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Texas A&M Transportation Institute Proving Ground

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MASH TL-3 TESTING AND EVALUATION OF THE W-BEAM GUARDRAIL ON SLOPE

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Technical Report Documentation Page

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16. Abstract

In Phase I of this research, a guardrail on slope design was recommended based on finite element impact simulations. A 2H:1V sloped ditch was excavated behind the rail to represent the sloped terrain. Along the sloped section, the 8-ft long posts were placed at 3 ft-1.5 inch spacing. *NCHRP Report 350* test designation 3-11 was performed on this installation with the 2000P vehicle at 62 mi/h and 15 degrees. The 2000P vehicle was contained and redirected. However, after exiting the installation, the vehicle rolled onto its left side. Due to this rollover, the guardrail on 2H:1V slope did not meet the criteria for *NCHRP Report 350* test 3-11.

During Phase II, further simulation was performed to improve the performance of the guardrail on slope design. In simulation Case 1 with 8-ft long posts spaced at 3 ft-1.5 inches apart, significant wheel snag and high ridedown acceleration was predicted. Simulation of Case 2 with 6 ft-3 inch spacing and 8-ft posts, predicted successful redirection and containment of the vehicle with less severe wheel snag or pocketing. The occupant risk factors were much lower than those from Case1. Hence, it was recommended to test a guardrail on slope system that represents the design used in modeling Case 2.

MASH tests 3-10 and 3-11 were performed on the design based on simulation Case 2. The guardrail on slope performed acceptably according to the specifications for *MASH* TL-3.

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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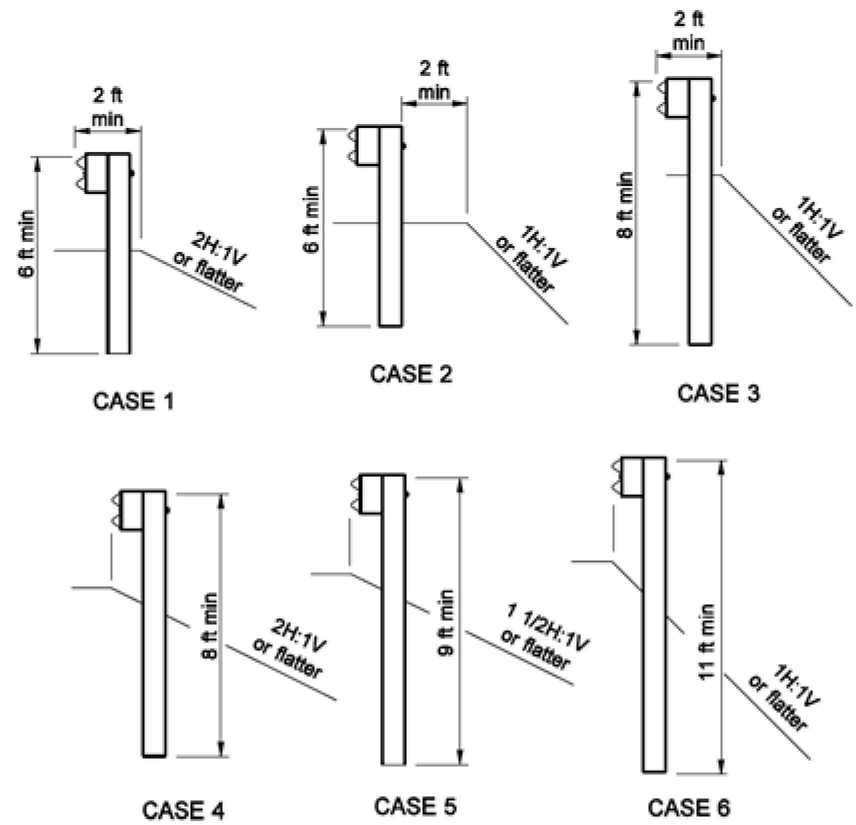
1.1 PROBLEM

The American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* recommends guardrail be installed with the back edges of the guardrail posts 2 ft from a slope break. In many mountainous areas or in locations with tight environmental controls, this width is difficult to provide. As a result, designers often have to make a trade-off between reduced shoulder width and a less than optimal guardrail placement. The Washington State Department of Transportation (WSDOT) Design Manual (*1*) provides for the placement of the guardrail post closer to or on slopes as steep as 1H:1V as illustrated in figure 1.1.



Notes:
Use cases 1, 2, and 3 when there is 2 ft or greater shoulder widening from face of guardrail to the breakpoint.
Use cases 4, 5, and 6 when there is less than 2 ft shoulder widening from face of guardrail to the breakpoint.

Figure 1.1. Allowable Post on Slope Installation Cases from WSDOT Design Manual Page 710-25.

1.2 BACKGROUND

Earliest known research about guardrail placement on slopes was conducted by ENSCO, Inc. (*2*), which included a series of pendulum tests on a single post and three full-scale crash tests. Two tests of a large sedan impacting a G4(1S) guardrail system installed on a break point of a 2H:1V slope were successful in redirecting the sedan per National Cooperative Highway Research Program (NCHRP) *Report 230* (*3*). One of the tests used a 6-ft post length while the other used a 7-ft post length. The 7-ft post length installation had better performance (less rail deflection and vehicle speed change) than the 6-ft post length installation.

Polivka, et al (*4*) performed a series of bogie tests and a crash test of steel post guardrail system with a 2000P test vehicle per *NCHRP Report 350* (*5*) Test Level 3 (TL-3). The impact region had 7-ft long W6×8.5 steel posts placed 3 ft-1.5 inches on centers. At 3 ft-1.5 inches, these posts were placed on the break of a 2H:1V slope with 4 ft-7 inch embedment depth. The crash test was considered successful per *NCHRP Report 350* test evaluation criteria.

In 2008, Polivka, et al. performed another test for a guardrail on 2H:1V slope due to the expensive cost of the original system tested with 3 ft-1.5 inch post spacing and 7 ft posts (*6*). The new system consisted of using the Midwest Guardrail System, installed on a 2H:1V slope break using 9 ft long posts with 75-inch spacing. The test vehicle was a 5013 lb Dodge Ram. The system successfully passed American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) performance criteria (*7*).

During the first phase of this research, TTI researchers conducted bogie tests to choose an optimal post length, simulated the bogie tests to validate component models, and performed impact simulations for three different design alternatives with varying post spacing and rail gauge. After a recommendation to use soil plates, another set of bogie tests were performed to test the characteristics of posts with a soil plate. Two scenarios with soil plate posts were simulated and added to the first three for analysis. A guardrail system was chosen for full scale crash testing based on the analysis of the five simulation outcomes.

1.3 PREVIOUS FULL-SCALE TEST

In Phase I of this research, a guardrail on slope design was recommended based on finite element impact simulations (*8*). The system was 175 ft in total length and was comprised of 12 gauge W-beam mounted on W6×8.5 steel posts. The guardrail length of need was 100 ft, and a 37.5 ft long ET Plus terminal anchored the guardrail on each end. A 2H:1V sloped ditch was excavated behind the rail to represent the sloped terrain. The ditch was centered along the installation length and was 68 ft-9 inches long and 8 ft wide. Six-ft long posts were placed at 6 ft-3 inch spacing on the flat terrain portion of the guardrail. Along the sloped section, the 8-ft long posts were placed at 3 ft-1.5 inch spacing. Standard size 6 inch × 8 inch × 14 inch routed wood blockouts were used in the length of need section. Rail mounting height to the top of the W-beam rail element was 27 inches A cross sectional view of the guardrail installation is shown in figure 1.2. Plan and elevation views are shown figure 1.3.

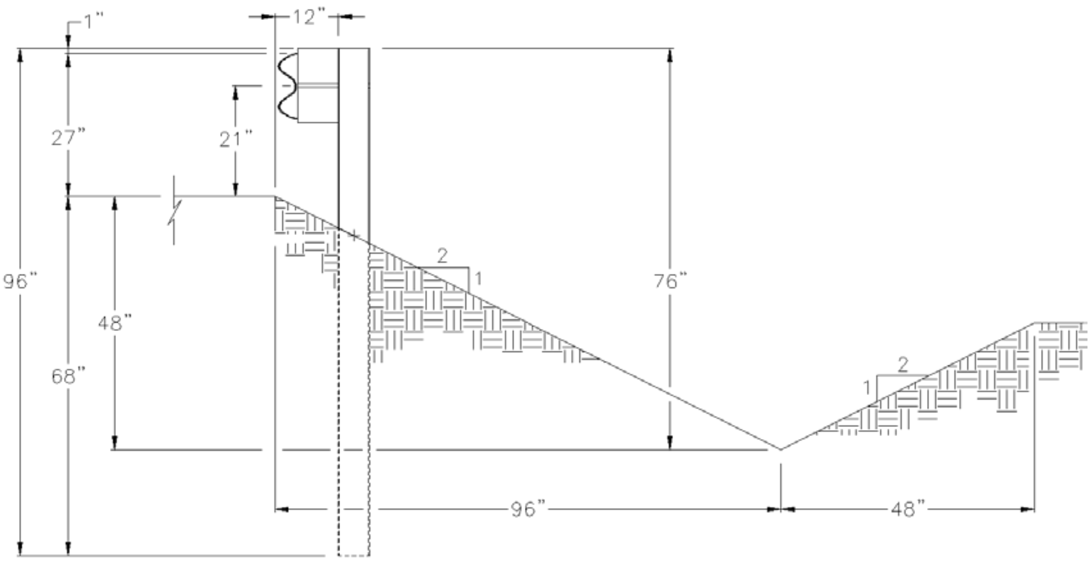


Figure 1.2. Cross section of the guardrail on slope system tested by TTI.

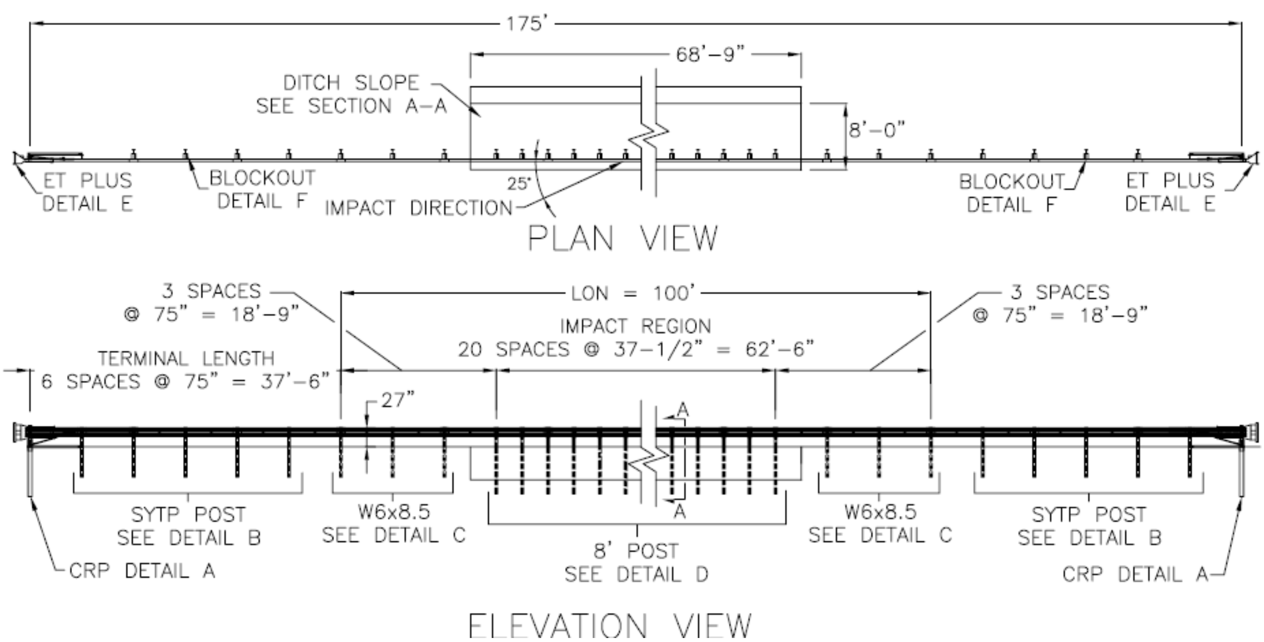


Figure 1.3. Guardrail on slope system as tested by TTI.

1.3.1 Test Description

The crash test performed was *NCHRP Report 350* test designation 3-11, which involved a 2000 kg (4409 lb) pickup truck impacting the CIP of the length of need section at a nominal speed of 100 km/h (62 mi/h) and a nominal angle of 25 degrees. The vehicle was redirected by the guardrail system; however, it rolled on its side upon exiting the guardrail system. Figure 1.4 shows sequential photos of the impact event. Figure 1.5 and figure 1.6 show damage to the guardrail and the vehicle respectively.

Figure 1.4. Impact sequentials for TTI test 405160-4-1.

Figure 1.5. Guardrail damage.

Figure 1.6. Vehicle damage.

1.3.2 Conclusions

In the full-scale crash test, the 2000P vehicle was contained and redirected. However, after exiting the installation, the vehicle rolled onto its left side and came to rest on its left side 135 ft. downstream of impact and 34 ft. forward of the traffic face of the rail. Due to this rollover event, the guardrail on 2H:1V slope did not meet the criteria for *NCHRP Report 350* test 3-11.

1.4 SIMULATION CASES FOR NEW GUARDRAIL ON SLOPE SYSTEM*

1.4.1 Guardrail Configurations

Following the previous crash test, various modifications in the rail design were considered in an effort to improve the performance. The first change to the guardrail on slope design of the system was to raise the height of the rail in order to improve vehicle stability and reduce the probability of vehicle climb. Moreover, the steel posts were placed offset from the rail splice in order to reduce the stress concentrations in the rail splice segments.

1.4.2 Simulation Cases

Two cases for *MASH* Test No. 3-11 were simulated.

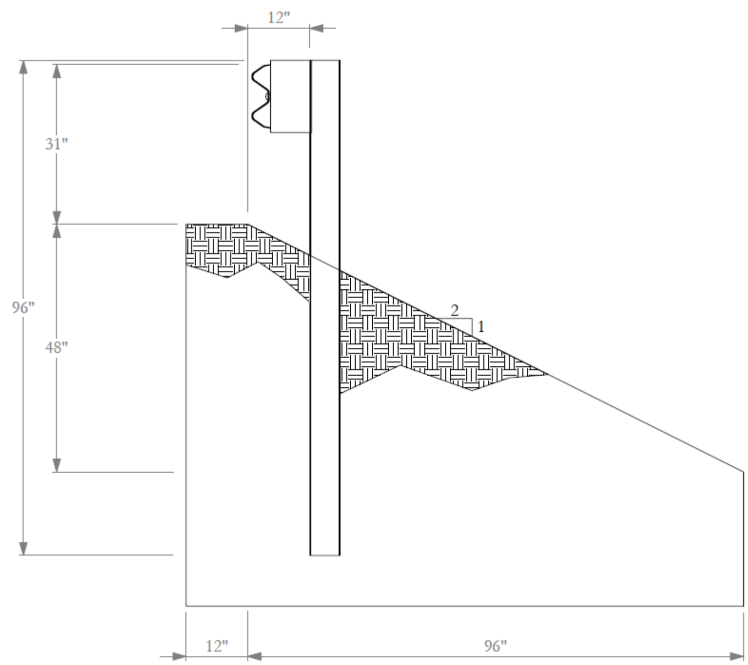


Figure 1.7. Cross section of 31-inch system.

- Case 1: 8-ft long W6×9 steel posts spaced at 3 ft-1.5 inch and a 12-guage W-beam rail element mounted at a rail height of 31 inches and aligned with the break point of a 2H:1V slope. The design vehicle was a *MASH* 2270P impacting at a speed of 62.3 mi/h and at an angle of 25 degrees.
- Case 2: 8-ft long W6×9 steel posts spaced at 6 ft-3 inches and a 12-guage W-beam rail element mounted at a rail height of 31 inches and aligned with the break point of a 2H:1V slope. The design vehicle was a *MASH* 2270P impacting at a speed of 62.3 mi/h and at an angle of 25 degrees.

* TTI Proving Ground's A2LA scope of accreditation does not include simulation analysis.

The steel post model used for the simulation was comprised of different parts with different thicknesses to accurately represent the shape and properties of a W6×9 steel post. The W-beam rail was raised 4 inches to a height of 31 inches. Therefore, the embedment depth of the steel post in the soil was decreased 4 inches. The model of the steel post is shown in figure 1.8.

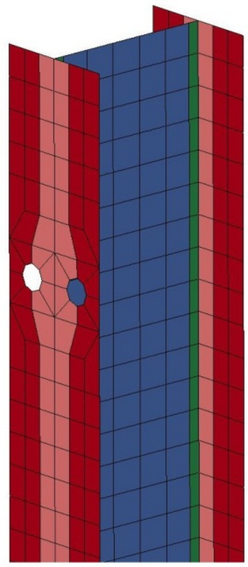


Figure 1.8 Steel post model.

The W-beam model had a finer mesh than the previous W-beam model. The reason for the finer mesh was to be able to capture more detailed deformation and stress profile of the W-beam as it engaged the impacting vehicle. The W-beam mesh is shown in figure 1.9.

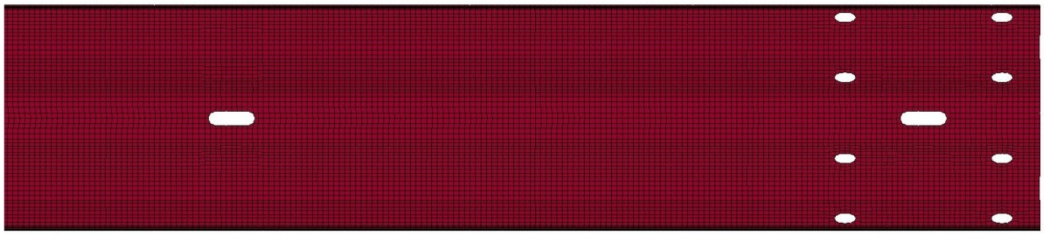


Figure 1.9. 12-gauge W-beam model.

Additionally, the soil in these simulation cases had a finer mesh than the previous soil model to provide more detailed deformation and interaction with the posts. The setup of the post and soil model is shown in figure 1.10. An initial simulation was conducted to capture steady state conditions under gravitational load such that the stresses in the soil were in equilibrium. Figure 1.11 shows the vertical stresses of the initialized soil model under gravitational load.

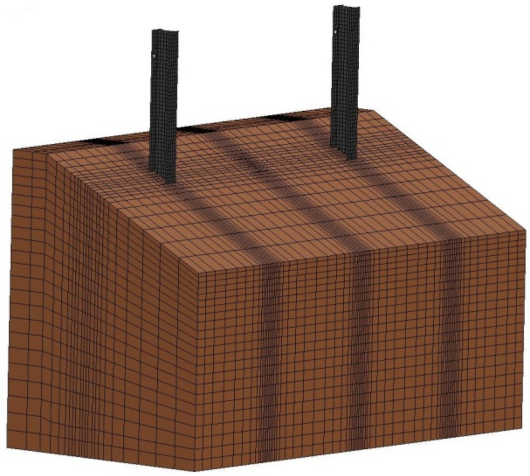


Figure 1.10. Mesh for combined soil and post models.

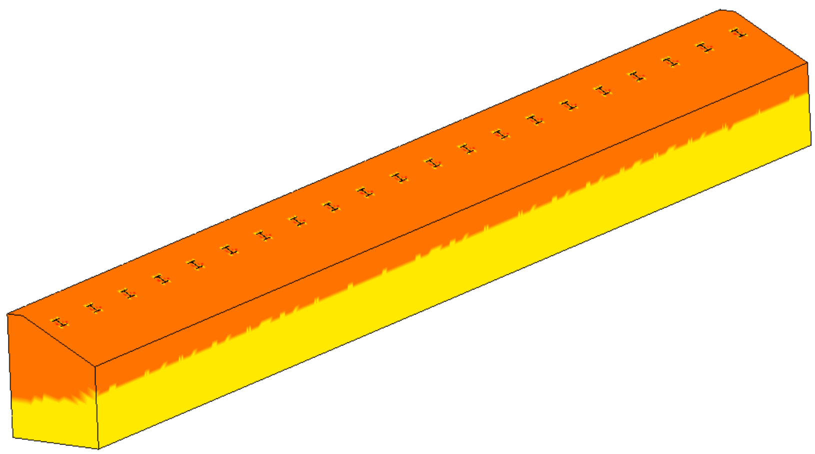


Figure 1.11. Initialized soil model.

The vehicle model in the simulations was the Chevrolet Silverado model. The Silverado model represents a *MASH* 2270P test vehicle. The Chevrolet Silverado vehicle model was developed by the National Crash Analysis Center (NCAC) at George Washington University. This vehicle model is shown in figure 1.12. At the time of this project, there was no vehicle model available representing the *MASH* 1100C test vehicle.

Figure 1.12. Chevrolet Silverado model.

1.4.3 Simulation Results

1.4.3.1 Case 1

In the simulation model for Case 1, there were 19 W6×9 steel posts (8-ft long) spaced at 3 ft-1.5 inches apart with standard 8-inch wood blockouts. The 12 gauge W-beam was connected to the steel posts by A325 5/8-inch diameter bolts and is placed with a top of rail height of 31 inches from the ground. The steel posts were offset from the rail splice locations. The modeled and simulated length was 60 ft. The setup for Case 1 is shown in figure 1.13.

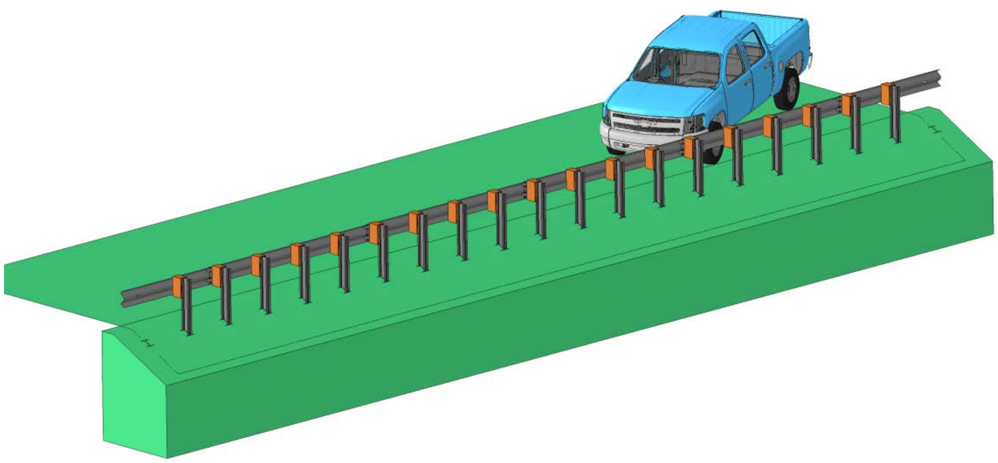


Figure 1.13. Model setup for Case 1.

1.4.3.1.1 Maximum Deflection of Guardrail System

Figure 1.14 shows the point of maximum deflection which occurred at approximately 0.14 seconds. The rail system reached a maximum deflection of 2.58 ft. At this point, the Silverado model had detached three posts from the rail and the driver side of the pickup truck was in contact with the rail system.

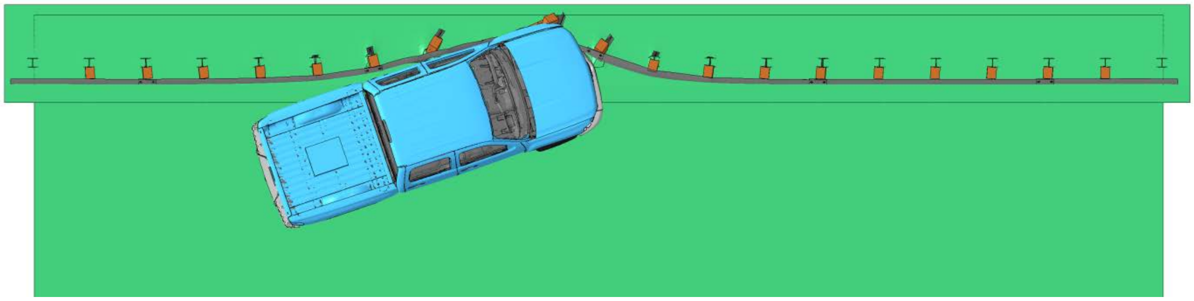


Figure 1.14. Top view of maximum deflection of system for Case 1 simulation.

Figure 1.15 shows the contours for the plastic strain within the W-beam at the time of maximum rail deflection. This indicates a low likelhood of rupture of the rail since the plastic strain values are well below rupture strain levels.

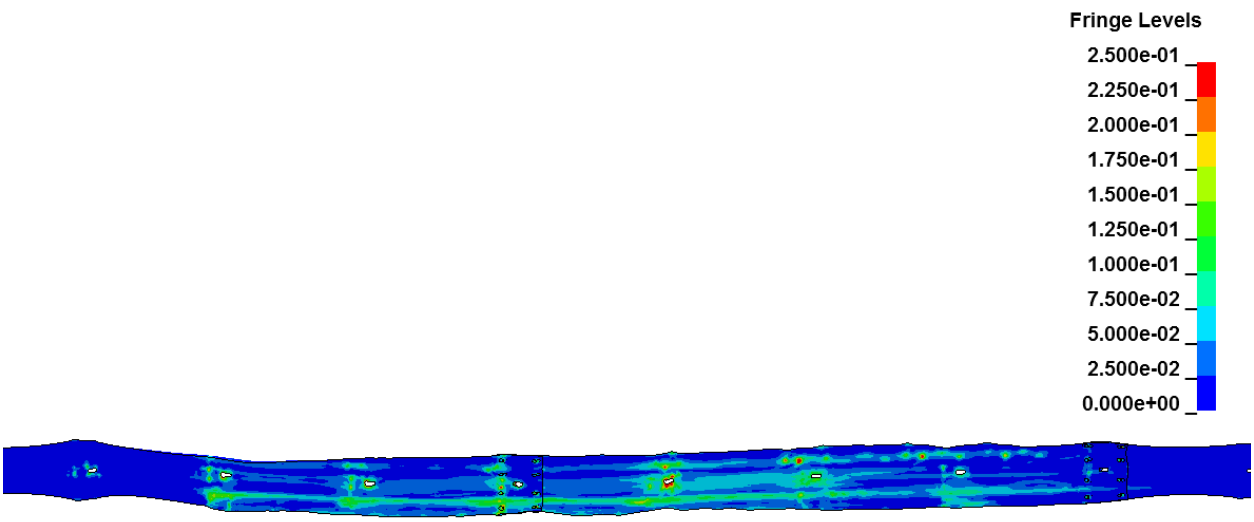


Figure 1.15. Contours of W-beam plastic strain during simulation.

1.4.3.1.2 Vehicle Roll, Pitch, and Yaw

The maximum roll, pitch, and yaw of the Silverado model were determined using TRAP. The maximum roll of the Silverado model was -8.3 degrees at 0.240 seconds, as shown in figure 1.16. The maximum pitch of the Silverado model was 8.6 degrees at 0.284 seconds which is shown in figure 1.17. The maximum yaw of the Silverado model was 22.6 degrees and occured at 0.297 seconds, as shown in figure 1.18.

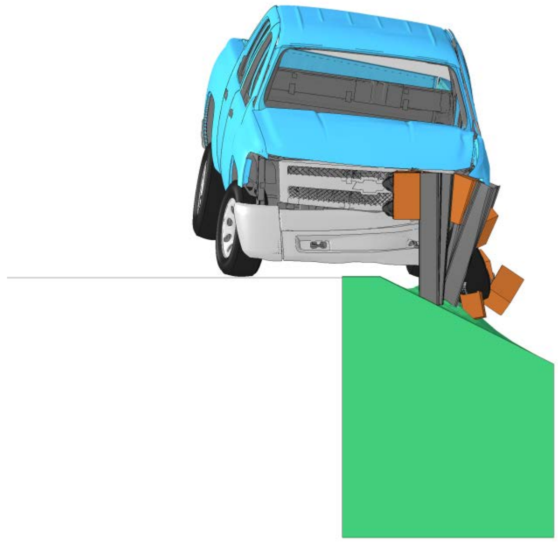


Figure 1.16. Case 1 Silverado model at maximum roll.

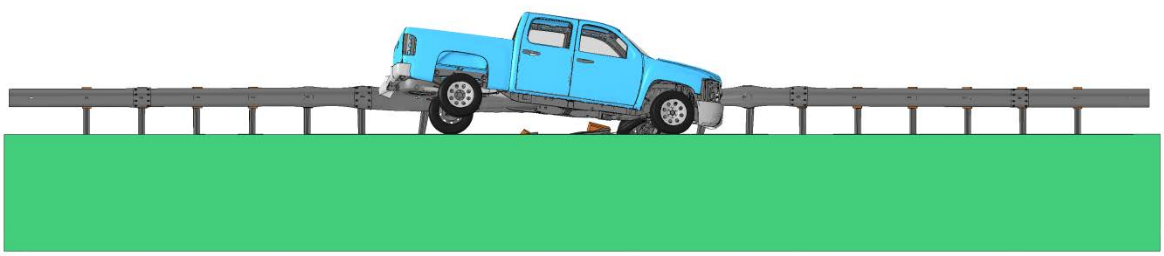


Figure 1.17. Case 1 Silverado model at maximum pitch.

