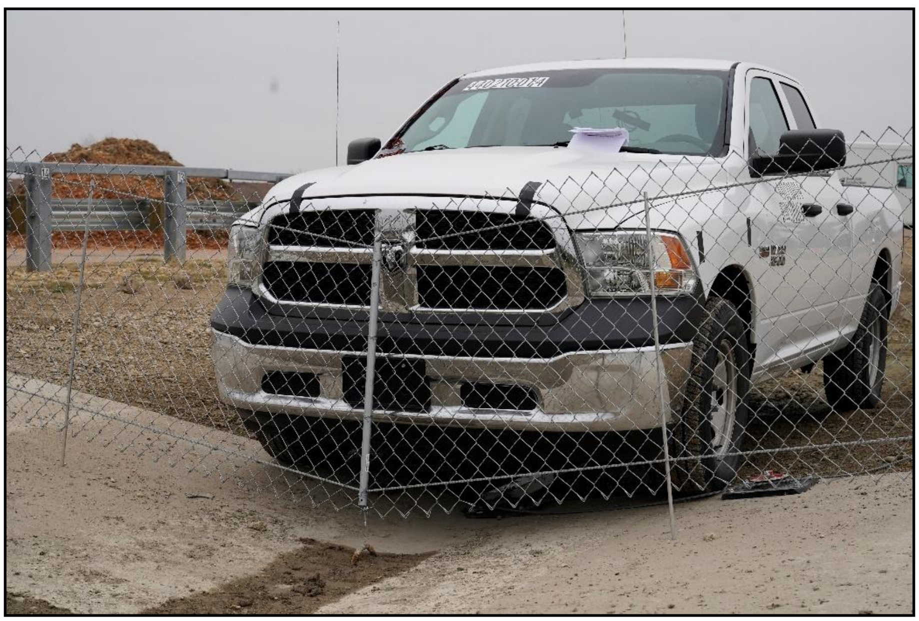


Figure 9.3. Front of Test Vehicle before Test 440210-01-4.

Figure 9.4. Back of Test Vehicle before Test 440210-01-4.

Table 9.4. Vehicle Measurements for Test 440210-01-4.

Test Parameter	Specification	Tolerance	Measured
Dummy (if applicable)[a] (lb)	165	N/A	N/A
Inertial Weight (lb)	5000	±110	5069
Gross Static[a] (lb)	5000	±110	5069
Wheelbase (inches)	148	±12	140.5
Front Overhang (inches)	39	±3	40
Overall Length (inches)	237	±13	227.5
Overall Width (inches)	78	±2	78.5
Hood Height (inches)	43	±4	46
Track Width[b] (inches)	67	±1.5	68.3
CG aft of Front Axle[c] (inches)	63	±4	61.9
CG above Ground[c,d] (inches)	28	28	28.3

Note: N/A = not applicable; CG = center of gravity.
[a] If a dummy is used, the gross static vehicle mass should be increased by the mass of the dummy.
[b] Average of front and rear axles.
[c] For test inertial mass.
[d] 2270P vehicle must meet minimum CG height requirement.

9.4. TEST DESCRIPTION

Table 9.5 lists events that occurred during Test 440210-01-4. Figures D.4, D.5, and D.6 in Appendix D.2 present sequential photographs during the test.

Table 9.5. Events during Test 440210-01-4.

Time (s)	Events
−0.6720	Vehicle impacted the first net
0.0000	Vehicle impacted the second net installation
0.1620	Second net began to deform hood
0.3070	Vehicle reached maximum intrusion and began to rebound
1.4030	Vehicle came to rest

9.5. DAMAGE TO TEST INSTALLATION

The first net was wrapped around the front bumper of the vehicle, while the second net was wrapped over the hood. Both nets remained attached to their straps. There was some slight gouging of the concrete at the second net. Table 9.6 describes the deflection and working width of the MOPS. Figure 9.5 and Figure 9.6 show the damage to the MOPS.

Table 9.6. Deflection and Working Width of the MOPS for Test 440210-01-4.

Test Parameter	Measured
Permanent Deflection/Location	52.7 ft toward field side
Dynamic Deflection	59.7 ft toward field side

Figure 9.5. MOPS after Test 440210-01-4.

Figure 9.6. Second Net Swivel Anchor and Energy Absorbers after Test 440210-01-4.

9.6. DAMAGE TO TEST VEHICLE

Figure 9.7 and Figure 9.8 show the damage sustained by the vehicle. Figure 9.9 and Figure 9.10 show the interior of the test vehicle. Table 9.7 and Table 9.8 provide details on the occupant compartment deformation and exterior vehicle damage. Figures D.2 and D.3 in Appendix D.1 provide exterior crush and occupant compartment measurements.

Figure 9.7. Front of Test Vehicle after Test 440210-01-4.

Figure 9.8. Right Side of Test Vehicle after Test 440210-01-4.

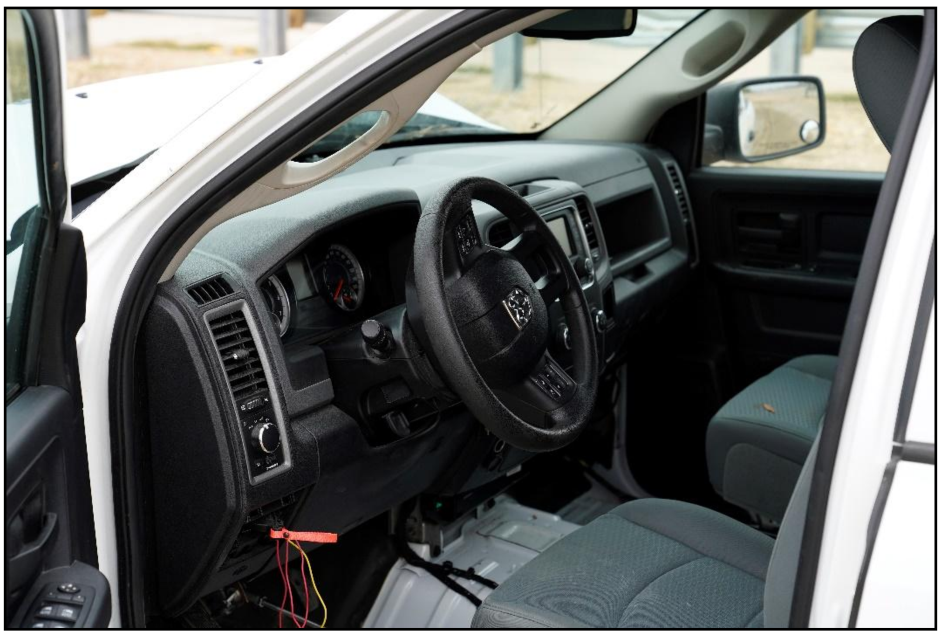


Figure 9.9. Overall Interior of Test Vehicle after Test 440210-01-4.

Figure 9.10. Right-Side Interior of Test Vehicle after Test 440210-01-4.

Table 9.7. Occupant Compartment Deformation for Test 440210-01-4.

Test Parameter	Specification (inches)	Measured (inches)
Roof	≤4.0	0.0
Windshield	≤3.0	0.0
A and B Pillars	≤5.0 overall/≤3.0 lateral	0.0
Foot Well/Toe Pan	≤9.0	0.0
Floor Pan/Transmission Tunnel	≤12.0	0.0
Side Front Panel	≤12.0	0.0
Front Door (above Seat)	≤9.0	0.0
Front Door (below Seat)	≤12.0	0.0

Table 9.8. Exterior Vehicle Damage for Test 440210-01-4.

Side Windows	The side windows remained intact
Maximum Exterior Deformation	10 inches in the front plane at bumper height
VDS	12FC4
CDC	12CEN3
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, hood, grill, right and left headlights, radiator and support, right and left fender, and right door were damaged. The right front door had a 3-inch-long and 1-inch-wide cut on the lower front corner. There was no penetration into the occupant compartment.

9.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 9.9. Figure D.7 in Appendix D.3 shows the vehicle angular displacements, and Figures D.8 through D.10 in Appendix D.4 show acceleration versus time traces.

Table 9.9. Occupant Risk Factors for Test 440210-01-4.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	15.7	0.3228 seconds on front of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	1.1	0.3228 seconds on front of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	13.3	0.8947–0.9047 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	2.2	0.9050–0.9150 seconds
THIV (m/s)	N/A	4.8	0.3228 seconds on front of interior
ASI	N/A	0.9	0.9738–1.0238 seconds
50-ms MA Longitudinal (g)	N/A	−9.6	0.9384–0.9884 seconds
50-ms MA Lateral (g)	N/A	−1.1	0.8740–0.9240 seconds
50-ms MA Vertical (g)	N/A	2.9	0.9545–1.0045 seconds
Roll (deg)	≤75	8.2	1.5000 seconds
Pitch (deg)	≤75	5.3	0.3736 seconds
Yaw (deg)	N/A	2.1	1.2051 seconds

[a] Values in italics are the preferred *MASH* values.

9.8. TEST SUMMARY

Figure 9.11 summarizes the results of *MASH* Test 440210-01-4.

0.000 s

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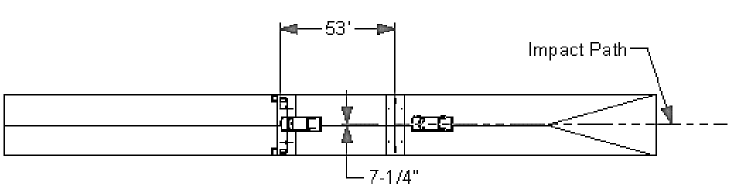
0.400 s

0.600 s

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	*MASH* 2016, Test 3-41
TTI Project No.	440210-01-4
Test Date	2021-01-20
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	2270P
Year, Make and Model	2016 RAM 1500
Inertial Weight (lb)	5069
Dummy (lb)	N/A
Gross Static (lb)	5069
IMPACT CONDITIONS	
Impact Speed (mi/h)	62.8
Impact Angle (deg)	0.0
Impact Location	Centerline of the vehicle aligned 7.3 inches to the right of the centerline of the MOPS
Kinetic Energy (kip-ft)	668.3
EXIT CONDITIONS	
Exit Speed (mi/h)	Vehicle did not exit the installation
Stopping Distance	52.7 ft downstream In line
TEST ARTICLE DEFLECTIONS	
Dynamic (ft)	59.7
Permanent (ft)	52.7
VEHICLE DAMAGE	
VDS	12FC4
CDC	12CEN3
Max. Ext. Deformation (inches)	10
Max Occupant Compartment Deformation	No occupant compartment deformation

OCCUPANT RISK VALUES

Long. OIV (ft/s)	15.7	Long. Ridedown (g)	13.3	Max 50-ms Long. (g)	−9.6	Max Roll (deg)	8.2
Lat. OIV (ft/s)	1.1	Lat. Ridedown (g)	2.2	Max 50-ms Lat. (g)	−1.1	Max Pitch (deg)	5.3
THIV (m/s)	4.8	ASI	0.9	Max 50-ms Vert. (g)	2.9	Max Yaw (deg)	2.1



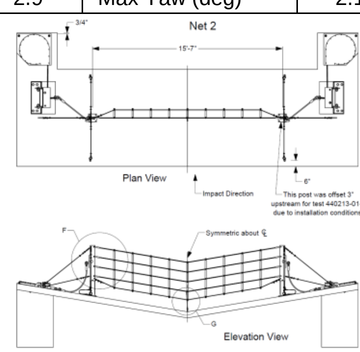


Figure 9.11. Summary of Results for *MASH* Test 3-41 on MOPS.

CHAPTER 10. RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440211-01-3)

10.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

See Table 10.1 for the impact conditions and Table 10.2 for the exit parameters for Test 440211-01-3.

Table 10.1. Impact Conditions for Research and Development Test, Crash Test 440211-01-3.

Test Parameter	Nominal	Measured
Impact Speed (mi/h)	50	51.8
Impact Angle (deg)	0	2.8
Kinetic Energy (kip-ft)	N/A	4499.3
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	Centerline of the vehicle aligned 8 inches to the left of the centerline of the first MOPS net and 17.8 inches to the left of the centerline of the second net
Comments:	—	The impact conditions were determined to sufficiently evaluate the test article according to the selected evaluation criteria

Table 10.2. Exit Parameters for Research and Development Test, Crash Test 440211-01-3.

Exit Parameter	Measured
Vehicle at rest position	524 ft downstream of impact point In line with the impact path
Comments:	Vehicle remained upright and stable

10.2. WEATHER CONDITIONS

Table 10.3 provides the weather conditions for Test 440211-01-3.

Table 10.3. Weather Conditions for Test 440211-01-3.

Date of Test	2021-04-13
Wind Speed (mi/h)	8
Wind Direction (deg)	302
Temperature (°F)	74
Relative Humidity (%)	81
Vehicle Traveling (deg)	130

10.3. TEST VEHICLE

A 2004 MCI D4500 was used for the crash test. Table 10.4 shows the vehicle measurements. Figure E.1 in Appendix E.1 gives additional dimensions and information on the vehicle.

Table 10.4. Vehicle Measurements for Test 440211-01-3.

Test Parameter	Measured
Dummy (if applicable) (lb)	330[a]
Curb Weight (lb)	37,120
Vehicle Inertial Weight (lb)	50,160
Wheelbase (inches)	318
Overall Height (inches)	130
Overall Width (inches)	101
Overall Length (inches)	544
Height to Base of Bumper (inches)	14

[a] Two 165-lb dummies were placed in the vehicle.

10.4. TEST DESCRIPTION

Table 10.5 lists events that occurred during Test 440211-01-3. Figures E.2, E.3, E.4, and E.5 in Appendix E.2 present sequential photographs during the test.

Table 10.5. Events during Test 440211-01-3.

Time (s)	Events
0.0000	Vehicle impacted the installation
1.2310	Straps from the first net released from the cannisters
0.7740	A cable on the second net began to rupture
0.9360	Second net completely ruptured

10.5. DAMAGE TO TEST INSTALLATION

The steel straps from the first net landed 197 ft downstream and 268 ft downstream, and the first net was 312 ft downstream. The second net ruptured and was still attached to the right side of the test vehicle and was laying 15 ft to the right from center. Table 10.6 describes the deflection and working width of the MOPS. Figure 10.1 and Figure 10.2 show the damage to the MOPS.

Table 10.6. Deflection and Working Width of the MOPS for Test 440211-01-3.

Test Parameter	Measured
Permanent Deflection/Location	N/A, test article failed
Dynamic Deflection	N/A, test article failed


Figure 10.1. Crash Site after Test 440211-01-3.


Figure 10.2. Second Net after Test 440211-01-3.

10.6. DAMAGE TO TEST VEHICLE

Figure 10.3 and Figure 10.4 show the damage sustained by the vehicle. Figure 10.5 and Figure 10.6 show the interior of the test vehicle. Table 10.7 provide details on the exterior vehicle damage. Due to the failure of the installation, occupant compartment deformation was not measured.

Figure 10.3. Front of Test Vehicle after Test 440211-01-3.

Figure 10.4. Oblique View of Test Vehicle after Test 440211-01-3.

Figure 10.5. Overall Rear Interior of Test Vehicle after Test 440211-01-3.

Figure 10.6. Overall Front Interior of Test Vehicle after Test 440211-01-3.

Table 10.7. Exterior Vehicle Damage for Test 440211-01-3.

Side Windows	The side windows remained intact
Maximum Exterior Deformation	Maximum exterior deformation was not measured due to installation failure
VDS	12FC1
CDC	12FCEN1
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, headlights, and front side panels were damaged.

10.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 10.8. Figure E.6 in Appendix E.3 shows the vehicle angular displacements, and Figures E.7 through E.9 in Appendix E.4 show acceleration versus time traces.

Table 10.8. Occupant Risk Factors for Test 440211-01-3.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	2.7	1.2950 seconds on left side of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	3.2	1.2950 seconds on left side of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	2.1	3.8040–3.8140 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	1.9	4.3376–4.3476 seconds
THIV (m/s)	N/A	1.3	1.2962 seconds on left side of interior
ASI	N/A	0.3	4.3262–4.3762 seconds
50-ms MA Longitudinal (g)	N/A	−1.5	3.7812–3.8312 seconds
50-ms MA Lateral (g)	N/A	−0.9	4.3072–4.3572 seconds
50-ms MA Vertical (g)	N/A	−2.8	4.3077–4.3577 seconds
Roll (deg)	N/A	5.5	2.3712 seconds
Pitch (deg)	N/A	7.1	4.7783 seconds
Yaw (deg)	N/A	1.7	0.9067 seconds

[a] Values in italics are the preferred *MASH* values.

10.8. TEST SUMMARY

Figure 10.7 summarizes the results of Test 440211-01-3. The second net’s wire rope cables failed during the impact. Upon inspection of the damaged test article, it was determined that swage fittings on each of the wire ropes were not installed correctly in the factory. This caused the wire ropes to slip out from the swage fittings and consequently allowed the test vehicle to penetrate through the net. Therefore, the research team performed the test again with properly manufactured nets, and this effort is documented in the next chapter.

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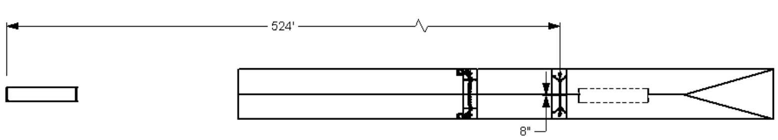
0.300 s

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	Research and Development Test
TTI Project No.	440211-01-3
Test Date	2021-04-13
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	Passenger Bus
Year, Make and Model	2004 MCI D4500
Curb (lb)	37,120
Inertial Weight (lb)	50,160
IMPACT CONDITIONS	
Impact Speed (mi/h)	51.8
Impact Angle (deg)	2.8
Impact Location	Centerline of the vehicle aligned 8 inches to the left of the centerline of the first MOPS net, and 17.8 inches to the left of the centerline of the second net
Kinetic Energy (kip-ft)	4499.3
EXIT CONDITIONS	
Exit Speed (mi/h)	N/A
Stopping Distance	524 ft downstream In line
TEST ARTICLE DEFLECTIONS	
Dynamic (inches)	N/A
Permanent (inches)	N/A
VEHICLE DAMAGE	
VDS	12FC1
CDC	12FCEN1
Max. Ext. Deformation (inches)	Not measured
Max Occupant Compartment Deformation	Not measured

OCCUPANT RISK VALUES

Long. OIV (ft/s)	2.7	Long. Ridedown (g)	2.1	Max 50-ms Long. (g)	−1.5	Max Roll (deg)	5.5
Lat. OIV (ft/s)	3.2	Lat. Ridedown (g)	1.9	Max 50-ms Lat. (g)	−0.9	Max Pitch (deg)	7.1
THIV (m/s)	1.3	ASI	0.3	Max 50-ms Vert. (g)	−2.8	Max Yaw (deg)	1.7



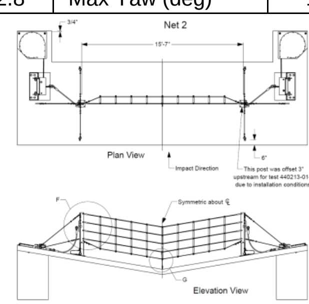


Figure 10.7. Summary of Results for Research and Development Test on MOPS.

CHAPTER 11. RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440211-01-5)

11.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

See Table 11.1 for the impact conditions and Table 11.2 for the exit parameters for Test 440211-01-5.

Table 11.1. Impact Conditions for Research and Development Test, Crash Test 440211-01-5.

Test Parameter	Nominal	Measured
Impact Speed (mi/h)	50	50.5
Impact Angle (deg)	0	0.7
Kinetic Energy (kip-ft)	N/A	4276.3
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	Centerline of the vehicle aligned 10.6 inches to the left of the centerline of the first MOPS net and 1.8 inches to the right of the centerline of the second net
Comments:	—	The impact conditions were determined to sufficiently evaluate the test article according to the selected evaluation criteria

Table 11.2. Exit Parameters for Research and Development Test, Crash Test 440211-01-5.

Exit Parameter	Measured
Vehicle at rest position	201 ft downstream of impact point 3 ft to the left side 1° left
Comments:	Vehicle remained upright and stable

11.2. WEATHER CONDITIONS

Table 11.3 provides the weather conditions for Test 440211-01-5.

Table 11.3. Weather Conditions for Test 440211-01-5.

Date of Test	2022-06-30
Wind Speed (mi/h)	4
Wind Direction (deg)	164
Temperature (°F)	89
Relative Humidity (%)	65
Vehicle Traveling (deg)	130

11.3. TEST VEHICLE

The 2004 MCI D4500 previously used in Test 440210-01-3 was reused for the crash test. Table 11.4 shows the vehicle measurements. Figure F.1 in Appendix F.1 gives additional dimensions and information on the vehicle.

Table 11.4. Vehicle Measurements for Test 440211-01-5.

Test Parameter	Measured
Dummy (if applicable) (lb)	330[a]
Curb Weight (lb)	37,120
Vehicle Inertial Weight (lb)	50,340
Wheelbase (inches)	318
Overall Height (inches)	130
Overall Width (inches)	101
Overall Length (inches)	544
Height to Base of Bumper (inches)	14

[a] Two 165-lb dummies were placed in the vehicle.

11.4. TEST DESCRIPTION

Table 11.5 lists events that occurred during Test 440211-01-5. Figures F.2, F.3, and F.4 in Appendix F.2 present sequential photographs during the test.

Table 11.5. Events during Test 440211-01-5.

Time (s)	Events
0.0000	Vehicle impacted the installation
0.0580	Straps began to let out on first net driver-side energy absorber
0.0760	Straps began to let out on first net passenger-side energy absorber
0.0860	Strap on driver’s side ruptured
1.5920	Strap from the second net on driver’s side ruptured

11.5. DAMAGE TO TEST INSTALLATION

The strap from the left cannister on the first net ruptured. The first net landed to the right of impact. The strap from the left cannister on the second net spooled out 71.5 ft. The strap from the right cannister on the second net ruptured and wrapped around the front of the bus. Table 11.6 describes the deflection and working width of the MOPS. Figure 11.1 and Figure 11.2 show the damage to the MOPS.

Table 11.6. Deflection and Working Width of the MOPS for Test 440211-01-5.

Test Parameter	Measured
Permanent Deflection/Location	N/A, test article failed
Dynamic Deflection	N/A, test article failed

Figure 11.1. Crash Site after Test 440211-01-5.

Figure 11.2. MOPS after Test 440211-01-5.

11.6. DAMAGE TO TEST VEHICLE

Figure 11.3 and Figure 11.4 show the damage sustained by the vehicle. Figure 11.5 and Figure 11.6 show the interior of the test vehicle. Table 11.7 provides details on the exterior vehicle damage. Due to the failure of the installation, occupant compartment deformation was not measured.

Figure 11.3. Front of Test Vehicle after Test 440211-01-5.

Figure 11.4. Oblique View of Test Vehicle after Test 440211-01-5.

Figure 11.5. Overall Interior of Front of Test Vehicle after Test 440211-01-5.

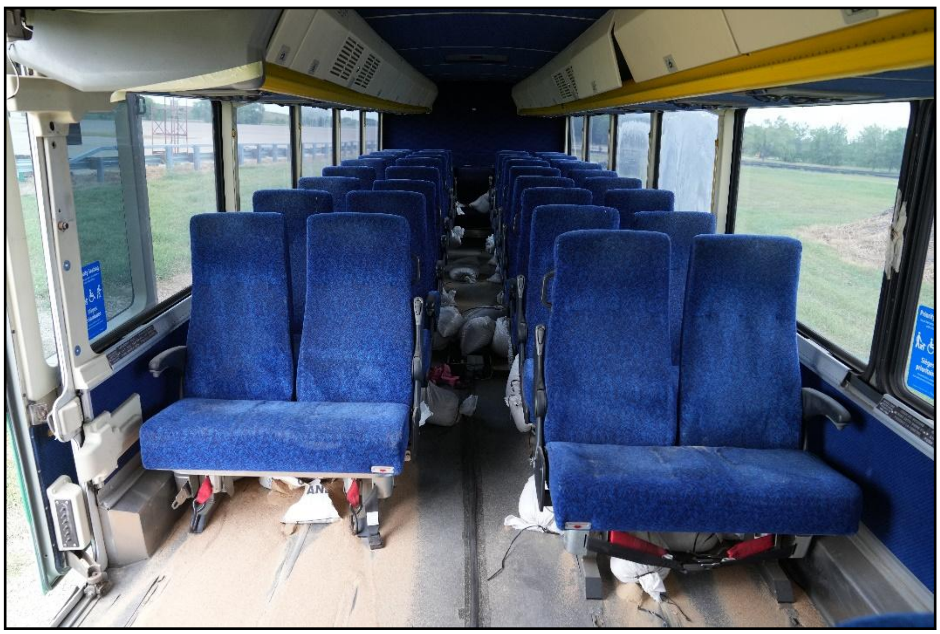


Figure 11.6. Overall Interior of Rear of Test Vehicle after Test 440211-01-5.

Table 11.7. Exterior Vehicle Damage for Test 440211-01-5.

Side Windows	The side windows remained intact
Maximum Exterior Deformation	Maximum exterior deformation was not measured due to installation failure
VDS	12FC2
CDC	12FCEN1
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, windshield, right-side mirror, and side panels were damaged. The windshield had some cracking and minor deformation. Due to the MOPS failing to contain and arrest the test vehicle, no measurements were taken on the deformation of the windshield.

11.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 11.8. Figure F.5 in Appendix F.3 shows the vehicle angular displacements, and Figures F.6 through F.8 in Appendix F.4 show acceleration versus time traces.

Table 11.8. Occupant Risk Factors for Test 440211-01-5.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	1.4	0.5148 seconds on right side of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	4.1	0.5148 seconds on right side of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	1.1	0.9932–1.0032 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	1.1	2.2788–2.2888 seconds
THIV (m/s)	N/A	1.3	0.5135 seconds on right side of interior
ASI	N/A	0.16	0.4070–0.4570 seconds
50-ms MA Longitudinal (g)	N/A	−1.0	2.2183–2.2683 seconds
50-ms MA Lateral (g)	N/A	−0.5	0.2249–0.2749 seconds
50-ms MA Vertical (g)	N/A	−1.6	0.3750–0.4250 seconds
Roll (deg)	N/A	2.9	4.7946 seconds
Pitch (deg)	N/A	7.5	2.0527 seconds
Yaw (deg)	N/A	2.0	4.8268 seconds

[a] Values in italics are the preferred *MASH* values.

11.8. TEST SUMMARY

Figure 11.7 summarizes the results of Test 440211-01-5. Upon investigation of the damaged test article, it was determined the bearings in the energy absorber failed during the impact. These bearings were reused throughout the previous tests without repair or replacement. The lack of repair or replacement following an impact event was believed to be the cause of the bearing failure and subsequent strap rupture. Because of the failing bearings, the test was repeated with new bearings installed within the energy absorbers. This identification of component failure and the need to replace the bearings after impact events provided additional information for future in-field use and maintenance planning.

0.000 s

0.100 s

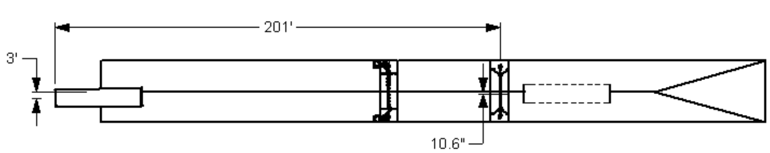
0.200 s

0.300 s

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	Research and Development Test
TTI Project No.	440211-01-5
Test Date	2022-06-30
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	Passenger Bus
Year, Make and Model	2004 MCI D4500
Curb (lb)	37,120
Inertial Weight (lb)	50,340
IMPACT CONDITIONS	
Impact Speed (mi/h)	50.5
Impact Angle (deg)	0.7
Impact Location	Centerline of the vehicle aligned 10.6 inches to the left of the centerline of the first MOPS net and 1.8 inches to the right of the centerline of the second net
Kinetic Energy (kip-ft)	4276.3
EXIT CONDITIONS	
Exit Speed (mi/h)	N/A
Stopping Distance	201 ft downstream 3 ft to the left side
TEST ARTICLE DEFLECTIONS	
Dynamic (inches)	N/A
Permanent (inches)	N/A
VEHICLE DAMAGE	
VDS	12FC2
CDC	12FCEN1
Max. Ext. Deformation (inches)	Not measured
Max Occupant Compartment Deformation	Not measured

OCCUPANT RISK VALUES

Long. OIV (ft/s)	1.4	Long. Ridedown (g)	1.1	Max 50-ms Long. (g)	−1.0	Max Roll (deg)	2.9
Lat. OIV (ft/s)	4.1	Lat. Ridedown (g)	1.1	Max 50-ms Lat. (g)	−0.5	Max Pitch (deg)	7.5
THIV (m/s)	1.3	ASI	0.16	Max 50-ms Vert. (g)	−1.6	Max Yaw (deg)	2.0



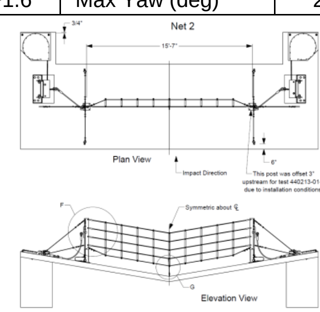


Figure 11.7. Summary of Results for Research and Development Test on MOPS.