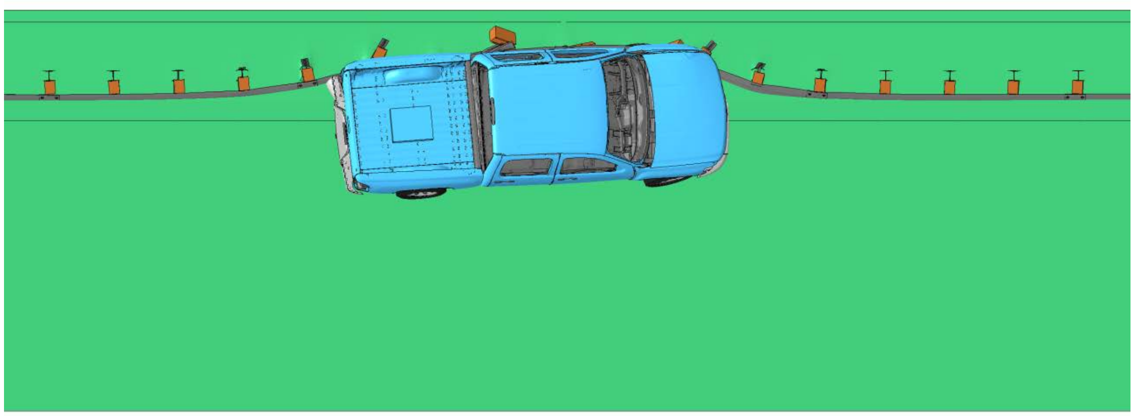


Figure 1.18. Case 1 Silverado model at maximum yaw.

1.4.3.1.3 Vehicle Exit

The Silverado did not exit the system due to pocketing and wheel snag of the front left tire. The simulation became numerically unstable at this point and terminated.

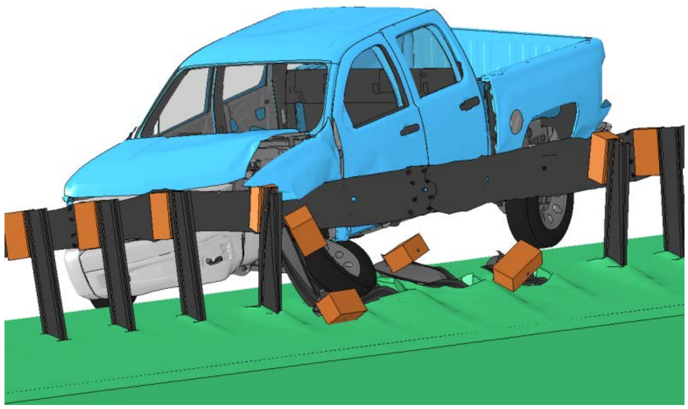


Figure 1.19. Vehicle pocketing and wheel snag upon exit.

A summary of occupant risk assessments is shown in table 1.1. Graphs of vehicular acceleration histories and angular displacement histories are shown in figures 1.20 through figure 1.23. A summary of pertinent data for the simulation is shown in figure 1.24.

Table 1.1. TRAP output from simulation Case 1.

Occupant Risk Factors			
Impact Velocity (m/s) at 0.1519sec on left side of interior			
x-direction:	6.3		Rec: <9 m/s
y-direction:	-4.3		Max: <12 m/s
THIV (km/hr):	32.7	at 0.1633sec on left side of interior	
THIV (m/s):	9.1		
Ridedown Acceleration (G's)			
x-direction:	-17.1	(0.2778-0.2878 sec)	Rec: <15 G's
y-direction:	7.7	(0.2000-0.2100 sec)	Max: <20 G's
PHD (G's):	17.6	(0.2778-0.2878 sec)	
ASI:	1.03	(0.2383-0.2883 sec)	
Maximum 50 msec Moving Average Acceleration (G's)			
x-direction:	-11.4	(0.2432-0.2932 sec)	
y-direction:	5.3	(0.1628-0.2128 sec)	
z-direction:	3.0	(0.2351-0.2851 sec)	

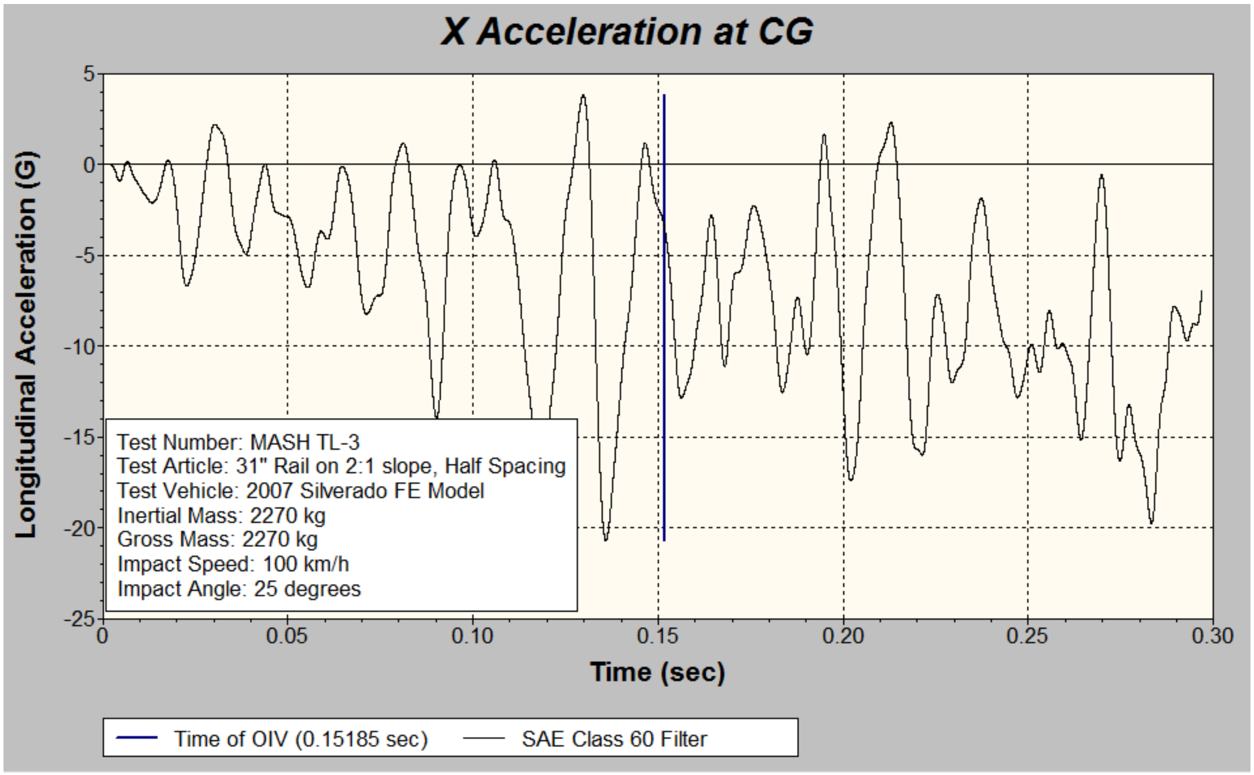


Figure 1.20. Longitudinal acceleration history at CG Case 1.

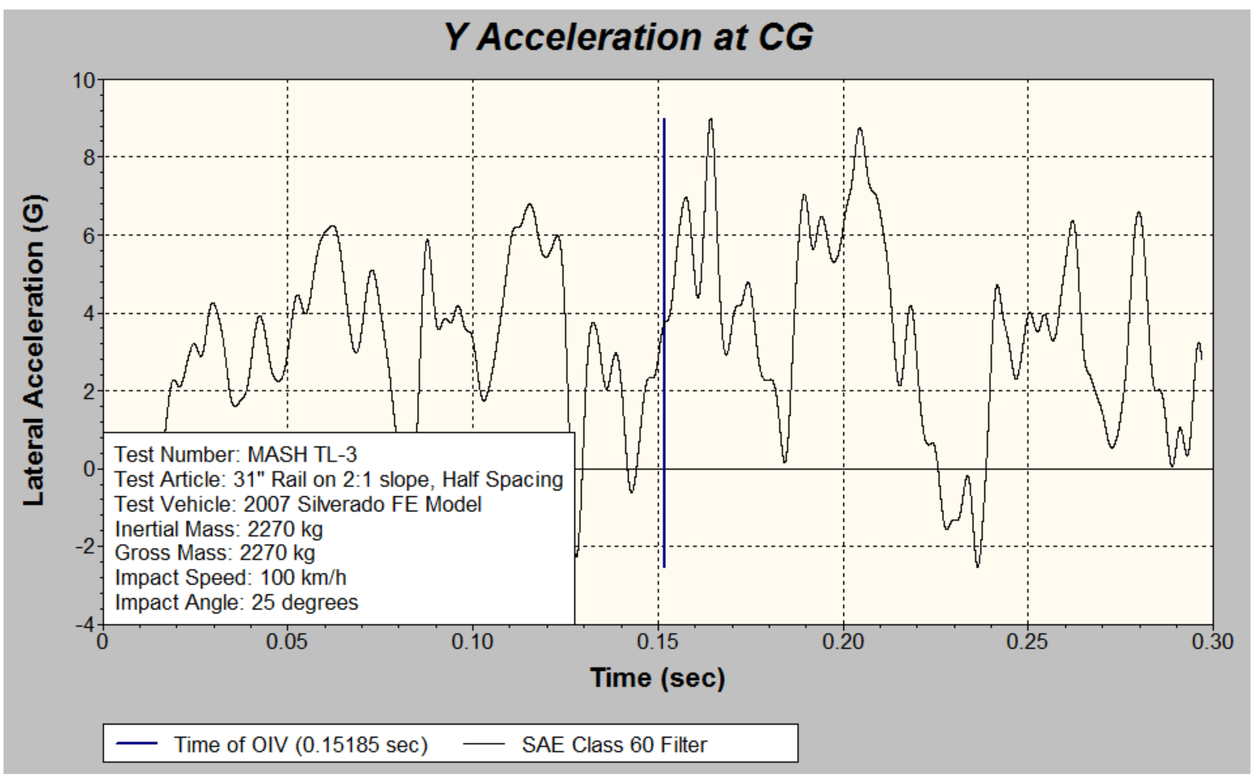


Figure 1.21. Lateral acceleration history at CG Case 1.

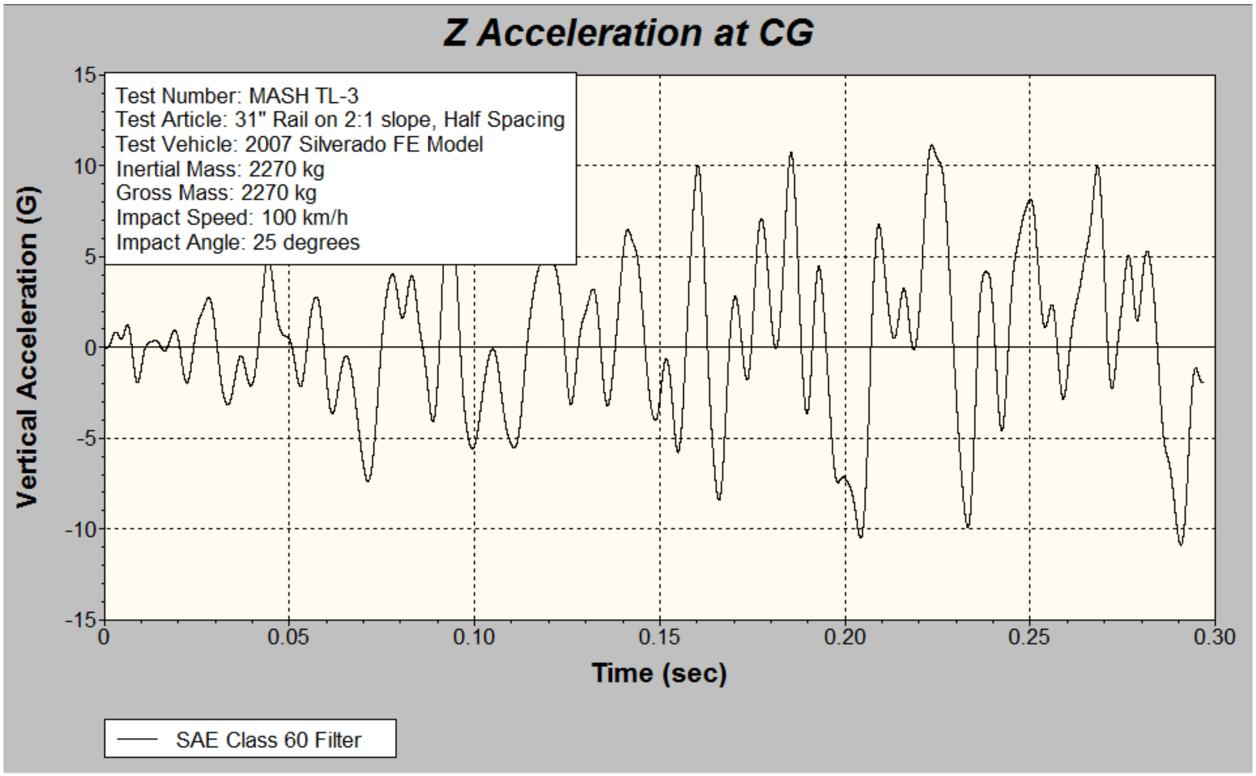


Figure 1.22. Vertical acceleration history at CG Case 1.

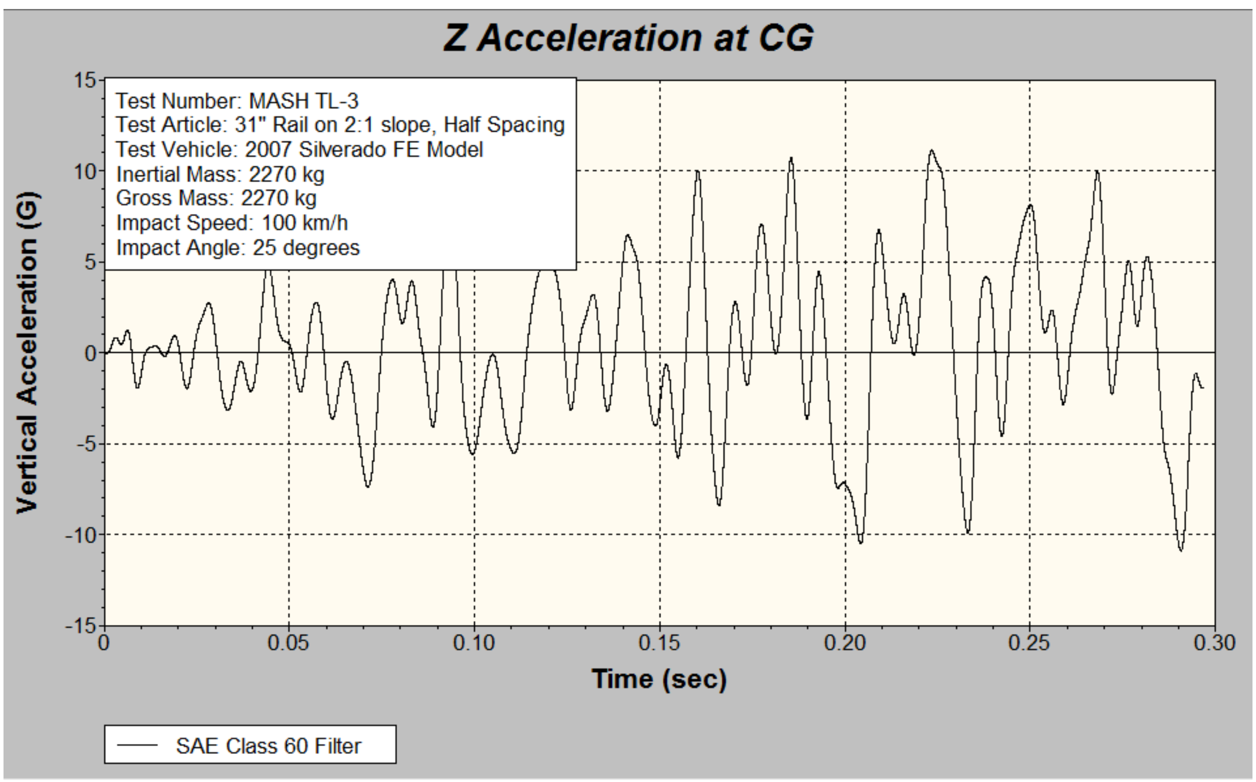
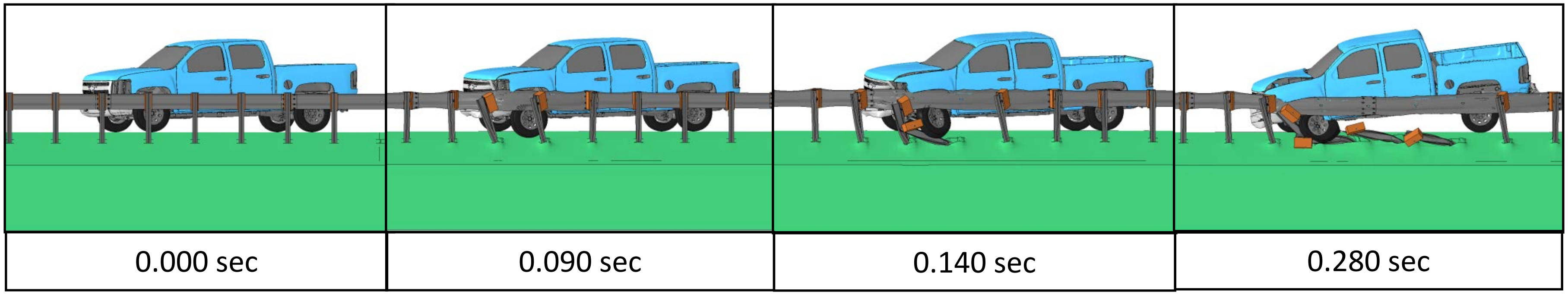


Figure 1.23. Roll, pitch, and yaw angles at CG Case 1.



General Information
- Test Agency .... Texas A&M Transportation Institute (TTI)
- Test Standard Test No. .... MASH test 3-11
- Test No. .... Case 1
- Date .... August 27, 2012

Test Article
- Type................................... Guardrail
- Name .... WSDOT Guardrail on Slope
- Installation Length .... 60 ft
- Material or Key Elements .... 31" rail on 2H:1V Slope, 3'-1.5" Spacing

Soil Type and Condition....... Standard soil

Test Vehicle
- Type/Designation 2270P
- Make and Model.................. Chevy Silverado
- Curb .... 2270 kg
- Test Inertial .... 2270 kg
- Dummy................................ No dummy
- Gross Static......................... 2270 kg

Impact Conditions
- Speed..................................100 km/h
- Angle...................................25 degrees
- Location/Orientation ....Post 6

Exit Conditions
- Speed..................................N/A
- Angle...................................N/A

Occupant Risk Values
- Impact Velocity
  - Longitudinal.......................4.3 m/s
  - Lateral ....6.3 m/s
- Ridedown Accelerations
  - Longitudinal.......................7.7 G
  - Lateral ....17.1 G
- THIV....................................32.7 km/h
- PHD ....17.6 G
- Max. 0.050-s Average
  - Longitudinal.......................-5.3 G
  - Lateral ....11.4 G
  - Vertical ....3.0 G

Post-Impact Trajectory
- Stopping Distance .... N/A

Vehicle Stability
- Maximum Yaw Angle.................. 22.6 degrees
- Maximum Pitch Angle................. 8.6 degrees
- Maximum Roll Angle................... 8.3 degrees
- Vehicle Snagging........................ Yes
- Vehicle Pocketing .... Yes

Test Article Deflections
- Dynamic .... 2.58 ft
- Permanent.................................. N/A
- Working Width .... N/A

Vehicle Damage
- VDS.. N/A
- CDC .... N/A
- Max. Exterior Deformation .... N/A
- OCDI .... N/A
- Max. Occupant Compartment Deformation......................... N/A

Figure 1.24. Summary of results for Case 1 simulation.

1.4.3.2 Case 2

In the simulation model for Case 2, there were ten W6×9 steel posts (8-ft long) spaced at 6 ft-3 inches apart with standard 8-inch wood blockouts. The 12 gauge W-beam was connected to the steel posts by A325 5/8-inch diameter bolts at a height of 31 inches from the ground. The steel posts were offset from the rail splices. The setup for Case 2 is shown in figure 1.25.

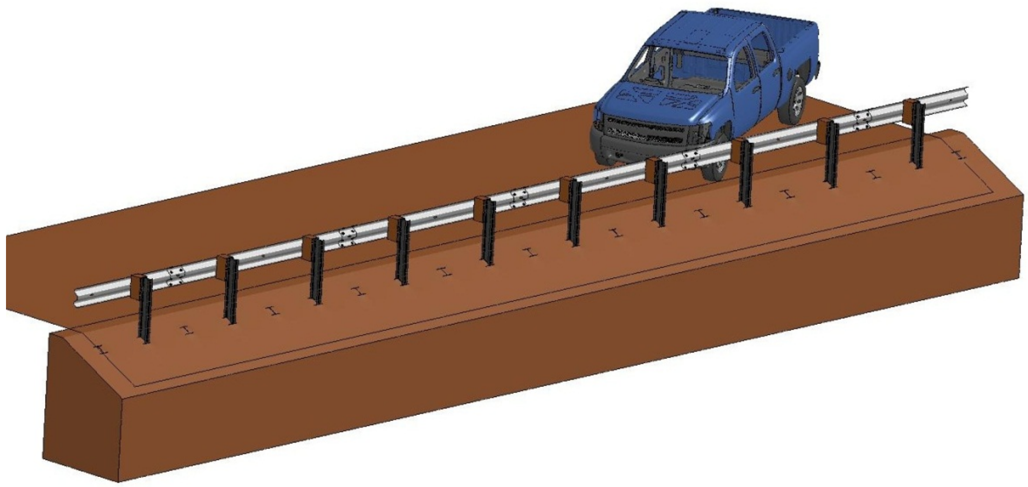


Figure 1.25. Model setup for Case 1.

1.4.3.2.1 Maximum Deflection of Guardrail System

Figure 1.26 shows the point of maximum deflection which occurred at approximately 0.23 seconds. The rail system reached maximum deflection of 3.4 ft. At this point the Silverado model had bent five steel posts to the ground and the driver side of the pickup truck was in contact with the rail system.

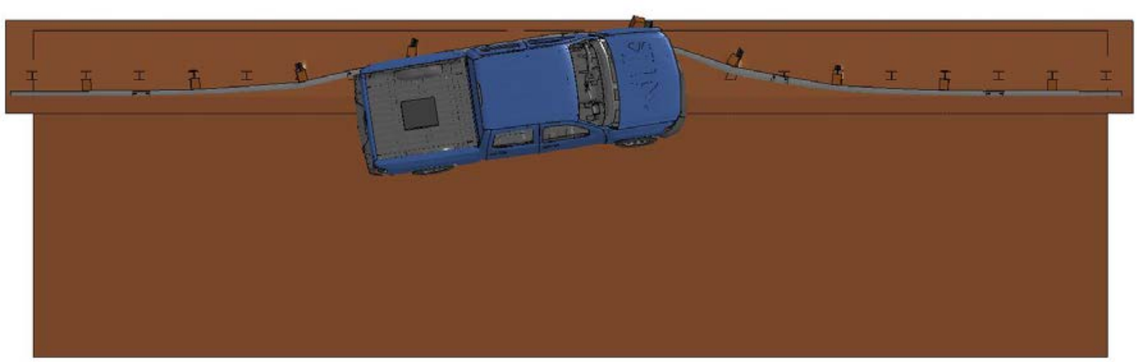


Figure 1.26. Case 2 top view of maximum deflection of system.

Figure 1.27 shows the contours for the plastic strain within the W-beam at the time of maximum rail deflection. This indicates a low likelhood of rupture of the rail since the plastic strain values are well below rupture strain levels.

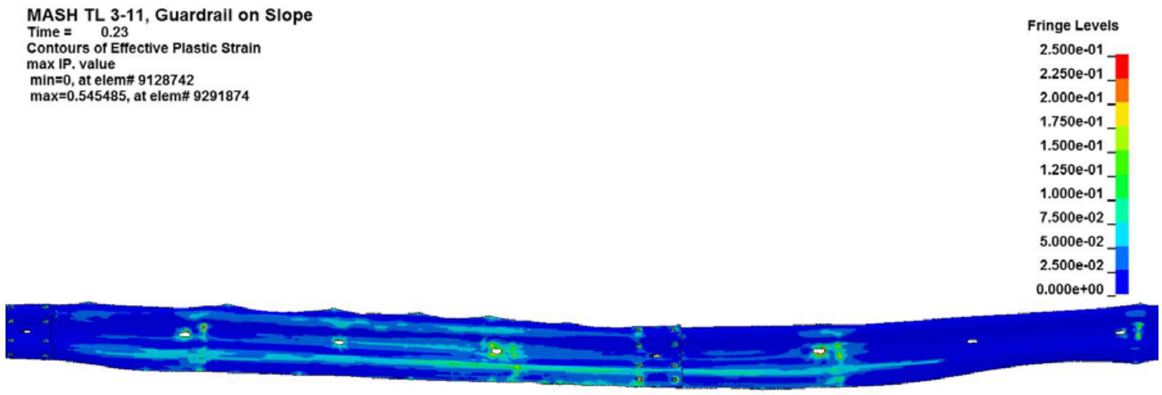


Figure 1.27. Contours of W-beam plastic strain during simulation.

1.4.3.2.2 Vehicle Suspension Failure

At 0.27 seconds, the front left suspension of the Silverado model started to fail as a result of post contact, and allowed the front left wheel of the truck began to deflect outward, as shown in figure 1.28 and figure 1.29.

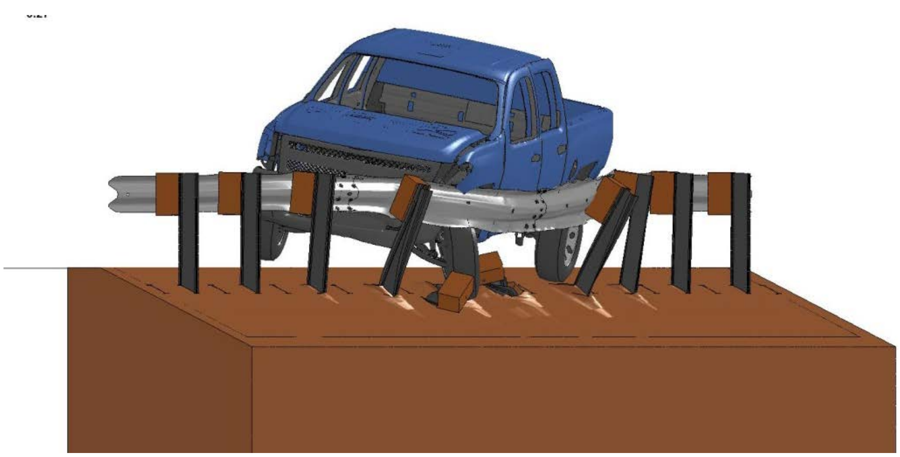


Figure 1.28. Case 2 suspension failure of Silverado model.

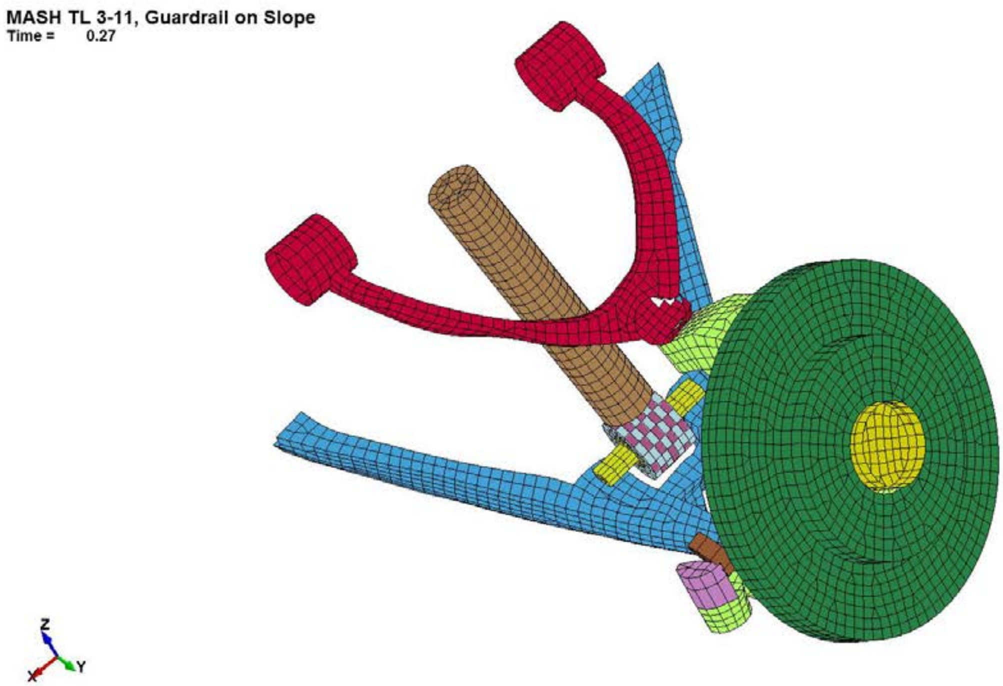


Figure 1.29. Front left suspension of Silverado model at failure.

1.4.3.2.3 Vehicle Roll, Pitch, and Yaw

The maximum roll, pitch, and yaw of the Silverado model were determined using TRAP. The maximum roll of the Silverado model was -11.7 degrees at 0.2941 seconds, as shown in figure 1.30. The maximum pitch of the Silverado model was 12.4 degrees at 0.6239 seconds, which is shown in figure 1.31. The maximum yaw of the Silverado model was 31.1 degrees at 0.4210 seconds, as shown in figure 1.32.

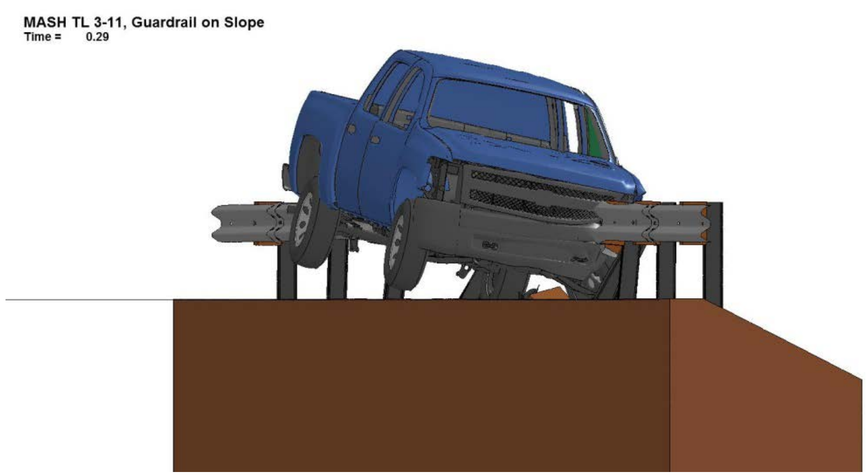


Figure 1.30. Case 2 Silverado model at maximum roll.

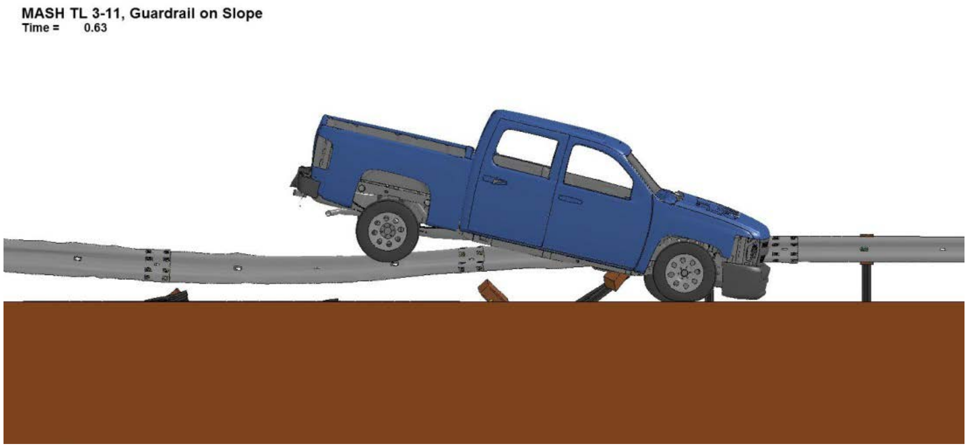


Figure 1.31. Case 2 Silverado model at maximum pitch.

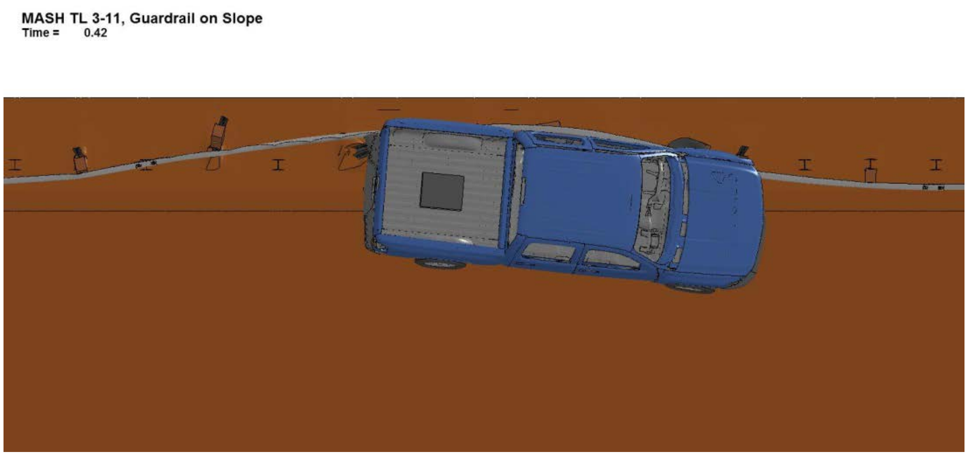


Figure 1.32. Case 2 Silverado model at maximum yaw.

1.4.3.2.4 Vehicle Exit

The Silverado model exited the rail system at a time of 0.63 seconds and an angle of 21 degrees, as shown in figure 1.33.

A summary of occupant risk assessments is shown in table 1.2. Graphs of vehicular acceleration histories and angular displacement histories are shown in figure 1.34 through figure 1.37. A summary of pertinent data for the simulation is shown in figure 1.38.

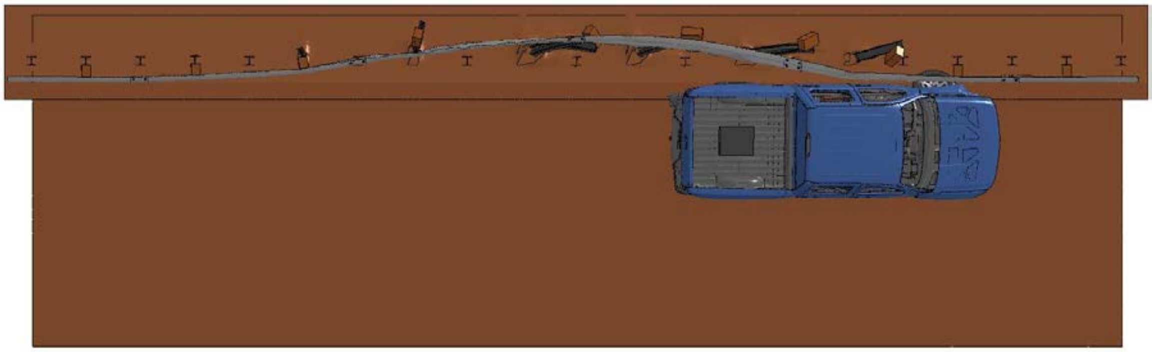


Figure 1.33. Top view of vehicle exit.

Table 1.2. TRAP output from Silverado simulation Case 2.

Occupant Risk Factors			
Impact Velocity (m/s) at 0.1683sec on left side of interior			
x-direction:	4.9		Rec: <9 m/s
y-direction:	-4.4		Max: <12 m/s
THIV (km/hr):	28.8	at 0.1792 sec on left side of interior	
THIV (m/s):	8.0		
Ridedown Acceleration (G's)			
x-direction:	-11.1	(0.1694-0.1794 sec)	Rec: <15 G's
y-direction:	9.1	(0.2534-0.2634 sec)	Max: <20 G's
PHD (G's):	12.6	(0.2495-0.2595 sec)	
ASI:	0.82	(0.2131-0.2631 sec)	
Maximum 50 msec Moving Average Acceleration (G's)			
x-direction:	-7.0	(0.1515-0.2015 sec)	
y-direction:	6.5	(0.2171-0.2671 sec)	
z-direction:	-2.8	(0.2041-0.2541 sec)	

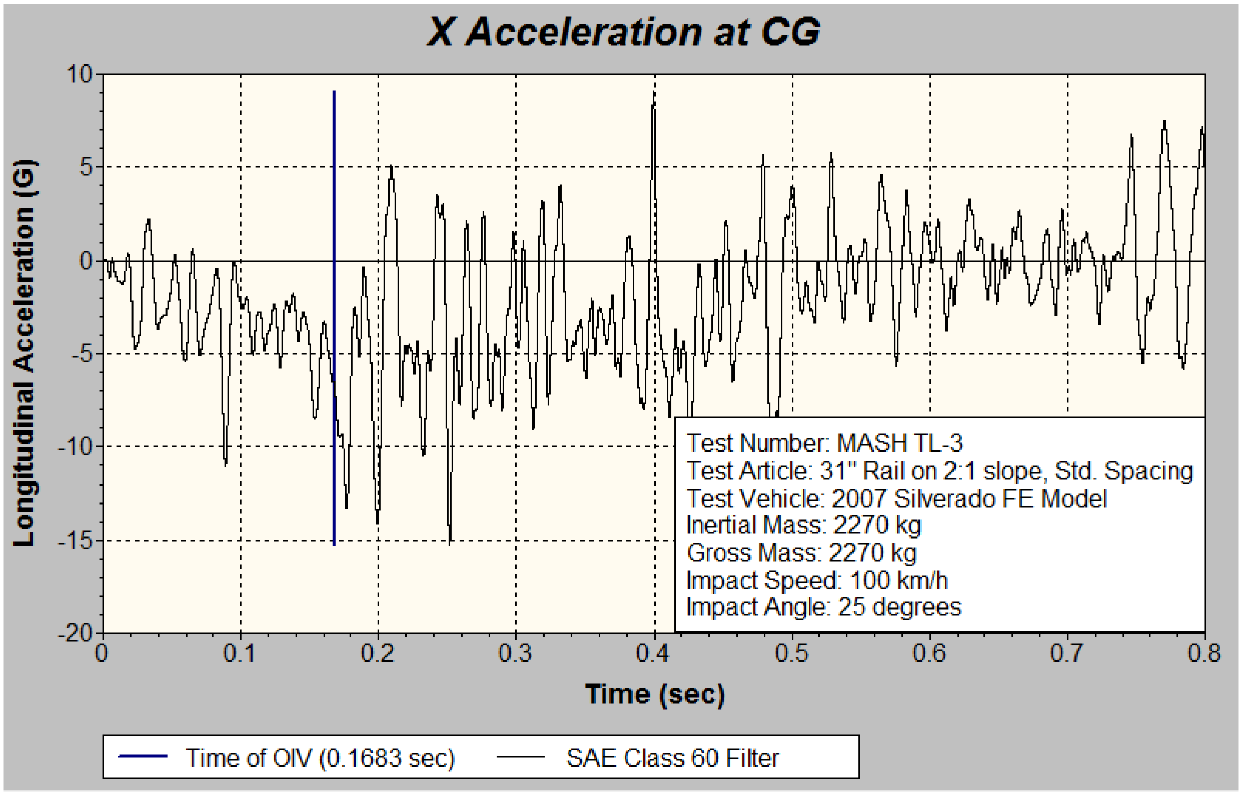


Figure 1.34. Longitudinal acceleration history at CG Case 2.

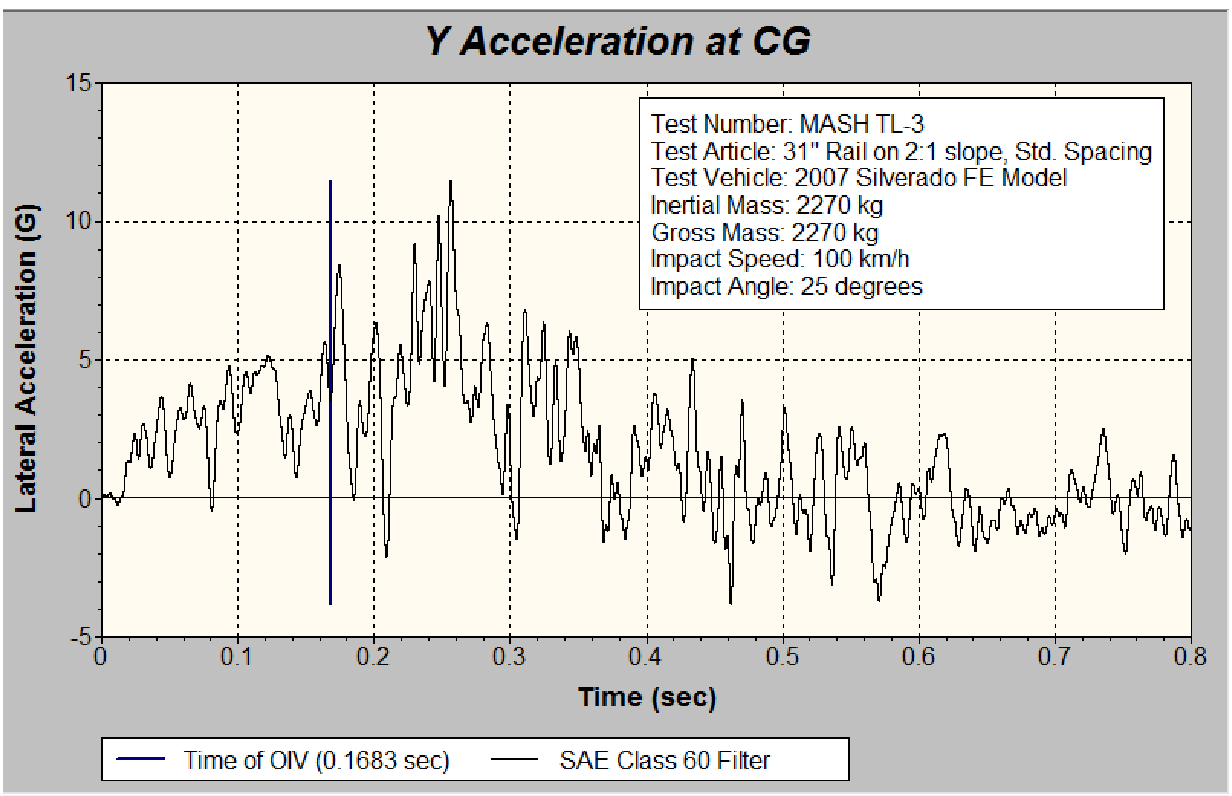


Figure 1.35. Lateral acceleration history at CG Case 2.

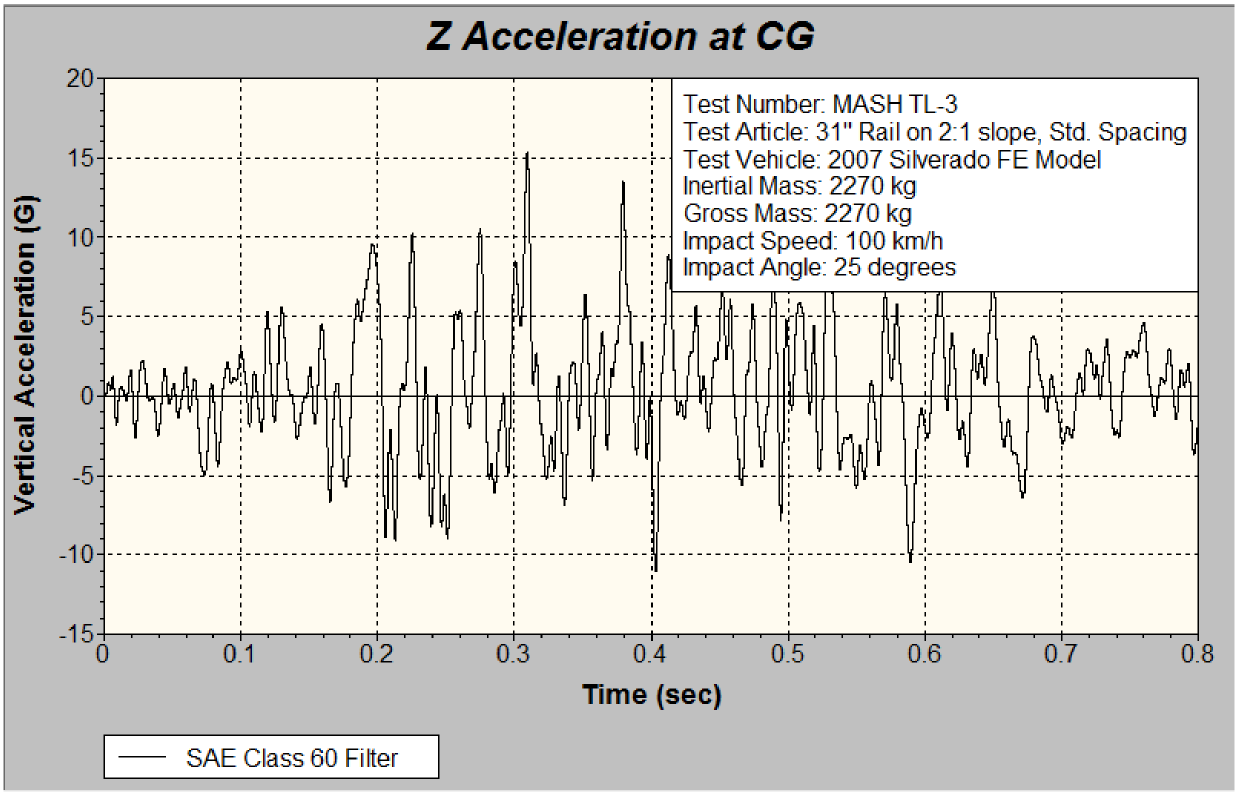


Figure 1.36. Vertical acceleration history at CG Case 2.

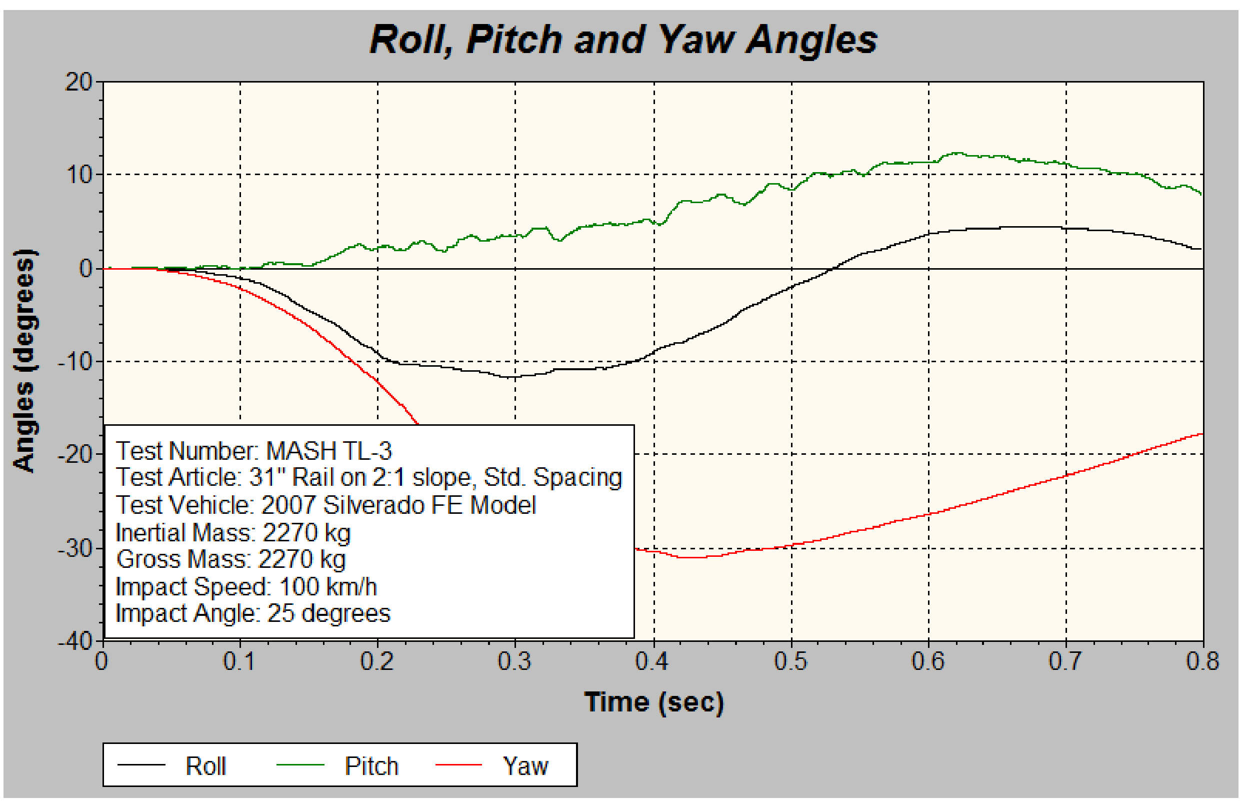
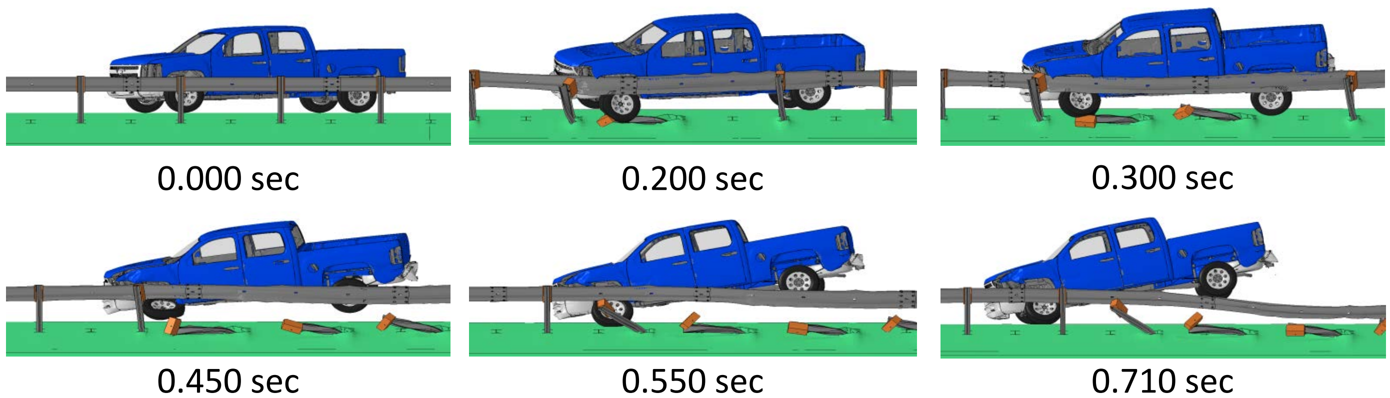


Figure 1.37. Roll, Pitch, and Yaw angles Case 2.



General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH test 3-11
Test No.	Case 2
Date	August 27, 2012

Test Article

Type	Guardrail
Name	WSDOT Guardrail on Slope
Installation Length	60 ft
Material or Key Elements	31" rail on 2H:1V Slope, 6'-3" Spacing
Soil Type and Condition	Standard soil

Test Vehicle

Type/Designation	2270P
Make and Model	Chevy Silverado
Curb	2270 kg
Test Inertial	2270 kg
Dummy	No dummy
Gross Static	2270 kg

Impact Conditions

Speed	100 km/h
Angle	25 degrees
Location/Orientation	Post 4

Exit Conditions

Speed	38.8 km/h
Angle	21 degrees

Occupant Risk Values

Impact Velocity	
Longitudinal	4.4 m/s
Lateral	4.9 m/s
Ridedown Accelerations	
Longitudinal	9.1 G
Lateral	11.1 G
THIV	28.8 km/h
PHD	12.6 G
Max. 0.050-s Average	
Longitudinal	-6.5 G
Lateral	-7.0 G
Vertical	-2.8 G

Post-Impact Trajectory

Stopping Distance	N/A

Vehicle Stability

Maximum Yaw Angle	31.1 degrees
Maximum Pitch Angle	12.4 degrees
Maximum Roll Angle	11.7 degrees
Vehicle Snagging	Yes
Vehicle Pocketing	No

Test Article Deflections

Dynamic	3.4 ft
Permanent	N/A
Working Width	N/A

Vehicle Damage

VDS	N/A
CDC	N/A
Max. Exterior Deformation	N/A
OCDI	N/A
Max. Occupant Compartment Deformation	N/A

Figure 1.38. Summary of results for Case 2 simulation.

1.5 CONCLUSIONS AND RECOMMENDATIONS FOR TESTING

In simulation Case 1, significant wheel snag and a high ridedown acceleration were observed. In simulation Case 2, with 6 ft-3 inch spacing and 8-ft posts, the 2270P vehicle was successfully redirected and contained without significant wheel snag or pocketing. The occupant risk factors were lower than those resulting from Case 1. Hence, it was recommended to test a guardrail on slope system that represents the design modeled in Case2.

2. SYSTEM DETAILS

2.1 TEST ARTICLE DESIGN AND CONSTRUCTION

The guardrail on slope system test installation had a total length of 181.25 ft. The system was comprised of a 106.25 ft length of need section and a 37.5 ft long ET Plus terminal on each end. The 12-gauge W-beam was mounted on W6×8.5 steel posts. The guardrail height was 31 inches above the flat terrain. A 2H:1V sloped ditch was excavated behind the rail to represent the sloped terrain. The ditch was centered along the installation length and was 75 ft long and 12 ft wide. An overview of the system installation and profile of the ditch section is shown in figure 2.1.

Six 6-ft long W6×8.5 posts were placed at 6 ft-3 inch spacing on the flat terrain portion of the test installation. These were posts 7-9 and 22-24. Along the sloped section, the 8-ft long posts were placed at 6 ft-3 inch spacing. These were post 10 through post 21, as shown in the drawing in figure 2.1. Standard size 8 inch × 6 inch × 14 inch wood blocks were used in the length of need section. The rail splices of the W-beam rail sections in the length of need portion are located between posts as shown in Figure 2.1.

Details of the installation are shown in figure 2.1 and in appendix A. Photos of the completed installation are shown in figure 2.2. The guardrail was constructed such that the face of the W-beam rail was aligned with the slope break of the ditch, as shown in figure 2.1.

2.2 MATERIAL SPECIFICATIONS

Materials used for this installation are summarized in appendix B. For further details of the certification documentation for these materials, please contact Texas A&M Transportation Institute (TTI) Proving Ground for documents on file.

2.3 SOIL CONDITIONS

The test installation was installed in standard soil meeting AASHTO standard specifications for "Materials for Aggregate and Soil Aggregate Subbase, Base and Surface Courses", designated M147-65(2004), grading B. In accordance with Appendix B of *MASH*, soil strength was measured the day of the crash test. During installation of the guardrail on slope for full-scale crash testing, two standard W6×16 posts were installed in the immediate vicinity of the guardrail on slope, utilizing the same fill materials and installation procedures used in the standard dynamic test (see Appendix C, figure C1).

As determined in the tests shown in Appendix C, figure C1, the minimum post load required for deflections at 5 inches, 10 inches, and 15 inches, measured at a height of 25 inches, is 3940 lb, 5500 lb, and 6540 lb, respectively (90 percent of static load for the initial standard installation). On the day of test 405160-20-1, January 18, 2012, load on the post at deflections of 5 inches, 10 inches, and 15 inches was 6454 lbf, 6576 lbf, and 6606 lbf, respectively. The strength of the backfill material met minimum requirements. On the day of test 405160-20-2, load on the post at deflections of 5 inches, 10 inches, and 15 inches was 8600 lbf, 9120 lbf, and 9180 lbf, respectively. Results of these loading tests are provided in Appendix C, figures C2 and C3, respectively.