CHAPTER 12. RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440213-01-6)

12.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

See Table 12.1 for the *MASH* impact conditions and Table 12.2 for the exit parameters for Test 440213-01-6.

Table 12.1. Impact Conditions for Research and Development Test, Crash Test 440213-01-6.

Test Parameter	Nominal	Measured
Impact Speed (mi/h)	50	50.0
Impact Angle (deg)	0	0.7
Kinetic Energy (kip-ft)	N/A	4190.4
Impact Location	Centerline of the vehicle aligned with the centerline of the MOPS	Centerline of the vehicle aligned 16.6 inches to the right of the centerline of the first MOPS net and 7.3 inches to the right of the centerline of the second net
Comments:	—	The impact conditions were determined to sufficiently evaluate the test article according to the selected evaluation criteria

Table 12.2. Exit Parameters for Research and Development Test, Crash Test 440213-01-6.

Exit Parameter	Measured
Vehicle at rest position	180 ft downstream of impact point 1.5 ft to the left side
Comments:	Vehicle remained upright and stable

12.2. WEATHER CONDITIONS

Table 12.3 provides the weather conditions for Test 440213-01-6.

Table 12.3. Weather Conditions for Test 440213-01-6.

Date of Test	2023-08-28
Wind Speed (mi/h)	11
Wind Direction (deg)	306
Temperature (°F)	92
Relative Humidity (%)	59
Vehicle Traveling (deg)	130

12.3. TEST VEHICLE

A 2002 Van Hool Commuter C2045 USA was used for the crash test. Table 12.4 shows the vehicle measurements. Figure G.1 in Appendix G.1 gives additional dimensions and information on the vehicle.

Table 12.4. Vehicle Measurements for Test 440213-01-6.

Test Parameter	Measured
Dummy (if applicable) (lb)	330[a]
Curb Weight (lb)	34,120
Vehicle Inertial Weight (lb)	50,140
Wheelbase (inches)	284
Overall Height (inches)	139
Overall Width (inches)	110.5
Overall Length (inches)	543.5
Height to Base of Bumper (inches)	13

[a] Two 165-lb dummies were placed in the vehicle.

12.4. TEST DESCRIPTION

Table 12.5 lists events that occurred during Test 440213-01-6. Figures G.2, G.3, and G.4 in Appendix G.2 present sequential photographs during the test.

Table 12.5. Events during Test 440213-01-6.

Time (s)	Events
0.0000	Vehicle impacted the installation
0.0700	Straps began to let out on first net driver-side energy absorber
0.7120	Vehicle made contact with second net
1.2730	Strap released from first net passenger-side energy absorber
1.4260	Strap released from first net driver-side energy absorber
1.9837	Second net, right net side, lower connector broke
2.0162	Second net, right net side, upper connector broke
2.1047	Second net, right net side fully disconnected, and the bus began to coast

12.5. DAMAGE TO TEST INSTALLATION

Both straps on the first net paid out before releasing from their cannisters. The cable on the left side of the second net failed after spooling out 50 ft. Table 12.6 describes the deflection and working width of the MOPS. Figure 12.1 and Figure 12.2 show the damage to the MOPS.

Table 12.6. Deflection and Working Width of the MOPS for Test 440213-01-6.

Test Parameter	Measured
Permanent Deflection/Location	N/A, test article failed
Dynamic Deflection	N/A, test article failed

Figure 12.1. Crash Site after Test 440213-01-6.

Figure 12.2. Second Net after Test 440213-01-6.

12.6. DAMAGE TO TEST VEHICLE

Figure 12.3 and Figure 12.4 show the damage sustained by the vehicle. Figure 12.5 and Figure 12.6 show the interior of the test vehicle. Table 12.7 provides details on the exterior vehicle damage. Due to the failure of the installation, occupant compartment deformation was not measured.

Figure 12.3. Front of Test Vehicle after Test 440213-01-6.

Figure 12.4. Oblique of Test Vehicle after Test 440213-01-6.

Figure 12.5. Rear Interior of Test Vehicle after Test 440213-01-6.

Figure 12.6. Front Interior of Test Vehicle on Impact Side after Test 440213-01-6.

Table 12.7. Exterior Vehicle Damage for Test 440213-01-6.

Side Windows	The side window on the door shattered
Maximum Exterior Deformation	Maximum exterior deformation was not measured due to installation failure
VDS	12FC1
CDC	12FCEN1
Fuel Tank Damage	None
Description of Damage to Vehicle:	The front bumper, windshield, headlights, door, and side panels were damaged. The windshield in front of the driver fell out due to ballast sandbags placed in the occupant compartment striking the windshield.

12.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 12.8. Figure G.5 in Appendix G.3 shows the vehicle angular displacements, and Figures G.6 through G.8 in Appendix G.4 show acceleration versus time traces.

Table 12.8. Occupant Risk Factors for Test 440213-01-6.

Test Parameter	Specification[a]	Measured	Time
OIV, Longitudinal (ft/s)	≤40.0 *30.0*	7.3	0.9335 seconds on right side of interior
OIV, Lateral (ft/s)	≤40.0 *30.0*	1.4	0.9335 seconds on right side of interior
Ridedown, Longitudinal (g)	≤20.49 *15.0*	2.2	1.9605–1.9705 seconds
Ridedown, Lateral (g)	≤20.49 *15.0*	1.0	2.0227–2.0327 seconds
THIV (m/s)	N/A	2.2	0.9262 seconds on right side of interior
ASI	N/A	0.1	1.9481–1.9981 seconds
50-ms MA Longitudinal (g)	N/A	−1.7	1.9227–1.9727 seconds
50-ms MA Lateral (g)	N/A	−0.5	2.0115–2.0615 seconds
50-ms MA Vertical (g)	N/A	−0.7	0.0679–0.1179 seconds
Roll (deg)	N/A	3.3	0.5706 seconds
Pitch (deg)	N/A	1.4	1.3337 seconds
Yaw (deg)	N/A	1.8	1.8104 seconds

[a] Values in italics are the preferred *MASH* values.

12.8. TEST SUMMARY

Figure 12.7 summarizes the results of Test 440213-01-6. After investigation of the test results, the research team believed unequal loading between the wire ropes of the second net caused the wire ropes to rupture. Once the wire ropes began to rupture, a zipper-like behavior occurred, with other wire ropes rupturing soon after. A modification in the wire rope design is recommended for evaluation in future research.

0.000 s

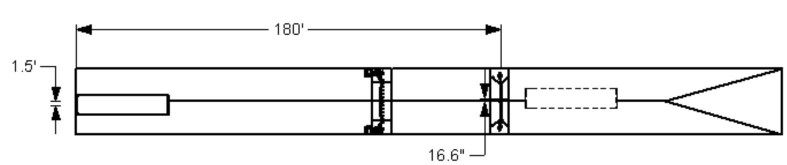
0.100 s

0.200 s

0.300 s

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard/Test No.	*MASH* Research and Development Test
TTI Project No.	440213-01-6
Test Date	2023-08-28
TEST ARTICLE	
Type	Non-Redirective Crash Cushions
Name	MOPS
Length	50 ft
Key Materials	Wire mesh nets, wire rope net, energy absorbers
Soil Type and Condition	AASHTO M147-65(2004), Type 1, Grade D Crushed Concrete
TEST VEHICLE	
Type/Designation	Passenger Bus
Year, Make and Model	2002 Van Hool Commuter C2045 USA
Curb (lb)	34,120
Inertial Weight (lb)	50,140
IMPACT CONDITIONS	
Impact Speed (mi/h)	50.0
Impact Angle (deg)	0.7
Impact Location	Centerline of the vehicle aligned 16.6 inches to the right of the centerline of the first MOPS net and 7.3 inches to the right of the centerline of the second net
Kinetic Energy (kip-ft)	4190.4
EXIT CONDITIONS	
Exit Speed (mi/h)	N/A
Stopping Distance	180 ft downstream 1.5 ft to the left side
TEST ARTICLE DEFLECTIONS	
Dynamic (inches)	N/A
Permanent (inches)	N/A
VEHICLE DAMAGE	
VDS	12FC1
CDC	12FCEN1
Max. Ext. Deformation (inches)	Not measured
Max Occupant Compartment Deformation	Not measured

OCCUPANT RISK VALUES							
Long. OIV (ft/s)	7.3	Long. Ridedown (g)	2.2	Max 50-ms Long. (g)	−1.7	Max Roll (deg)	3.3
Lat. OIV (ft/s)	1.4	Lat. Ridedown (g)	1.0	Max 50-ms Lat. (g)	−0.5	Max Pitch (deg)	1.4
THIV (m/s)	2.2	ASI	0.1	Max 50-ms Vert. (g)	−0.7	Max Yaw (deg)	1.8



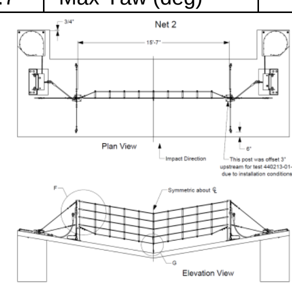


Figure 12.7. Summary of Results for Research and Development Test on MOPS.

CHAPTER 13. SUMMARY AND IMPLEMENTATION

13.1. ASSESSMENT OF TEST RESULTS

The crash tests reported herein were performed in accordance with *MASH* TL-3, which involves two tests, on the MOPS.

13.2. SUMMARY

Table 13.1 shows that the MOPS met the performance criteria for *MASH* TL-3 non-redirective crash cushions for passenger vehicle impacts. Further modification of the second net design and additional evaluation efforts is recommended for accommodating larger vehicle impacts.

Table 13.1. Assessment Summary for *MASH* TL-3 Tests on MOPS.

Evaluation Criteria	Description	Test 440210-01-1 1100C	Test 440210-01-2 2270P	Test 440211-01-3 Bus	Test 440211-01-4 2270P	Test 440211-01-5 Bus	Test 440211-01-6 Bus
C	Redirect, Controlled Penetration, or Controlled Stop	S	S	**FAIL**	S	**FAIL**	**FAIL**
D	No Penetration into Occupant Compartment	S	S	S	S	S	S
F	Roll and Pitch Limit	S	S	N/A	S	S	S
G	Rolling is acceptable	N/A	N/A	S	N/A	S	S
H	OIV Threshold	S	S	S	S	S	S
I	Ridedown Threshold	S	S	S	S	S	S
N	Vehicle Trajectory Behind Test Article Acceptable	S	S	S	S	S	S
Overall	Evaluation	Pass	Pass	FAIL	Pass	FAIL	FAIL

Note: S = Satisfactory; N/A = not applicable.
[1] See Table 5.2 for details.

13.3. IMPLEMENTATION[*]

The MOPS successfully arrested both the *MASH* small car and pickup truck and met *MASH* evaluation criteria for both Tests 3-40 and 3-41. The drawings of this system can be found in Appendix A. Therefore, the MOPS is suitable for implementation in median ditches for passenger vehicle considerations. The MOPS failed to arrest the motorcoach during the Research and Development testing, and therefore additional research is needed prior to implementation for larger vehicle protection.

As presented in Chapter 2, the research team completed a systematic approach analysis of the crash data and roadway characteristics. This analysis identified characteristics that can be used to identify sites that might benefit from MOPS implementation.

Median ditches are designed with a wide range of widths and slopes. Consequently, site-specific modifications to the general dimensions utilized in the as-tested MOPS are required when slopes and widths differ from the as-tested condition. However, the height from grade to the lower cables, as shown in the Appendix A drawings, is to be maintained to minimize risk of override or underride.

The successful Test 3-41 may be used to establish baseline runout distances required to arrest impacting passenger vehicles. The pickup truck was arrested in approximately 60 ft in Test 3-41, so this can be used as a baseline to estimate runout distances based on site-specific slopes. Test 3-41 utilized a flat longitudinal slope, but median opening areas may slope in the longitudinal direction (i.e., parallel to the roadway). This slope is an important consideration when designing a MOPS because it affects the runout distance of impacting vehicles once the net is engaged. If the median is sloped downward longitudinally (aligned with the impact direction), the runout distance would be longer because gravity aids the vehicle in maintaining speed. Conversely, the runout distance would be shorter if the median is sloped upward longitudinally (aligned against the impacting direction) because gravity aids in slowing the vehicle. This slowing effect can be seen in runaway truck ramps, where uncontrolled tractor-trailers are slowed to a stop with the use of gravity and the frictional resistance of driving through gravel. Consequently, the net manufacturer can be engaged in the runout distance design and discussion based on site-specific longitudinal slopes.

[*] The opinions/interpretations identified/expressed in this section of the report are outside the scope of TTI Proving Ground's A2LA Accreditation.

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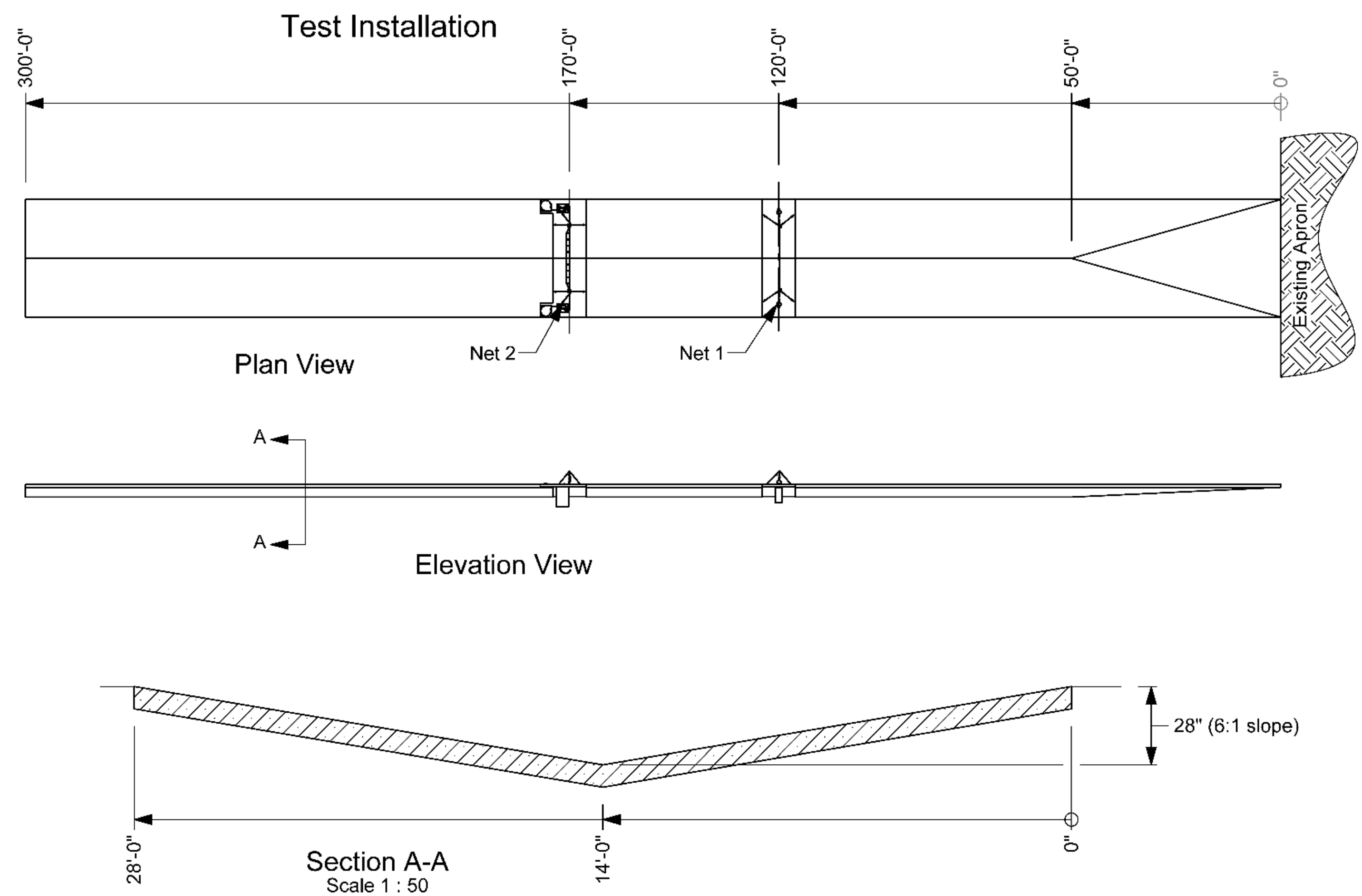
APPENDIX A. DETAILS OF MOPS



Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground

Project #440212 Median Net		2023-08-24
Drawn by GES	Scale 1:400	Sheet 1 of 10 Test Installation

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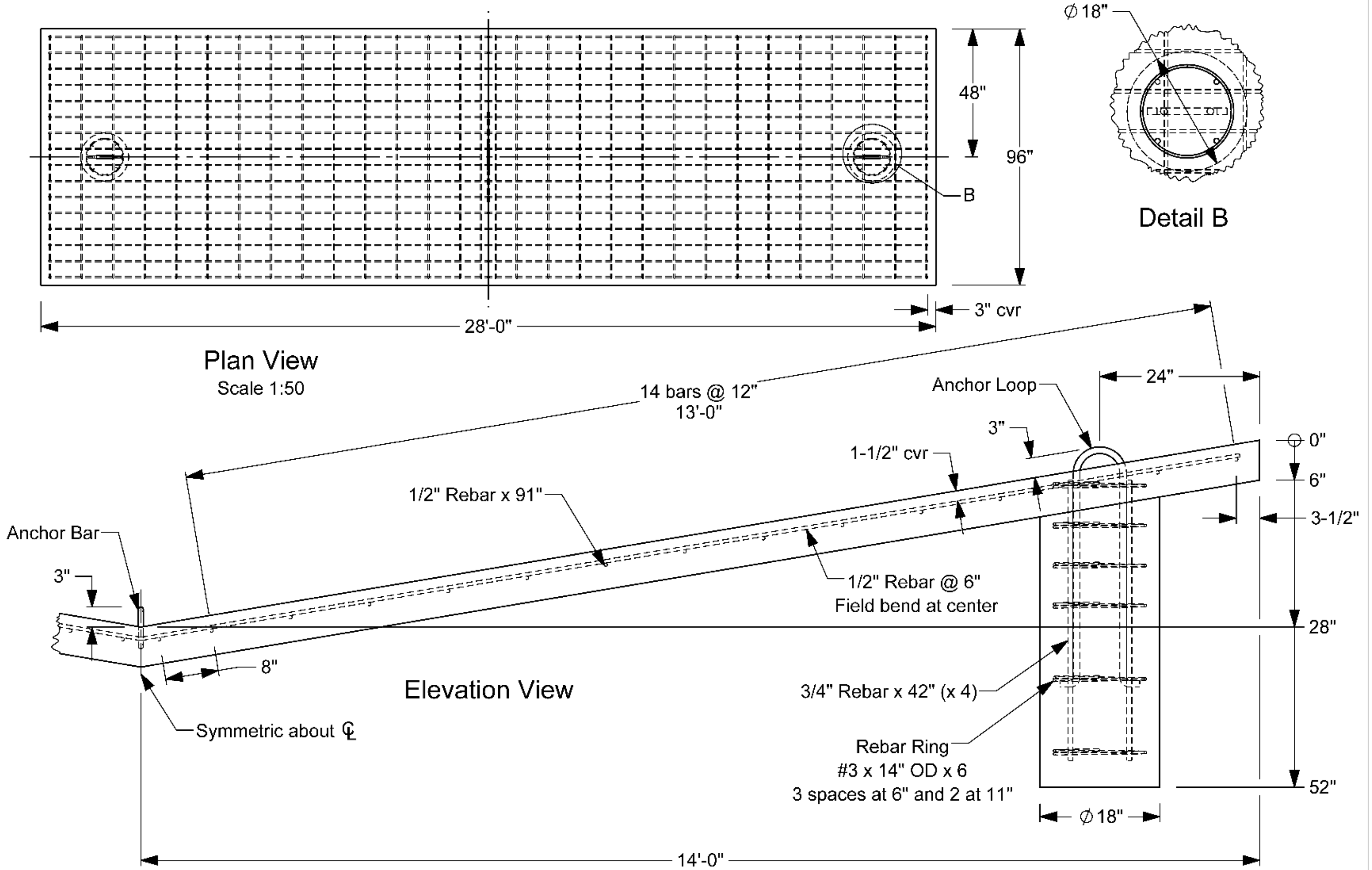
Net 1 Concrete Details



2a. Rebar is grade 60. All rebar dimensions are to center of bar unless otherwise indicated by "cvr" (cover).

2b. Minimum rebar lap for Ø1/2" bars is 39".

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #440212 Median Net		2023-08-24
Drawn by GES	Scale 1:20	Sheet 2 of 10 Net 1 Concrete Details

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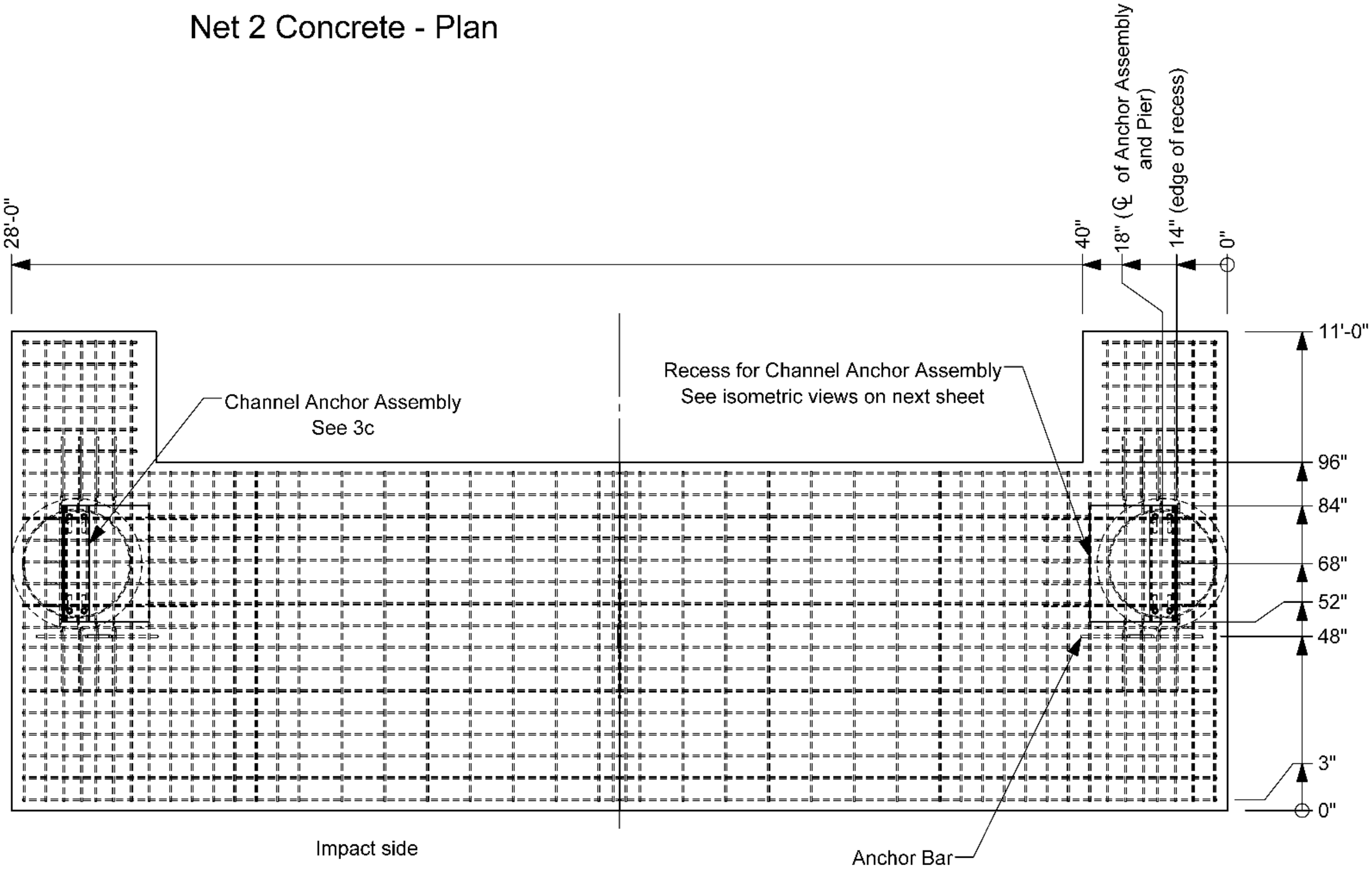
Net 2 Concrete - Plan



3a. Rebar is grade 60. All rebar dimensions are to center of bar unless otherwise indicated by "cvr" (cover).

3b. Minimum rebar lap for Ø1/2" bars is 39".

3c. Cover or plug Coupling Nuts to protect threads. Adjust rebar spacing as needed to avoid conflict with Anchor Assembly.