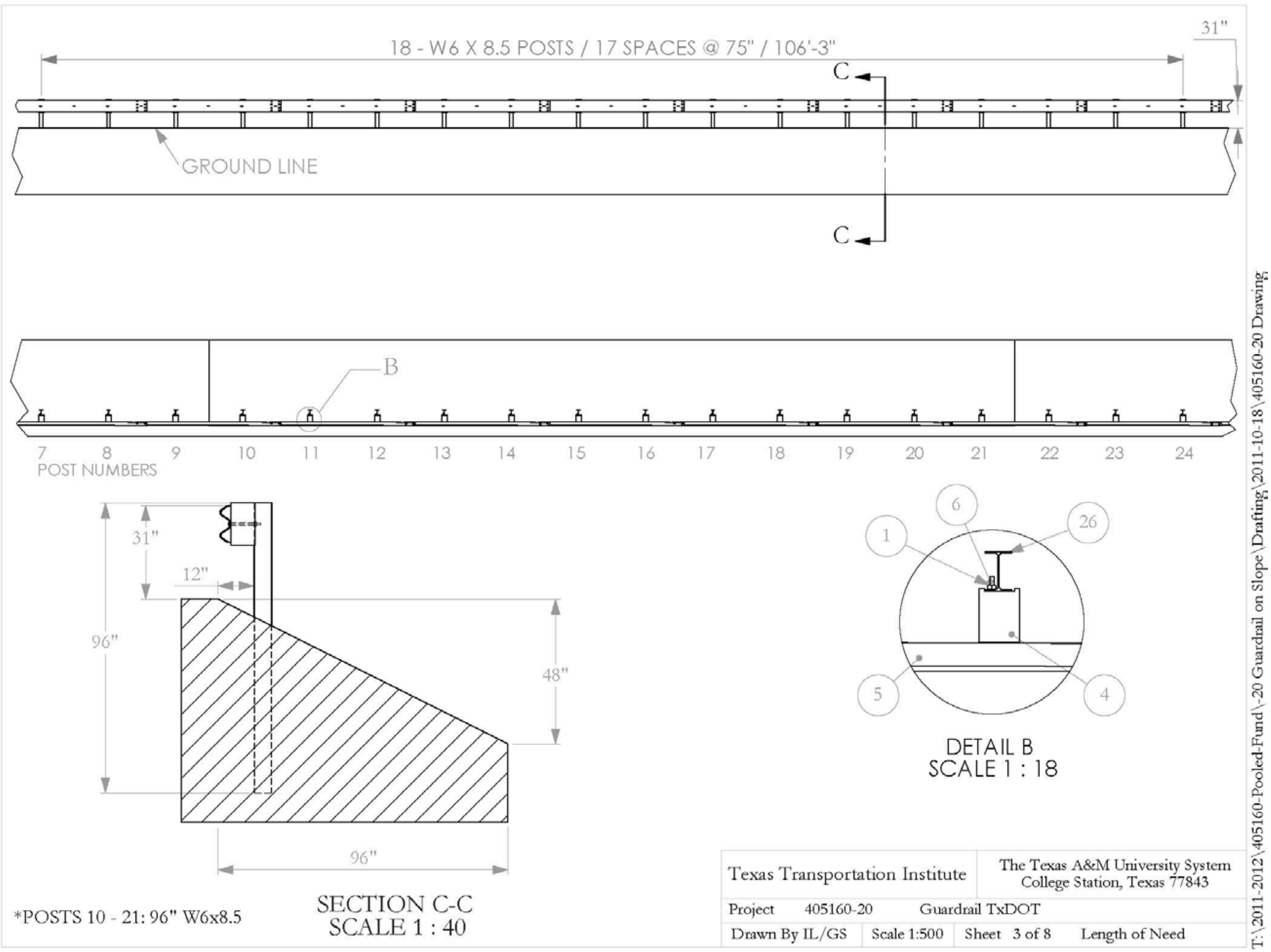


Figure 2.1. Layout of the guardrail on slope.

Figure 2.2. Guardrail on slope prior to testing.

3. TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 CRASH TEST MATRIX

According to *MASH*, two tests are recommended to evaluate longitudinal barriers to test level three (TL-3).

> ***MASH* Test Designation 3-10:** A 2425 lb vehicle impacting the length of need section at a speed of 62 mi/h and an angle of 20 degrees.
>
> ***MASH* Test Designation 3-11:** A 5000 lb pickup truck impacting the length of need section at a speed of 62 mi/h and an angle of 25 degrees.

Both *MASH* TL-3 tests were performed. The critical impact point for these tests were determined using *MASH* guidelines. Target impact point for *MASH* test 3-11 was 3 inches upstream of post 14. Target impact point for *MASH* test 3-10 was 33 inches upstream of post 15 (near rail splice between posts 14 and 15).

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

3.2 EVALUATION CRITERIA

The crash test was evaluated in accordance with the criteria presented in *MASH*. The performance of the guardrail on slope is judged on the basis of three factors: structural adequacy, occupant risk, and post impact vehicle trajectory. Structural adequacy is judged upon the ability of the guardrail on slope to contain and redirect the vehicle, or bring the vehicle to a controlled stop in a predictable manner. Occupant risk criteria evaluates the potential risk of hazard to occupants in the impacting vehicle, and to some extent other traffic, pedestrians, or workers in construction zones, if applicable. Post impact vehicle trajectory is assessed to determine potential for secondary impact with other vehicles or fixed objects, creating further risk of injury to occupants of the impacting vehicle and/or risk of injury to occupants in other vehicles. The appropriate safety evaluation criteria from table 5.1 of *MASH* were used to evaluate the crash test reported herein, and are listed in further detail under the assessment of the crash test.

4. TEST CONDITIONS

4.1 TEST FACILITY

The full-scale crash test reported herein was performed at Texas A&M Transportation Institute (TTI) Proving Ground. TTI Proving Ground is an International Standards Organization (ISO) 17025 accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing certificate 2821.01. The full-scale crash test was performed according to TTI Proving Ground quality procedures and according to the *MASH* guidelines and standards.

The test facilities at the TTI Proving Ground consist of a 2000 acre complex of research and training facilities situated 10 miles northwest of the main campus of Texas A&M University. The site, formerly an Air Force 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, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for the installation of the guardrail on slope was along the edge of a wide out-of-service apron. The apron consists of an unreinforced jointed concrete pavement in 12.5 ft × 15 ft blocks nominally 6 inches deep. The aprons are over 50 years old and the joints have some displacement, but are otherwise flat and level.

4.2 VEHICLE TOW AND GUIDANCE SYSTEM

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, 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 two-to-one speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs.

4.3 DATA ACQUISITION SYSTEMS

4.3.1 Vehicle Instrumentation and Data Processing

The test vehicle was instrumented with a self-contained, on-board data acquisition system. The signal conditioning and acquisition system is a 16-channel, Tiny Data Acquisition System (TDAS) Pro produced by Diversified Technical Systems, Inc. The accelerometers, that 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 size, solid state units designs for crash test service. The TDAS Pro hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each of the 16 channels is capable of providing precision amplification, scaling and filtering based on transducer specifications and calibrations. During the test, data are recorded from each channel at a rate of 10,000 values per second with a resolution of one part in 65,536. Once recorded, the data are backed up inside the unit by internal batteries should the primary battery cable be severed. Initial contact of the pressure switch on the vehicle bumper provides a time zero mark as well as initiating the recording process. After each test, the data are downloaded from the TDAS Pro unit into a laptop computer at the test site. The raw data are then processed by the Test Risk Assessment Program (TRAP) software to produce detailed reports of the test results. Each of the TDAS Pro units are returned to the factory annually for complete recalibration. Accelerometers and rate transducers are also calibrated annually with traceability to the National Institute for Standards and Technology. Acceleration data is measured with an expanded uncertainty of ±1.7% at a confidence fracture of 95% (k=2).

TRAP uses the data from the TDAS Pro to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the 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 a 60-Hz 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 of the vehicle-fixed coordinate systems being initial impact. Rate of rotation data is measured with an expanded uncertainty of ±0.7% at a confidence factor of 95% (k=2).

4.3.2 Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the driver's position of the 1100C vehicle. The dummy was uninstrumented. Use of a dummy in the 2270P vehicle is optional according to *MASH*, and there was no dummy used in the tests with the 2270P vehicle.

4.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of the test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one placed behind the installation at an angle; and a third placed to have a field of view parallel to and aligned with the installation at the downstream end. A flashbulb activated by pressure-sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the installation and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked motion analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A mini-DV camera and still cameras recorded and documented conditions of the test vehicle and installation before and after the test.

5. CRASH TEST 405160-20-1 (*MASH* TEST NO. 3-11)

5.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH test 3-11 involves a 2270P vehicle weighing 5000 lb ±110 lb and impacting the guardrail on slope at an impact speed of 62.2 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. The target impact point was 3 inches upstream of post 14. The 2006 Dodge Ram 1500 pickup truck used in the test weighed 5044 lb and the actual impact speed and angle were 63.9 mi/h and 25.0 degrees, respectively. The actual impact point was 11.1 inches upstream of post 14. Target impact severity (IS) was 115.1 kip-ft, and actual IS was 123.0 kip-ft, or 6.9 percent greater than target.

5.2 TEST VEHICLE

A 2006 Dodge Ram 1500 pickup truck, shown in figures 5.1 and 5.2, was used for the crash test. Test inertia weight of the vehicle was 5044 lb, and its gross static weight was 5044 lb. The height to the lower edge of the vehicle front bumper was 13.75 inches, and the height to the upper edge of the front bumper was 25.38 inches. The height to the center of gravity was 28.62 inches. Additional dimensions and information on the vehicle are given in appendix D, tables D1 and D2. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

5.3 WEATHER CONDITIONS

The crash test was performed the morning of January 18, 2012. Weather conditions at the time of testing were: Wind speed: 2 mi/h; wind direction: 187 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 49ºF; relative humidity: 50 percent.

5.4 TEST DESCRIPTION

The 2006 Dodge Ram 1500 pickup truck, traveling at an impact speed of 63.9 mi/h, impacted the guardrail on slope 11.1 inches upstream of post 14 at an impact angle of 25.0 degrees. Shortly after impact, post 14 began to deflect toward the field side, and 0.012 s, post 15 began to deflect toward the field side. Post 13 began to deflect toward the field side at 0.024 s, the vehicle began to redirect at 0.041 s. At 0.056 s, post 12 began to deflect toward the field side, and at 0.141 s, the left front tire continued to ride under the rail and contacted post 15. The rear of the vehicle contacted the guardrail at 0.179 s, and the left front tire rode under the rail and contacted post 16 at 0.233 s. At 0.263 s, the vehicle began to travel parallel with the guardrail traveling at a speed of 51.1 mi/h. The left front tire, still under the rail element, contacted posts 17 and 18 at 0.333 s and 0.433 s, respectively. At 0.549 s, the vehicle lost contact with the guardrail. At this time, the vehicle was out of view of the overhead camera and exit speed and angle were not obtainable from the camera. Judging from vehicle tire path, the exit angle was estimated to be 10 degrees. Brakes on the vehicle were not applied, and the vehicle yawed counterclockwise 180 degrees and came to rest 106.2 ft downstream of impact and 2 ft forward of the traffic face of the guardrail. Sequential photographs of the test period are shown in appendix D, figures D1 and D2.

Figure 5.1. Vehicle/installation geometrics for test 405160-20-1.

Figure 5.2. Vehicle before test 405160-20-1.

5.5 TEST ARTICLE AND COMPONENT DAMAGE

Damage to the guardrail on slope is shown in figures 5.3 and 5.4. Post 1 was pulled downstream 1.75 inches at ground level and post 2 through 9 rotated 5 degrees counterclockwise. Post 13 was deflected toward the field side 1 inch at ground level and rotated 5 degrees counterclockwise. Post 14 was rotated 75 degrees counterclockwise. Post 15 was rotated toward the field side 90 degrees and downstream 45 degrees. Posts 16 through 18 rotated 80 degrees, and the blockout separated from post 17. Post 19 was deflected toward the field side 15 degrees and downstream 5 degrees, and post 20 was deflected toward the field side 5 degrees. The W-beam rail element separated from posts 10 and 11, and posts 14 through 19. Post 30 was pulled upstream 0.25 inch at ground level. Length of contact of the vehicle with the guardrail was 41.4 ft. Working width was 4.6 ft. Maximum dynamic deflection of the rail element during the test was 4.3 ft, and maximum permanent deformation of the rail element after the test was 3.1 ft.

5.6 TEST VEHICLE DAMAGE

Figure 5.5 shows the damage sustained by the vehicle. The left tie rod end, left lower A-arm, and left frame rail were deformed. Also damaged were the front bumper, grill, hood, left front fender, left front tire and wheel rim, left front and left rear doors, left rear exterior bed, and the rear bumper. Maximum exterior crush to the vehicle was 11.0 inches in the front plane at the left front corner at bumper height. No occupant compartment deformation occurred. Photographs of the interior of the vehicle are shown in figure 5.6. Exterior vehicle crush and occupant compartment measurements are shown in appendix D, tables D3 and D4.

5.7 OCCUPANT RISK VALUES

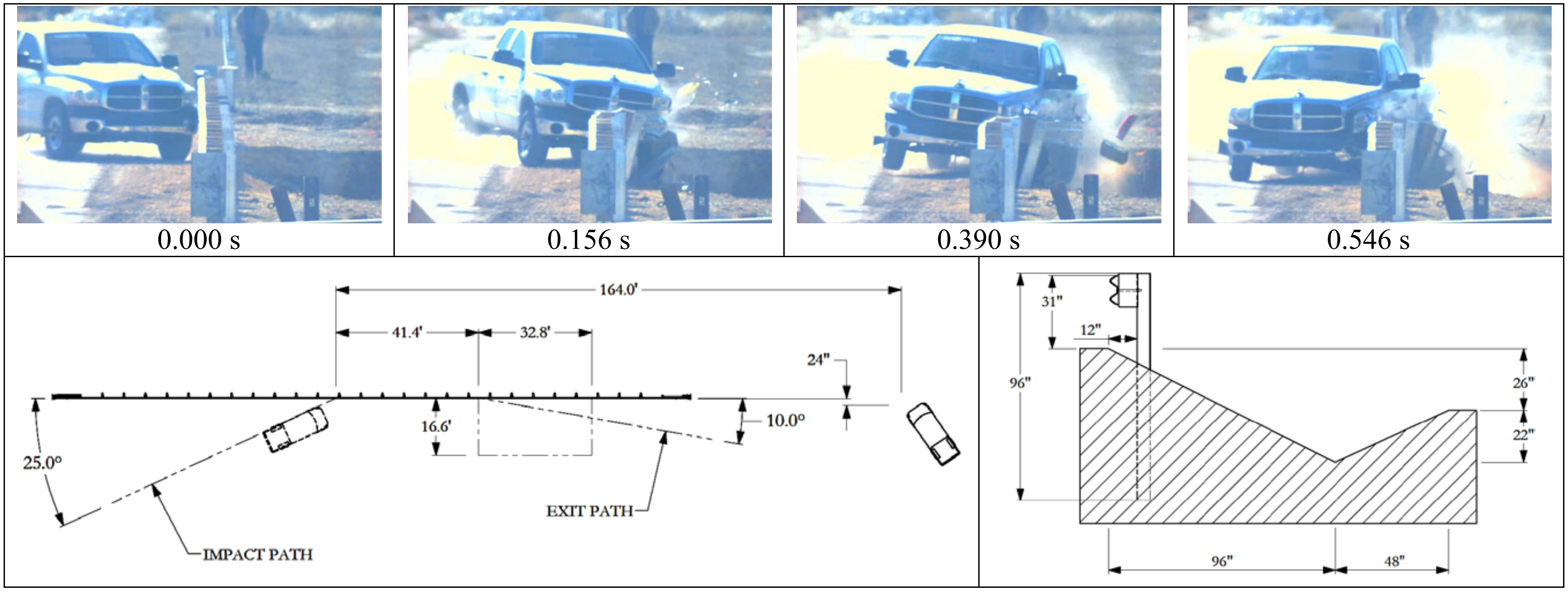
Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 15.1 ft/s at 0.153 s, the highest 0.010-s occupant ridedown acceleration was 9.0 Gs from 0.264 to 0.274 s, and the maximum 0.050-s average acceleration was -4.5 Gs between 0.101 and 0.151 s. In the lateral direction, the occupant impact velocity was 15.4 ft/s at 0.153 s, the highest 0.010-s occupant ridedown acceleration was 6.9 Gs from 0.218 to 0.228 s, and the maximum 0.050-s average was 5.1 Gs between 0.214 and 0.264 s. Theoretical Head Impact Velocity (THIV) was 22.3 km/h or 6.2 m/s at 0.148 s; Post-Impact Head Decelerations (PHD) was 10.1 Gs between 0.264 and 0.274 s; and Acceleration Severity Index (ASI) was 0.61 between 0.219 and 0.269 s. These data and other pertinent information from the test are summarized in figure 5.7. Vehicle angular displacements and accelerations versus time traces are presented in appendix D, figures D3 through D9.

Figure 5.3. Vehicle/installation positions after test 405160-20-1.

Figure 5.4. Installation after test 405160-20-1.

Figure 5.5. Vehicle after test 405160-20-1.

Figure 5.6. Interior of vehicle for test 405160-20-1.



General Information
- Test Agency .... Texas A&M Transportation Institute (TTI)
- Test Standard Test No. .... MASH test 3-11
- TTI Test No. 405160-20-1
- Date .... January 18, 2012

Test Article
- Type.................................. Guardrail
- Name .... WSDOT Guardrail on Slope
- Installation Length .... 181 ft 3 inches
- Material or Key Elements .... 12 gauge W-Beam Mounted on 8-ft long W6x8.5 Steel Posts on 2H:1V Slope

Soil Type and Condition....... Standard soil, dry

Test Vehicle
- Type/Designation 2270P
- Make and Model.................. 2006 Dodge Ram 1500
- Curb .... 4977 lb
- Test Inertial .... 5044 lb
- Dummy............................... No dummy
- Gross Static........................ 5044 lb

Impact Conditions
- Speed..............................63.9 mi/h
- Angle...............................25.0 degrees
- Location/Orientation ....0.9 ft upstream of post 14

Impact Severity..................123.0 kip-ft, >6.9%

Exit Conditions
- Speed..............................Not obtainable
- Angle...............................~10 degrees

Occupant Risk Values
- Impact Velocity
  - Longitudinal...................15.1 ft/s
  - Lateral...........................15.4 ft/s
- Ridedown Accelerations
  - Longitudinal...................9.0 G
  - Lateral...........................6.9 G
- THIV................................22.3 km/h
- PHD ....10.1 G
- ASI 0.61

Max. 0.050-s Average
- Longitudinal...................-4.5 G
- Lateral........................... 5.1 G
- Vertical.......................... 1.8 G

Post-Impact Trajectory
- Stopping Distance .... 106.2 ft dwnstrm 2.0 ft twd traffic

Vehicle Stability
- Maximum Yaw Angle................. 34 degrees
- Maximum Pitch Angle................ 3 degrees
- Maximum Roll Angle.................. 13 degrees
- Vehicle Snagging....................... No
- Vehicle Pocketing...................... No

Test Article Deflections
- Dynamic .... 4.3 ft
- Permanent.................................. 3.1 ft
- Working Width .... 4.6 ft

Vehicle Damage
- VDS... 11LFQ4
- CDC 11LFEW3
- Max. Exterior Deformation .... 11.0 inches
- OCDI .... nil
- Max. Occupant Compartment Deformation......................... LS0000000

Figure 5.7. Summary of results for *MASH* test 3-11 on the guardrail on slope.

5.8 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the following applicable *MASH* safety evaluation criteria is presented below.

5.8.1 Structural Adequacy

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

Results: The guardrail on slope contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 4.3 ft. (PASS)

5.8.2 Occupant Risk

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches)

Results: The rail element separated from some of the posts and one blockout separated from a post. However, these elements did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area. (PASS)
No occupant compartment deformation occurred. (PASS)

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

Results: The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 13 degrees and 3 degrees, respectively. (PASS)

H. Occupant impact velocities should satisfy the following:

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
30 ft/s	*40 ft/s*

Results: Longitudinal occupant impact velocity was 15.1 ft/s, and lateral occupant impact velocity was 15.4 ft/s. (PASS)

I. *Occupant ridedown accelerations should satisfy the following:*

Longitudinal and Lateral Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Results: Longitudinal ridedown acceleration was 9.0 G, and lateral ridedown acceleration was 6.9 G. (PASS)

5.8.3 Vehicle Trajectory

For redirective devices, the vehicle shall exit the barrier within the exit box (not less than 32.8 ft).

Result: The vehicle exited the guardrail within the exit box. (PASS)

6. CRASH TEST 405160-20-2 (*MASH* TEST NO. 3-10)

6.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH test 3-10 involves a 1100C vehicle weighing 2425 lb ±55 lb and impacting the guardrail on slope at an impact speed of 62.2 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. The target impact point was 33 inches upstream of post 15 (near joint between posts 14 and 15). The 2006 Kia Rio used in the test weighed 2593 lb and the actual impact speed and angle were 60.3 mi/h and 25.9 degrees, respectively. The actual impact point was 36.0 inches upstream of post 15. Target impact severity (IS) was 55.7 kip-ft, and actual IS was 60.1 kip-ft, or 7.9 percent greater than target.

6.2 TEST VEHICLE

A 2006 Kia Rio, shown in figures 6.1 and 6.2, was used for the crash test. Test inertia weight of the vehicle was 2429 lb, and its gross static weight was 2593 lb. The height to the lower edge of the vehicle front bumper was 7.12 inches, and the height to the upper edge of the front bumper was 21.0 inches. Additional dimensions and information on the vehicle are given in appendix E, table E1. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

6.3 WEATHER CONDITIONS

The crash test was performed the morning of April 20, 2012. Weather conditions at the time of testing were: Wind speed: 13 mi/h; wind direction: 213 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 73ºF; relative humidity: 76 percent.

6.4 TEST DESCRIPTION

The 2006 Kia Rio, traveling at an impact speed of 60.3 mi/h, impacted the guardrail on slope 36.0 inches upstream of post 15 at an impact angle of 25.9 degrees. Shortly after impact, posts 14 and 15 began to deflect toward the field side of the guardrail, and at 0.036 s, the left front tire contacted post 15. The vehicle began to redirect at 0.050 s, and post 16 began to deflect toward the field side at 0.062 s. At 0.089 s, the left front tire contacted post 16, and at 0.105 s, post 17 began to deflect toward the field side. Post 18 began to deflect toward the field side at 0.111 s, and the left front tire contacted post 17 at 0.179 s. At 0.275 s, the vehicle began to travel parallel with the guardrail at a speed of 37.5 mi/h. The left front tire contacted post 18 at 0.276 s. At 0.545 s, the vehicle lost contact with the guardrail traveling at an exit speed and angle of 31.3 mi/h and 32.3 degrees, respectively. Brakes on the vehicle were applied at 2.4 s, and the vehicle yawed 180 degrees and came to rest 162.4 ft downstream of impact and forward of the traffic face of the guardrail. Sequential photographs of the test period are shown in appendix E, figures E1 and E2.

Figure 6.1. Vehicle/installation geometrics for test 405160-20-2.

Figure 6.2. Vehicle before test 405160-20-2.

6.5 TEST ARTICLE AND COMPONENT DAMAGE

Damage to the guardrail on slope is shown in figures 6.3 and 6.4. The soil around post 1 was disturbed. Post 14 was pushed toward the field side 1 .0 inch at ground level. The metal rail element was separated from post 15 through 19. Post 15 was pushed toward the field side 5.0 inches at ground level and was leaning downstream 20 degrees. Post 16 through 18 were pushed toward the field side 5.0 inches and were leaning downstream 65 degrees. Post 19 was leaning toward the field side and downstream 45 degrees and rotated 60 degrees counterclockwise in the soil. Post 20 was leaning toward the field side 0.5 inch at ground level. Length of contact of the vehicle with the guardrail was 25.3 ft. Working width was 3.1 ft. Maximum dynamic deflection of the rail element during the test was 2.7 ft, and maximum permanent deformation of the rail element after the test was 1.9 ft.

6.6 TEST VEHICLE DAMAGE

Figure 6.5 shows the damage sustained by the vehicle. The left front strut and strut tower, left inner CV joint, and left lower A-arm and ball joint were deformed. Also damaged were the front bumper, grill, hood, left front fender, left front tire and wheel rim, left front and left rear doors, and left rear quarter panel. The windshield sustained stress cracks radiating from the left lower corner. Maximum exterior crush to the vehicle was 10.5 inches in the front plane at the left front corner at bumper height. No occupant compartment deformation occurred. Photographs of the interior of the vehicle are shown in figure 6.6. Exterior vehicle crush and occupant compartment measurements are shown in appendix E, tables E2 and E3.

6.7 OCCUPANT RISK VALUES

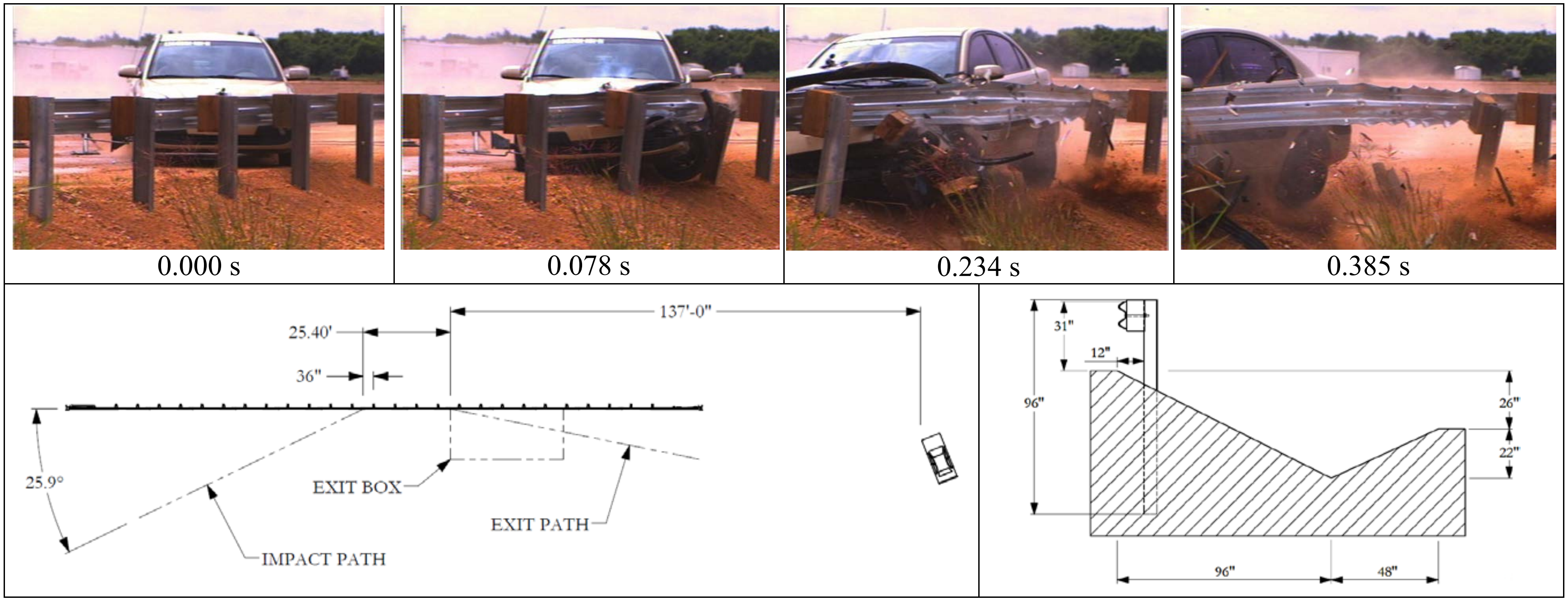
Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 17.4 ft/s at 0.128 s, the highest 0.010-s occupant ridedown acceleration was 7.3 Gs from 0.182 to 0.192 s, and the maximum 0.050-s average acceleration was -5.7 Gs between 0.050 and 0.100 s. In the lateral direction, the occupant impact velocity was 16.1 ft/s at 0.128 s, the highest 0.010-s occupant ridedown acceleration was 6.8 Gs from 0.263 to 0.273 s, and the maximum 0.050-s average was 5.5 Gs between 0.015 and 0.065 s. Theoretical Head Impact Velocity (THIV) was 24.6 km/h or 6.8 m/s at 0.123 s; Post-Impact Head Decelerations (PHD) was 9.3 Gs between 0.182 and 0.192 s; and Acceleration Severity Index (ASI) was 0.75 between 0.143 and 0.193 s. These data and other pertinent information from the test are summarized in figure 6.7. Vehicle angular displacements and accelerations versus time traces are presented in appendix E, figures E3 through E9.

Figure 6.3. Vehicle/installation positions after test 405160-20-2.

Figure 6.4. Installation after test 405160-20-2.

Figure 6.5. Vehicle after test 405160-20-2.

Figure 6.6. Interior of vehicle for test 405160-20-2.



General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH test 3-10
TTI Test No.	405160-20-2
Date	April 20, 2012

Test Article

Type	Guardrail
Name	WSDOT Guardrail on Slope
Installation Length	181 ft 3 inches
Material or Key Elements	12 gauge W-Beam Mounted on 8-ft long W6x8.5 Steel Posts on 2H:1V Slope
Soil Type and Condition	Standard soil, dry

Test Vehicle

Type/Designation	1100C
Make and Model	2006 Kia Rio
Curb	2457 lb
Test Inertial	2429 lb
Dummy	164 lb
Gross Static	2593 lb

Impact Conditions

Speed	60.3 mi/h
Angle	25.9 degrees
Location/Orientation	3.0 ft upstrm post 15
Impact Severity	60.1 kip-ft, >7.9%

Exit Conditions

Speed	31.3 mi/h
Angle	32.3 degrees

Occupant Risk Values

Impact Velocity	
Longitudinal	17.4 ft/s
Lateral	16.1 ft/s
Ridedown Accelerations	
Longitudinal	7.3 G
Lateral	6.8 G
THIV	24.6 km/h
PHD	9.3 G
ASI	0.75
Max. 0.050-s Average	
Longitudinal	-5.7 G
Lateral	5.5 G
Vertical	-2.3 G

Post-Impact Trajectory

Stopping Distance	162.4 ft dwnstrm twd traffic

Vehicle Stability

Maximum Yaw Angle	38 degrees
Maximum Pitch Angle	5 degrees
Maximum Roll Angle	7 degrees
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	2.7 ft
Permanent	1.9 ft
Working Width	3.1 ft

Vehicle Damage

VDS	11LFQ3
CDC	11FLEW3
Max. Exterior Deformation	10.5 inches
OCDI	FS0000000
Max. Occupant Compartment Deformation	None

Figure 6.7. Summary of results for *MASH* test 3-10 on the guardrail on slope.