Texas A&M Transportation Institute | Roadside Safety and Physical Security Division - Proving Ground

Project #440212 Median Net | 2023-08-24

Drawn by GES | Scale 1:15 | Sheet 3 of 10 Net 2 Concrete - Plan

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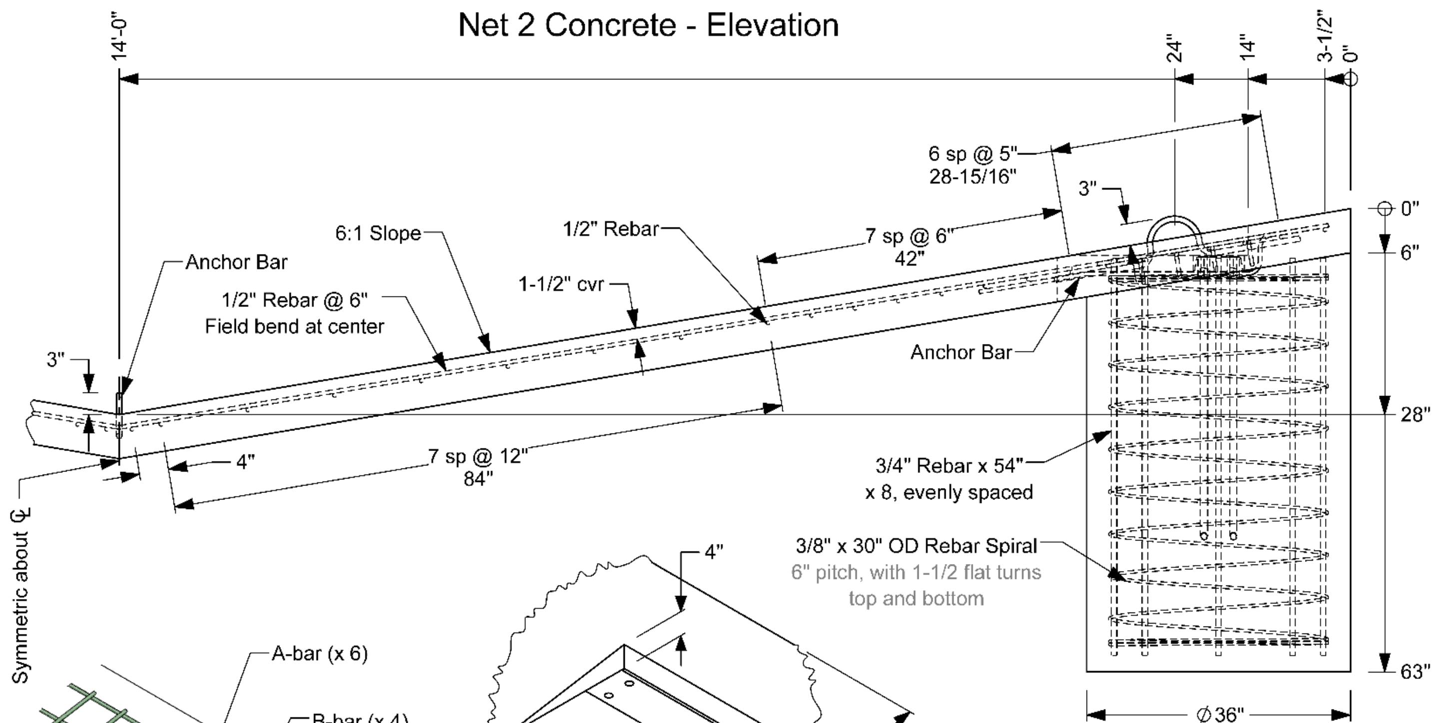
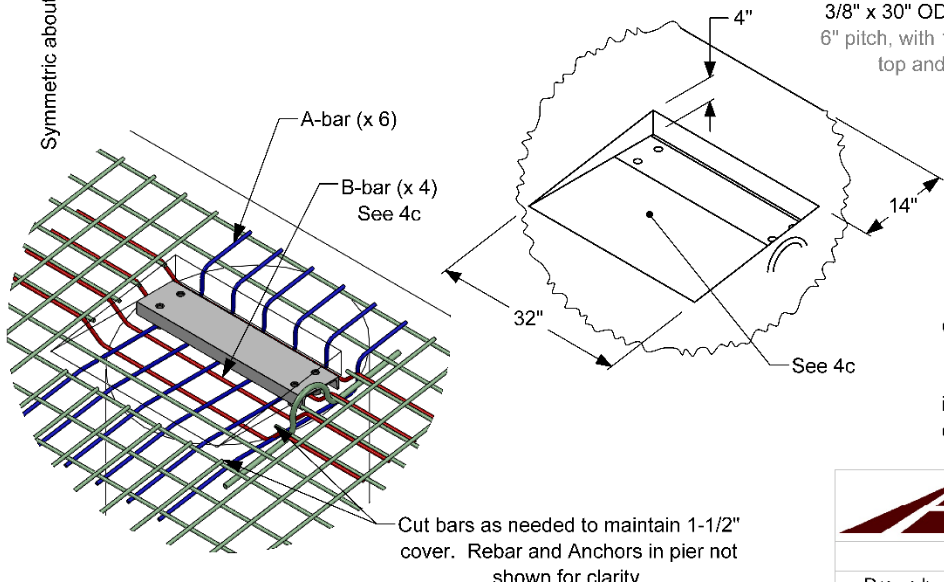
Net 2 Concrete - Elevation





4a. Rebar is grade 60. All rebar dimensions are to center of bar unless otherwise indicated by "cvr" (cover).
4b. Minimum rebar lap for Ø1/2" bars is 39".
4c. Recess for Channel Anchor Assembly isERROR!:RD1@Drawing View51deep at 14" from the edge of the slab, with a flat level bottom.
4d. Rotate B-bars as needed to tie to A-bars.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #440212 Median Net		2023-08-24
Drawn by GES	Scale 1:20	Sheet 4 of 10 Net 2 Concrete - Elevation

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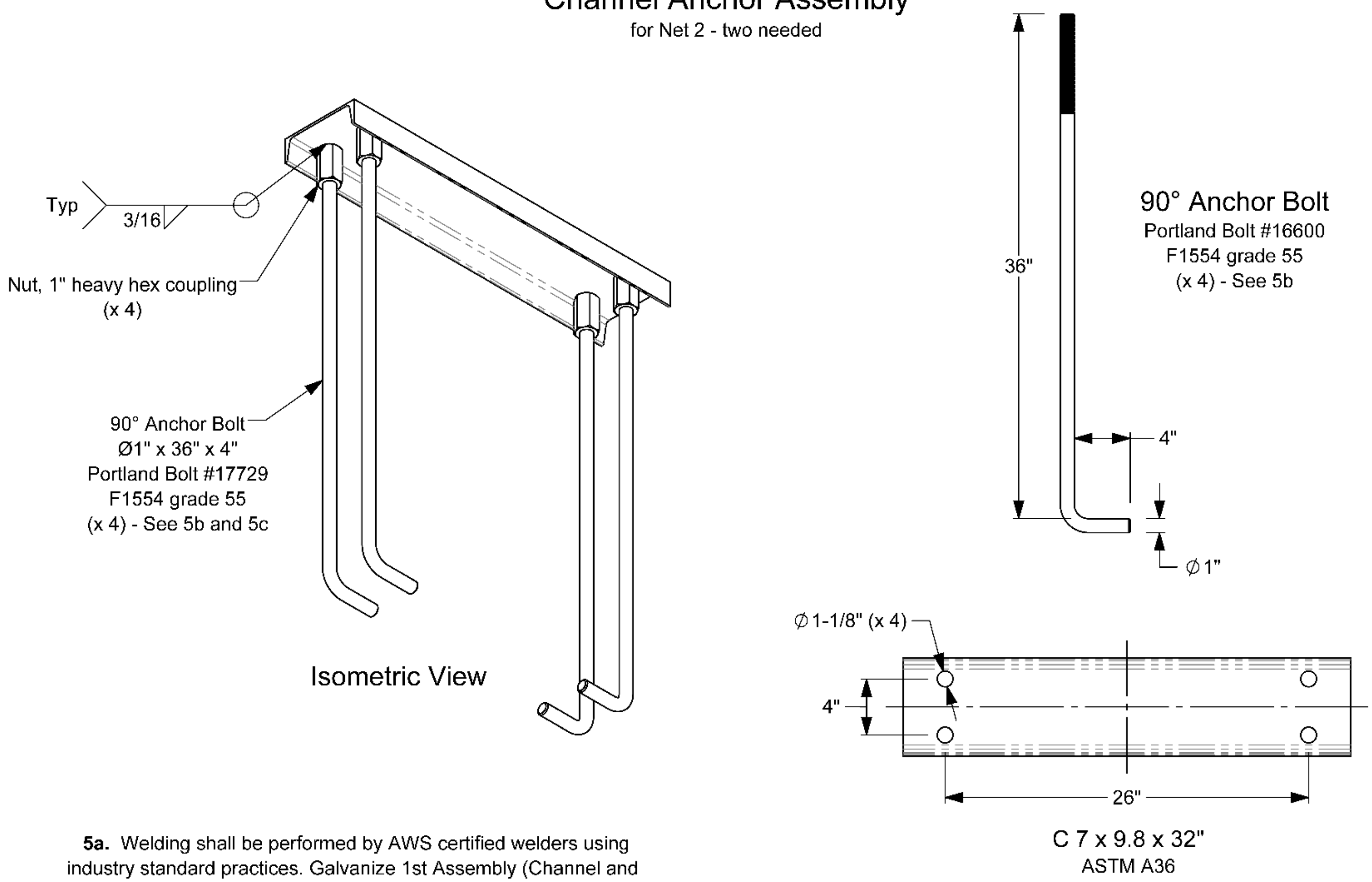
Channel Anchor Assembly

for Net 2 - two needed



5a. Welding shall be performed by AWS certified welders using industry standard practices. Galvanize 1st Assembly (Channel and Coupling Nuts) after all drilling and welding is complete. Protect threads.

5b. Thread 90° Anchor Bolts to center (± 1/8") of Heavy Hex Coupling Nuts before welding coupling nuts to channel.

5c. Equivalent Anchor Bolts from another supplier may be substituted for Portland Bolt Anchors.

5d. Threads not shown in some views for clarity.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground		
Project #440212 Median Net			2023-08-24
Drawn by GES	Scale 1:10	Sheet 5 of 10 Channel Anchor Assembly	

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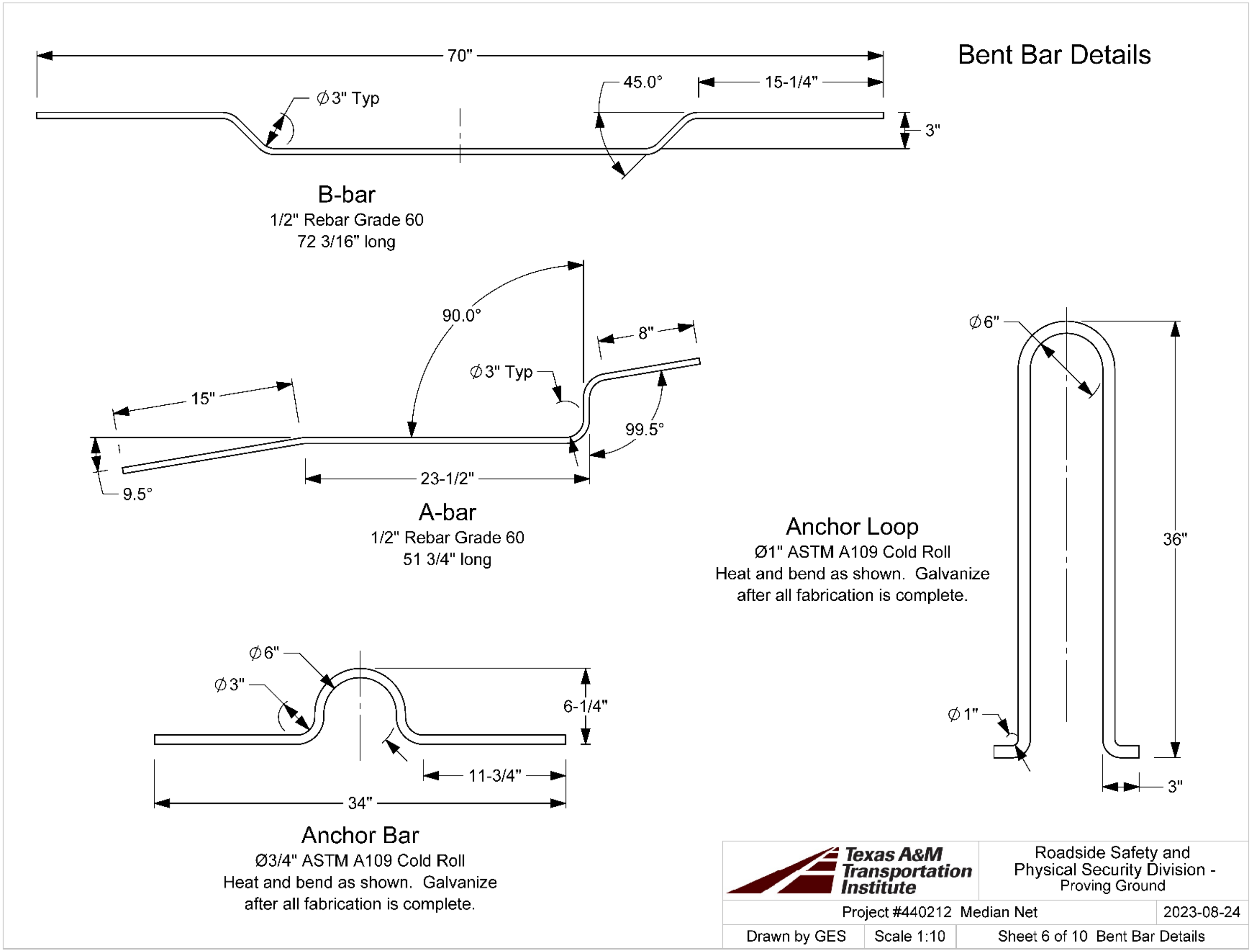

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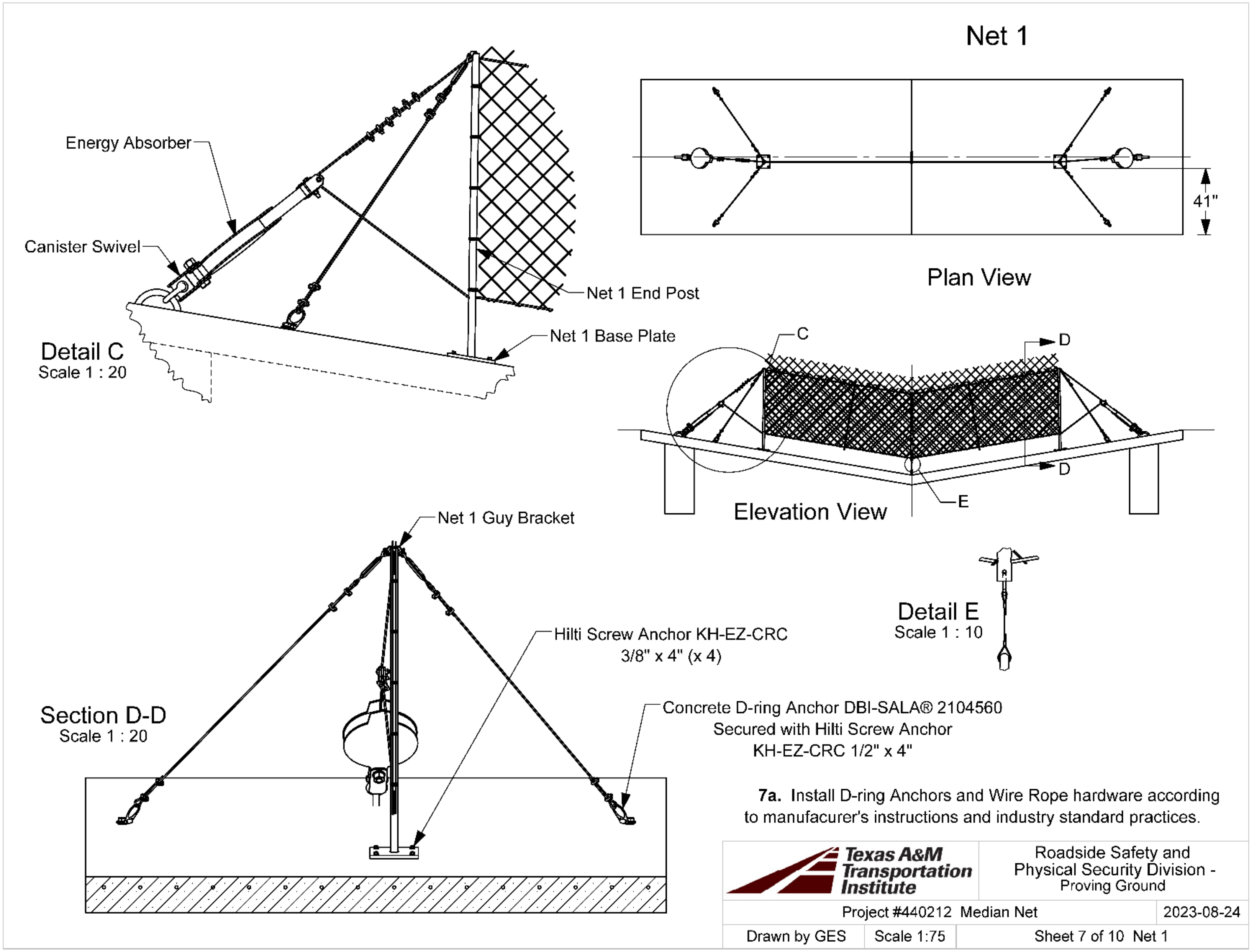

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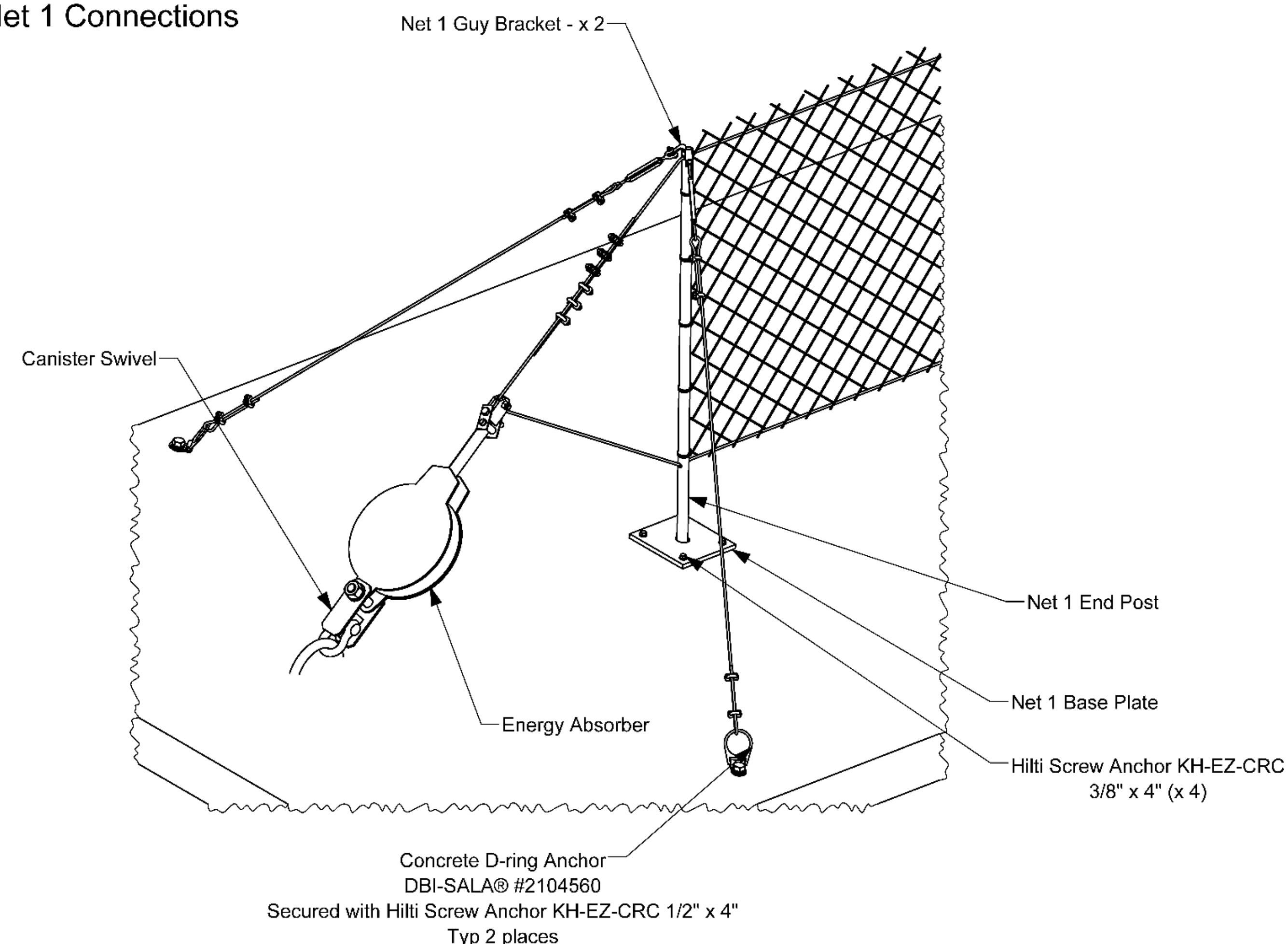
Net 1 Connections



Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #440212 Median Net		2023-08-24
Drawn by GES	Scale 1:15	Sheet 8 of 10 Net 1 Connections

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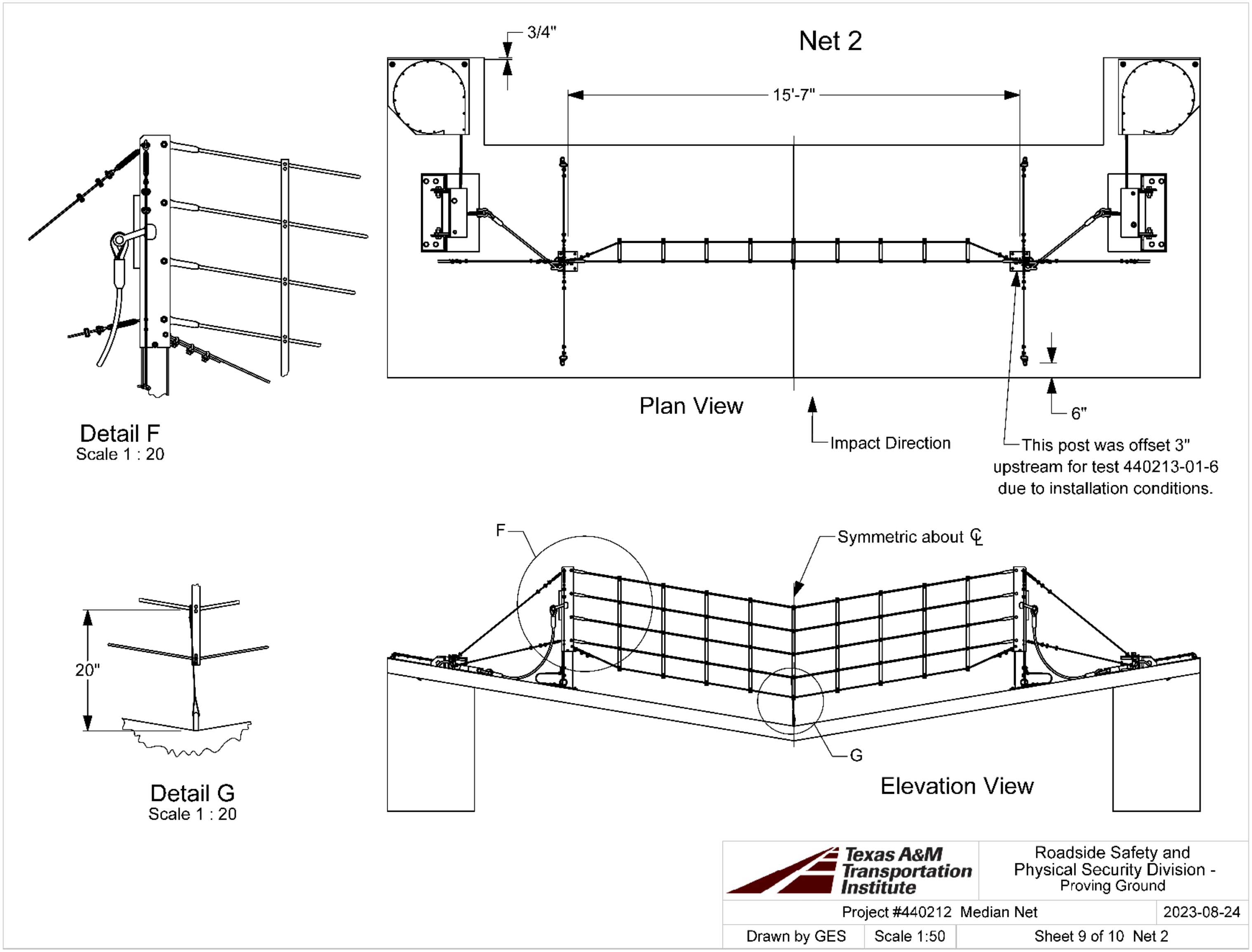

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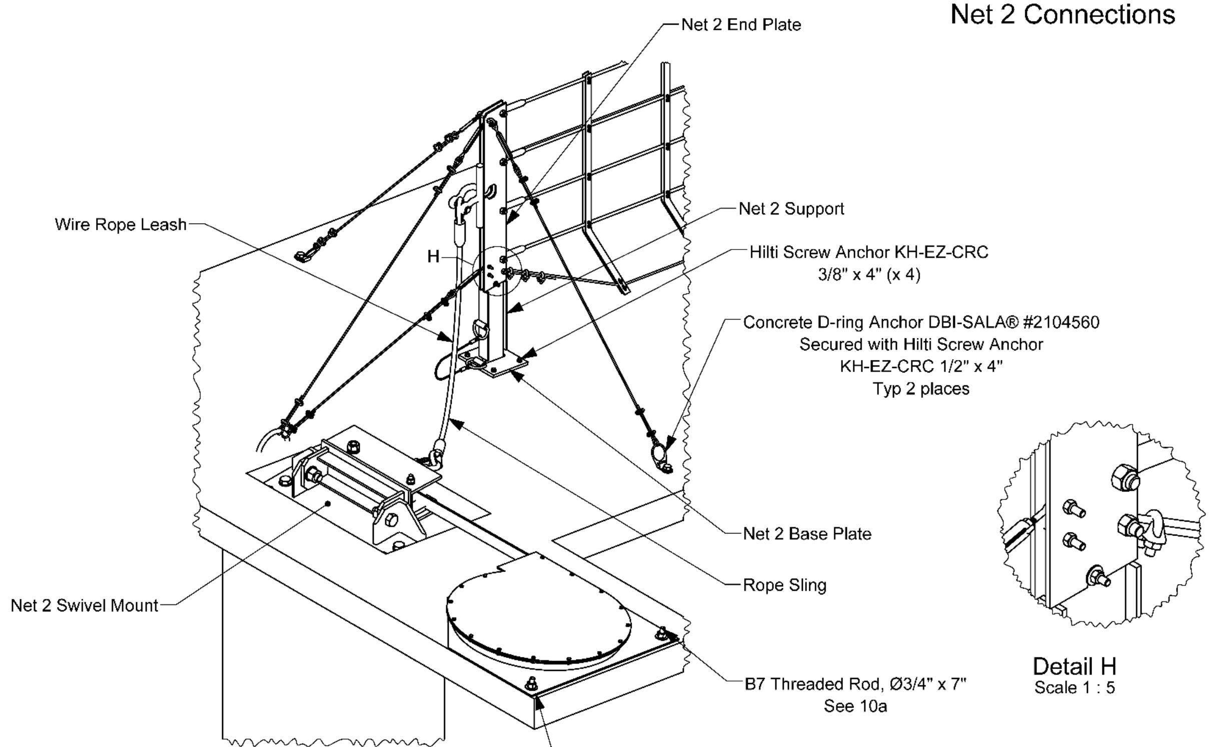
Net 2 Connections



10a. Typical x 3, with F436 Washer and Heavy Hex Nut. Secure with Hilti HIT-RE 500 V3 epoxy according to manufacturer's instructions, with 5" embedment.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #440212 Median Net		2023-08-24
Drawn by GES	Scale 1:20	Sheet 10 of 10 Net 2 Connections

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APPENDIX B. *MASH* TEST 3-40 (CRASH TEST 440210-01-1)

B.1. VEHICLE PROPERTIES AND INFORMATION

Date: 2020-08-20 Test No.: 440210-01-1 VIN No.: 3N1CN7AP6GL808971

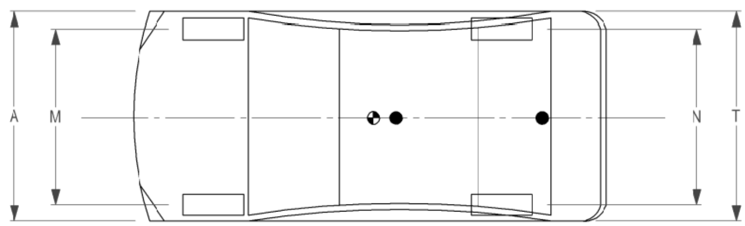
Year: 2016 Make: NISSAN Model: VERSA

Tire Inflation Pressure: 36 PSI Odometer: 79073 Tire Size: P185//65R15

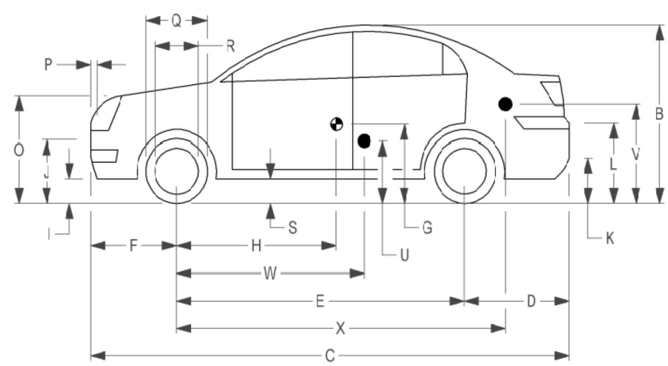
Describe any damage to the vehicle prior to test: None

● Denotes accelerometer location.

NOTES: None



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



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

Geometry: inches

A	66.70	F	32.50	K	12.50	P	4.50	U	15.50
B	59.60	G		L	26.00	Q	24.00	V	21.25
C	175.40	H	40.62	M	58.30	R	16.25	W	40.60
D	40.50	I	7.00	N	58.50	S	7.50	X	79.75
E	102.40	J	22.25	O	30.50	T	64.50		

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

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

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	1750	M_{front}	1430	1460	1545
Back	1687	M_{rear}	958	960	1040
Total	3389	M_{Total}	2388	2420	2585

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

Mass Distribution:
lb LF: 730 RF: 730 LR: 496 RR: 464

Figure B.1. Vehicle Properties for Test 440210-01-1.

TR No. 0-7021-01 131 2025-05-20

TR No. 0-7021-01 132 2025-05-20

Date: 2020-8-20 Test No.: 440210-01-1 VIN No.: 3N1CN7AP6GL808971

Year: 2016 Make: NISSAN Model: VERSA

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bumper ht	60	1	60	1		1	1		1	0
	Measurements recorded										
	☑ inches or ☐ mm										

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

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

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

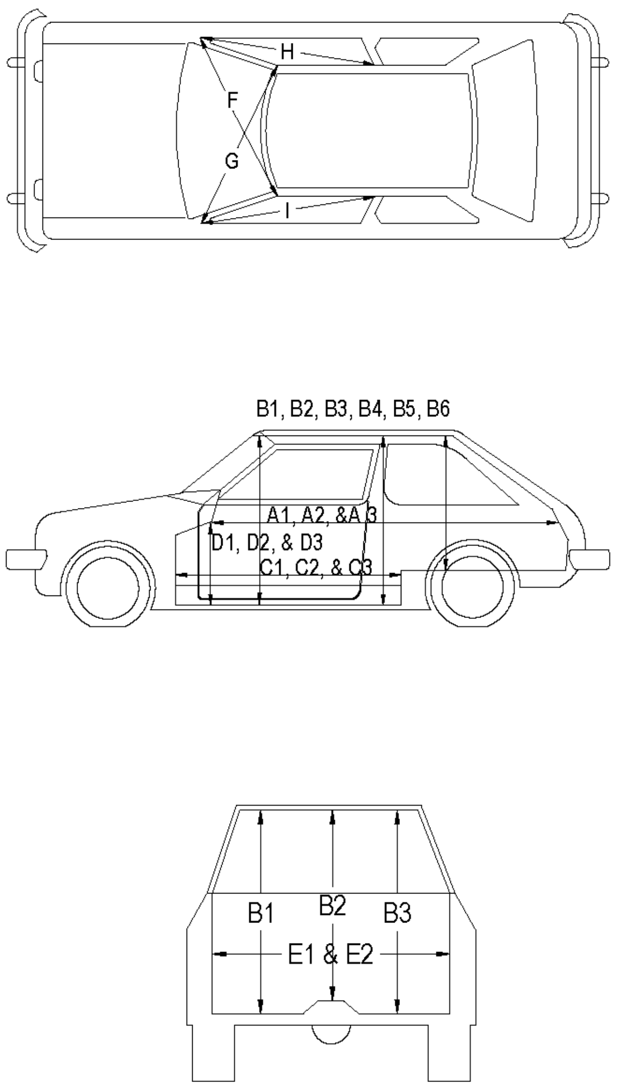
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

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

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

Figure B.2. Exterior Crush Measurements for Test 440210-01-1.

Date:	2020-8-20	Test No.:	440210-01-1	VIN No.:	3N1CN7AP6GL808971
Year:	2016	Make:	NISSAN	Model:	VERSA



OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

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

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

Figure B.3. Occupant Compartment Measurements for Test 440210-01-1.

TR No. 0-7021-01 133 2025-05-20

B.2. SEQUENTIAL PHOTOGRAPHS

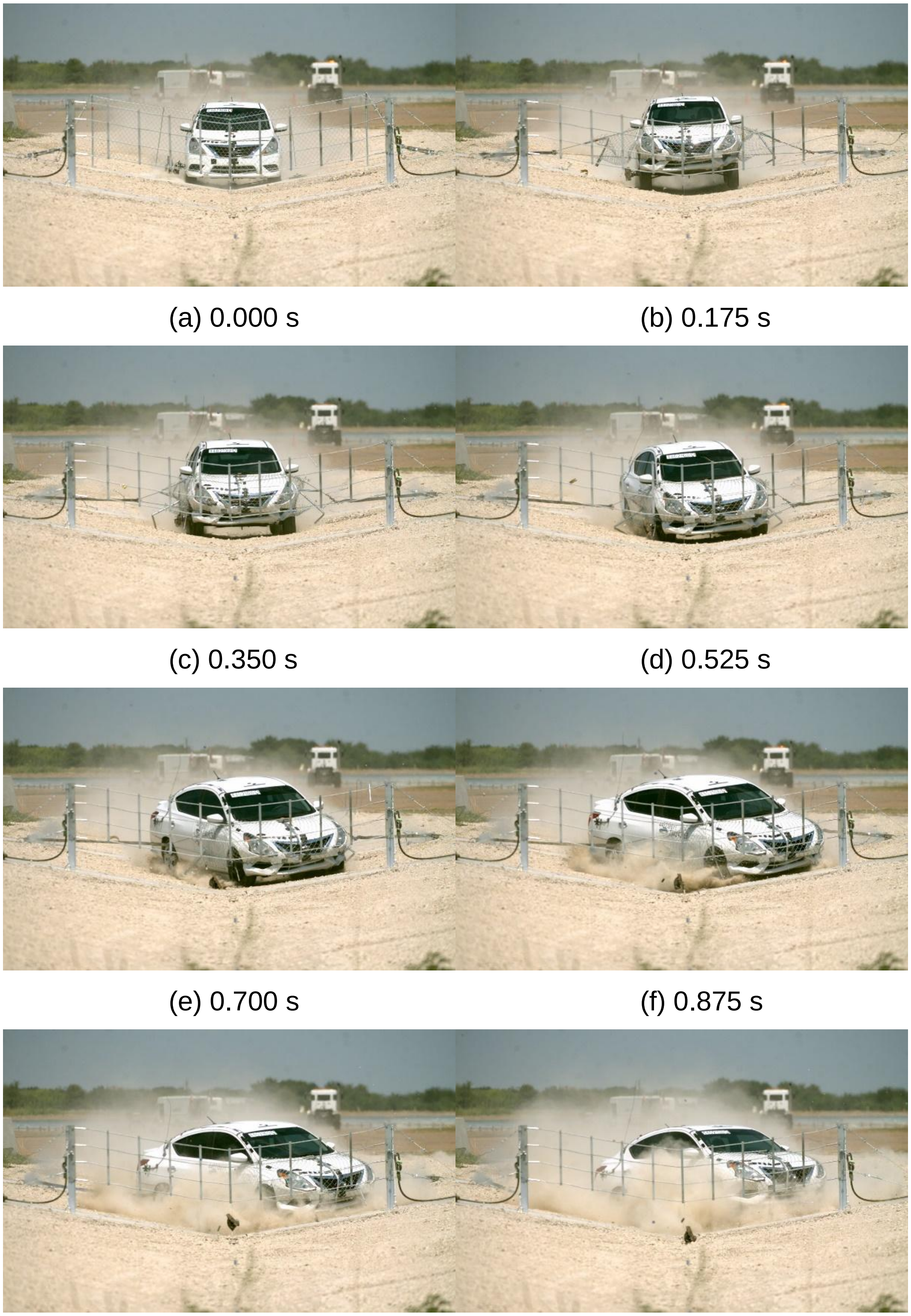
(a) 0.000 s (b) 0.175 s

(c) 0.350 s (d) 0.525 s

(e) 0.700 s (f) 0.875 s

(g) 1.050 s (h) 1.225 s

Figure B.4. Sequential Photographs for Test 440210-01-1 (Overhead Views).



(a) 0.000 s (b) 0.175 s

(c) 0.350 s (d) 0.525 s

(e) 0.700 s (f) 0.875 s

(g) 1.050 s (h) 1.225 s

Figure B.5. Sequential Photographs for Test 440210-01-1 (Frontal Views).

TR No. 0-7021-01 135 2025-05-20

TR No. 0-7021-01
136
2025-05-20

(a) 0.000 s (b) 0.175 s

(c) 0.350 s (d) 0.525 s

(e) 0.700 s (f) 0.875 s

(g) 1.050 s (h) 1.225 s

Figure B.6. Sequential Photographs for Test 440210-01-1 (Oblique Views).

TR No. 0-7021-01 137 2025-05-20

(a) 0.000 s

(b) 0.175 s

(c) 0.350 s

(d) 0.525 s

(e) 0.700 s

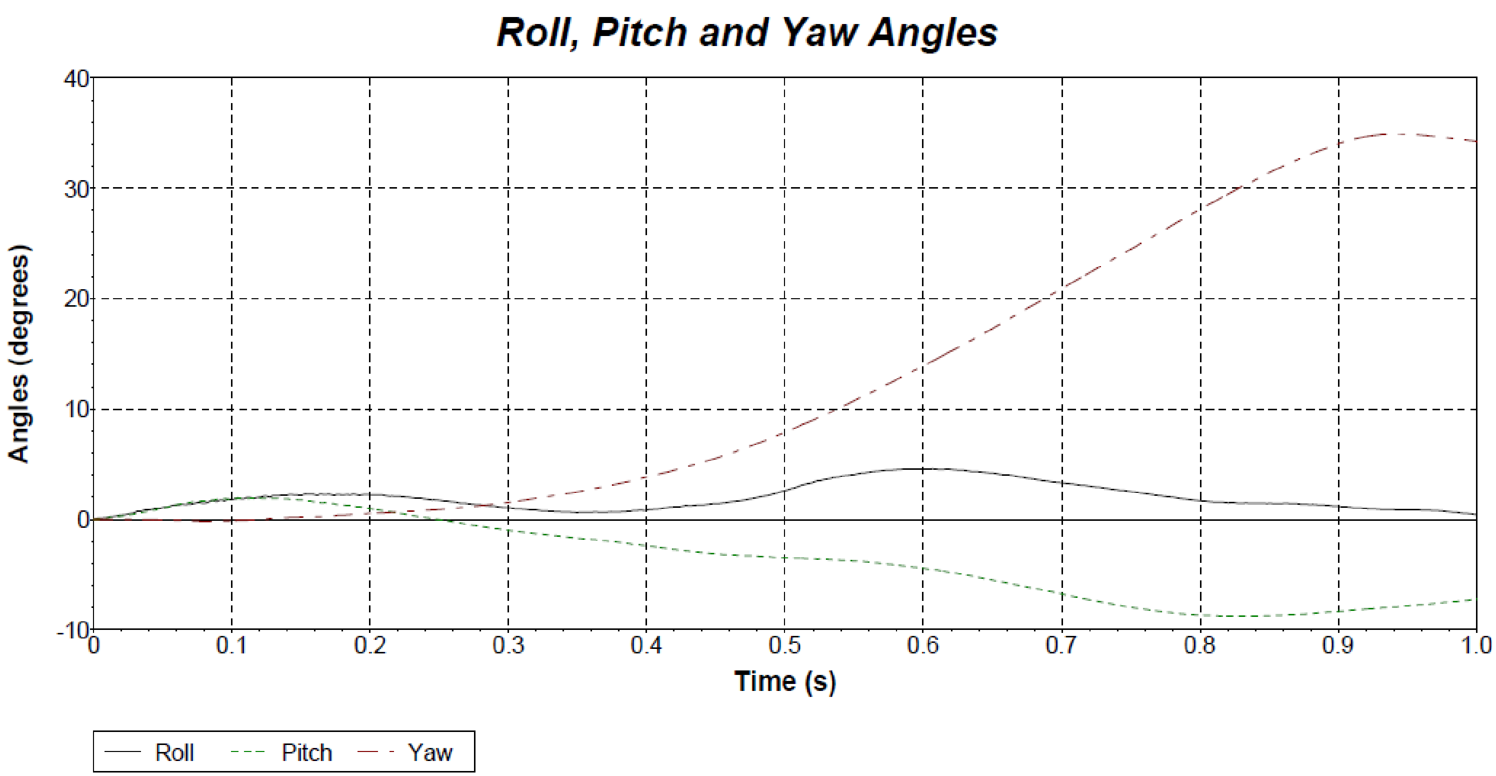
(f) 0.875 s

(g) 1.050 s

(h) 1.225 s

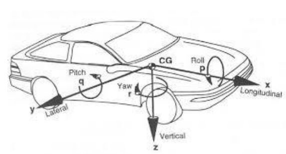
Figure B.7. Sequential Photographs for Test 440210-01-1 (Right Angle Views).

B.3. VEHICLE ANGULAR DISPLACEMENTS



Axes are vehicle-fixed.
Sequence for determining orientation:

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



Test Number: 440210-01-1
Test Standard/Test Number: *MASH* Test 3-40 Modified
Test Article: Median Net
Test Vehicle: 2016 Nissan Versa
Inertial Mass: 2420 lb
Gross Mass: 2585 lb
Impact Speed: 62.0 mi/h
Impact Angle: 0°

Figure B.8. Vehicle Angular Displacements for Test 440210-01-1.

B.4. VEHICLE ACCELERATIONS

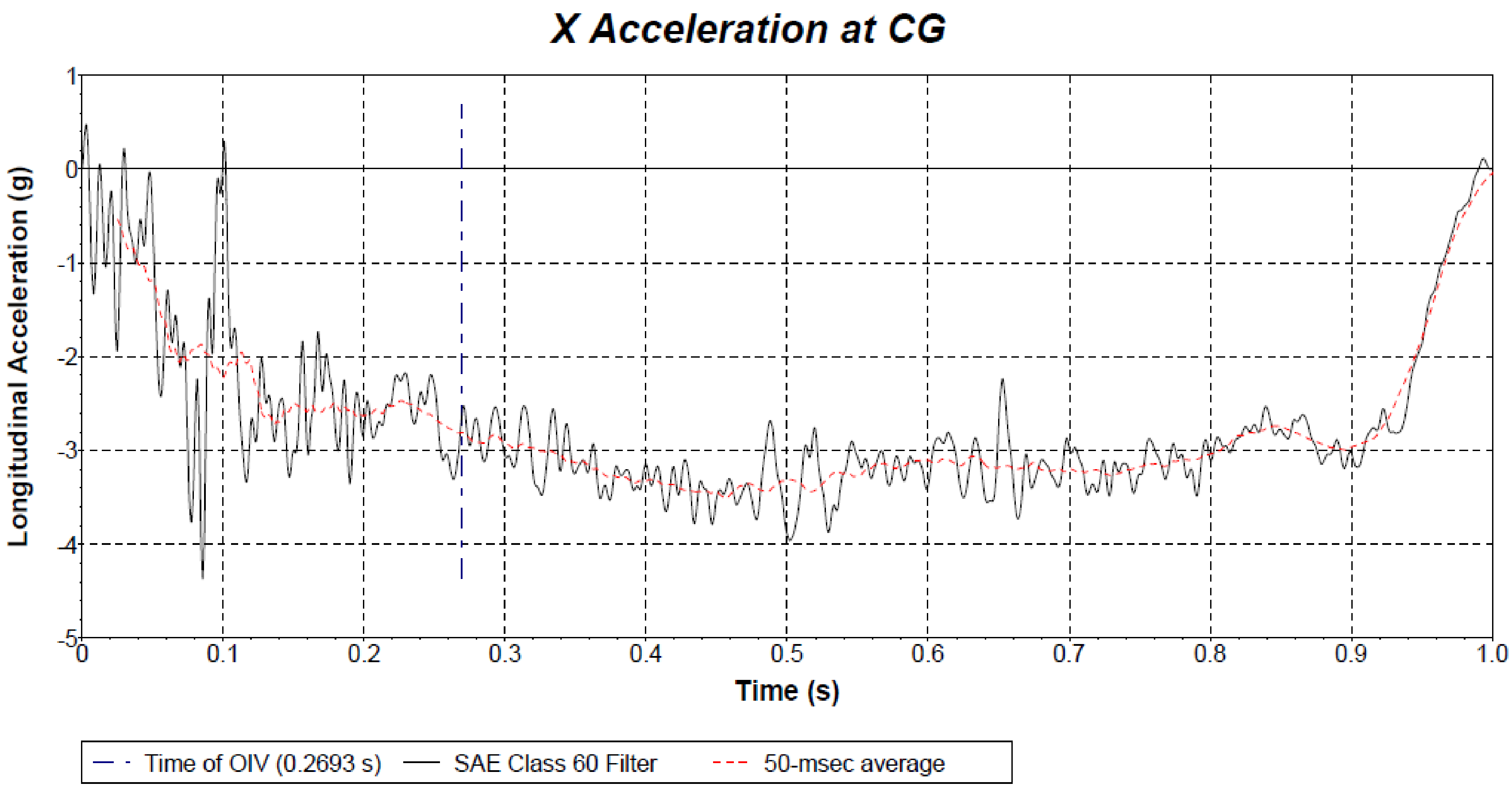


Figure B.9. Vehicle Longitudinal Accelerometer Trace for Test 440210-01-1 (Accelerometer Located at Center of Gravity).

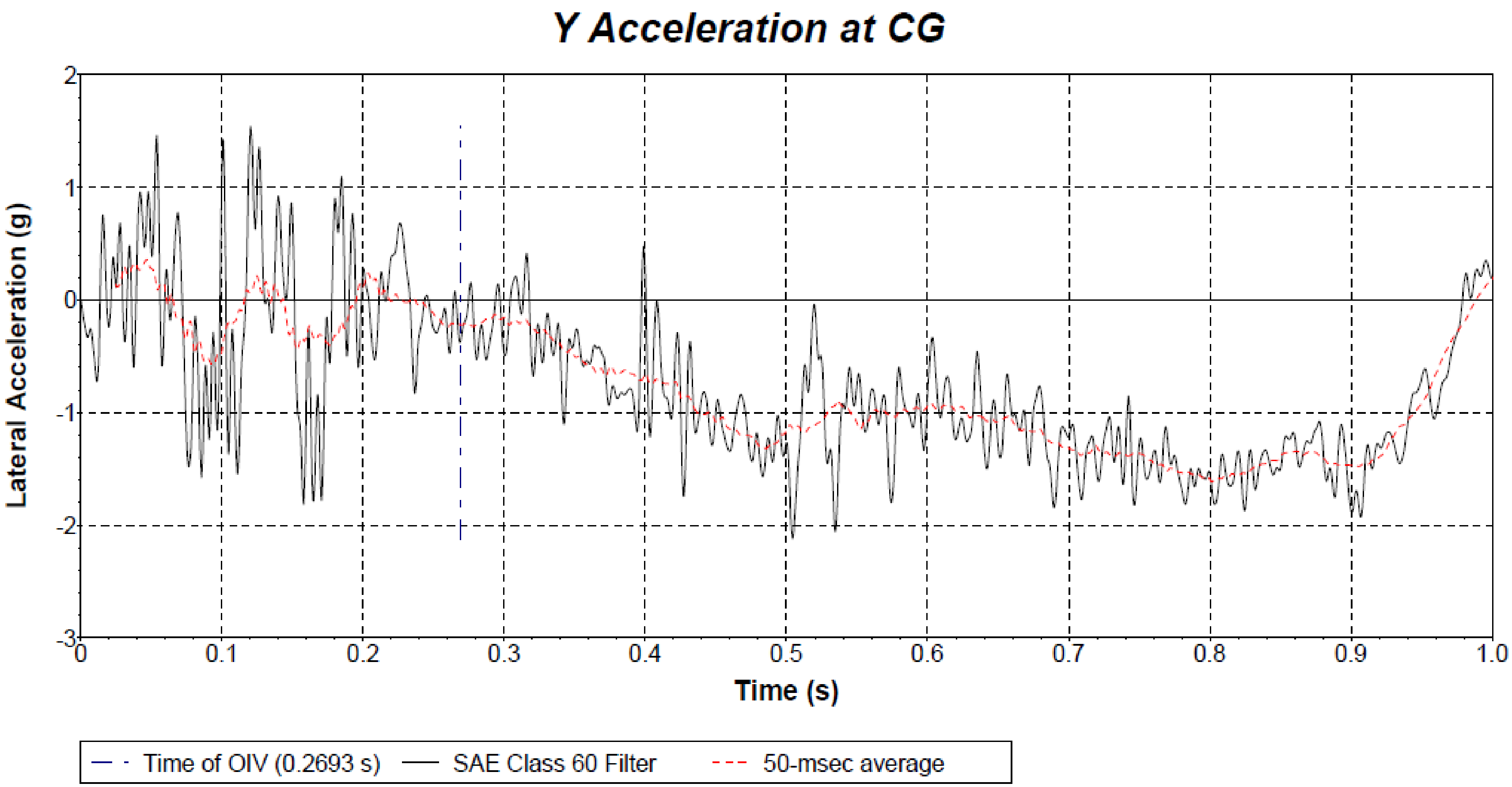


Figure B.10. Vehicle Lateral Accelerometer Trace for Test 440210-01-1 (Accelerometer Located at Center of Gravity).

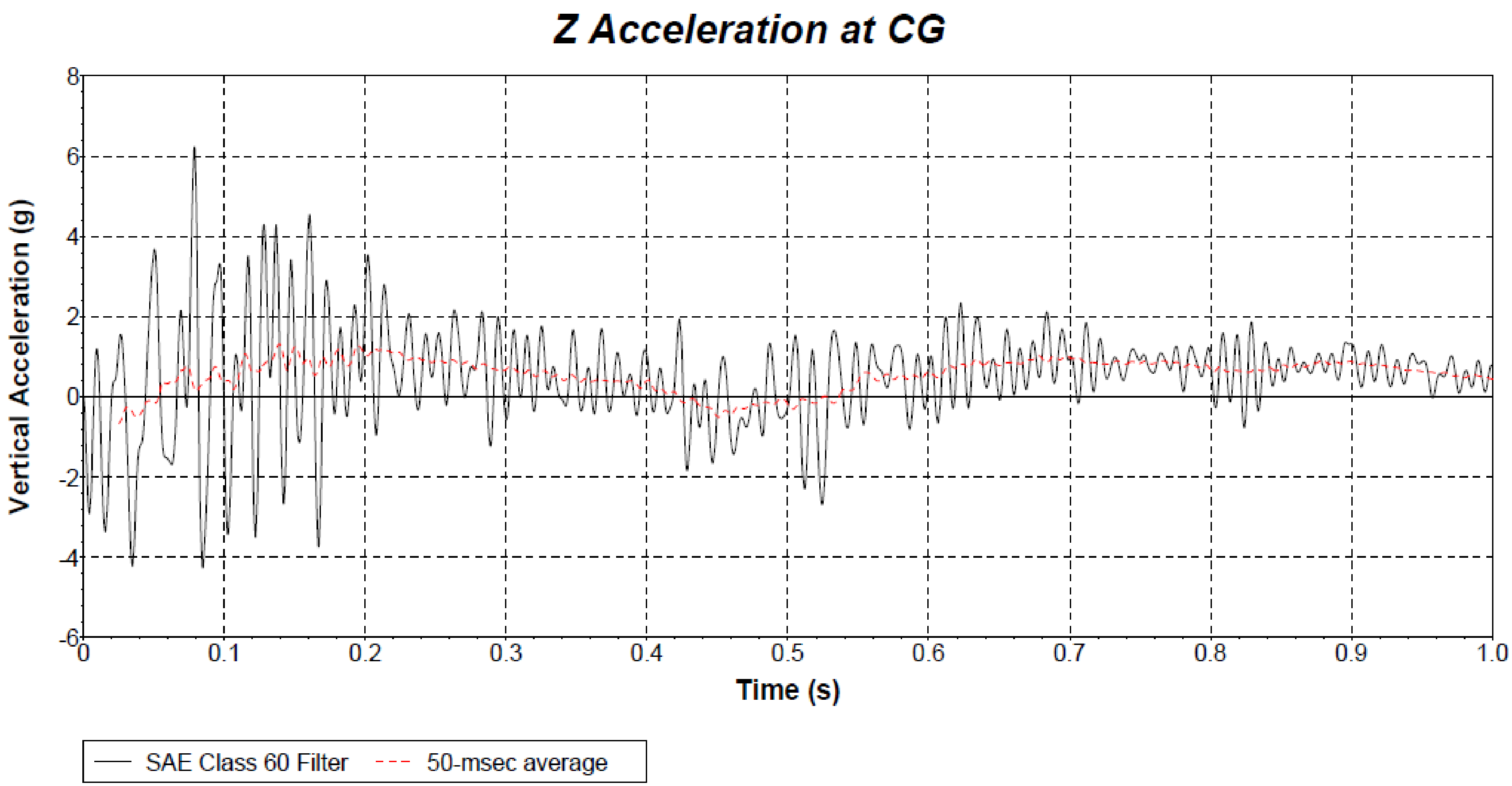


Figure B.11. Vehicle Vertical Accelerometer Trace for Test 440210-01-1 (Accelerometer Located at Center of Gravity).

APPENDIX C. *MASH* TEST 3-41 (CRASH TEST 440210-01-2)

C.1. VEHICLE PROPERTIES AND INFORMATION

Date: 2020-8-24 Test No.: 440210-01-2 VIN No.: 1C6RR6GTXFS577669

Year: 2015 Make: RAM Model: 1500

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

Tread Type: Highway Odometer: 149713

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

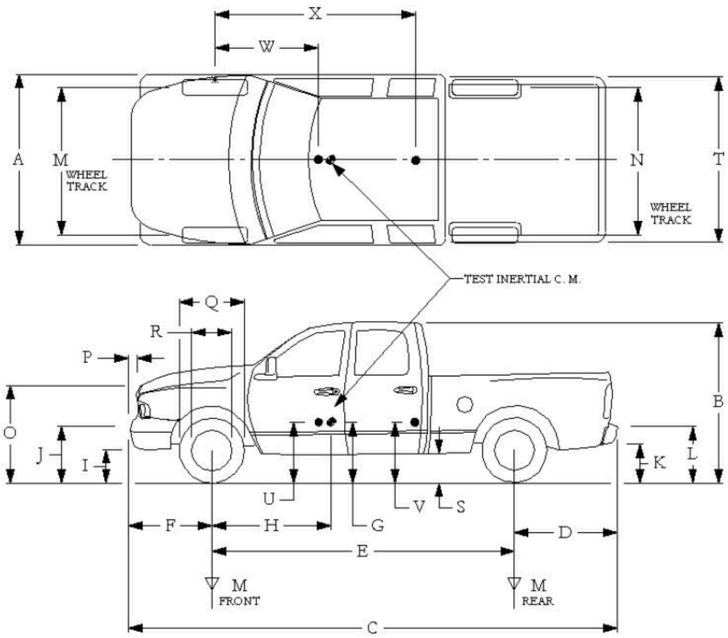
NOTES: None

Engine Type: V-8
Engine CID: 5.7 L

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

Optional Equipment:
None

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



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	30.25
C	227.50	H	60.76	M	68.50	R	18.00	W	60.7
D	44.00	I	11.75	N	68.00	S	13.00	X	79.00
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}	2928	2849	2849
Back	3900	M_{rear}	2065	2171	2171
Total	6700	M_{Total}	4993	5020	5020

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

Mass Distribution:
lb LF: 1432 RF: 1417 LR: 1088 RR: 1083

Figure C.1. Vehicle Properties for Test 440210-01-2.