6.8 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the following applicable *MASH* safety evaluation criteria is presented below.

6.8.1 Structural Adequacy

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

Results: The guardrail on slope contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 2.7 ft. (PASS)

6.8.2 Occupant Risk

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches)

Results: The rail element separated from some of the posts. However, the rail element did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area. (PASS)
No occupant compartment deformation occurred. (PASS)

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

Results: The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 7 degrees and 5 degrees, respectively. (PASS)

I. Occupant impact velocities should satisfy the following:

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
30 ft/s	*40 ft/s*

Results: Longitudinal occupant impact velocity was 17.4 ft/s, and lateral occupant impact velocity was 16.1 ft/s. (PASS)

I. *Occupant ridedown accelerations should satisfy the following:*

Longitudinal and Lateral Occupant Ridedown Accelerations	
Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Results: Longitudinal ridedown acceleration was 7.3 G, and lateral ridedown acceleration was 6.8 G. (PASS)

6.8.3 Vehicle Trajectory

For redirective devices, the vehicle shall exit the barrier within the exit box (not less than 32.8 ft).

Result: The 1100C vehicle crossed the exit box at the end of the guardrail. (PASS)

7. SUMMARY AND CONCLUSIONS

7.1 SUMMARY OF RESULTS

7.1.1 *MASH* Test 3-11 (Test No. 405160-20-1)

The guardrail on slope contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 4.3 ft. The rail element separated from some of the posts and one blockout separated from a post. However, these elements did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area. No occupant compartment deformation occurred. The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 13 degrees and 3 degrees, respectively. Occupant risk factors were below the preferred limits specified in *MASH*. The 2270P vehicle exited within the exit box.

7.1.2 *MASH* Test 3-10 (Test No. 405160-20-2)

The guardrail on slope contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 2.7 ft. The rail element separated from some of the posts. However, the rail element did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area. No occupant compartment deformation occurred. The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 7 degrees and 5 degrees, respectively. Occupant risk factors were below the preferred limits specified in *MASH*. The 1100C vehicle crossed the exit box at the end of the guardrail.

7.2 CONCLUSIONS

The guardrail on slope performed acceptably for *MASH* TL-3, as shown in tables 7.1 and 7.2.

Table 7.1. Performance evaluation summary for *MASH* test 3-11 on the guardrail on slope.

Test Agency: Texas A&M Transportation Institute | Test No.: 405160-20-1 | Test Date: 2012-01-18

***MASH* Test 3-11 Evaluation Criteria**	**Test Results**	**Assessment**
<u>Structural Adequacy</u> A. *Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable*	The guardrail on slope contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 4.3 ft.	Pass
<u>Occupant Risk</u> D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	The rail element separated from some of the posts and one blockout separated from a post. However, these elements did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	No occupant compartment deformation occurred.	Pass
F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*	The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 13 degrees and 3 degrees, respectively.	Pass
H. *Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9.1 m/s (30 ft/s), or at least below the maximum allowable value of 12.2 m/s (40 ft/s).*	Longitudinal occupant impact velocity was 15.1 ft/s, and lateral occupant impact velocity was 15.4 ft/s.	Pass
I. *Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.*	Longitudinal ridedown acceleration was 9.0 G, and lateral ridedown acceleration was 6.9 G.	Pass
<u>Vehicle Trajectory</u> *For redirective devices, the vehicle shall exit the barrier within the exit box (not less than 32.8 ft).*	The 2270P vehicle exited within the exit box	Pass

Table 7.2. Performance evaluation summary for *MASH* test 3-10 on the guardrail on slope.

Test Agency: Texas A&M Transportation Institute | Test No.: 405160-20-2 | Test Date: 2012-04-20

***MASH* Test 3-10 Evaluation Criteria**	**Test Results**	**Assessment**
<u>Structural Adequacy</u> *A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable*	The guardrail on slope contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 4.3 ft.	Pass
<u>Occupant Risk</u> *D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	The rail element separated from some of the posts. However, the rail element did not penetrate, nor show potential to penetrate the occupant compartment, nor to present undue hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	No occupant compartment deformation occurred.	Pass
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 7 degrees and 5 degrees, respectively.	Pass
H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9.1 m/s (30 ft/s), or at least below the maximum allowable value of 12.2 m/s (40 ft/s).	Longitudinal occupant impact velocity was 17.4 ft/s, and lateral occupant impact velocity was 16.1 ft/s.	Pass
I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.	Longitudinal ridedown acceleration was 7.3 G, and lateral ridedown acceleration was 6.8 G.	Pass
<u>Vehicle Trajectory</u> *For redirective devices, the vehicle shall exit the barrier within the exit box (not less than 32.8 ft).*	The 1100C vehicle crossed the exit box at the end of the guardrail.	Pass

REFERENCES

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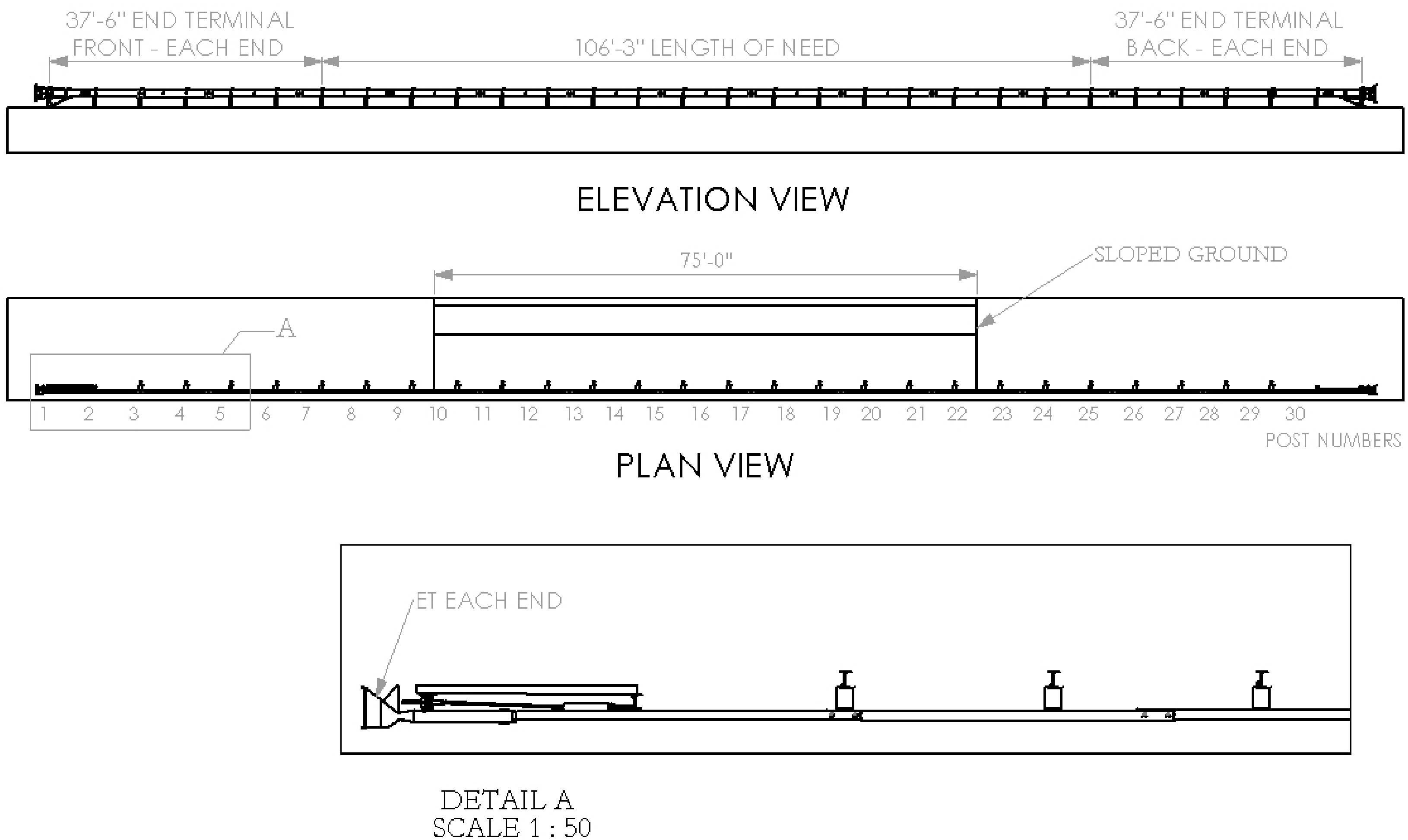
7. AASHTO, *Manual for Assessing Safety Hardware*, American Association of State Highways and Transportation Officials, Washington, D.C., 2009.

8. A. Y. Abu-Odeh, R. P. Bligh, D. L. Bullard, Jr., and W. L. Menges. *Crash Testing and Evaluation of the Modified G4(1S) W-Beam Guardrail on 2:1 Slope*, Test Report No. 405160-4-1Texas Transportation Institute, November 2008.

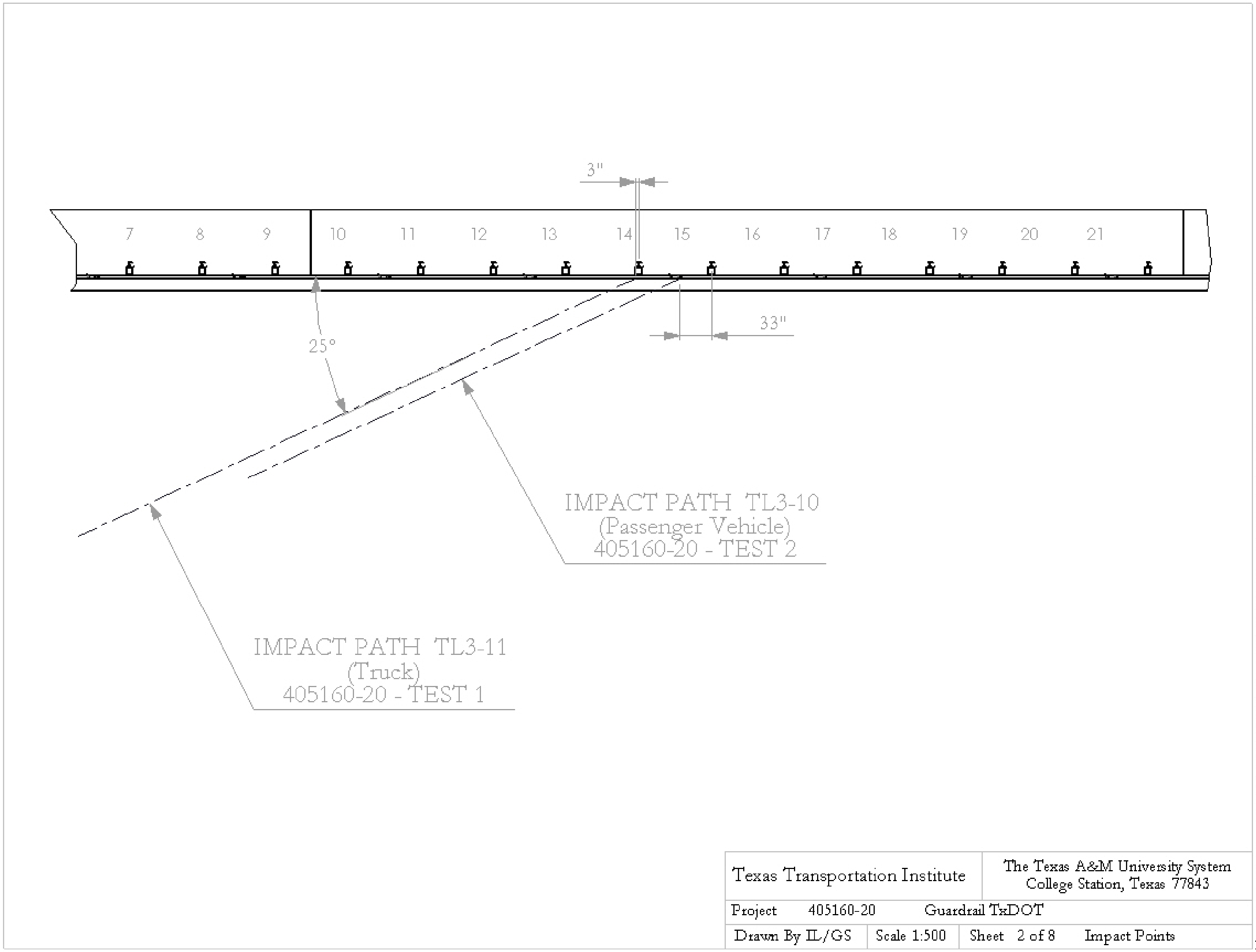
APPENDIX A. DETAILS OF TEST ARTICLE



*ALL POST SPACES - 75"
POSTS 1 AND 30 ARE CRP POSTS. POSTS 2 - 6 AND 25 - 29 ARE SYTP's, 7-9 AND 22 - 24 ARE 72" W6x8.5, AND POSTS 10 - 21 ARE 96" W6x8.5.

Texas Transportation Institute	The Texas A&M University System College Station, Texas 77843	
Project 405160-20	Guardrail TxDOT	
Drawn By IL/GS	Scale 1:500	Sheet 1 of 8 Full Rail
Approved: Akram Abu-Odeh:	Signature:	Date: 2011-10-18

T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing



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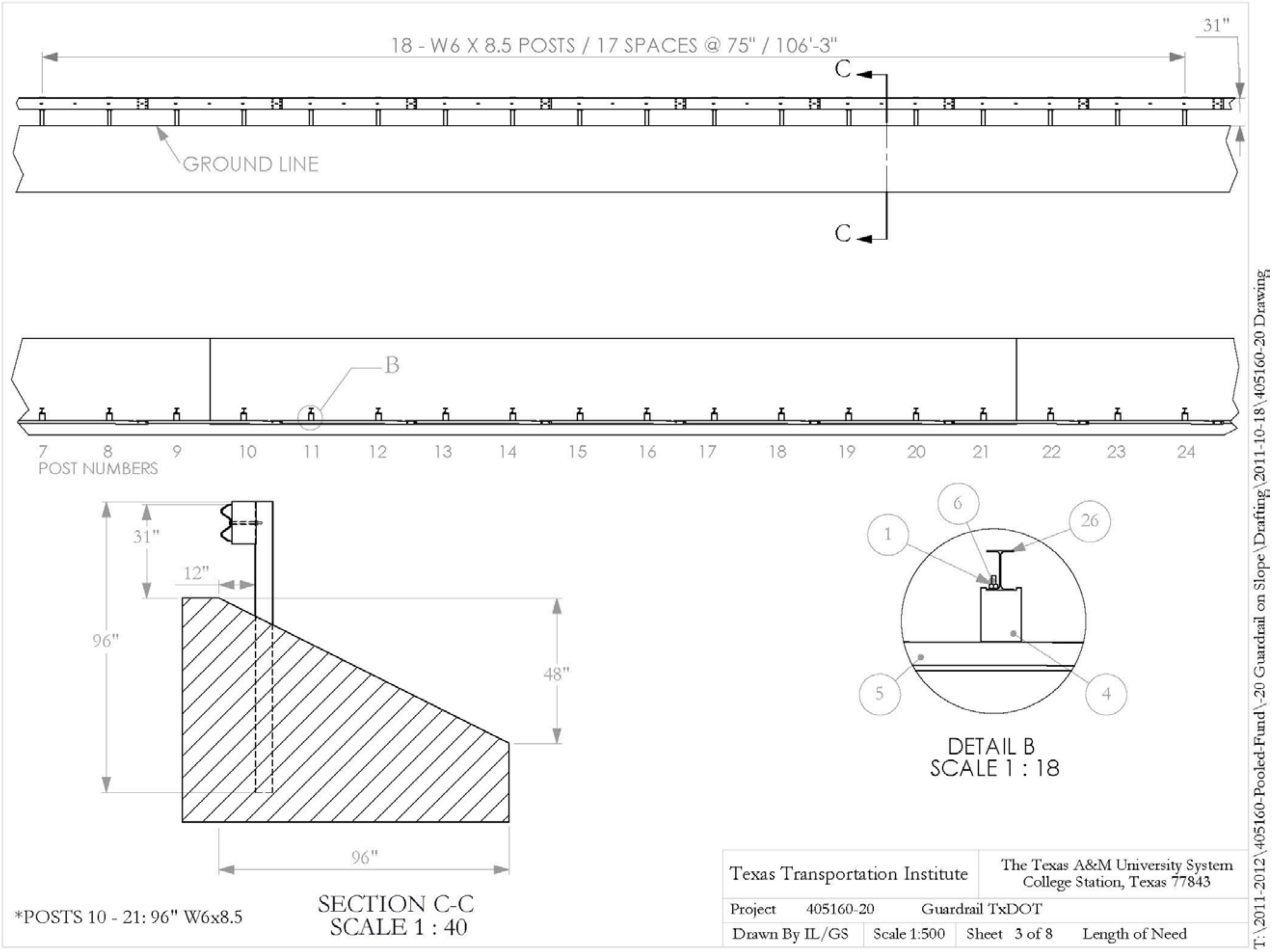
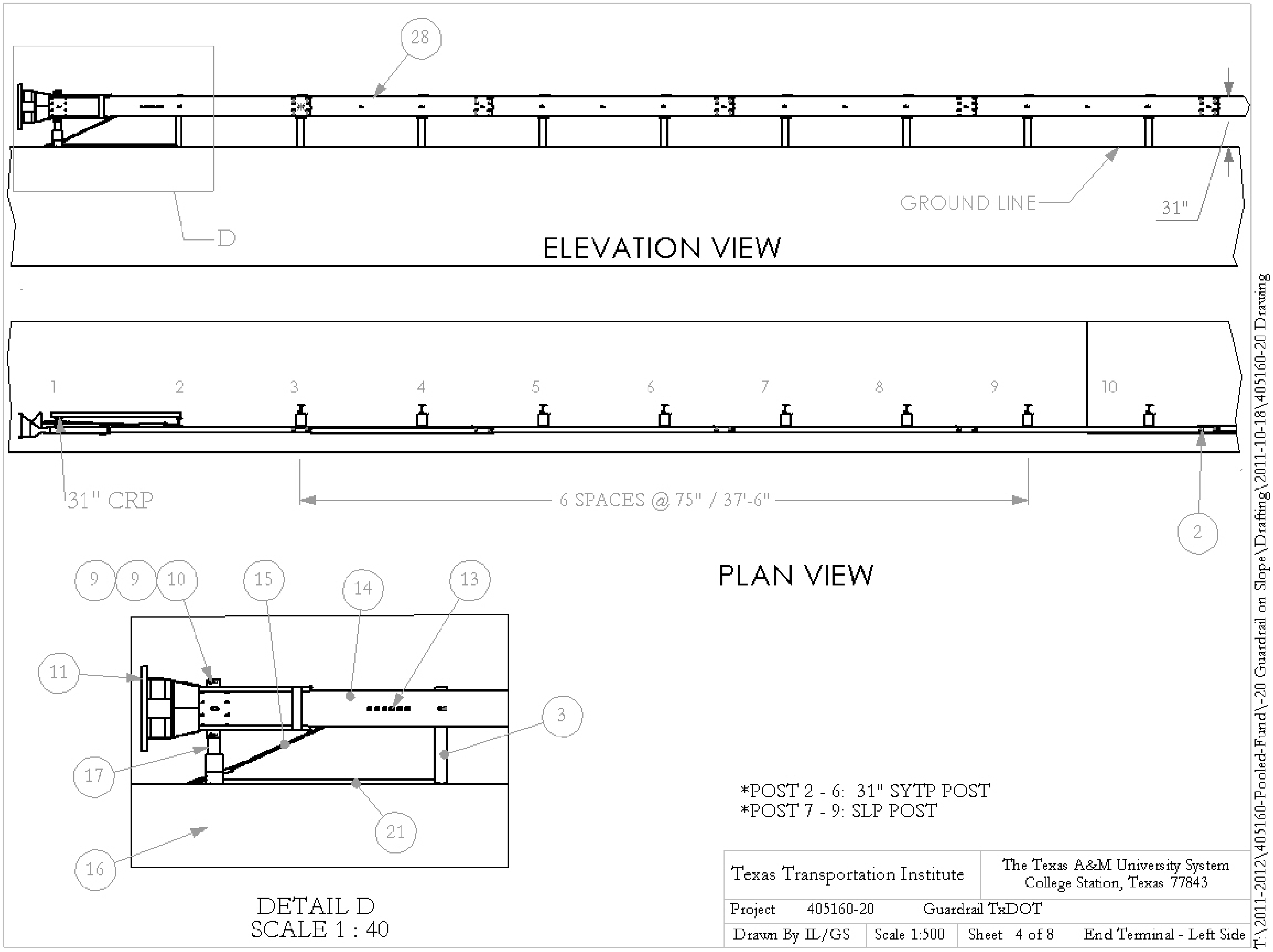
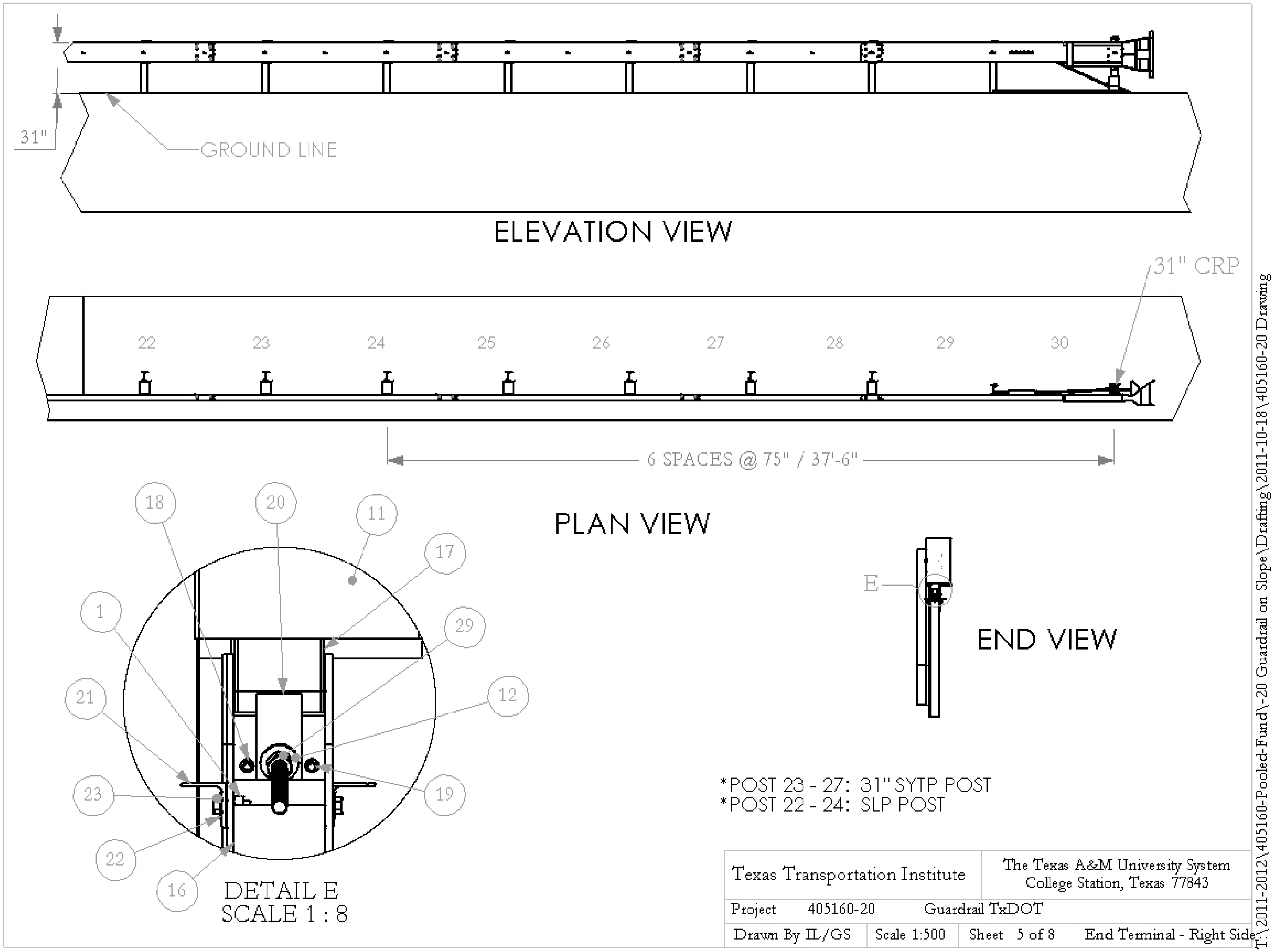


18 - W6 X 8.5 POSTS / 17 SPACES @ 75" / 106'-3"
31"
C
C
GROUND LINE
B
7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
POST NUMBERS
31"
12"
96"
48"
96"
SECTION C-C
SCALE 1 : 40
*POSTS 10 - 21: 96" W6x8.5
1
6
26
5
4
DETAIL B
SCALE 1 : 18
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843
Project 405160-20 Guardrail TxDOT
Drawn By IL/GS Scale 1:500 Sheet 3 of 8 Length of Need
T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing


28
D
GROUND LINE
31"
ELEVATION VIEW
1
2
3
4
5
6
7
8
9
10
31" CRP
6 SPACES @ 75" / 37'-6"
2
PLAN VIEW
9
9
10
15
14
13
11
3
17
21
16
DETAIL D
SCALE 1 : 40
*POST 2 - 6: 31" SYTP POST
*POST 7 - 9: SLP POST
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843
Project 405160-20
Guardrail TxDOT
Drawn By IL/GS
Scale 1:500
Sheet 4 of 8
End Terminal - Left Side
T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing


31"
GROUND LINE
ELEVATION VIEW
31" CRP
22
23
24
25
26
27
28
29
30
6 SPACES @ 75" / 37'-6"
PLAN VIEW
18
20
11
17
1
29
21
12
23
19
22
16
DETAIL E
SCALE 1 : 8
E
END VIEW
*POST 23 - 27: 31" SYTP POST
*POST 22 - 24: SLP POST
Texas Transportation Institute
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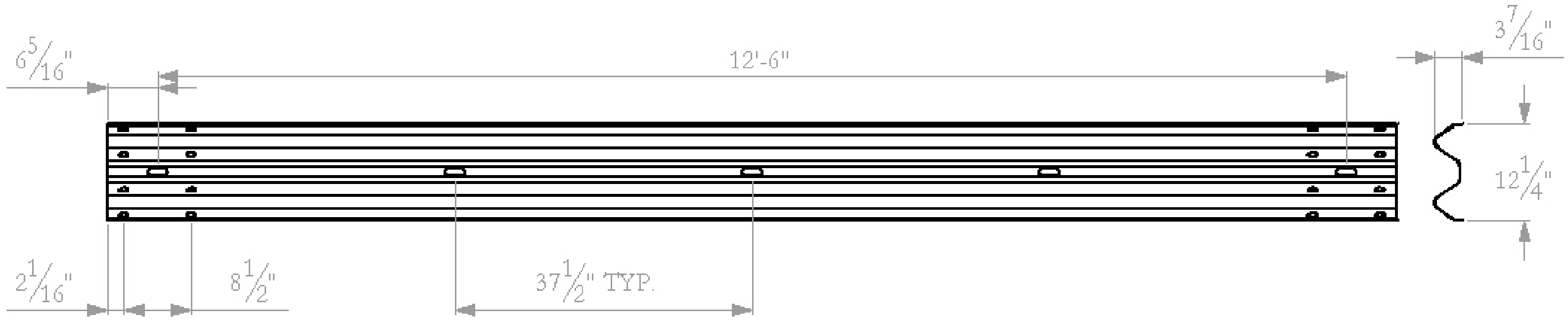
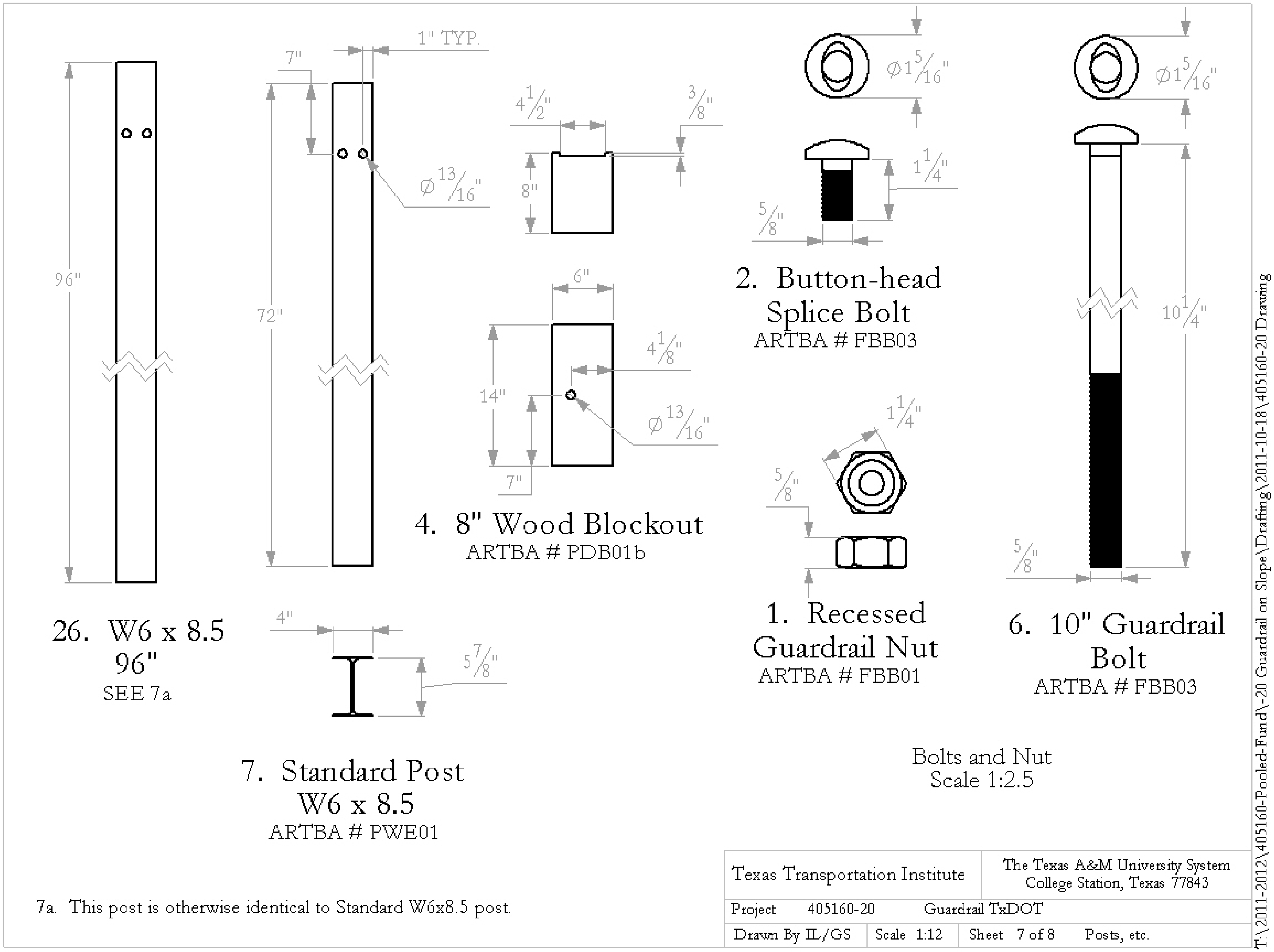
College Station, Texas 77843
Project 405160-20
Guardrail TxDOT
Drawn By IL/GS
Scale 1:500
Sheet 5 of 8
End Terminal - Right Side
T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing



5. 4 Space 12-ga. W-beam
RWM02

Texas Transportation Institute		The Texas A&M University System College Station, Texas 77843	
Project 405160-20	Guardrail TxDOT		
Drawn By IL/GS	Scale 1:20	Sheet 6 of 8	Guardrail

T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing


96"
26. W6 x 8.5
96"
SEE 7a
7"
1" TYP.
72"
Ø13/16"
4"
5 7/8"
7. Standard Post
W6 x 8.5
ARTBA # PWE01
4 1/2"
3/8"
8"
6"
4 1/8"
14"
7"
Ø13/16"
4. 8" Wood Blockout
ARTBA # PDB01b
Ø1 5/16"
1 1/4"
5/8"
2. Button-head
Splice Bolt
ARTBA # FBB03
1 1/4"
5/8"
1. Recessed
Guardrail Nut
ARTBA # FBB01
Ø1 5/16"
10 1/4"
5/8"
6. 10" Guardrail
Bolt
ARTBA # FBB03
Bolts and Nut
Scale 1:2.5
7a. This post is otherwise identical to Standard W6x8.5 post.
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843
Project 405160-20 Guardrail TxDOT
Drawn By IL/GS Scale 1:12 Sheet 7 of 8 Posts, etc.
T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing

#	PART NAME	QTY.
1	Nut, 5/8 Guardrail	134
2	Bolt, Button-head 1 1/4"	114
3	Post, W6x8.5 SYTP for 31" Rail	10
4	Blockout, Wood W-beam Routered ARTBA #PDB01b	26
5	W-Beam, 4- space 12 gauge RWM02	11
6	Bolt, Button-head 10 inch ARTBA #FBB03	26
7	Post, 72" W6 x 8.5 SLP	6
8	5/16" nut	4
9	5/16" flat washer	8
10	Bolt, 5/16" -18 x 1-1/2" hex	4
11	ET plus head	2
12	Washer, 1" flat	4
13	Anchor Bracket, ET Cable	2
14	W-beam, ET	2
15	3/4" Anchor Cable	2
16	Post, CRP Bottom	2
17	CRP top, 31"	2

#	PART NAME	QTY.
18	5/16" flat washer	8
19	Bolt, 5/16"-18x2 Hex	4
20	CRP bent plate washer	2
21	Strut, CRP	2
22	Washer, 5/8 flat	6
23	Bolt, 5/8"-11x2" Hex	6
26	Post, 96" W6 x 8.5 SLP	12
28	W-Beam, 9'-4.5" long	2
29	Nut, 1.0 -8 hex	4

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Project 405160-20 Guardrail TxDOT

Drawn By IL/GS | Scale 1:500 | Sheet 8 of 8 | Parts List

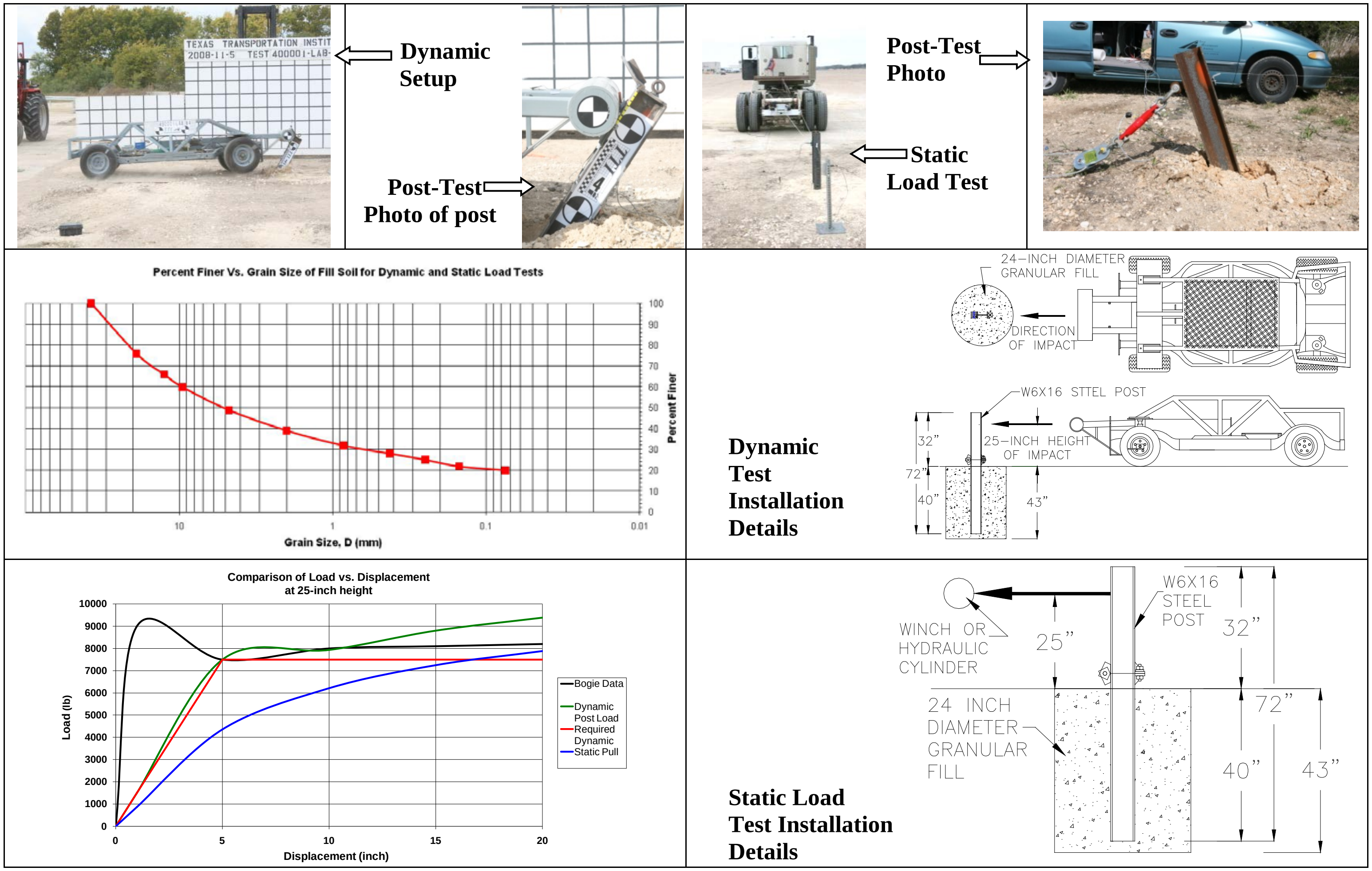
T:\2011-2012\405160-Pooled-Fund\-20 Guardrail on Slope\Drafting\2011-10-18\405160-20 Drawing

APPENDIX B. SUPPORTING CERTIFICATION DOCMENTS

MATERIAL USED

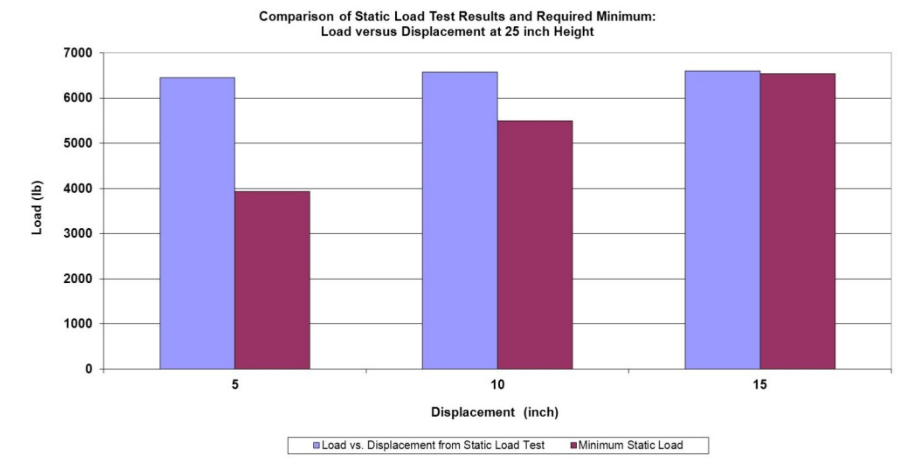
TEST NUMBER	405160-20-1
TEST NAME	Guardrail on Slope
DATE	2012-01-18

DATE RECEIVED	ITEM NUMBER	DESCRIPTION	SUPPLIER	HEAT #
2011-11-18	Parts-14	Guardrail Parts	Trinity	none

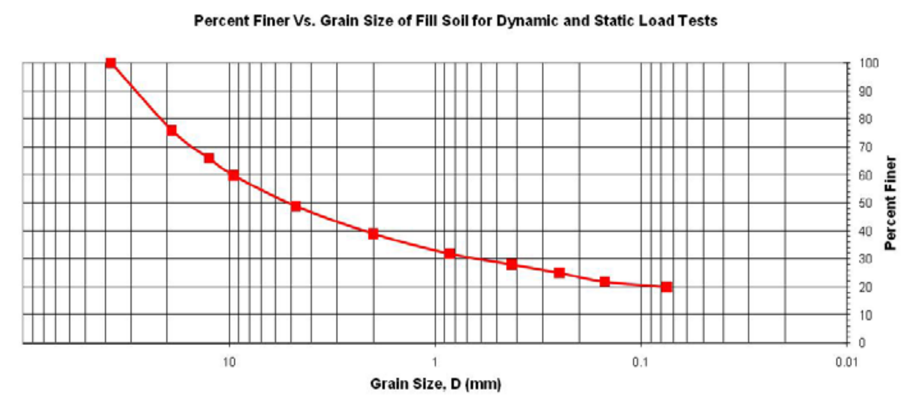


Date	2008-11-05
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX 77807
In Situ Soil Description (ASTM D2487	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis above)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor
Bogie Weight	5009 lb
Impact Velocity	20.5 mph

Figure C1. Summary of strong soil test results for establishing installation procedure.



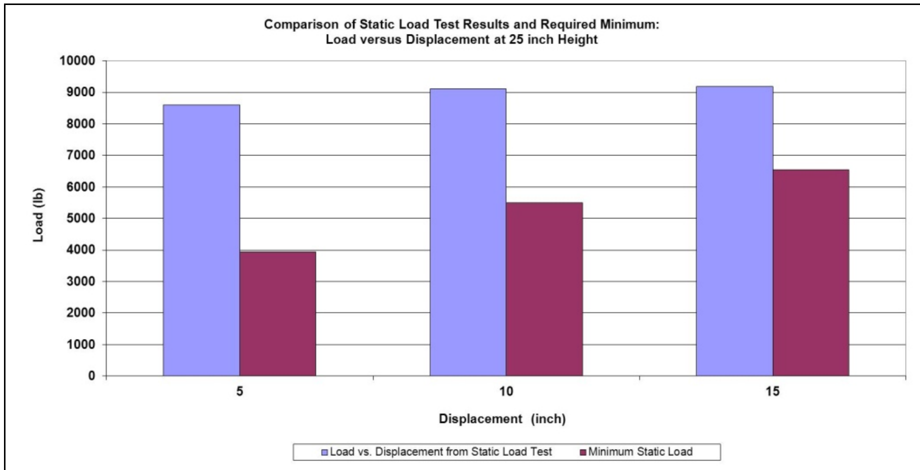
Static Load Setup



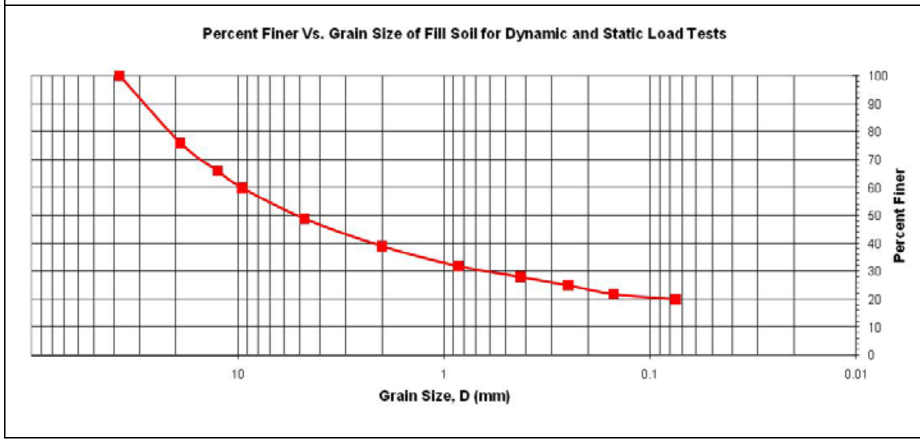
Post-Test Photo of Post

Date	2012-01-18
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Figure C2. Test day static soil strength documentation for test 405160-20-1.



Static Load Setup



Post-Test Photo of Post

Date	2012-04-25
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Figure C3. Test day static soil strength documentation for test 405160-20-2.

APPENDIX D. CRASH TEST NO. 405160-20-1

D1. VEHICLE PROPERTIES AND INFORMATION

Table D1. Vehicle properties for test 405160-20-1.

Date: 2012-01-18 Test No.: 405160-20-1 VIN No.: 1D7HA18N865659307

Year: 2006 Make: Dodge Model: Ram 1500

Tire Size: P265/70R17 Tire Inflation Pressure: 35 psi

Tread Type: Highway Odometer: 150328

Note any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

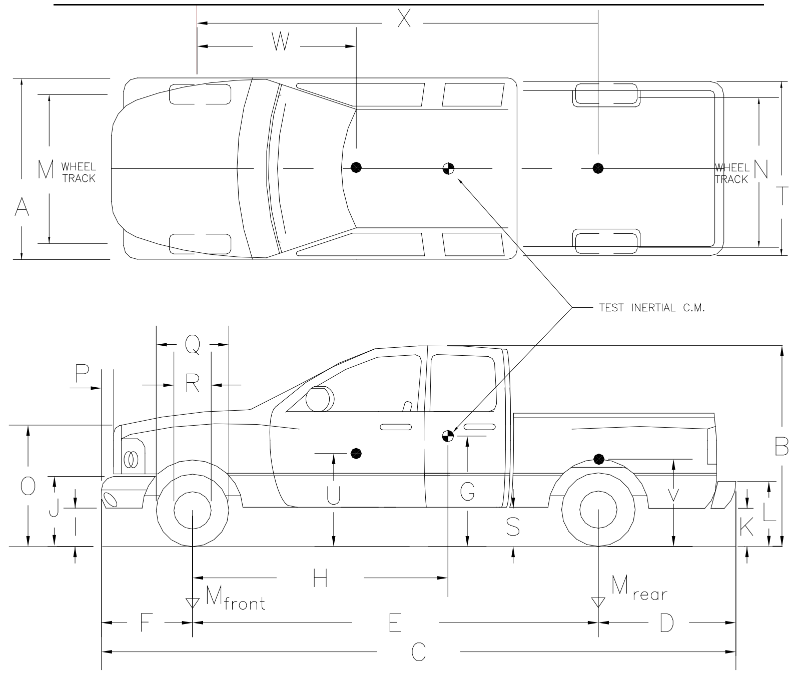
NOTES: ______

Engine Type: V-8
Engine CID: 4.7 liter

Transmission Type:
x Auto or ____ Manual
____ FWD ____ RWD ____ 4WD

Optional Equipment: ______

Dummy Data:
Type: No dummy
Mass: ______
Seat Position: ______



Geometry: inches

A	78.25	F	36.00	K	20.50	P	2.88	U	30.00
B	75.00	G	28.62	L	29.12	Q	31.25	V	31.50
C	223.75	H	63.12	M	68.50	R	18.38	W	63.00
D	47.25	I	13.75	N	68.00	S	12.00	X	98.00
E	140.5	J	25.38	O	44.50	T	72.50		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	5.00	Bottom Frame Height - Front	17.125
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	10.25	Bottom Frame Height - Rear	24.75

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}	2868	2778	
Back	3900	M_{rear}	2109	2266	
Total	6700	M_{Total}	4977	5044	

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

Mass Distribution:
lb LF: 1408 RF: 1370 LR: 1103 RR: 1163

Table D2. Measurements of vehicle vertical CG for test 405160-20-1.

Date: 2012-01-18 Test No.: 405160-20-1 VIN: 1D7HA18N865659307

Year: 2006 Make: Dodge Model: Ram 1500

Body Style: Quad Cab Mileage: 150328

Engine: 4.7 liter V-8 Transmission: Automatic

Fuel Level: Empty Ballast: 247 lb in front of bed (440 lb max)

Tire Pressure: Front: 35 psi Rear: 35 psi Size: 265/70R17

Measured Vehicle Weights: (lb)								
LF:	1380		RF:	1405		Front Axle:	2785	
LR:	1135		RR:	1122		Rear Axle:	2257	
Left:	2515		Right:	2527		Total:	5042	
						5000 ±110 lb allowed		
Wheel Base:	140.5	inches	Track: F:	38.5	inches	R:	68	inches
	148 ±12 inches allowed			Track = (F+R)/2 = 67 ±1.5 inches allowed				
Center of Gravity, SAE J874 Suspension Method								
X:	62.89	in	Rear of Front Axle	(63 ±4 inches allowed)				
Y:	0.05	in	Left -	Right +	of Vehicle Centerline			
Z:	28.625	in	Above Ground	(minumum 28.0 inches allowed)				

Hood Height: 44.50 inches (43 ±4 inches allowed) — Front Bumper Height: 28.375 inches

Front Overhang: 36.00 inches (39 ±3 inches allowed) — Rear Bumper Height: 29.125 inches

Overall Length: 223.75 inches (237 ±13 inches allowed)

Table D3. Exterior crush measurements for test 405160-20-1.

Date: 2012-01-18 Test No.: 405160-20-1 VIN No.: 1D7HA18N865659307

Year: 2006 Make: Dodge Model: Ram 1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front plane at bumper ht	15.0	11.0	51	11	9.5	8.5	6	4	1.5	-8
2	Side plane at bumper ht	15.0	8.0	55	0	0.75	---	---	4.5	8	+60
	Measurements recorded										
	in inches										

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

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

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

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

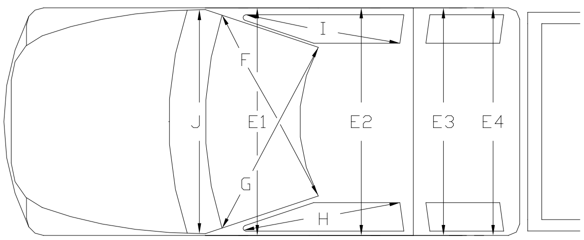
***Measure and document on the vehicle diagram the location of the maximum crush.

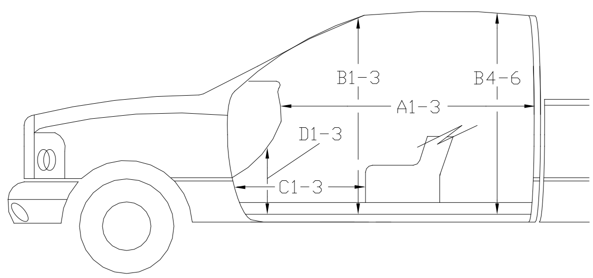
Note: Use as many lines/columns as necessary to describe each damage profile.

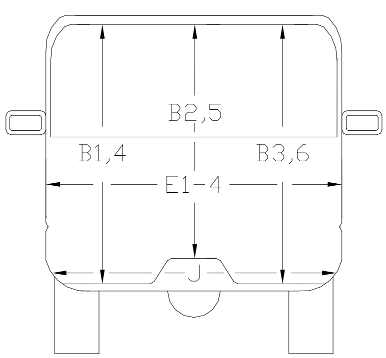
Table D4. Occupant compartment measurements for test 405160-20-1.

Date: 2012-01-18 Test No.: 405160-20-1 VIN No.: 1D7HA18N865659307

Year: 2006 Make: Dodge Model: Ram 1500







OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	**After** (inches)
A1	64.75	64.75
A2	64.50	64.50
A3	65.00	65.00
B1	45.25	45.25
B2	37.00	37.00
B3	45.25	45.25
B4	42.25	42.25
B5	42.75	42.75
B6	42.25	42.25
C1	29.00	29.00
C2	-----	-----
C3	27.00	27.00
D1	12.75	12.75
D2	2.00	2.00
D3	11.50	11.50
E1	62.75	62.75
E2	64.50	64.50
E3	64.00	64.00
E4	64.12	64.12
F	60.00	60.00
G	60.00	60.00
H	39.00	39.00
I	39.00	39.00
J*	62.00	62.00

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

D2. SEQUENTIAL PHOTOGRAPHS

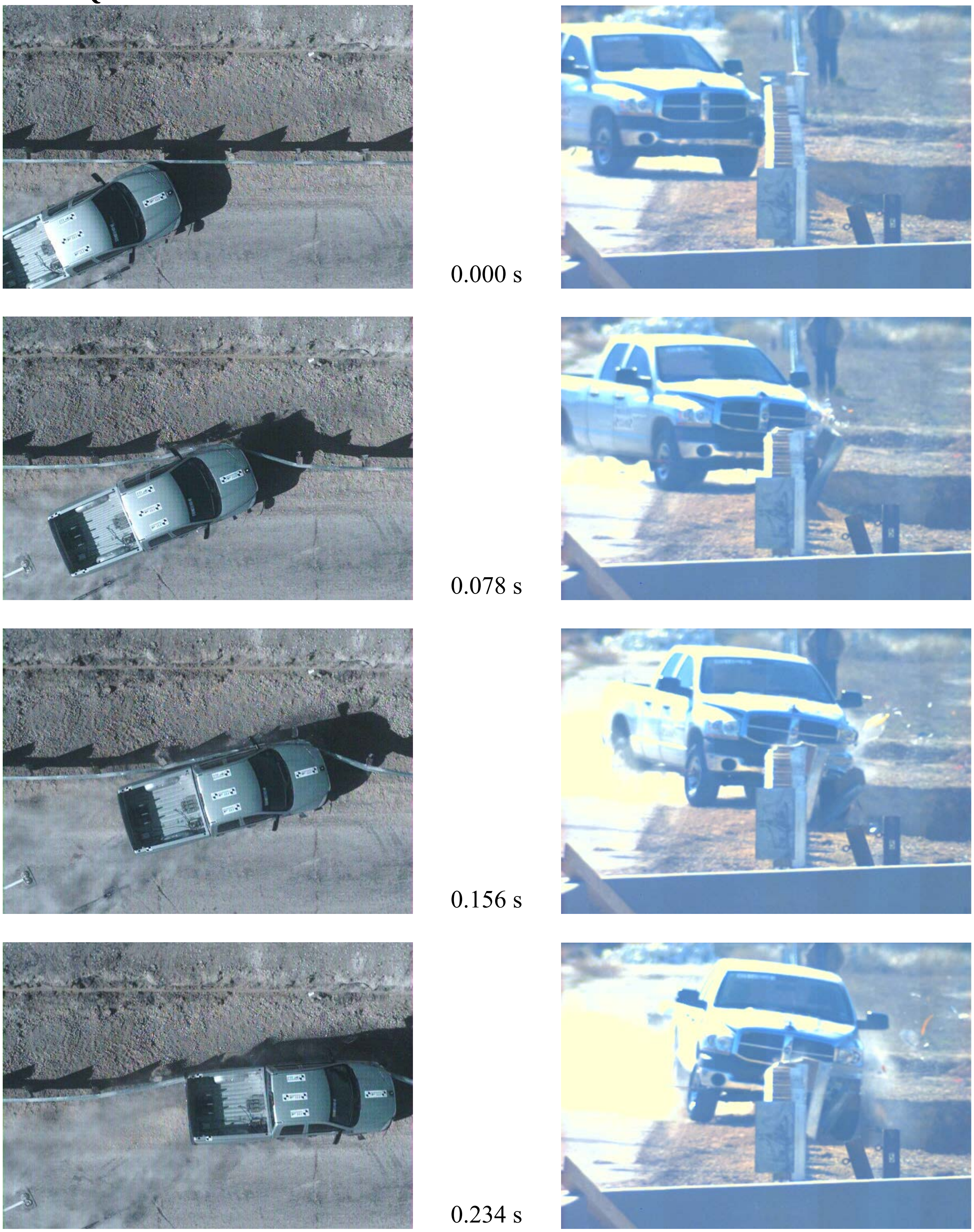


Figure D1. Sequential photographs for test 405160-20-1
(overhead and frontal views).

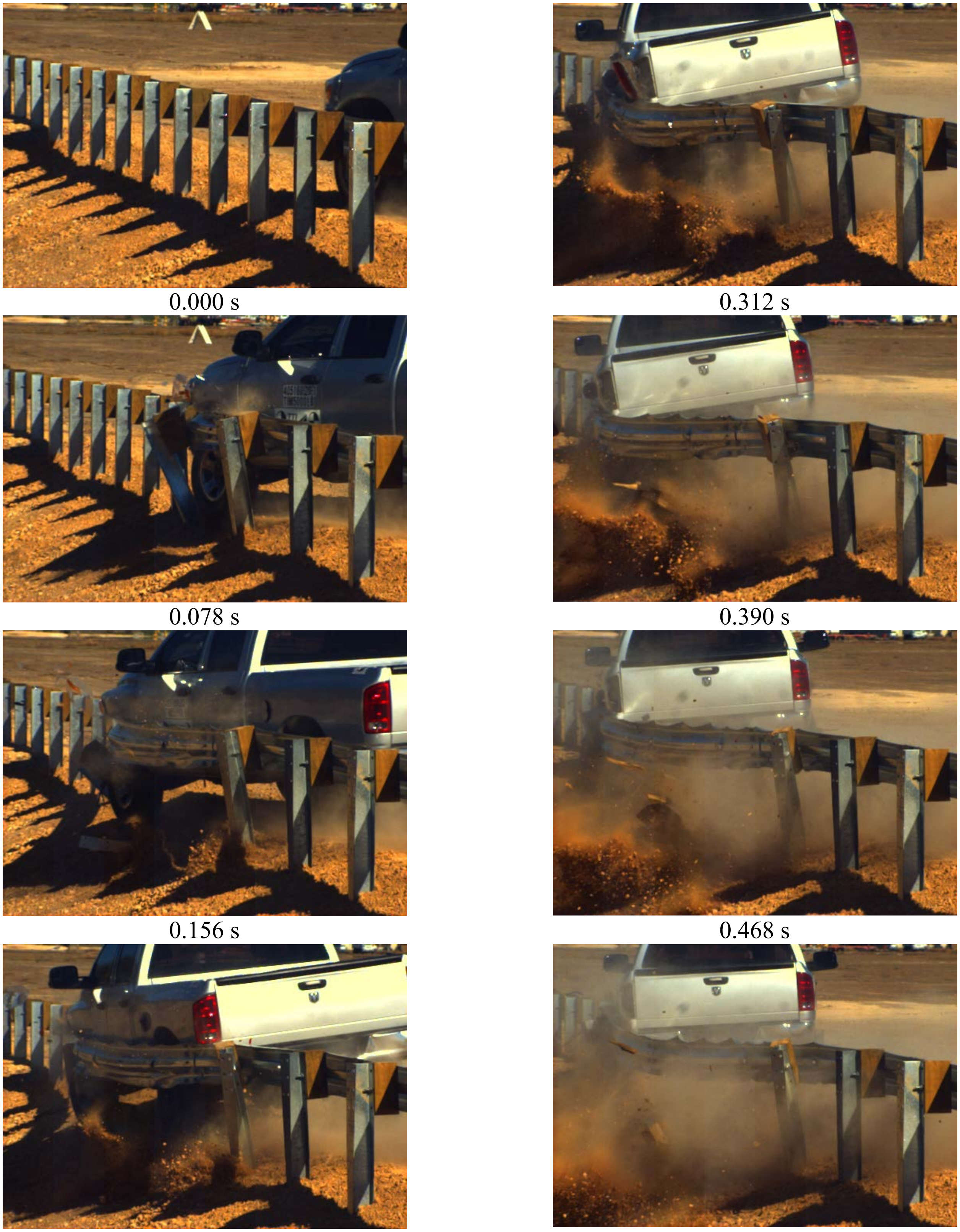
0.312 s

0.390 s

0.468 s

0.546 s

Figure D1. Sequential photographs for test 405160-20-1
(overhead and frontal views) (continued).