Date:	2020-8-24	Test No.:	440210-01-2	VIN No.:	1C6RR6GTXFS577669
Year:	2015	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
	Front-<0.25 inches			-							
	Right Rear Bed		1.5								
	Measurements recorded										
	☑ inches or ☐ mm										

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

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

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

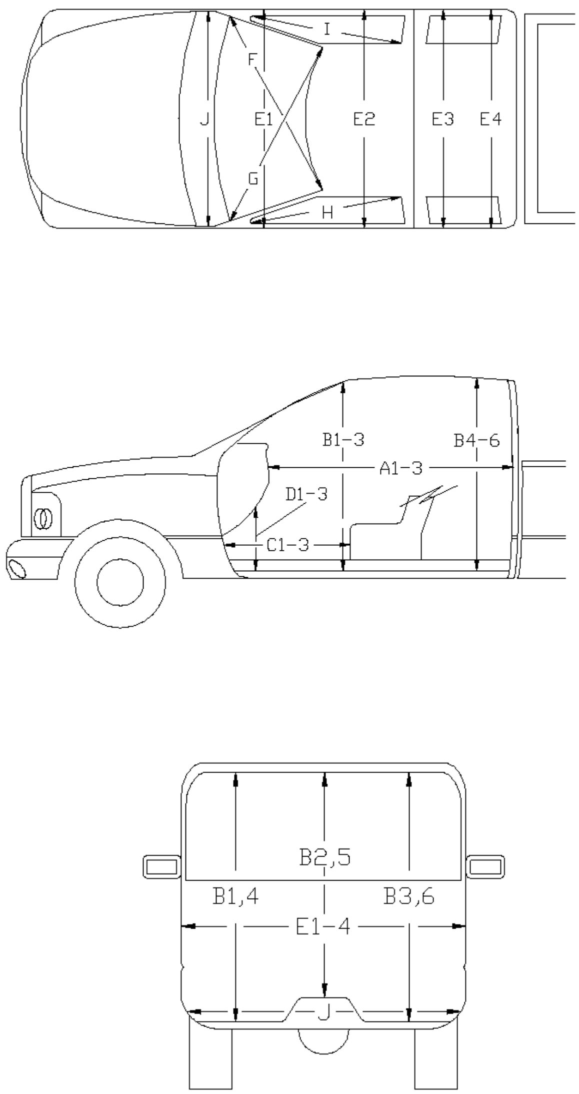
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

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

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

Figure C.2. Exterior Crush Measurements for Test 440210-01-2.

Date:	2020-8-24	Test No.:	440210-01-2	VIN No.:	1C6RR6GTXFS577669
Year:	2015	Make:	RAM	Model:	1500



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

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	65.00	65.00	0.00
A2	63.00	63	0.00
A3	65.50	65.50	0.00
B1	45.00	45.00	0.00
B2	38.00	38.00	0.00
B3	45.00	45.00	0.00
B4	39.50	39.50	0.00
B5	43.00	43.00	0.00
B6	39.50	39.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	26.00	0.00
D1	11.00	11.00	0.00
D2	0.00	0.00	0.00
D3	11.50	11.50	0.00
E1	58.50	58.50	0.00
E2	63.50	63.50	0.00
E3	63.50	63.50	0.00
E4	63.50	63.50	0.00
F	59.00	59.00	0.00
G	59.00	59.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	25.00	25.00	0.00

Figure C.3. Occupant Compartment Measurements for Test 440210-01-2.

C.2. SEQUENTIAL PHOTOGRAPHS

(a) 0.000 s

(b) 0.175 s

(c) 0.350 s

(d) 0.525 s

(e) 0.700 s

(f) 0.875 s

(g) 1.050 s

(h) 1.225 s

Figure C.4. Sequential Photographs for Test 440210-01-2 (Overhead Views).

(a) 0.000 s (b) 0.175 s

(c) 0.350 s (d) 0.525 s

(e) 0.700 s (f) 0.875 s

(g) 1.050 s (h) 1.225 s

Figure C.5. Sequential Photographs for Test 440210-01-2 (Frontal Views).

(a) 0.000 s

(b) 0.175 s

(c) 0.350 s

(d) 0.525 s

(e) 0.700 s

(f) 0.875 s

(g) 1.050 s

(h) 1.225 s

Figure C.6. Sequential Photographs for Test 440210-01-2 (Oblique Views).

(a) 0.480 s (b) 0.655 s

(c) 0.830 s (d) 1.005 s

(e) 1.180 s (f) 1.355 s

(g) 1.530 s (h) 1.705 s

Figure C.7. Sequential Photographs for Test 440210-01-2 (Right Angle Views).

C.3. VEHICLE ANGULAR DISPLACEMENTS

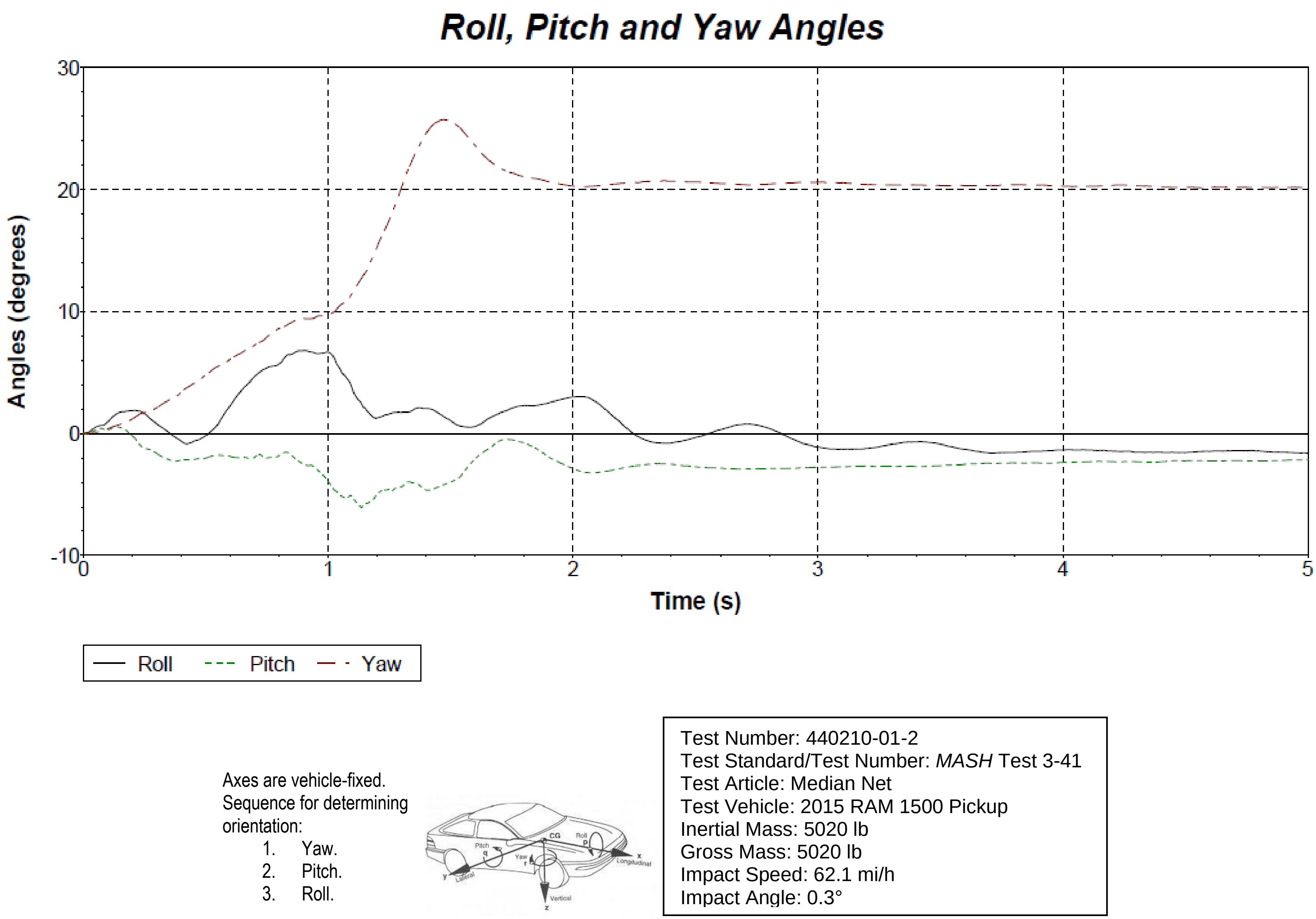


Figure C.8. Vehicle Angular Displacements for Test 440210-01-2.

C.4. VEHICLE ACCELERATIONS

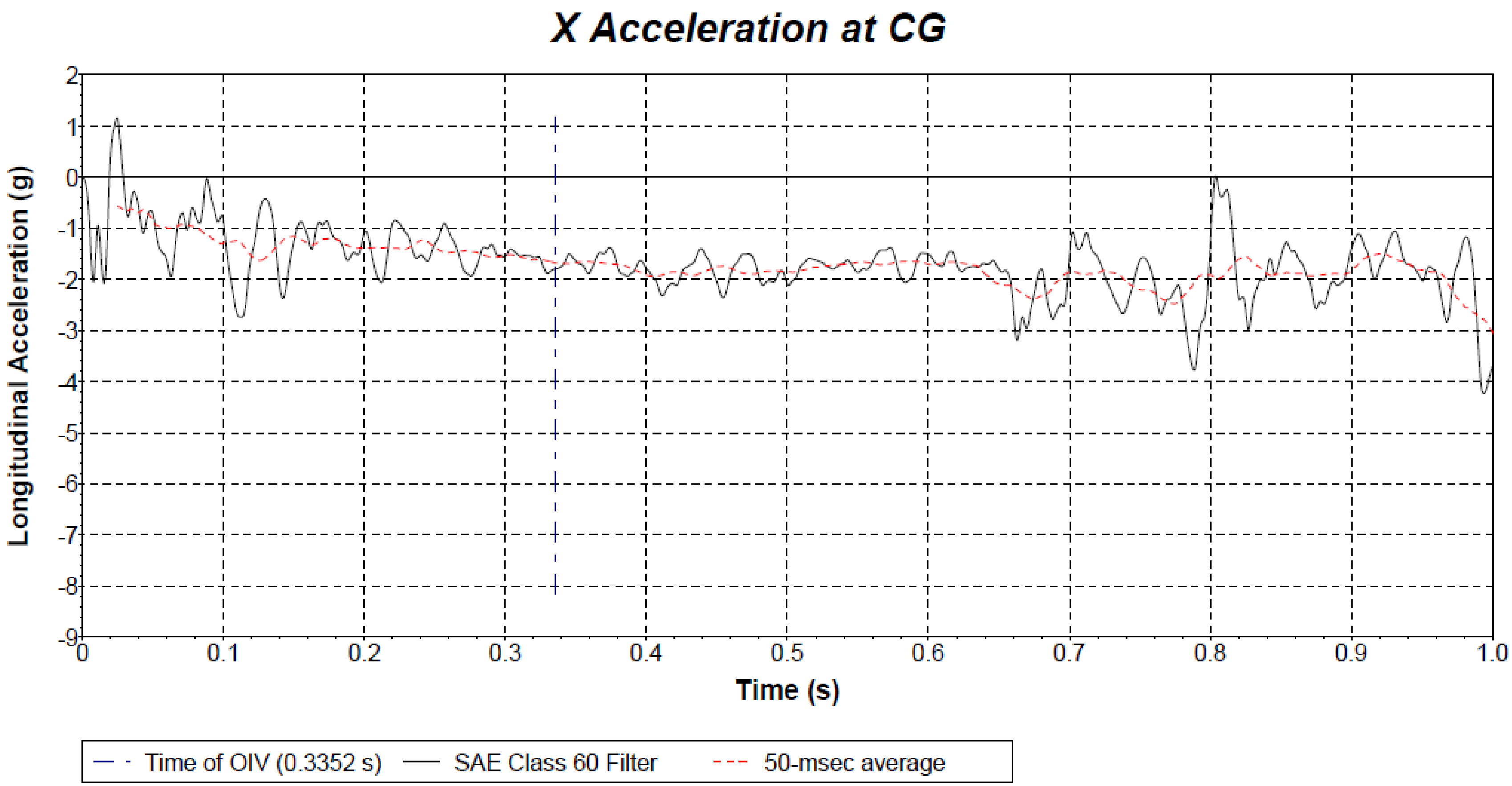


Figure C.9. Vehicle Longitudinal Accelerometer Trace for Test 440210-01-2 (Accelerometer Located at Center of Gravity).

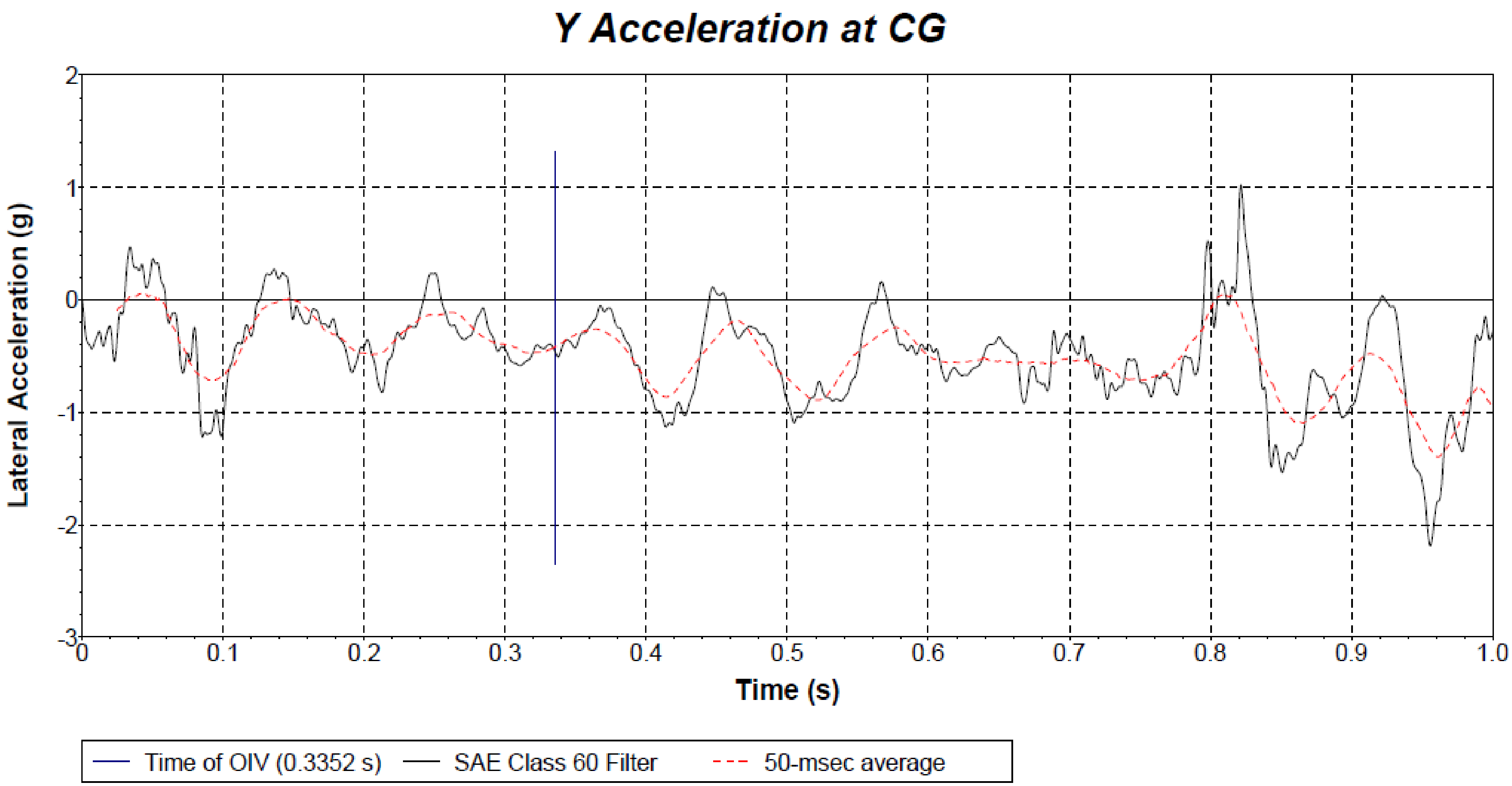


Figure C.10. Vehicle Lateral Accelerometer Trace for Test 440210-01-2 (Accelerometer Located at Center of Gravity).

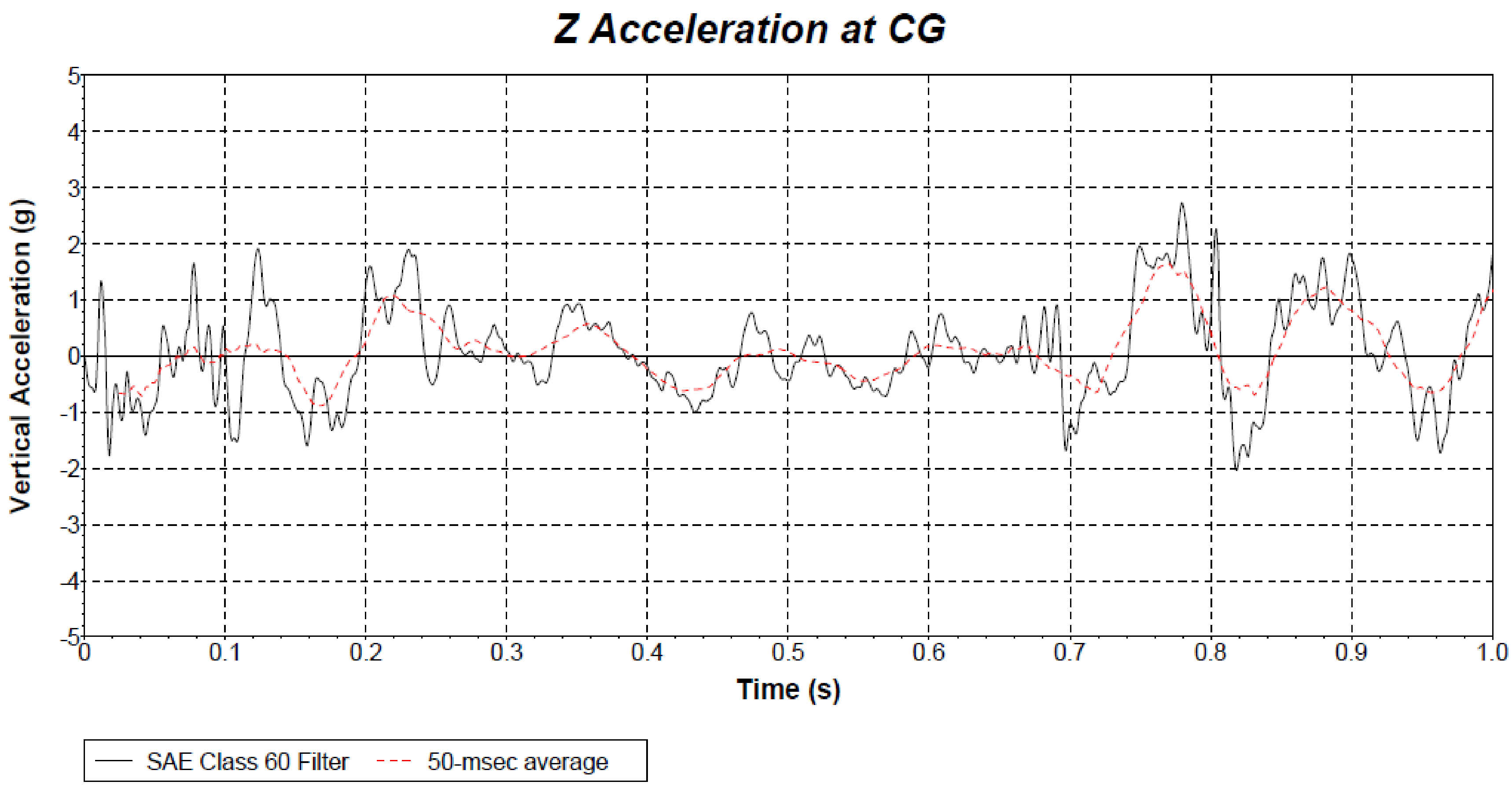


Figure C.11. Vehicle Vertical Accelerometer Trace for Test 440210-01-2 (Accelerometer Located at Center of Gravity).

APPENDIX D. *MASH* TEST 3-41 (CRASH TEST 440210-01-4)

D.1. VEHICLE PROPERTIES AND INFORMATION

Date: 2021-1-20 | Test No.: 440210-01-4 | VIN No.: 1C6RR6FT4GS324298

Year: 2016 | Make: RAM | Model: 1500

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

Tread Type: Highway | Odometer: 151071

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

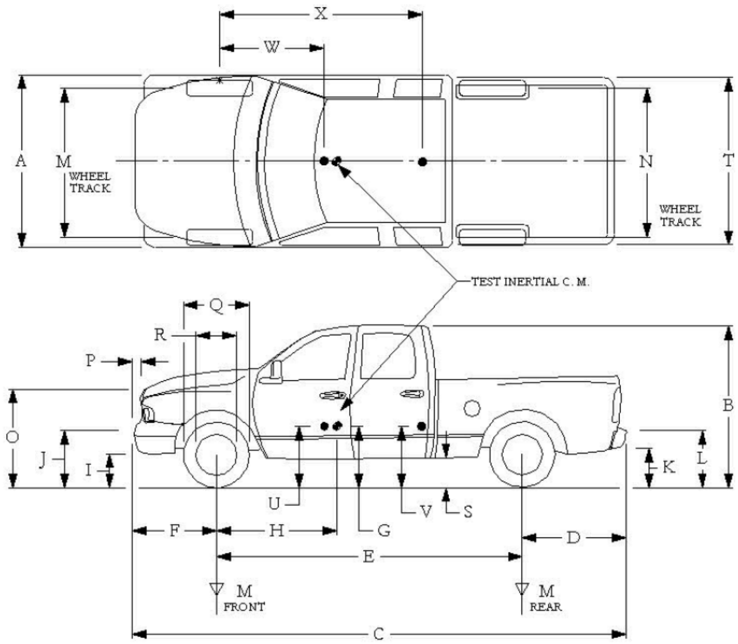
NOTES: None

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	28.25	L	30.00	Q	30.50	V	30.25
C	227.50	H	61.89	M	68.50	R	18.00	W	61.80
D	44.00	I	11.75	N	68.00	S	13.00	X	79.00
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}	2962	2836	2836
Back	3900	M_{rear}	2142	2233	2233
Total	6700	M_{Total}	5104	5069	5069

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

Mass Distribution:
lb LF: 1437 RF: 1399 LR: 1115 RR: 1118

Figure D.1. Vehicle Properties for Test 440210-01-4.

Date:	2021-1-20	Test No.:	440210-01-4	VIN No.:	1C6RR6FT4GS324298
Year:	2016	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bmp ht	72	10	72	-	-	-	-	-	-	0
	Measurements recorded										
	☑ **inches** or ☐ **mm**										

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

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

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

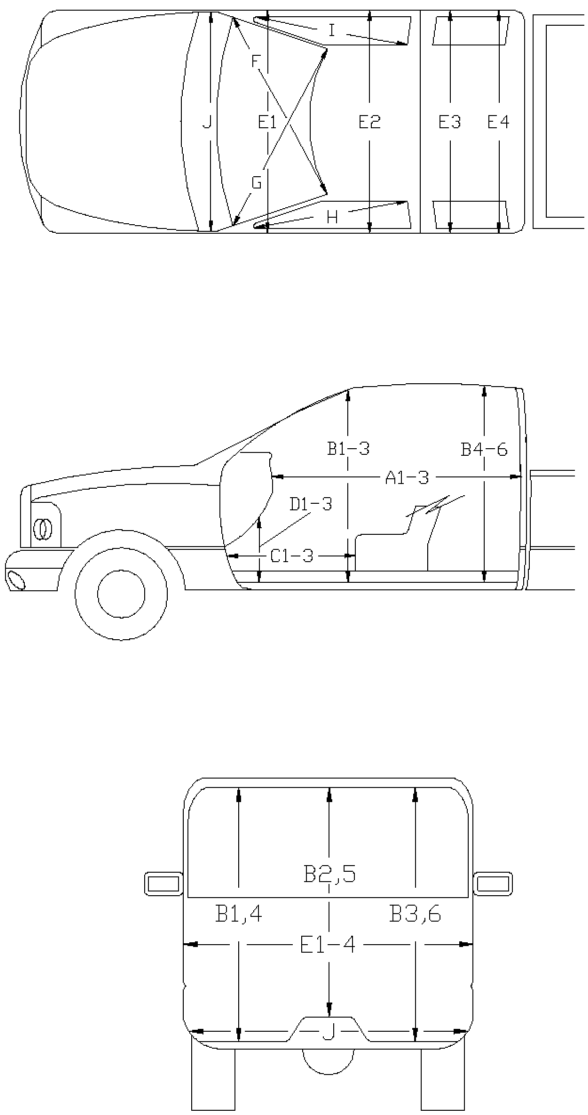
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

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

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

Figure D.2. Exterior Crush Measurements for Test 440210-01-4.

Date:	2021-1-20	Test No.:	440210-01-4	VIN No.:	1C6RR6FT4GS324298
Year:	2016	Make:	RAM	Model:	1500



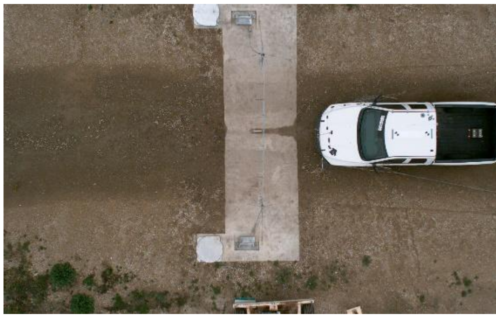
*Lateral area across the cab from driver's side kickpanel to passenger's side kickpanel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

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

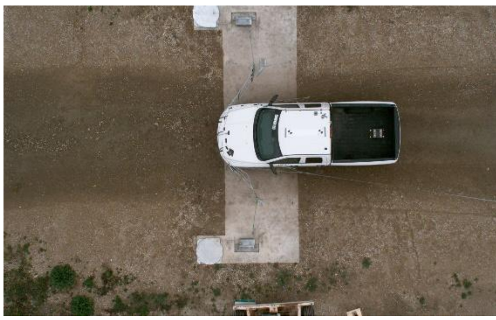
Figure D.3. Occupant Compartment Measurements for Test 440210-01-4.

D.2. SEQUENTIAL PHOTOGRAPHS

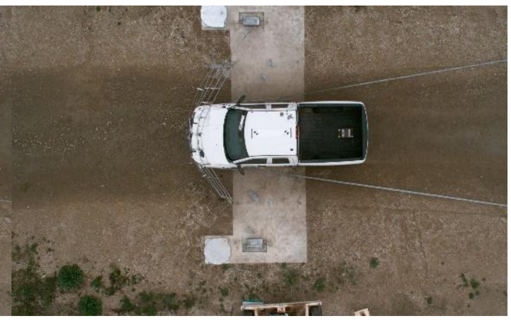


(a) −0.100 s

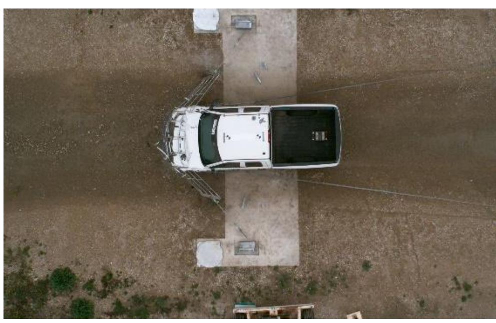
(b) 0.000 s



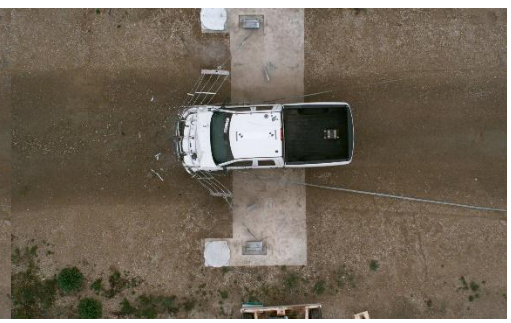
(c) 0.100 s



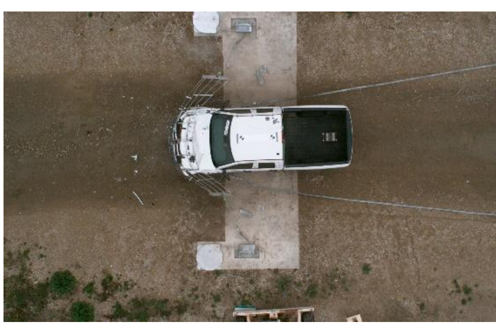
(d) 0.200 s



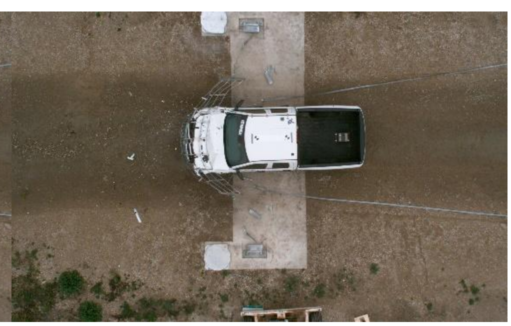
(e) 0.300 s



(f) 0.400 s



(g) 0.500 s



(h) 0.600 s

Figure D.4. Sequential Photographs for Test 440210-01-4 (Overhead Views).

(a) −0.100 s (b) 0.000 s

(c) 0.100 s (d) 0.200 s

(e) 0.300 s (f) 0.400 s

(g) 0.500 s (h) 0.600 s

Figure D.5. Sequential Photographs for Test 440210-01-4 (Frontal Views).

(a) −0.100 s (b) 0.000 s

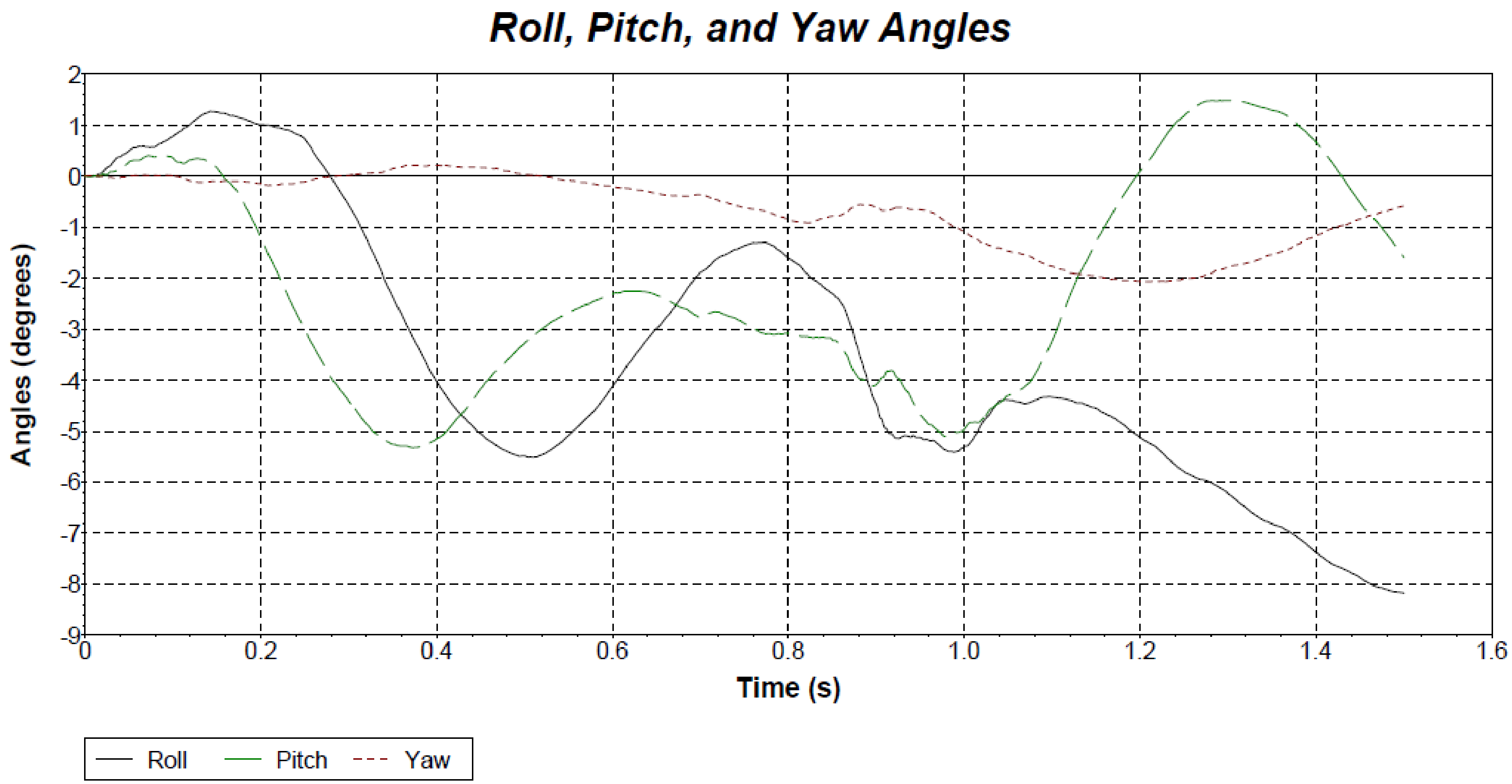
(c) 0.100 s (d) 0.200 s

(e) 0.300 s (f) 0.400 s

(g) 0.500 s (h) 0.600 s

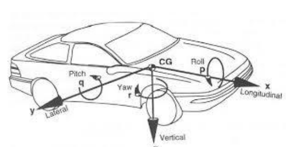
Figure D.6. Sequential Photographs for Test 440210-01-4 (Right Angle Views).

D.3. VEHICLE ANGULAR DISPLACEMENTS



Axes are vehicle-fixed.
Sequence for determining orientation:

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



Test Number: 440211-01-4
Test Standard/Test Number: *MASH* Test 3-41
Test Article: Modified Median Net
Test Vehicle: 2016 RAM 1500 Pickup
Inertial Mass: 5069 lb
Gross Mass: 5069 lb
Impact Speed: 62.8 mi/h
Impact Angle: 0°

Figure D.7. Vehicle Angular Displacements for Test 440210-01-4.

D.4. VEHICLE ACCELERATIONS

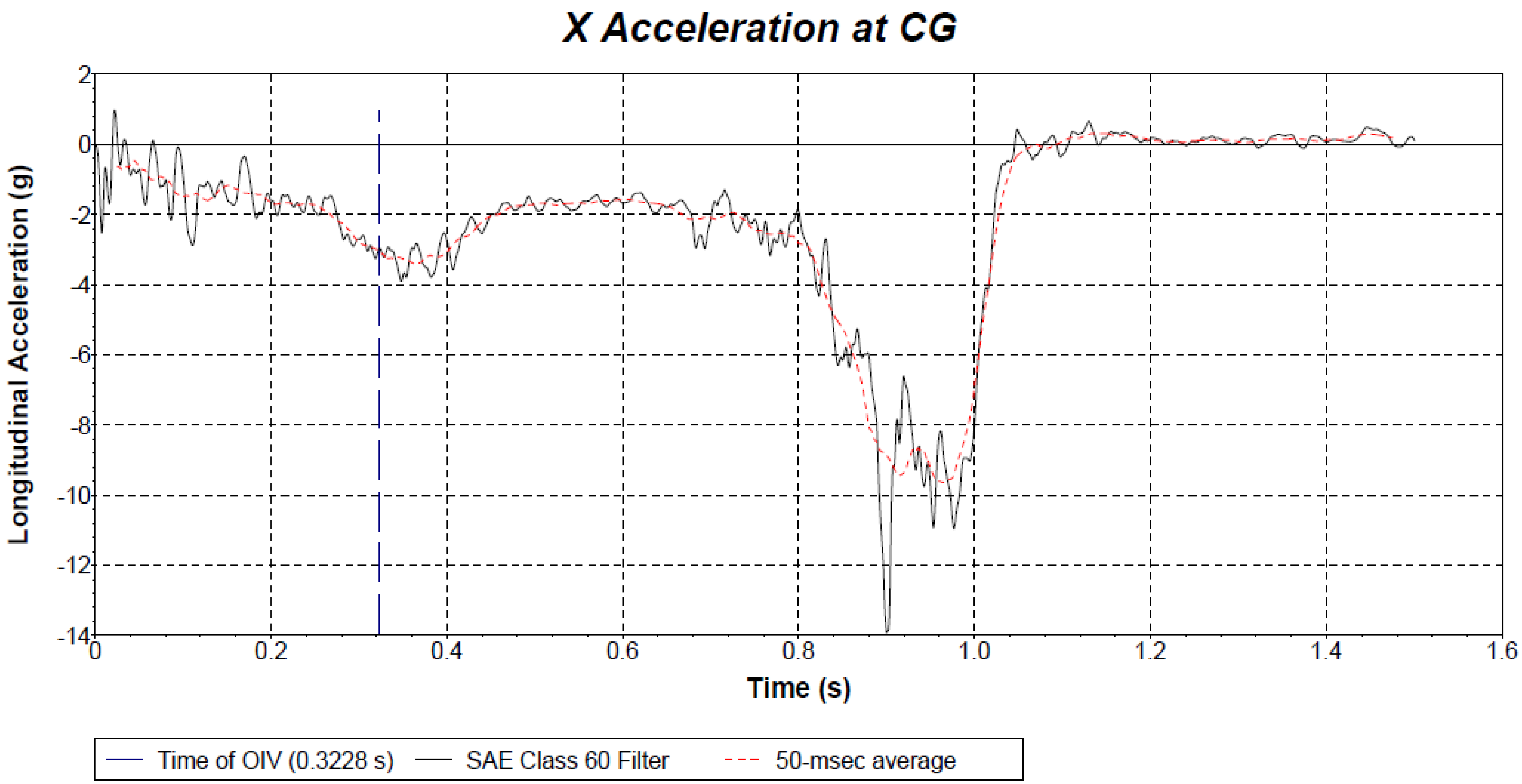


Figure D.8. Vehicle Longitudinal Accelerometer Trace for Test 440210-01-4 (Accelerometer Located at Center of Gravity).

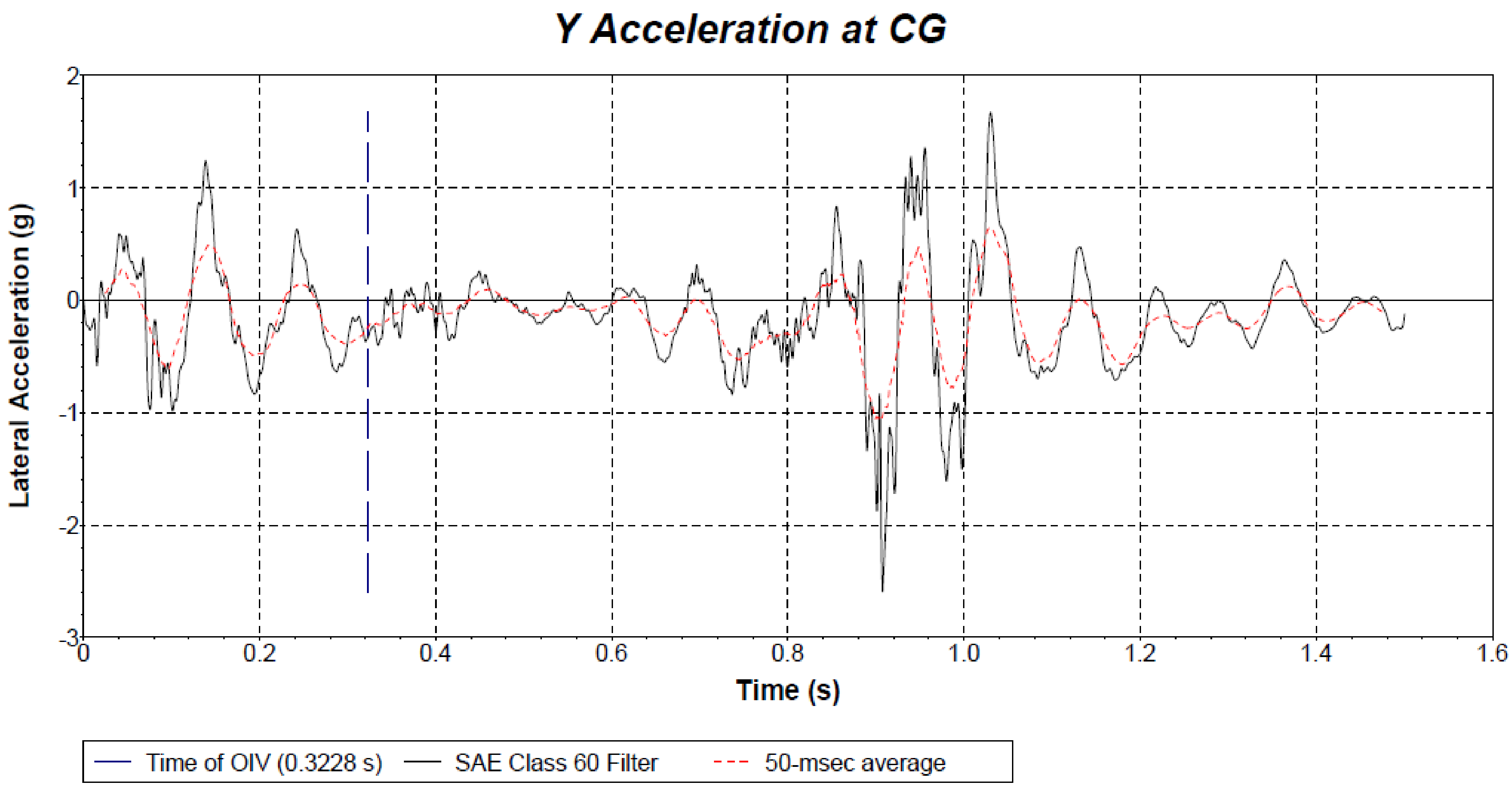


Figure D.9. Vehicle Lateral Accelerometer Trace for Test 440210-01-4 (Accelerometer Located at Center of Gravity).

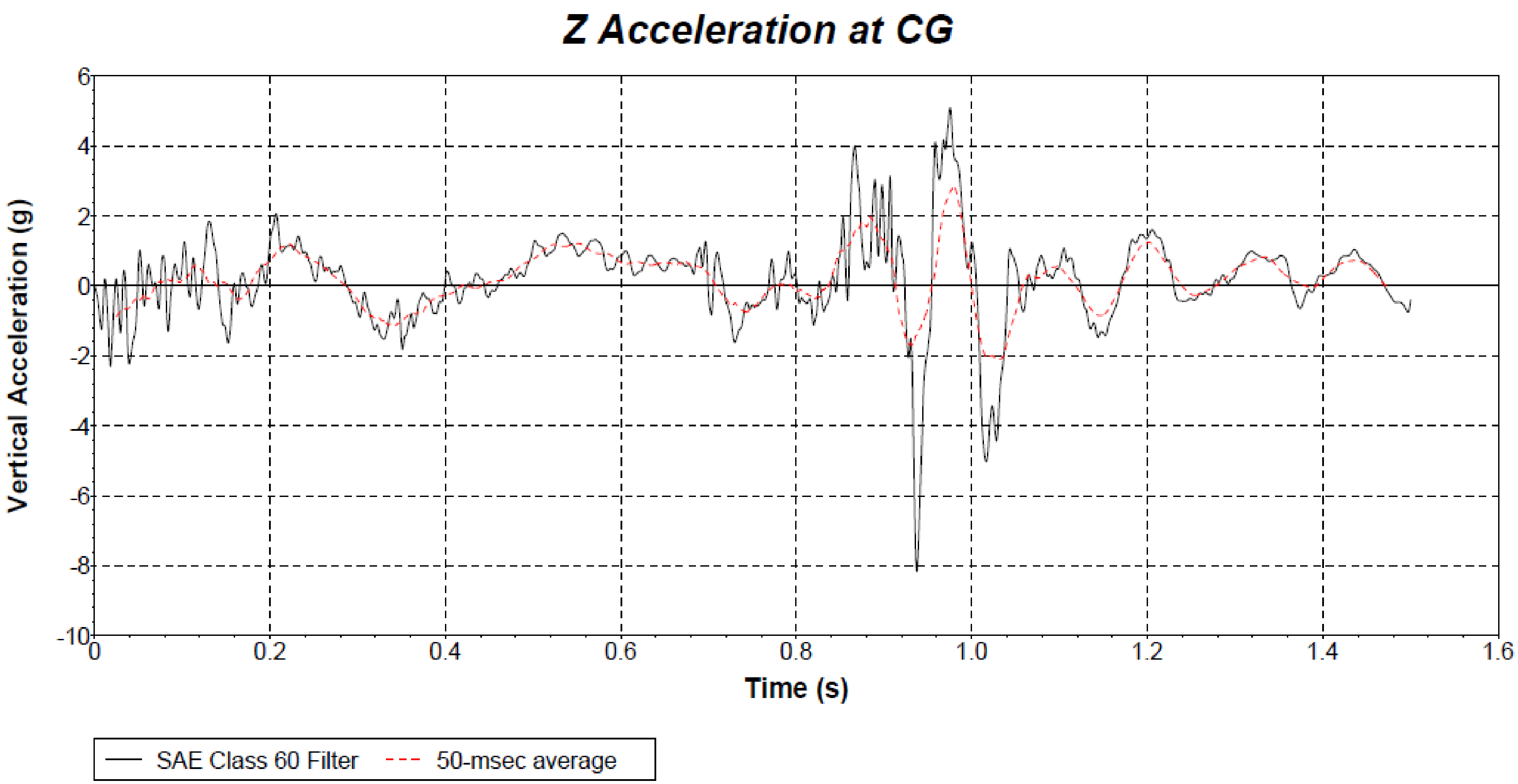


Figure D.10. Vehicle Vertical Accelerometer Trace for Test 440210-01-4 (Accelerometer Located at Center of Gravity).

APPENDIX E. *MASH* RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440211-01-3)

E.1. VEHICLE PROPERTIES AND INFORMATION

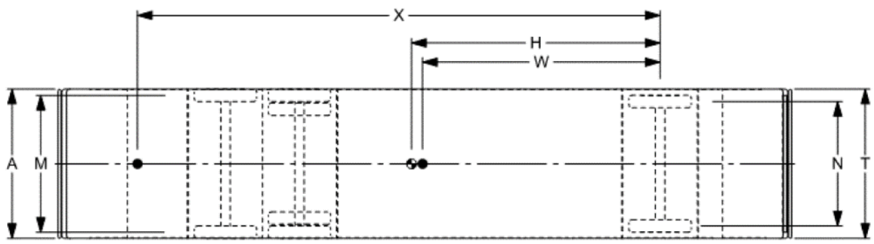
Date: 2021-4-13 Test No.: 440211-01-3 VIN No.: 1M8PDMRA34P056292

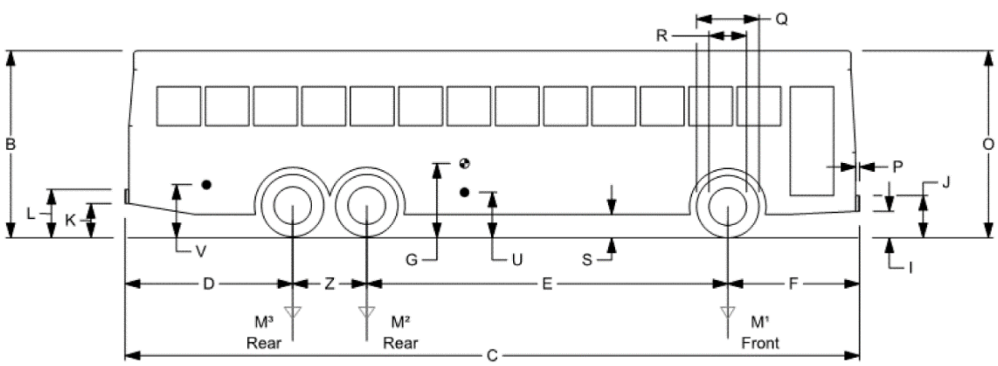
Year: 2004 Make: MCI Model: D4500

Tire Size: 315/80 R22.5 J Tire Inflation Pressure: 120 100 85

Tread Type: HIGHWAY Odometer: 1150562

Note any damage to the vehicle prior to test:





Geometry: inches

A	101	F	72	K	18.5	P	4.5	U	53.5
B	130	G		L	30.25	Q	43	V	53.5
C	544	H	176.51	M	85 75	R	23.5	W	176.5 + 16
D	106	I	14	N	85	S	12	X	192.5
E	318	J	33	O	130	T	101	Z	48

GVWR Ratings:		Mass: lb	Curb	Test Inertial	Gross Static
Front	16,000	$M1_{front}$	10,620	16,160	
Back	22,500	$M2_{rear}$	17,600	22,540	
Back	12,000	$M3_{rear}$	8,900	11,460	
Total	48,000	M_{Total}	37,120	50,160	

Figure E.1. Vehicle Properties for Test 440211-01-3.

E.2. SEQUENTIAL PHOTOGRAPHS

(a) 0.000 s (b) 0.150 s

(c) 0.300 s (d) 0.450 s

(e) 0.600 s (f) 0.750 s

(g) 0.900 s (h) 1.050 s

Figure E.2. Sequential Photographs for Test 440211-01-3 (Overhead Views).

(a) 0.000 s

(b) 0.150 s

(c) 0.300 s

(d) 0.450 s

(e) 0.600 s

(f) 0.750 s

(g) 0.900 s

(h) 1.050 s

Figure E.3. Sequential Photographs for Test 440211-01-3 (Frontal Views).

(a) 0.000 s (b) 0.150 s

(c) 0.300 s (d) 0.450

(e) 0.600 s (f) 0.750 s

(g) 0.900 s (h) 1.050 s

Figure E.4. Sequential Photographs for Test 440211-01-3 (Oblique Views).


(a) 0.000 s (b) 0.100 s

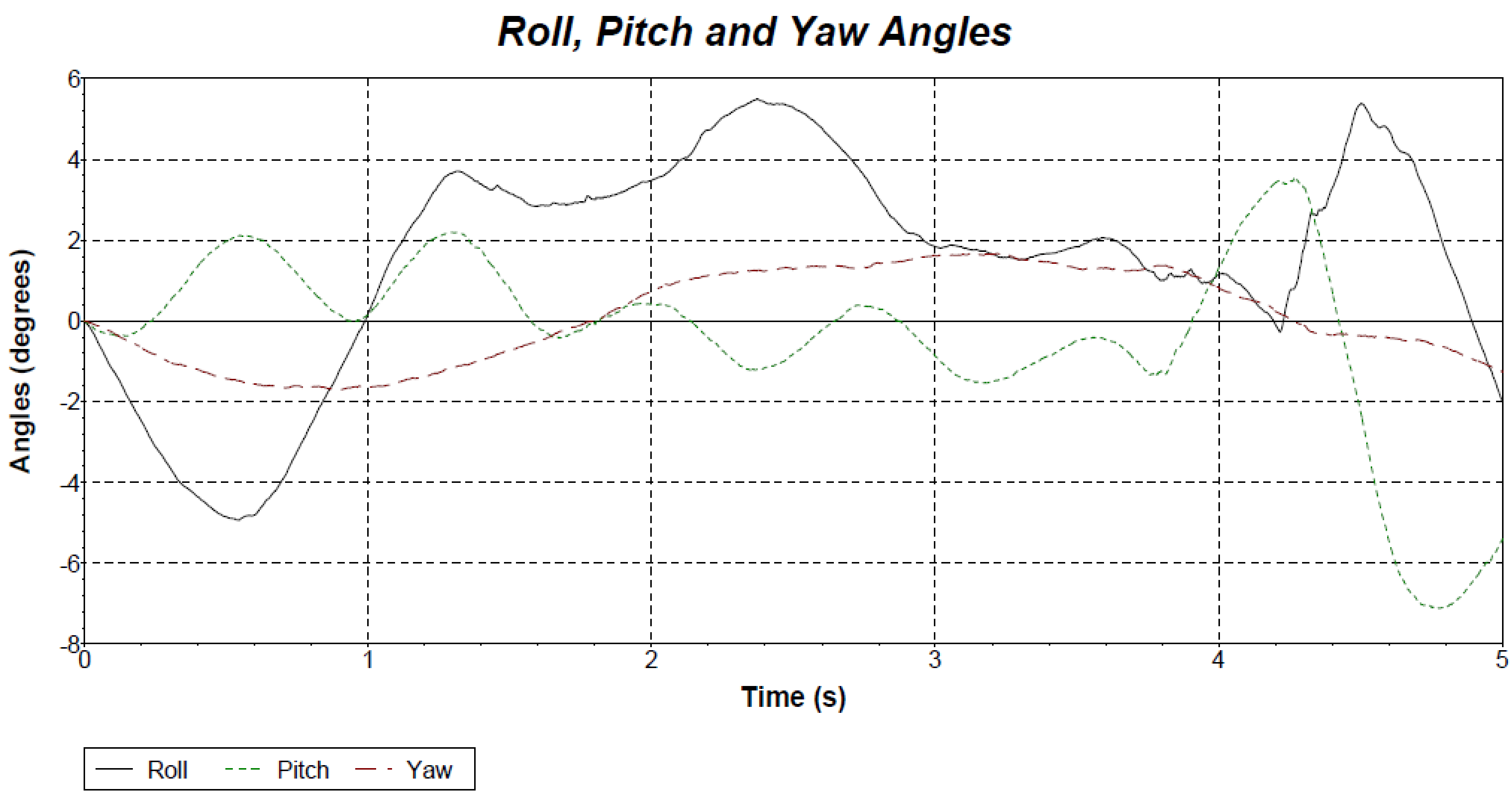

(c) 0.200 s (d) 0.300 s


(e) 0.400 s (f) 0.500 s


(g) 0.600 s (h) 0.700 s

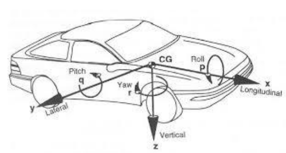
Figure E.5. Sequential Photographs for Test 440211-01-3 (Right Angle Views).

E.3. VEHICLE ANGULAR DISPLACEMENTS



Axes are vehicle-fixed.
Sequence for determining orientation:

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



Test Number: 440211-01-3
R&D Component Test
Test Article: Median Net
Test Vehicle: 2004 MCI D4500
Curb Mass: 37,120 lb
Inertial Mass: 50,160 lb
Impact Speed: 51.8 mi/h
Impact Angle: 2.8°

Figure E.6. Vehicle Angular Displacements for Test 440211-01-3.

E.4. VEHICLE ACCELERATIONS

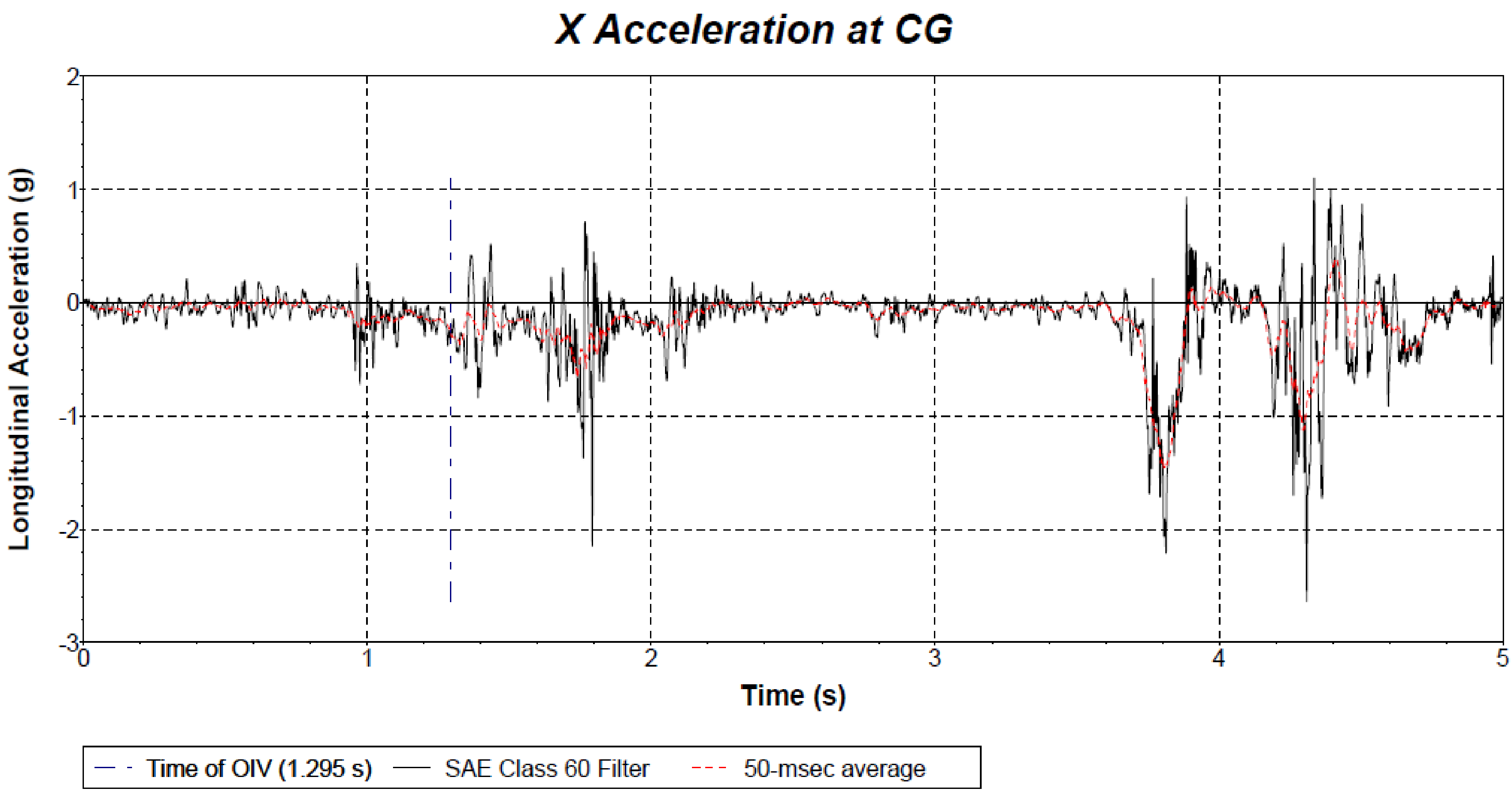


Figure E.7. Vehicle Longitudinal Accelerometer Trace for Test 440211-01-3 (Accelerometer Located at Horizontal Center of Gravity).