0.000 s 0.312 s

0.078 s 0.390 s

0.156 s 0.468 s

0.234 s 0.546 s

Figure D2. Sequential photographs for test 405160-20-1
(rear view).

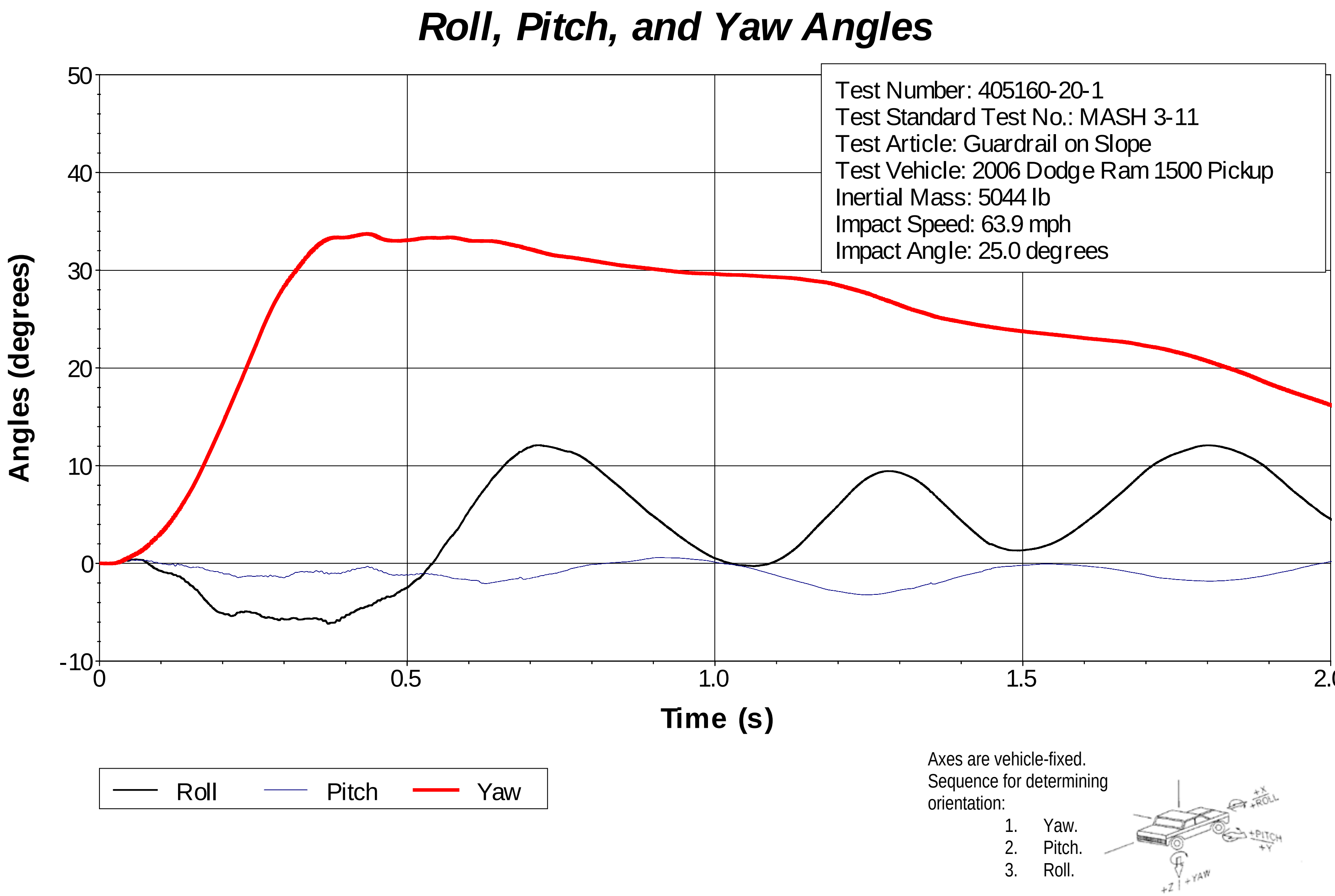


Figure D3. Vehicle angular displacements for test 405160-20-1.

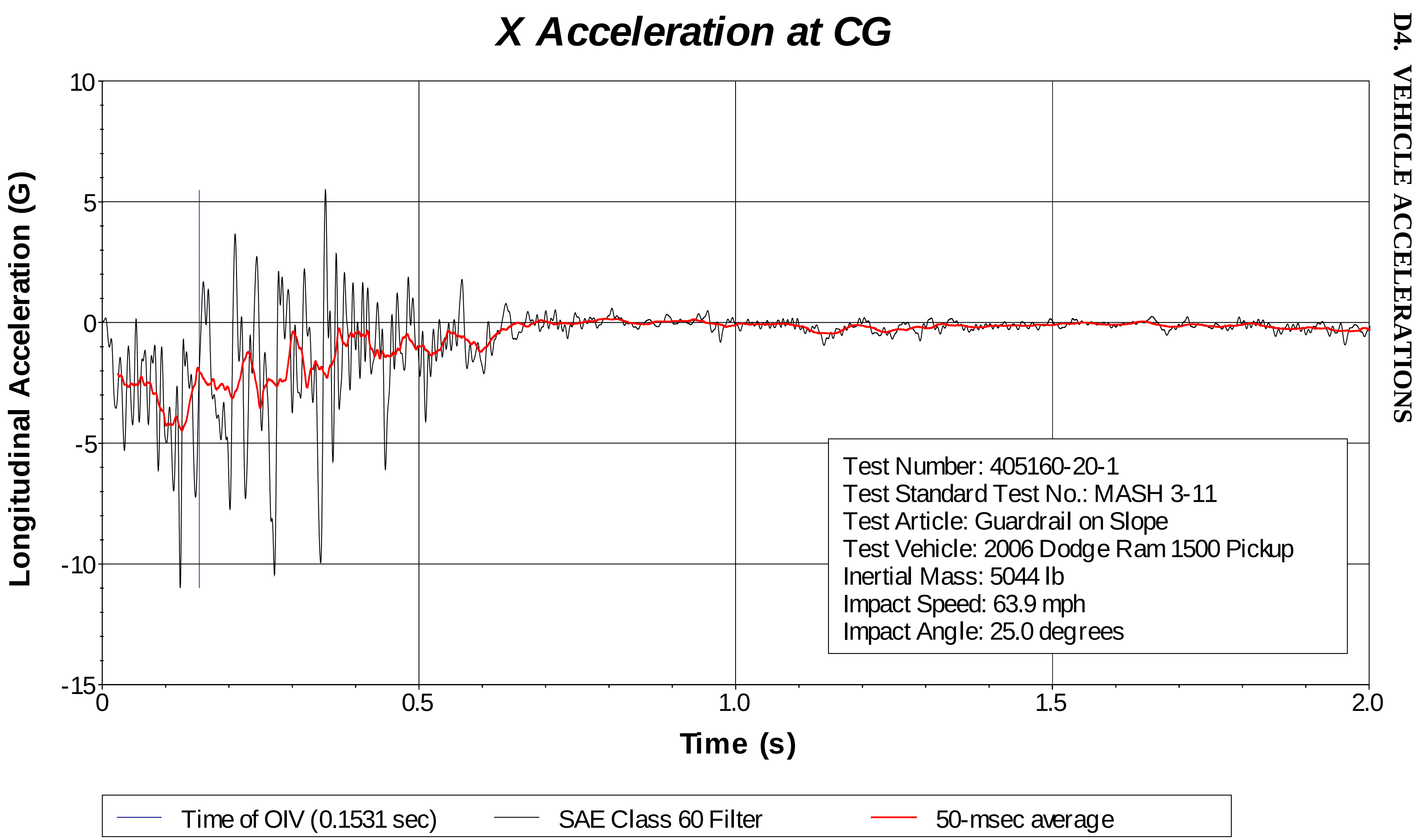


Figure D4. Vehicle longitudinal accelerometer trace for test 405160-20-1 (accelerometer located at center of gravity).

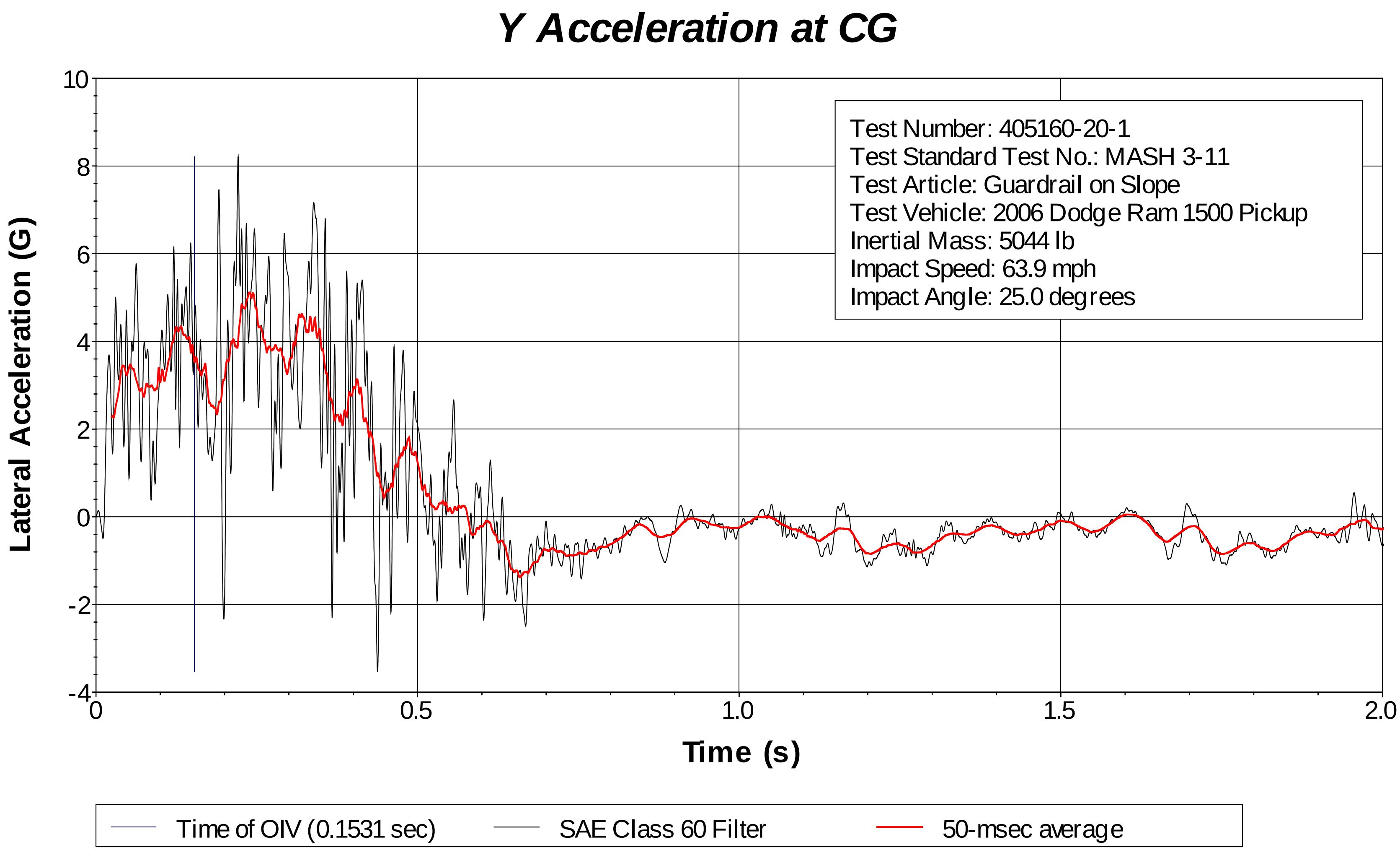


Figure D5. Vehicle lateral accelerometer trace for test 405160-20-1
(accelerometer located at center of gravity).

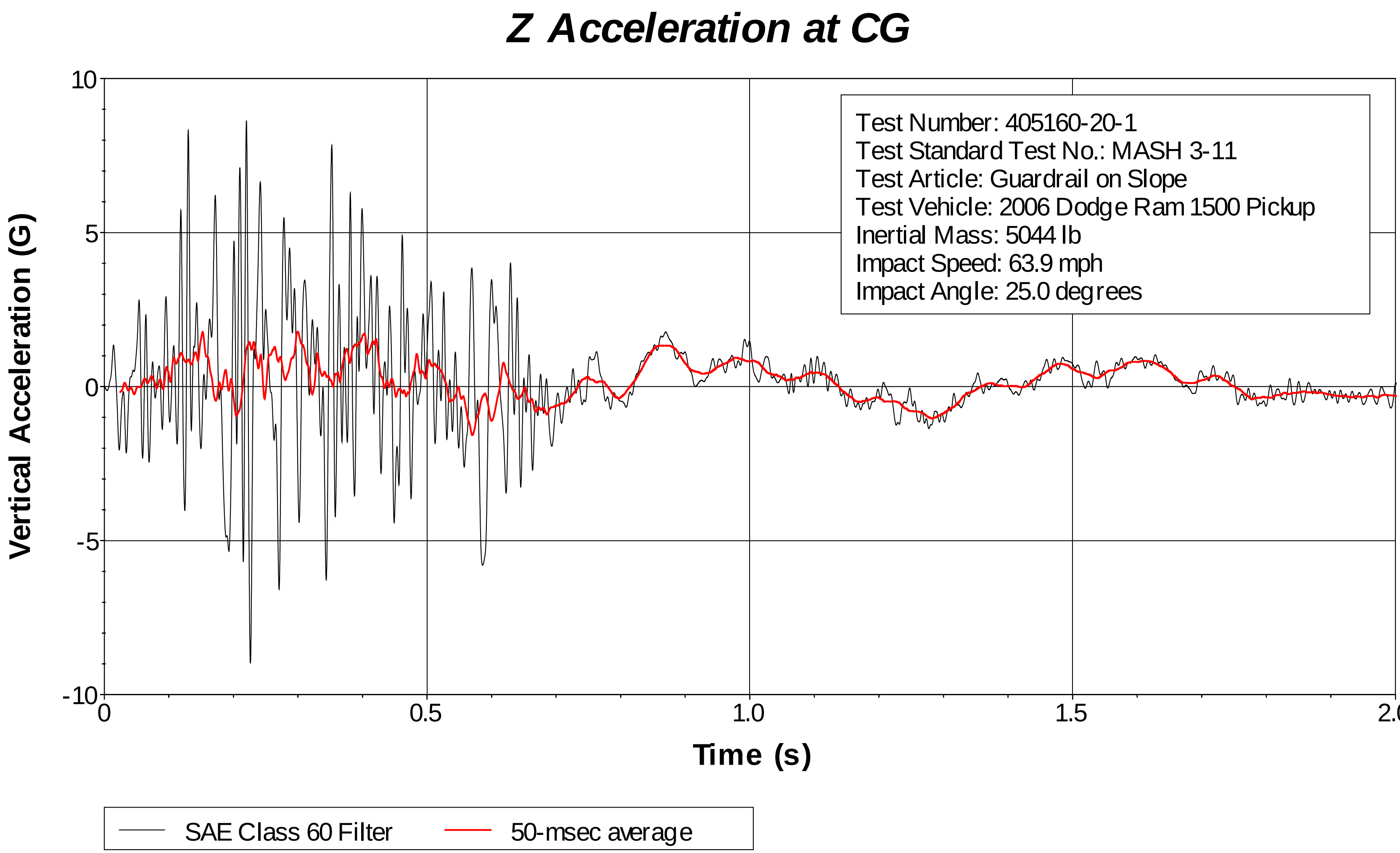


Figure D6. Vehicle vertical accelerometer trace for test 405160-20-1 (accelerometer located at center of gravity).

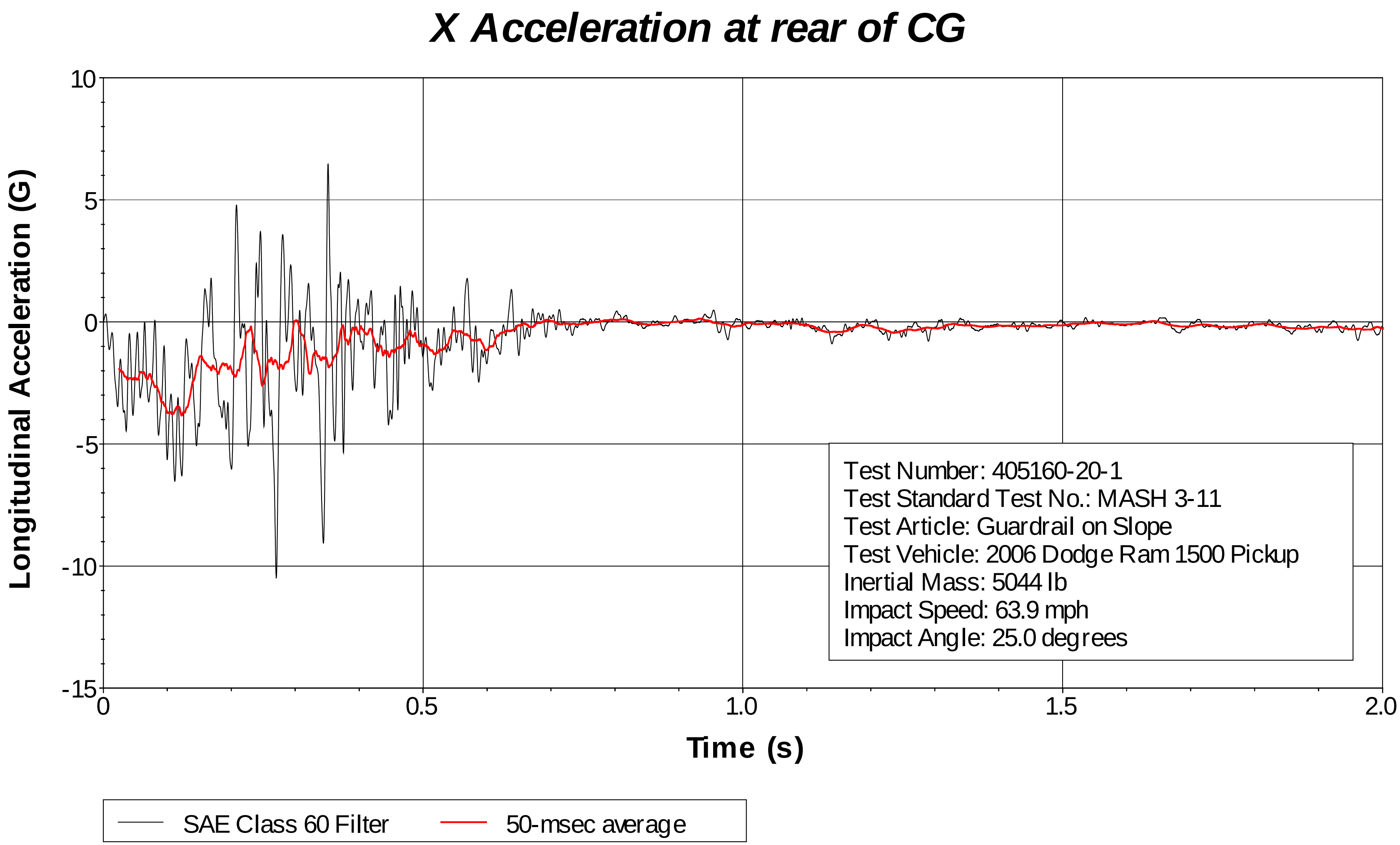


Figure D7. Vehicle longitudinal accelerometer trace for test 405160-20-1
(accelerometer located rear of center of gravity).

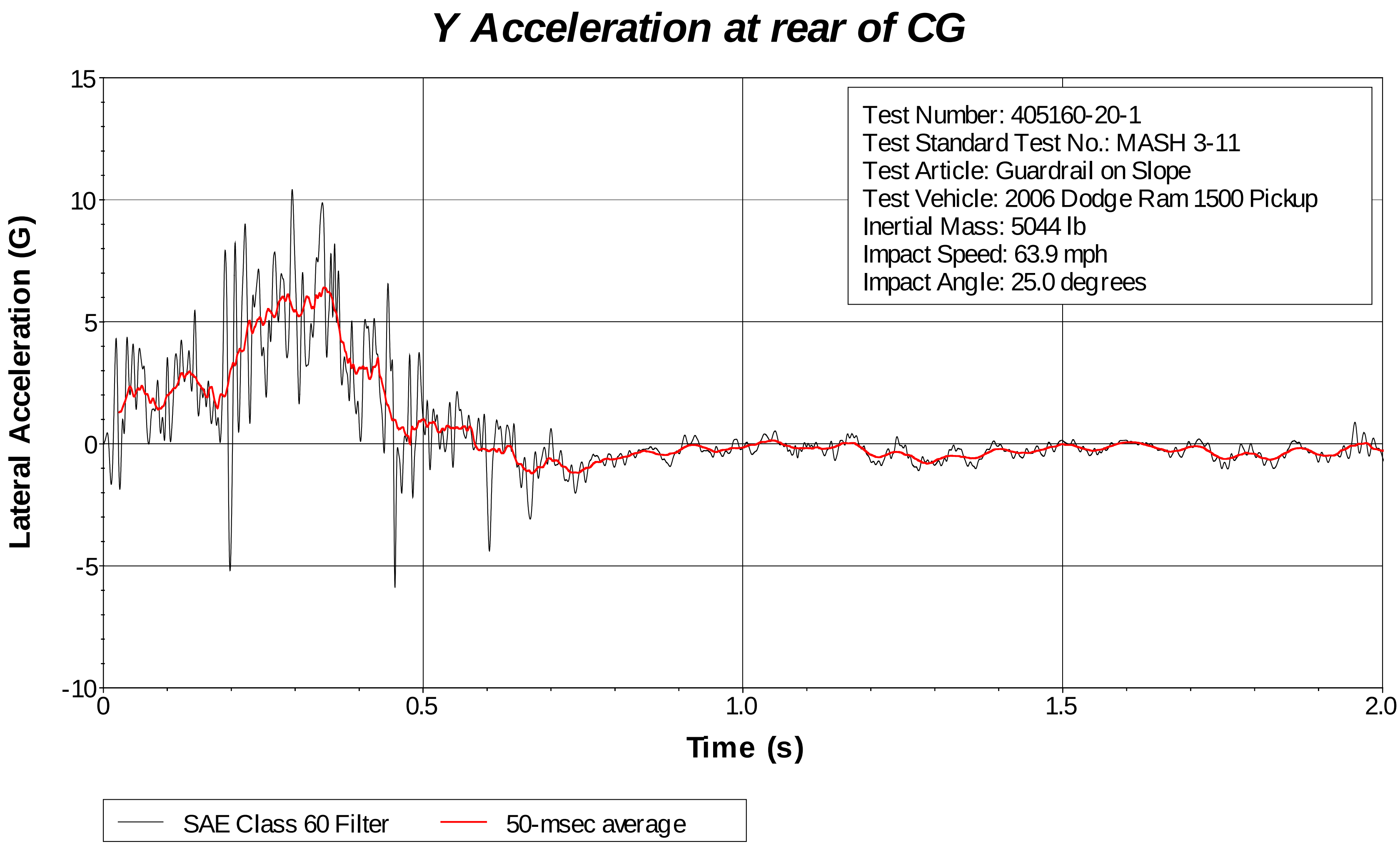


Figure D8. Vehicle lateral accelerometer trace for test 405160-20-1 (accelerometer located rear of center of gravity).

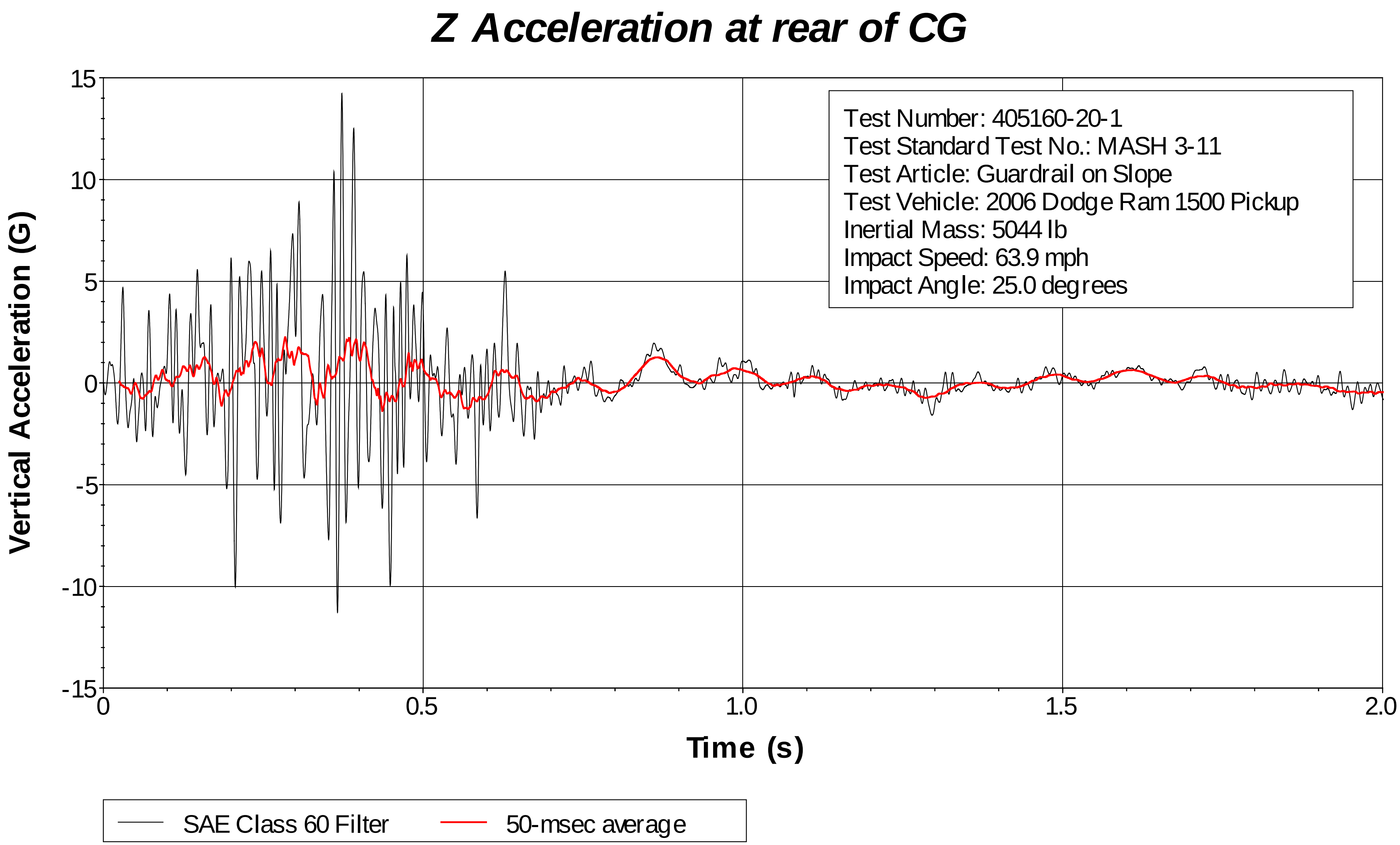


Figure D9. Vehicle vertical accelerometer trace for test 405160-20-1
(accelerometer located rear of center of gravity).

APPENDIX E. CRASH TEST NO. 405160-20-2

E1. VEHICLE PROPERTIES AND INFORMATION

Table E1. Vehicle properties for test 405160-20-2.