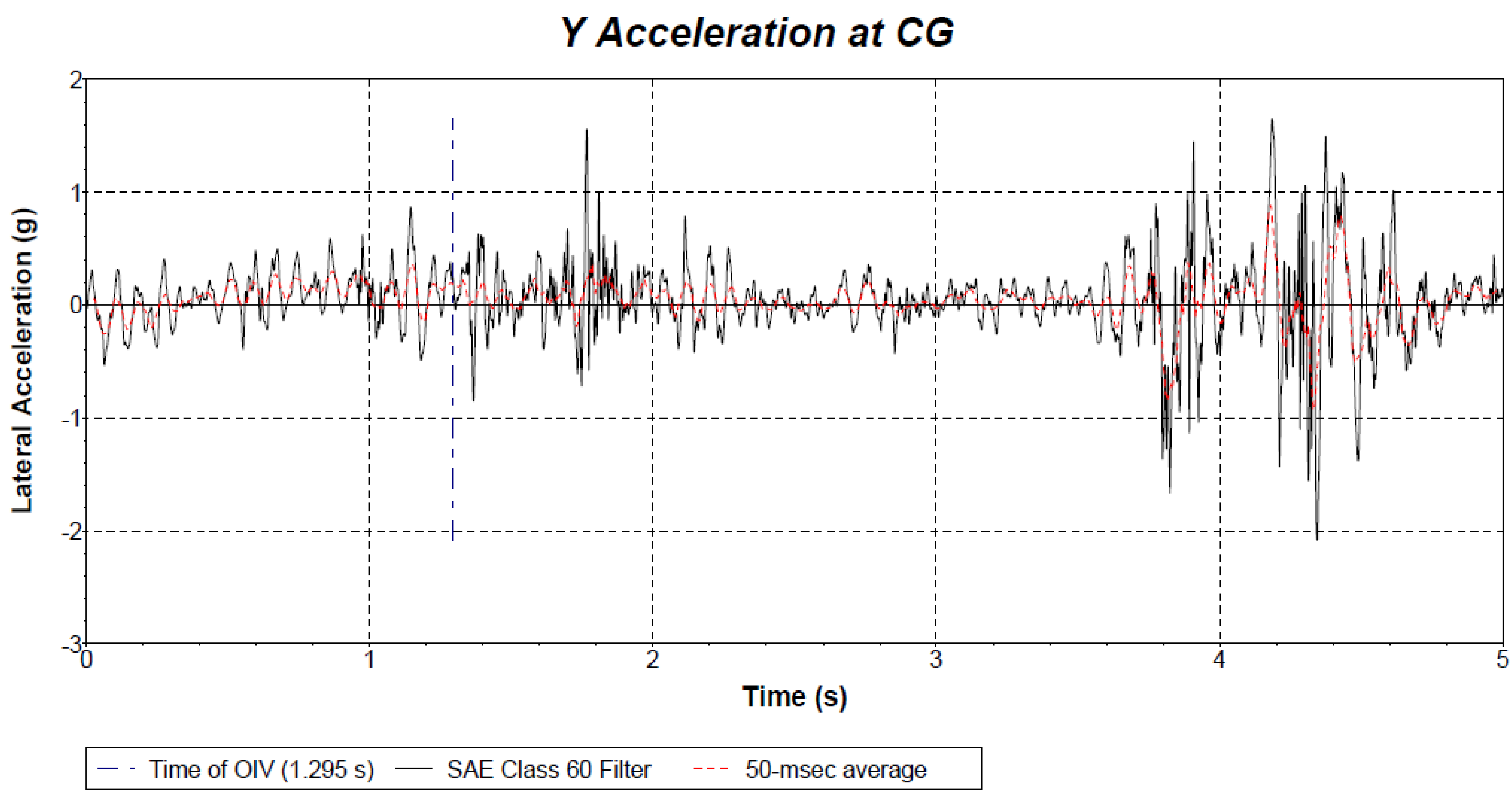


Figure E.8. Vehicle Lateral Accelerometer Trace for Test 440211-01-3 (Accelerometer Located at Horizontal Center of Gravity).

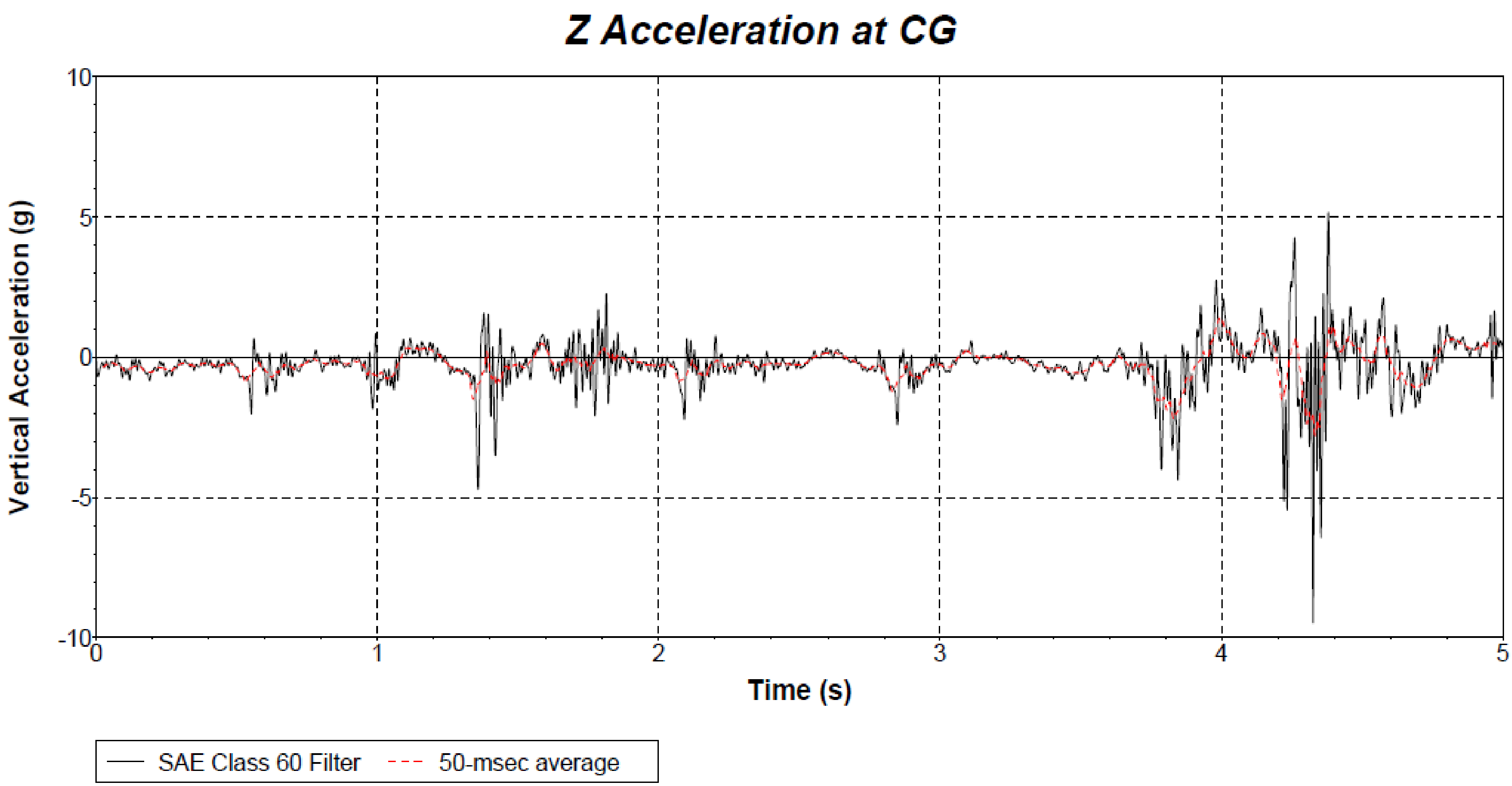


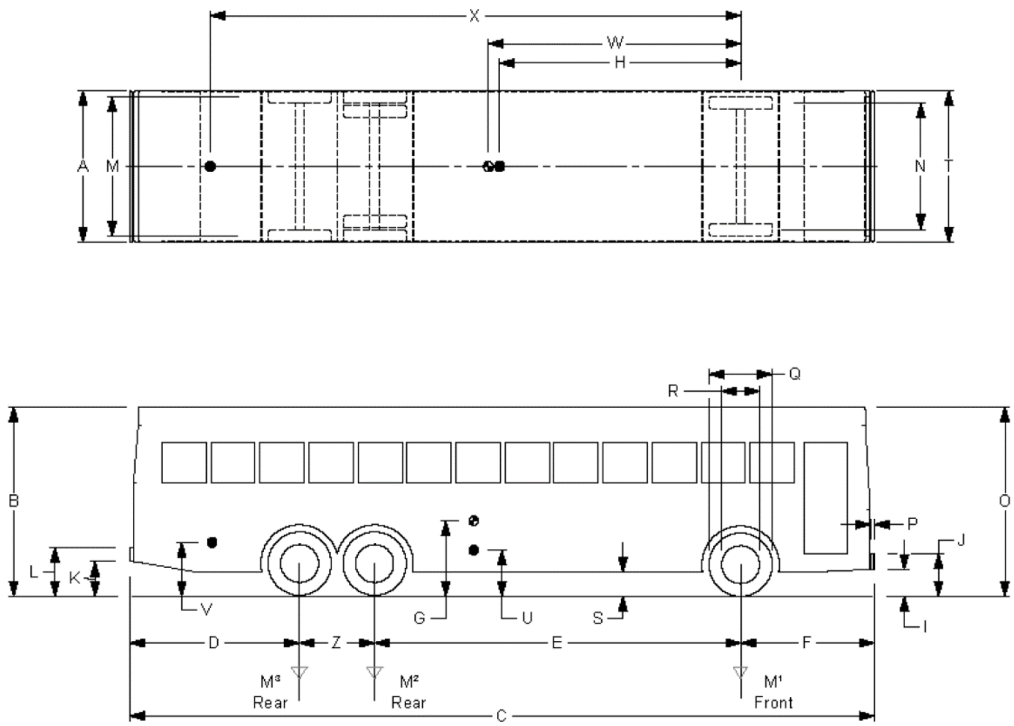
Figure E.9. Vehicle Vertical Accelerometer Trace for Test 440211-01-3 (Accelerometer Located at Horizontal Center of Gravity).

APPENDIX F. *MASH* RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440211-01-5)

F.1. VEHICLE PROPERTIES AND INFORMATION

Date:	2022-06-30	Test No.:	440211-01-5	VIN No.:	1M8PDMRA34PO56292
Year:	2004	Make:	MCI	Model:	D4500
Tire Size:	315/80 R22.5 J			Tire Inflation Pressure:	120 100 85
Tread Type:	HIGHWAY			Odometer:	1150607

Note any damage to the vehicle prior to test: HEADLIGHTS



Geometry: inches

A	101	F	72	K	18.5	P	4.5	U	53.5
B	130	G	-	L	30.25	Q	43	V	53.5
C	544	H	223.165	M	85 75	R	23.5	W	223.165+12
D	106	I	14	N	85	S	12	X	192.5
E	318	J	33	O	130	T	101	Z	48

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	16,000	$M1_{front}$	10,620	16,780	
Back	22,500	$M2_{rear}$	17,600	21,850	
Back	12,000	$M3_{rear}$	8,900	11,710	
Total	50,500	M_{Total}	37,120	50,340	0

Figure F.1. Vehicle Properties for Test 440211-01-5.

F.2. SEQUENTIAL PHOTOGRAPHS

(a) 0.000 s (b) 0.200 s

(c) 0.400 s (d) 0.600 s

(e) 0.800 s (f) 1.000 s

(g) 1.200 s (h) 1.400 s

Figure F.2. Sequential Photographs for Test 440211-01-5 (Overhead Views).

(a) 0.000 s

(b) 0.200 s

(c) 0.400 s

(d) 0.600 s

(e) 0.800 s

(f) 1.000 s

(g) 1.200 s

(h) 1.400 s

Figure F.3. Sequential Photographs for Test 440211-01-5 (Frontal Views).

(a) 0.000 s

(b) 0.200 s

(c) 0.400 s

(d) 0.600 s

(e) 0.800 s

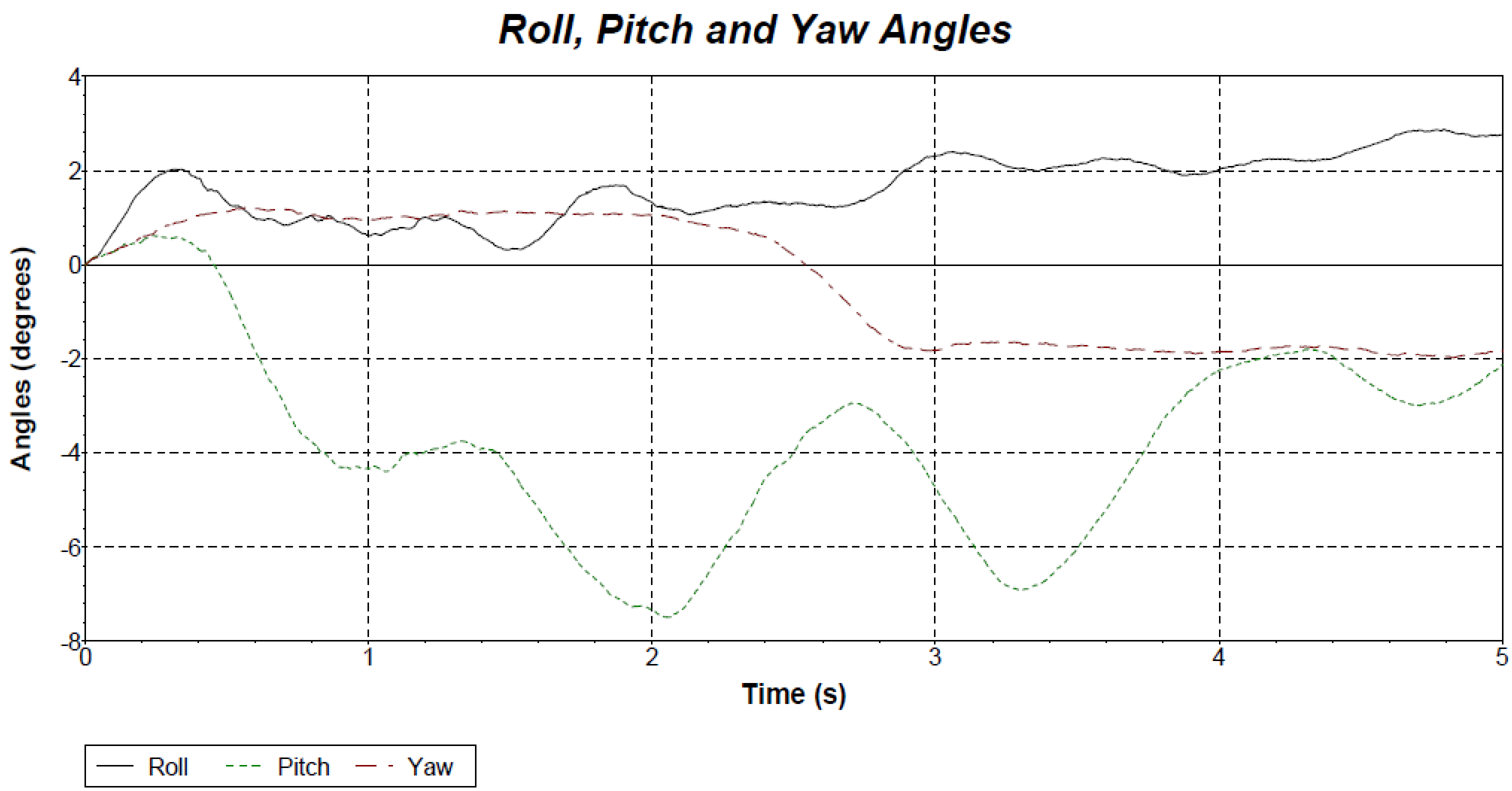
(f) 1.000 s

(g) 1.200 s

(h) 1.400 s

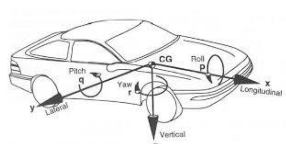
Figure F.4. Sequential Photographs for Test 440211-01-5 (Rear Views).

F.3. VEHICLE ANGULAR DISPLACEMENTS



Axes are vehicle-fixed.
Sequence for determining orientation:

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



Test Number: 440211-01-5
R&D Component Test
Test Article: Median Net
Test Vehicle: 2004 MCI D4500
Curb Mass: 37,120 lb
Inertial Mass: 50,340 lb
Impact Speed: 50.5 mi/h
Impact Angle: 0.7°

Figure F.5. Vehicle Angular Displacements for Test 440211-01-5.

F.4. VEHICLE ACCELERATIONS

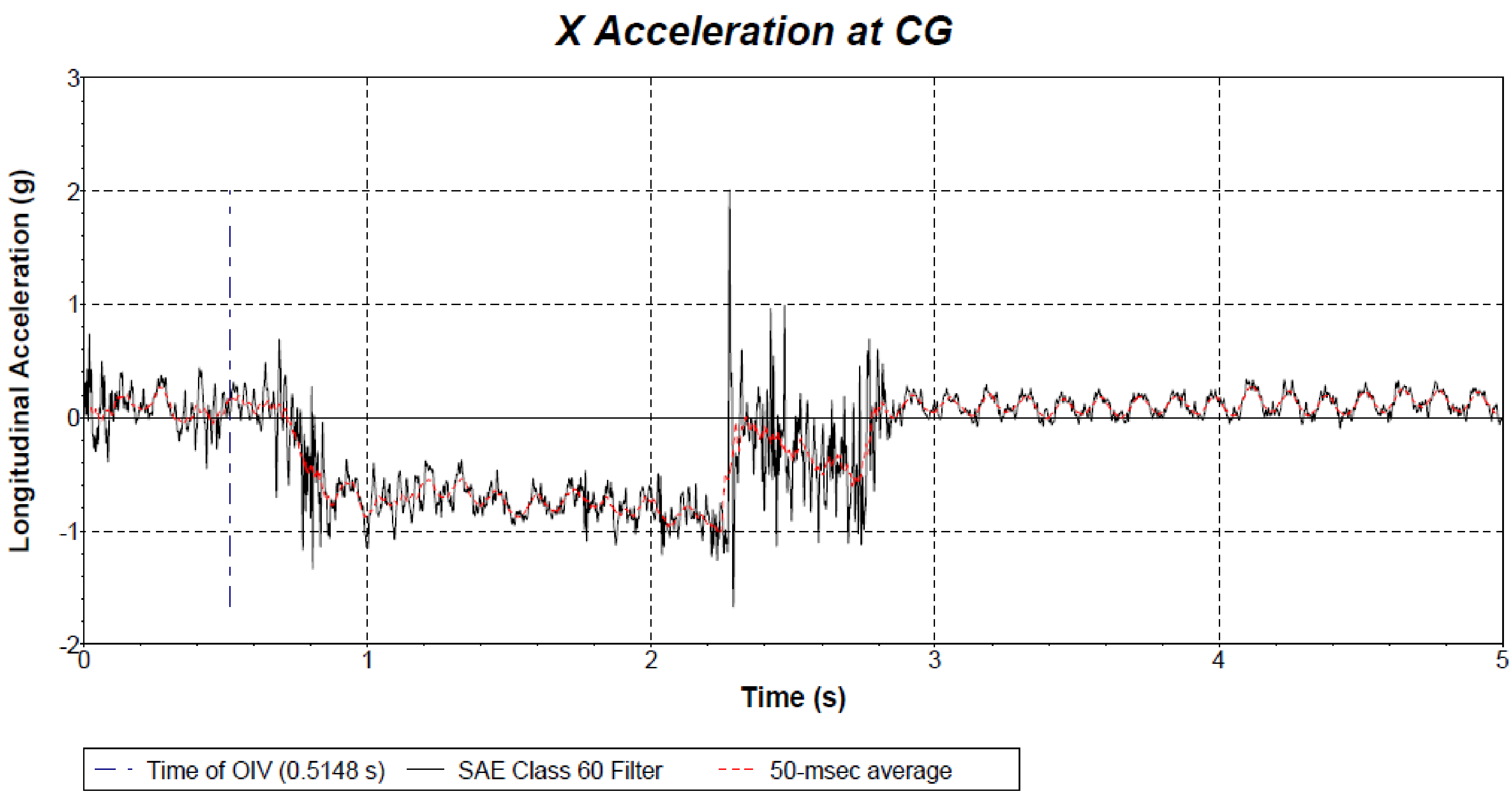


Figure F.6. Vehicle Longitudinal Accelerometer Trace for Test 440211-01-5 (Accelerometer Located at Horizontal Center of Gravity).

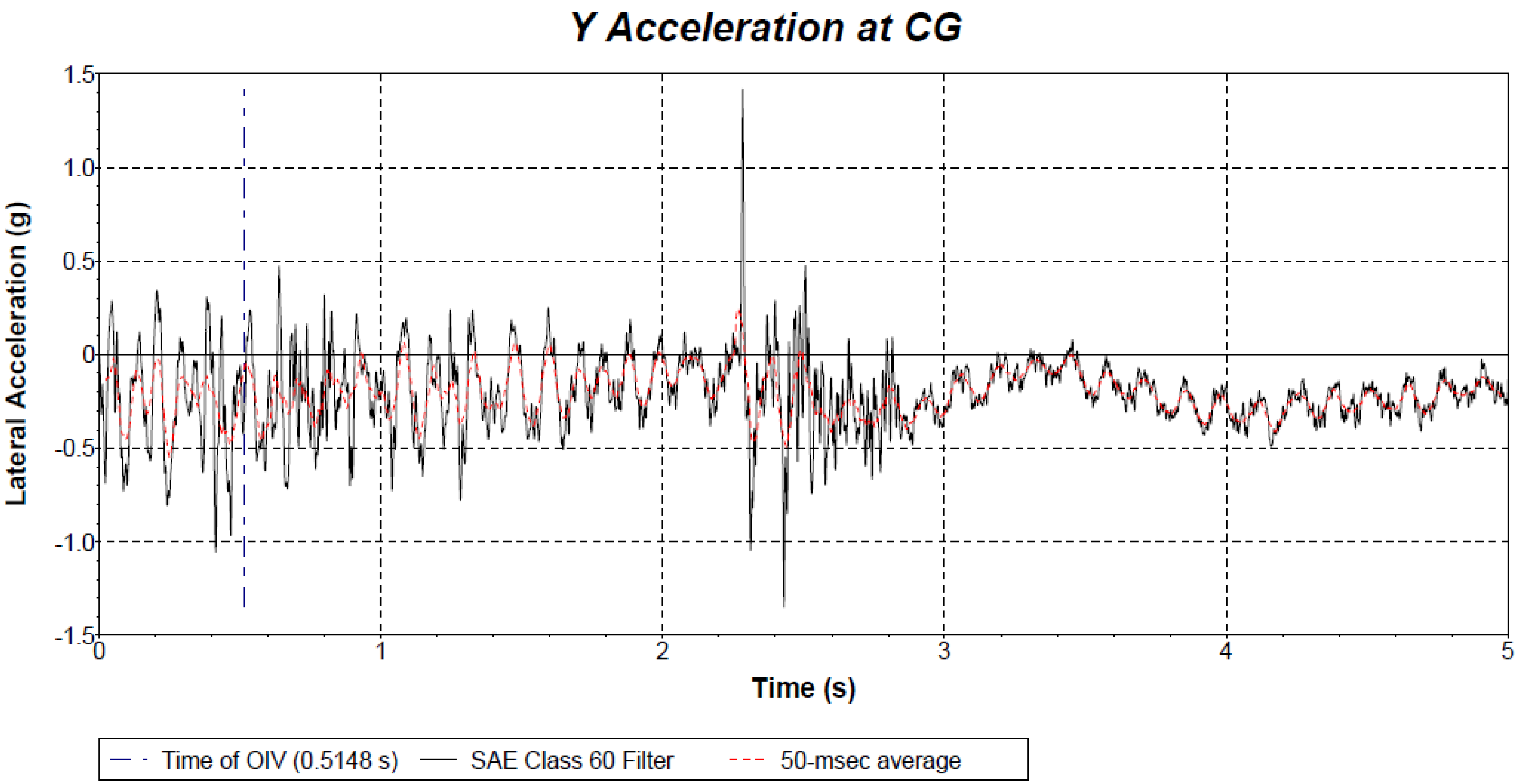


Figure F.7. Vehicle Lateral Accelerometer Trace for Test 440211-01-5 (Accelerometer Located at Horizontal Center of Gravity).

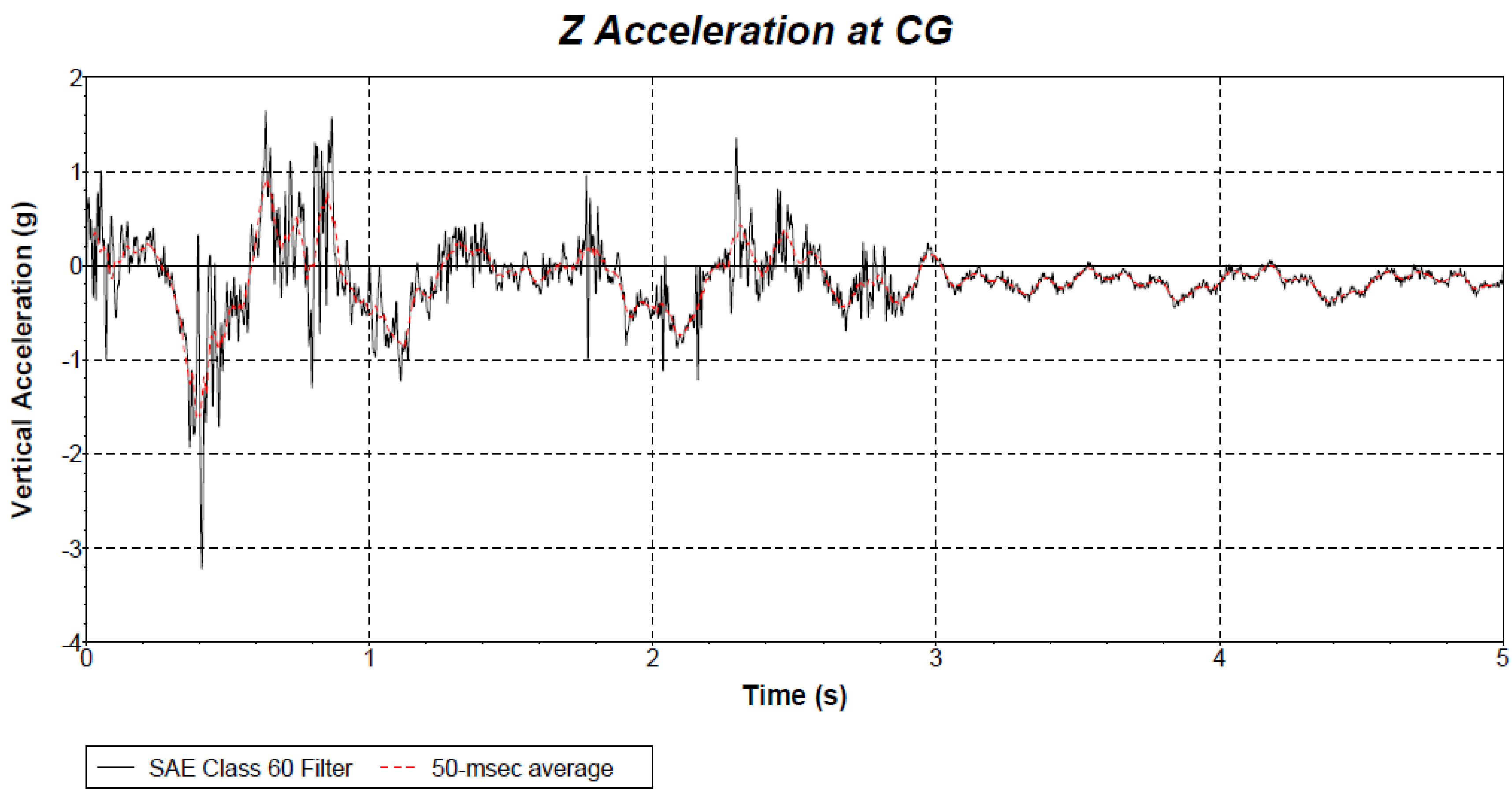


Figure F.8. Vehicle Vertical Accelerometer Trace for Test 440211-01-5 (Accelerometer Located at Horizontal Center of Gravity).

APPENDIX G. *MASH* RESEARCH AND DEVELOPMENT TEST (CRASH TEST 440213-01-6)

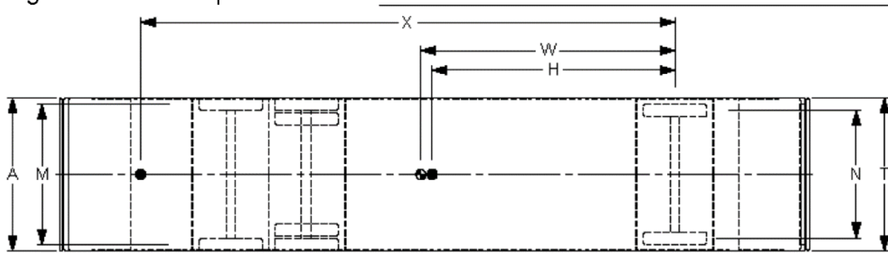
G.1. VEHICLE PROPERTIES AND INFORMATION

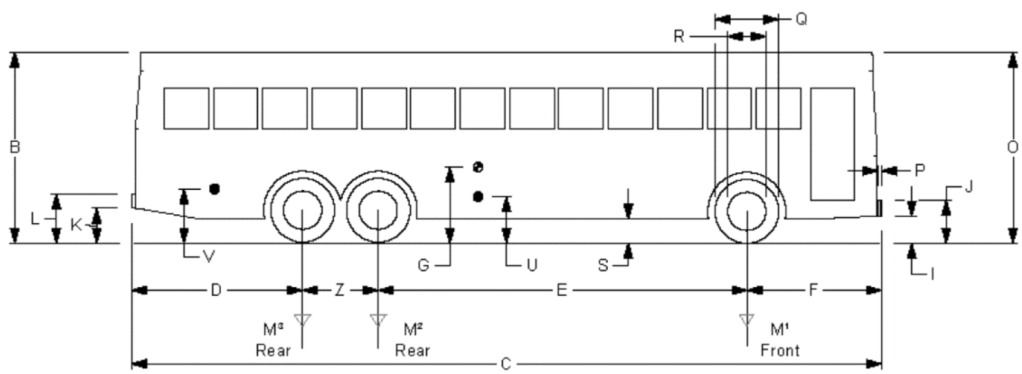
Date:	2023-08-28	Test No.:	440213-01-6	VIN No.:	YE2TC13B122044254
Year:	2002	Make:	VAN HOOL	Model:	COMMUTER C2045 USA

Tire Size: 315/80R/22.5 Tire Inflation Pressure: 110/95/110

Tread Type: HIGHWAY Odometer: 47094.8 ?

Note any damage to the vehicle prior to test:





Geometry: inches

A	110.5	F	83.5	K	18.5	P	3.5	U	56.5
B	139	G	-	L	30.5	Q	41	V	56.5
C	543.5	H	208.37	M	83	R	22.5	W	214
D	125	I	13	N	84	S	11	X	-
E	284	J	31	O	138	T	97	Z	51

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	15,000	$M1_{front}$	9,220	15,790	15790
Back	24,250	$M2_{rear}$	15,580	20,770	20770
Back	15,000	$M3_{rear}$	9,320	13,580	13580
Total	54,250	M_{Total}	34,120	50140	50140

Figure G.1. Vehicle Properties for Test 440213-01-6.

G.2. SEQUENTIAL PHOTOGRAPHS

(a) 0.000 s

(b) 0.300 s

(c) 0.600 s

(d) 0.900 s

(e) 1.200 s

(f) 1.500 s

(g) 1.800 s

(h) 2.100 s

Figure G.2. Sequential Photographs for Test 440213-01-6 (Overhead Views).

(a) 0.000 s (b) 0.300 s

(c) 0.600 s (d) 0.900 s

(e) 1.200 s (f) 1.500 s

(g) 1.800 s (h) 2.100 s

Figure G.3. Sequential Photographs for Test 440213-01-6 (Frontal Views).

(a) 0.000 s

(b) 0.100 s

(c) 0.200 s

(d) 0.300 s

(e) 0.400 s

(f) 0.500 s

(g) 0.600 s

(h) 0.700 s

Figure G.4. Sequential Photographs for Test 440213-01-6 (Right Angle Views).

G.3. VEHICLE ANGULAR DISPLACEMENTS

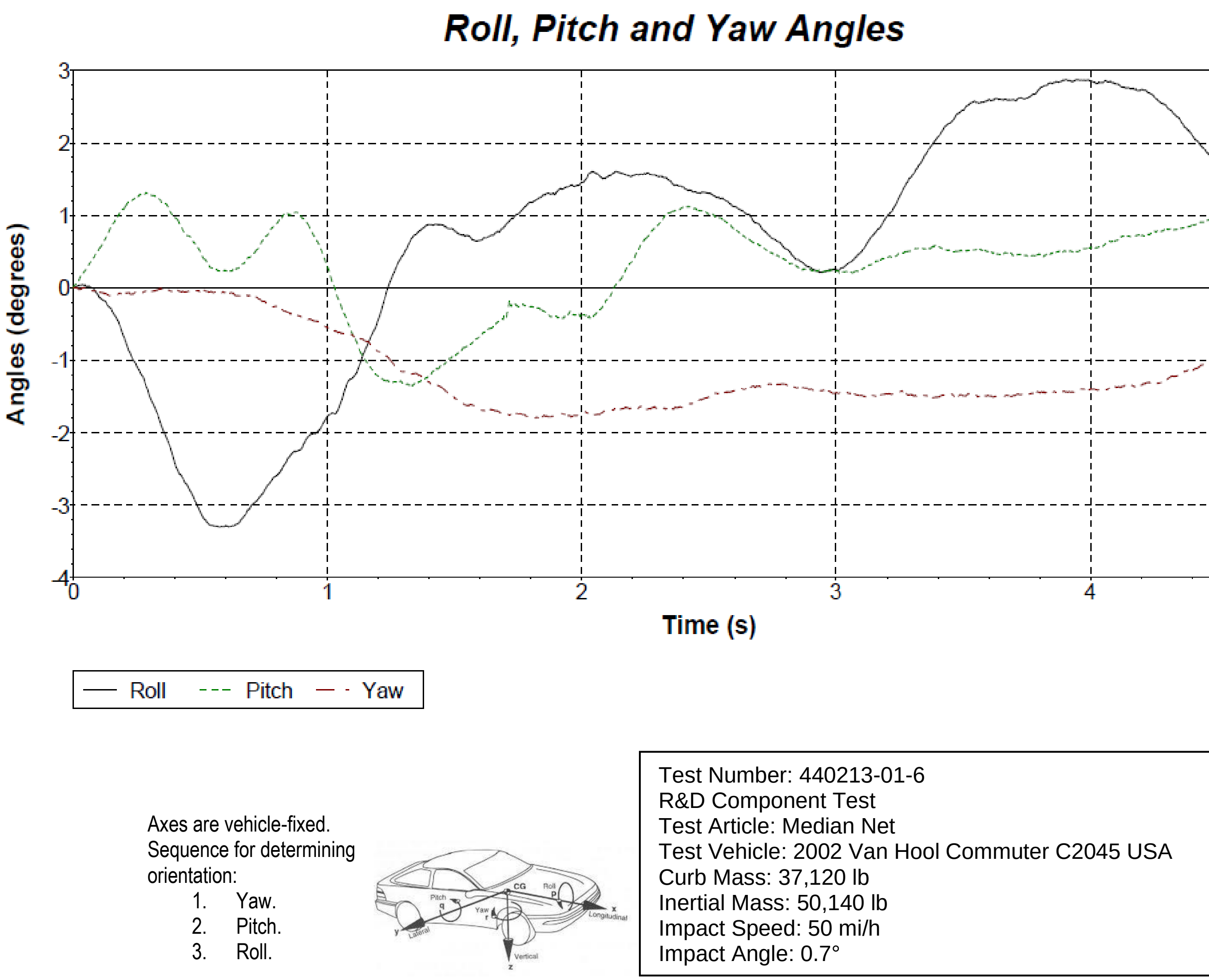


Figure G.5. Vehicle Angular Displacements for Test 440213-01-6.

G.4. VEHICLE ACCELERATIONS

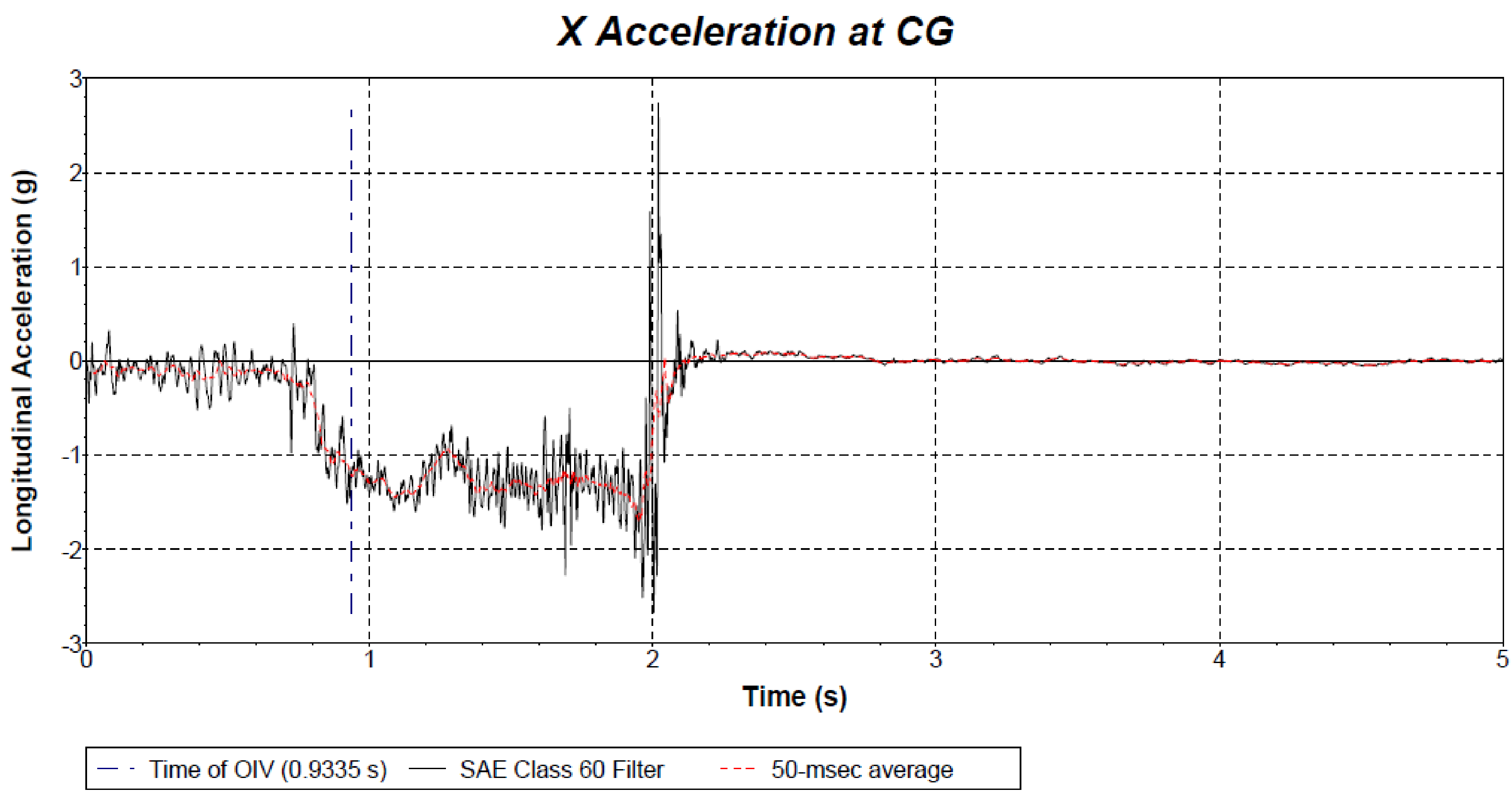


Figure G.6. Vehicle Longitudinal Accelerometer Trace for Test 440213-01-6 (Accelerometer Located at Horizontal Center of Gravity).

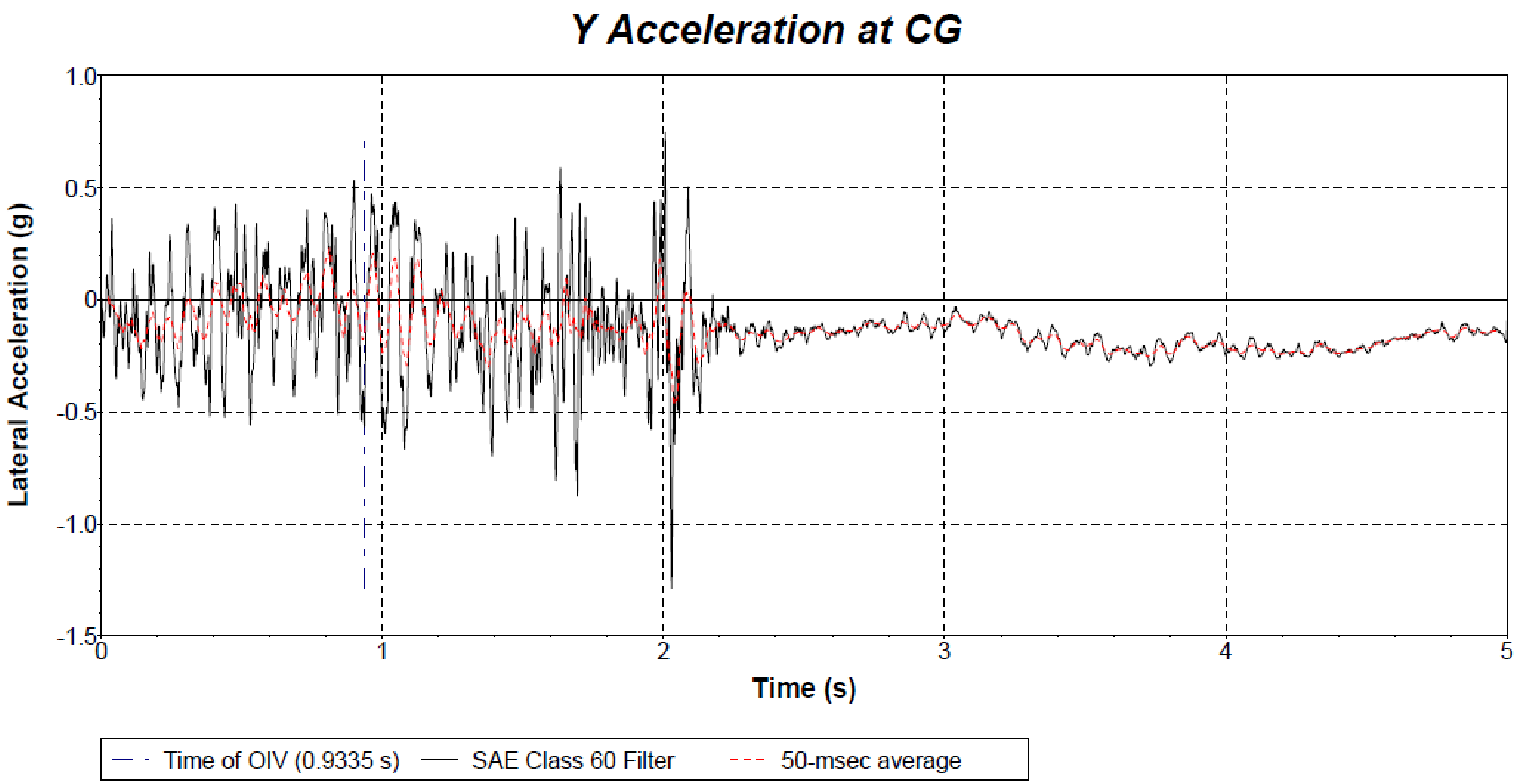


Figure G.7. Vehicle Lateral Accelerometer Trace for Test 440213-01-6 (Accelerometer Located at Horizontal Center of Gravity).

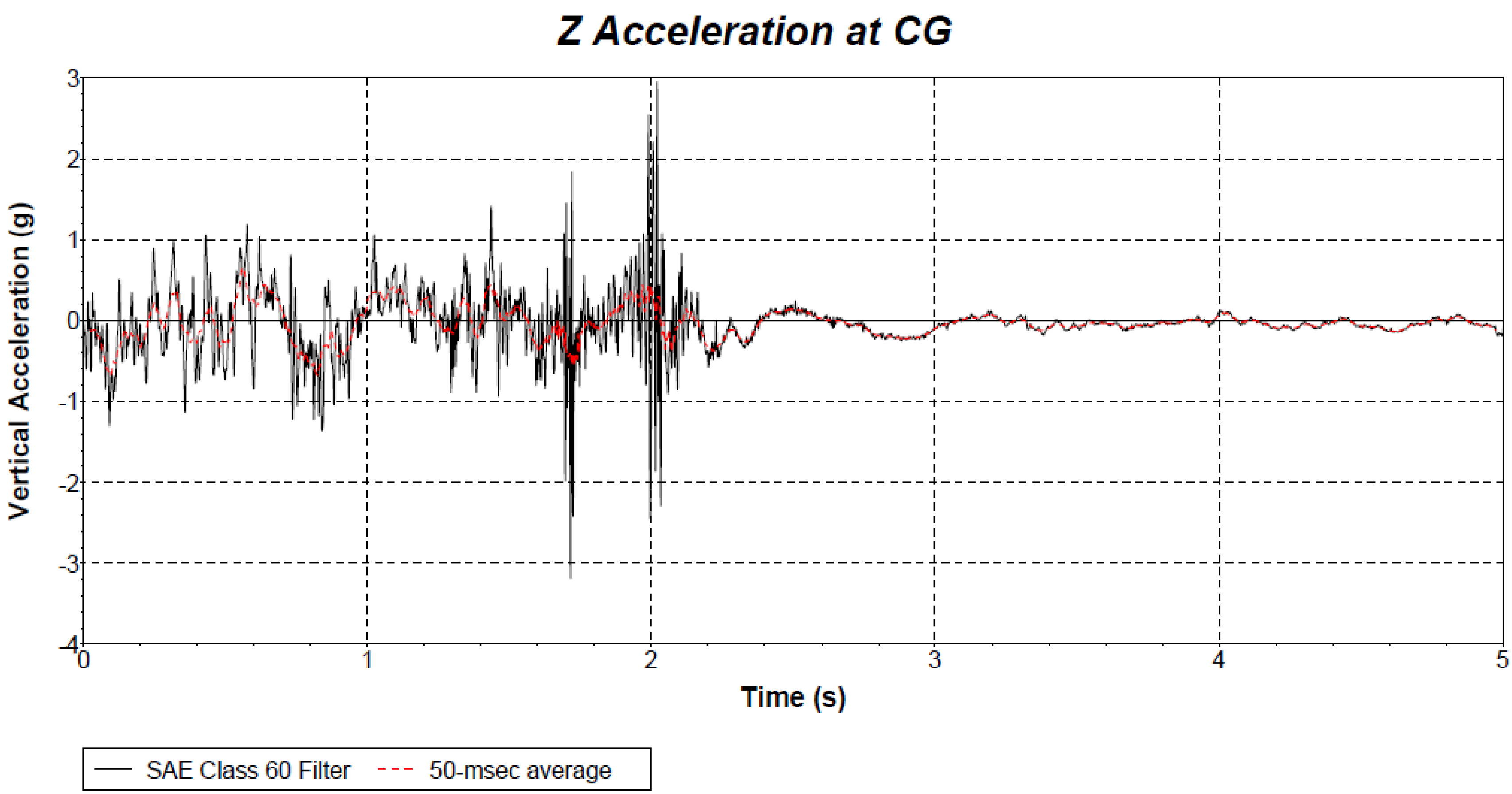


Figure G.8. Vehicle Vertical Accelerometer Trace for Test 440213-01-6 (Accelerometer Located at Horizontal Center of Gravity).

APPENDIX H. VALUE OF RESEARCH

H.1. INTRODUCTION

In accordance with the scope of TxDOT Project 0-7021-01, Developing an Enhanced Protection of Median Openings between Parallel Bridge Structures, the TTI research team prepared an estimate for the value of research (VoR) associated with the research product delivered for this project. The benefit areas deemed relevant and identified in the project agreement for the purpose of establishing the VoR encompass both qualitative and economic areas. The benefit areas identified for this project are summarized in Table H.1.

Table H.1. Selected Benefit Areas for Project 0-7021-01.

Selected	Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
X	Level of Knowledge	X			X		
X	Management and Policy	X			X		
X	Customer Satisfaction	X			X		
X	Increased Service Life		X		X		
X	Safety			X			X

H.2. ECONOMIC BENEFITS

The VoR for this project can be defined in terms of economic benefits derived from safety improvements. Currently, the majority of the median opening areas investigated in this project are not shielded with *MASH*-compliant hardware. Therefore, the implementation of the MOPS in median opening areas could significantly reduce the number of crashes presented in Chapter 2. This reduction could be quantitatively analyzed to calculate the safety-related economic benefit and expressed in terms of lives saved and associated societal cost averted.

Table H.2 shows the annual total and fatal/suspected serious injury (KA) crashes across Texas between 2010 and 2019 that occurred in medians between parallel bridges. On average, 31 crashes occurred each year in these median areas in this time range. Furthermore, an average of seven KA crashes each year occurred in these areas within this time range. The National Safety Council (*14*) has calculated the cost associated with a fatal (K) crash as $1,869,000 and a disabling event (A) as $162,000. This equates to an average cost of $1,015,500 for a KA event. The other event categories (B, C, and O) average to a cost of $25,033. With these cost estimates, the annual cost for median opening crashes can be calculated for each year. These costs can then be averaged to estimate an average annual cost for median opening crashes within Texas of $7,912,400. Table H.2 shows a summary of these calculations.

Table H.2. Costs of Parallel Structure Crashes.

Year	Total	KA	Non-KA	Total KA Cost	Total Non-KA Cost	Total Annual Cost
2010	10	2	8	$2,031,000	$200,267	$2,231,267
2011	8	3	5	$3,046,500	$125,167	$3,171,667
2012	31	9	22	$9,139,500	$550,733	$9,690,233
2013	30	8	22	$8,124,000	$550,733	$8,674,733
2014	67	10	57	$10,155,000	$1,426,900	$11,581,900
2015	39	9	30	$9,139,500	$751,000	$9,890,500
2016	36	11	25	$11,170,500	$625,833	$11,796,333
2017	41	9	32	$9,139,500	$801,067	$9,940,567
2018	31	6	25	$6,093,000	$625,833	$6,718,833
2019	19	5	14	$5,077,500	$350,467	$5,427,967

As noted previously, an average of seven KA crashes occurred each year in median openings. Assuming a reasonable implementation rate of the MOPS at critical locations across the state, a 10 percent overall reduction in KA crashes is assumed. This 10 percent reduction equates to 0.7 KA crashes per year. Using the National Safety Council costs presented earlier, this equates to a savings of $710,850 per year. The expected lifespan of the MOPS is estimated to be 25 years based on other applications of similar technology and median ditch environmental conditions. A discount rate of 5 percent was selected as a conservative estimate for future values.

Figure H.1 shows the VoR calculations based upon the previously discussed crash data analysis. As noted, a savings of $710,850 is anticipated each year from the reduction in crashes. Over a 25-year period, this equates to a total savings of $16,626,584. Additionally, the savings results in a cost-benefit ratio of 21.

	Project #	0-7021-01		
	Project Name:	Developing Enhanced Protection of Median Openings between Parallel Bridge Structures		
	Agency:	TTI	Project Budget	$ 433,816
	Project Duration (Yrs)	4.0	Exp. Value (per Yr)	$ 710,850
Expected Value Duration (Yrs)		25	Discount Rate	5%

Economic Value			
Total Savings:	$ 16,626,584	Net Present Value (NPV):	$ 9,160,681
Payback Period (Yrs):	0.610277	Cost Benefit Ratio (CBR, $1 : $___):	$ 21

Years	Expected Value
0	$277,034
1	$0
2	$710,850
3	$710,850
4	$710,850
5	$710,850
6	$710,850
7	$710,850
8	$710,850
9	$710,850
10	$710,850
11	$710,850
12	$710,850
13	$710,850
14	$710,850
15	$710,850
16	$710,850
17	$710,850
18	$710,850
19	$710,850
20	$710,850
21	$710,850
22	$710,850
23	$710,850
24	$710,850
25	$710,850

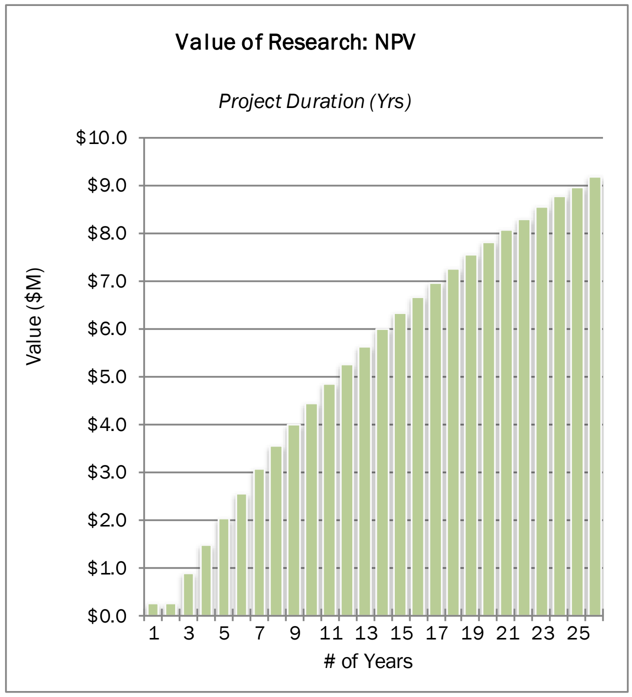


Figure H.1. Value of Research for Project 0-7021-01.