Date: 2012-04-20 Test No.: 405160-20-2 VIN No.: KNADE123566032879

Year: 2006 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 112442 Tire Size: P185/65R14

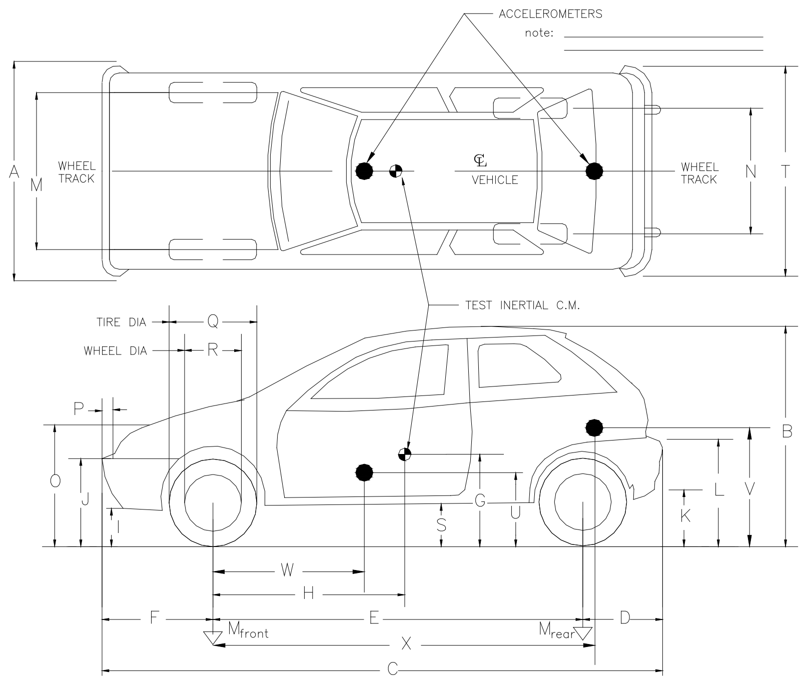
Describe any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

NOTES: ______

Engine Type: 4 cylinder
Engine CID: 1.6 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment: ______

Dummy Data:
Type: 50th percentile male
Mass: 164 lb
Seat Position: Driver



Geometry: inches

A	66.38	F	33.00	K	11.00	P	4.12	U	15.75
B	57.75	G		L	24.12	Q	22.18	V	21.50
C	165.75	H	34.27	M	57.75	R	15.38	W	39.50
D	34.00	I	7.12	N	57.12	S	7.62	X	108.50
E	98.75	J	21.00	O	30.62	T	66.12		

Wheel Center Ht Front 11.00 Wheel Center Ht Rear 11.00

RANGE LIMIT: A = 65 ±3 inches; C = 168 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; G = 39 ±4 inches; O = 24 ±4 inches; M+N/2 = 56 ±2 inches

GVWR Ratings:		Mass: lb	Curb	Test Inertial	Gross Static
Front	1918	M_{front}	1596	1586	1672
Back	1874	M_{rear}	861	843	921
Total	3638	M_{Total}	2457	2429	2593

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

Mass Distribution:
lb LF: 813 RF: 773 LR: 423 RR: 420

Table E2. Exterior crush measurements for test 405160-20-2.

Date: 2012-04-20 Test No.: 405160-20-2 VIN No.: KNADE123566032879

Year: 2006 Make: Kia Model: Rio

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	14.0	9.0	34.0	9.0	5.0	3.0	2.5	1.0	0	-12.0
2	Side plane above bumper	14.0	10.5	36.0	0	4.0	7.0	7.5	8.5	10.5	+44.0
	Measurements recorded										
	in inches										

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

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

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

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

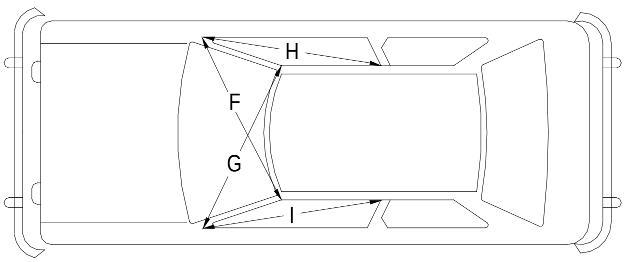
***Measure and document on the vehicle diagram the location of the maximum crush.

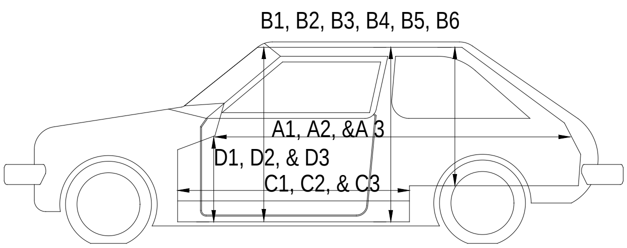
Note: Use as many lines/columns as necessary to describe each damage profile.

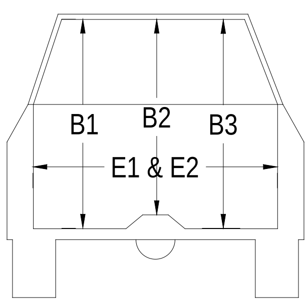
Table E3. Occupant compartment measurements for test 405160-20-2.

Date: 2012-04-20 Test No.: 405160-20-2 VIN No.: KNADE123566032879

Year: 2006 Make: Kia Model: Rio







OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	**After** (inches)
A1	67.50	67.50
A2	67.50	67.50
A3	67.50	67.50
B1	40.75	40.75
B2	36.75	36.75
B3	40.75	40.75
B4	36.25	36.25
B5	35.75	35.75
B6	36.25	36.25
C1	26.00	26.00
C2	----	----
C3	27.50	27.50
D1	9.75	9.75
D2	----	----
D3	9.50	9.50
E1	48.00	48.00
E2	51.00	51.00
F	51.00	51.00
G	51.00	51.00
H	37.00	37.00
I	37.00	37.00
J*	50.75	50.75

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

E2. SEQUENTIAL PHOTOGRAPHS

0.000 s

0.078 s

0.156 s

0.234 s

Figure E1. Sequential photographs for test 405160-20-2
(overhead and frontal views).

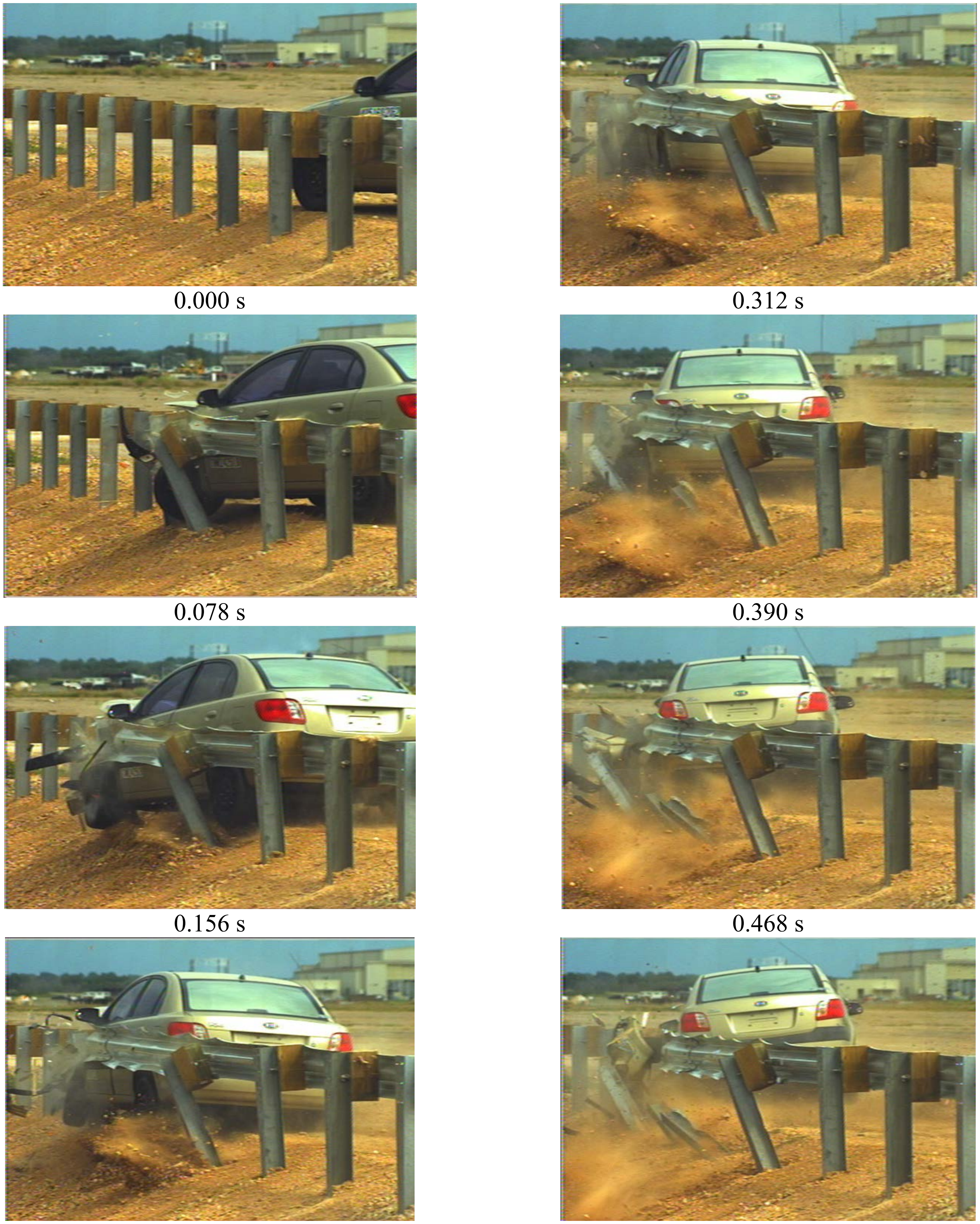
0.312 s

0.390 s

0.468 s

0.546 s

Figure E1. Sequential photographs for test 405160-20-2
(overhead and frontal views) (continued).



0.000 s

0.078 s

0.156 s

0.234 s

0.312 s

0.390 s

0.468 s

0.546 s

Figure E2. Sequential photographs for test 405160-20-2
(rear view).

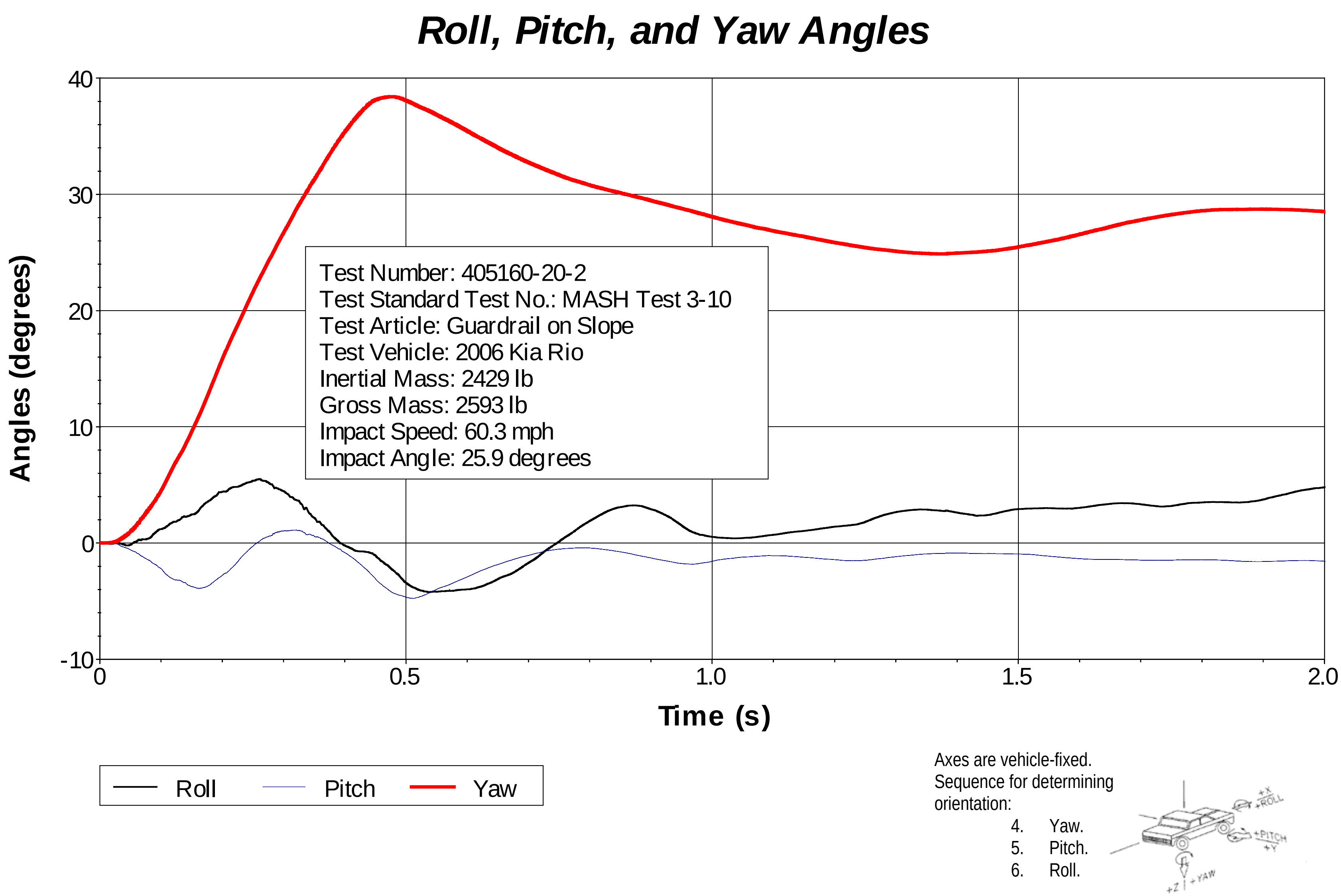


Figure E3. Vehicle angular displacements for test 405160-20-2.

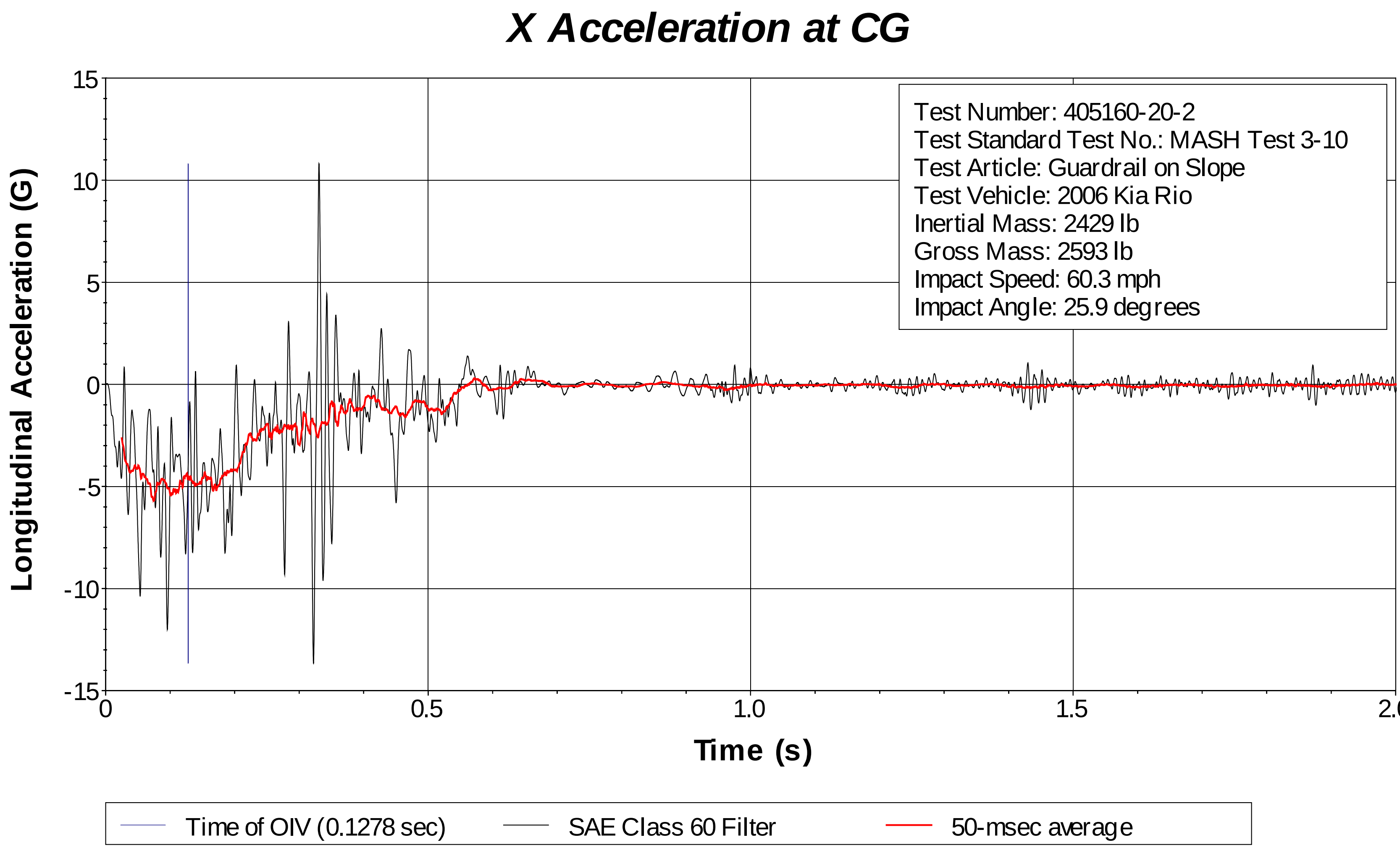


Figure E4. Vehicle longitudinal accelerometer trace for test 405160-20-2
(accelerometer located at center of gravity).

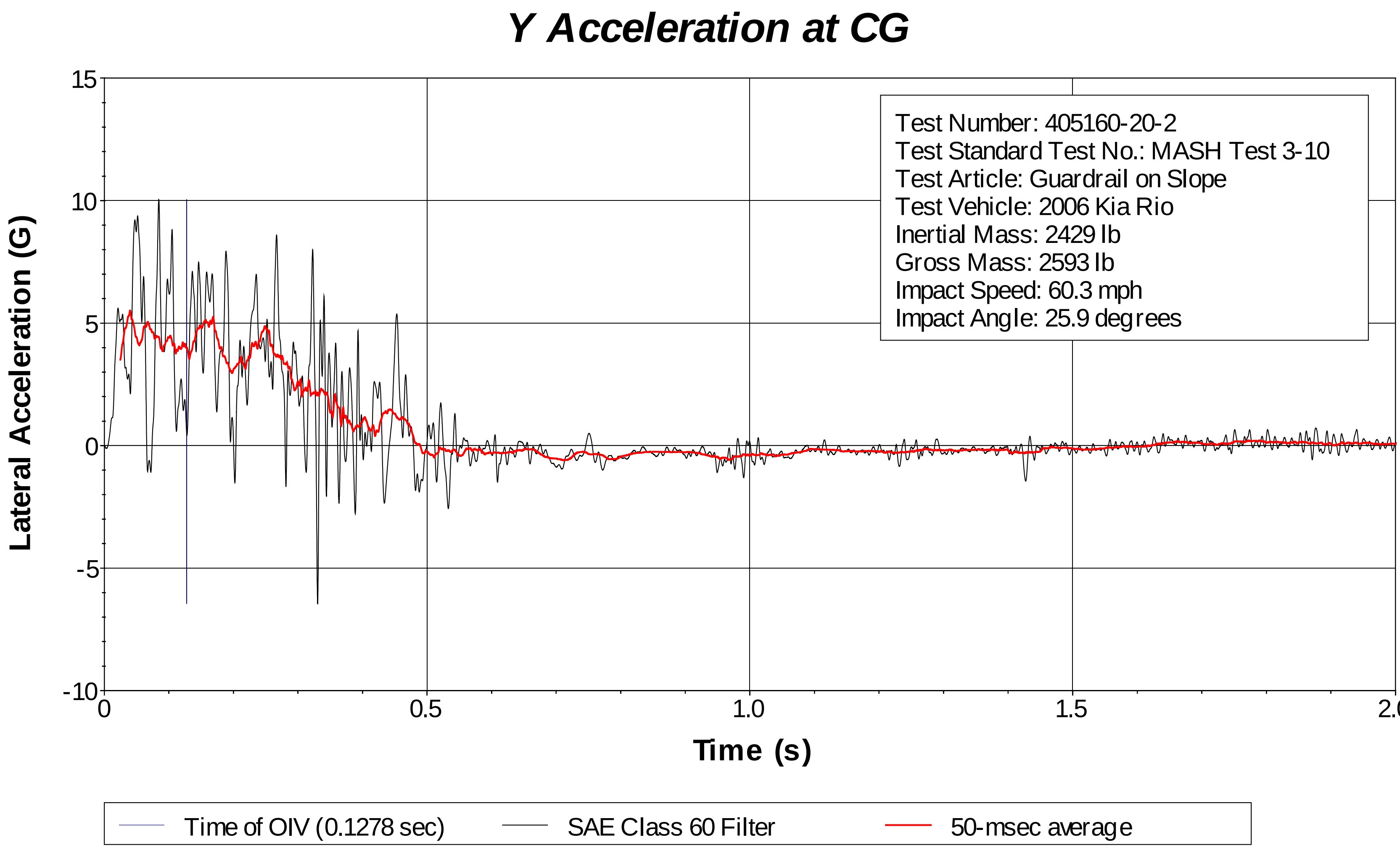


Figure E5. Vehicle lateral accelerometer trace for test 405160-20-2
(accelerometer located at center of gravity).

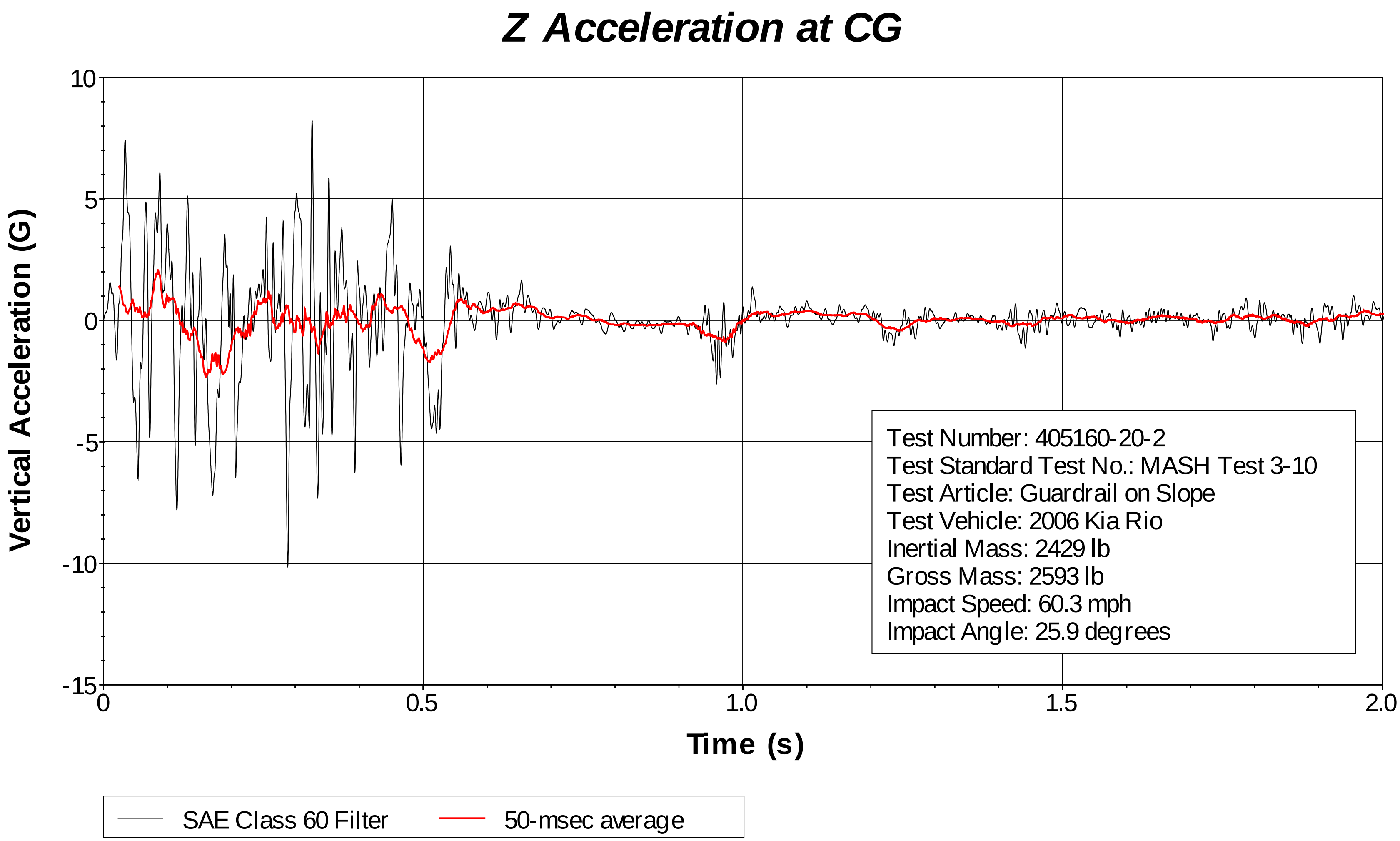


Figure E6. Vehicle vertical accelerometer trace for test 405160-20-2
(accelerometer located at center of gravity).

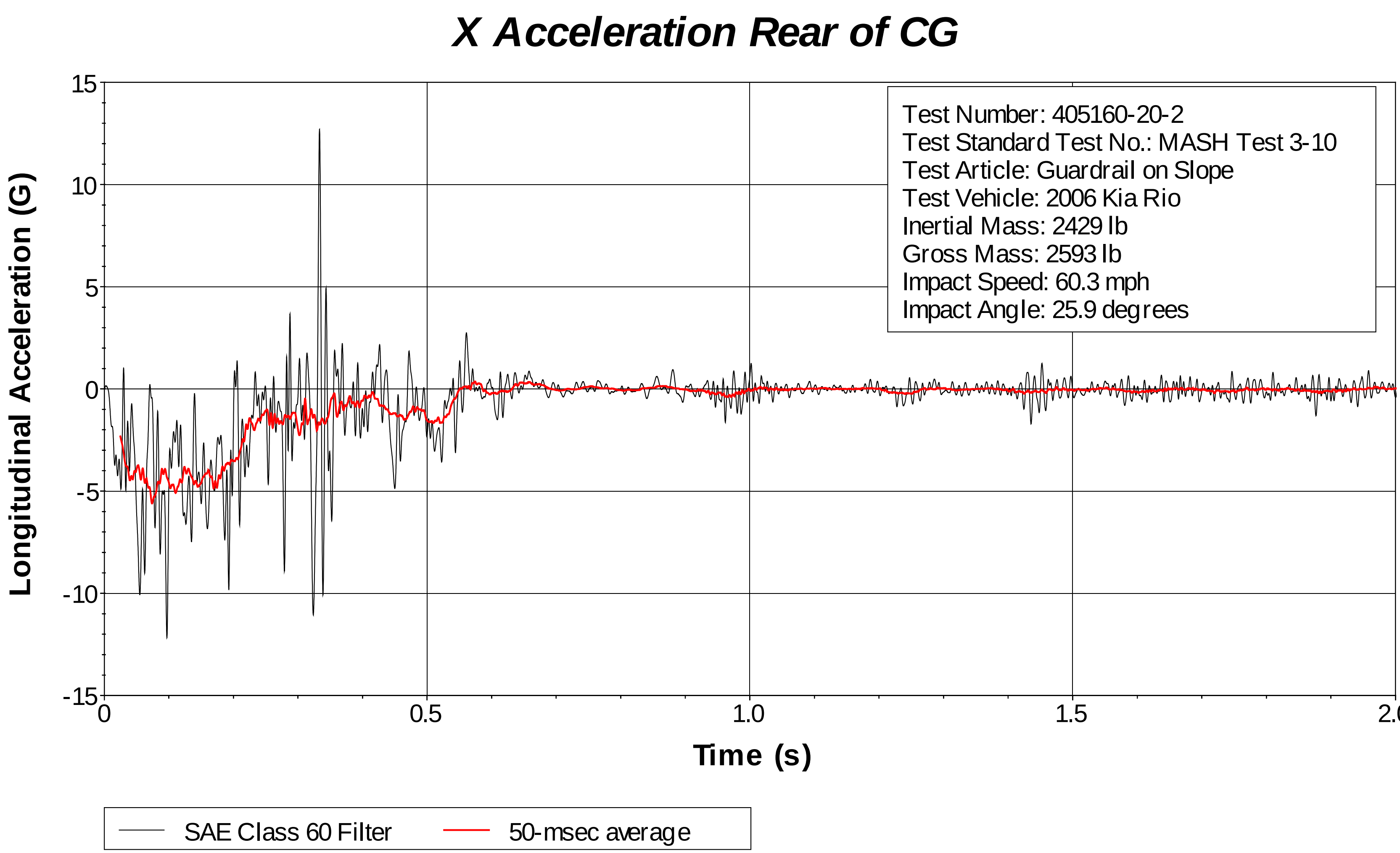


Figure E7. Vehicle longitudinal accelerometer trace for test 405160-20-2
(accelerometer located rear of center of gravity).

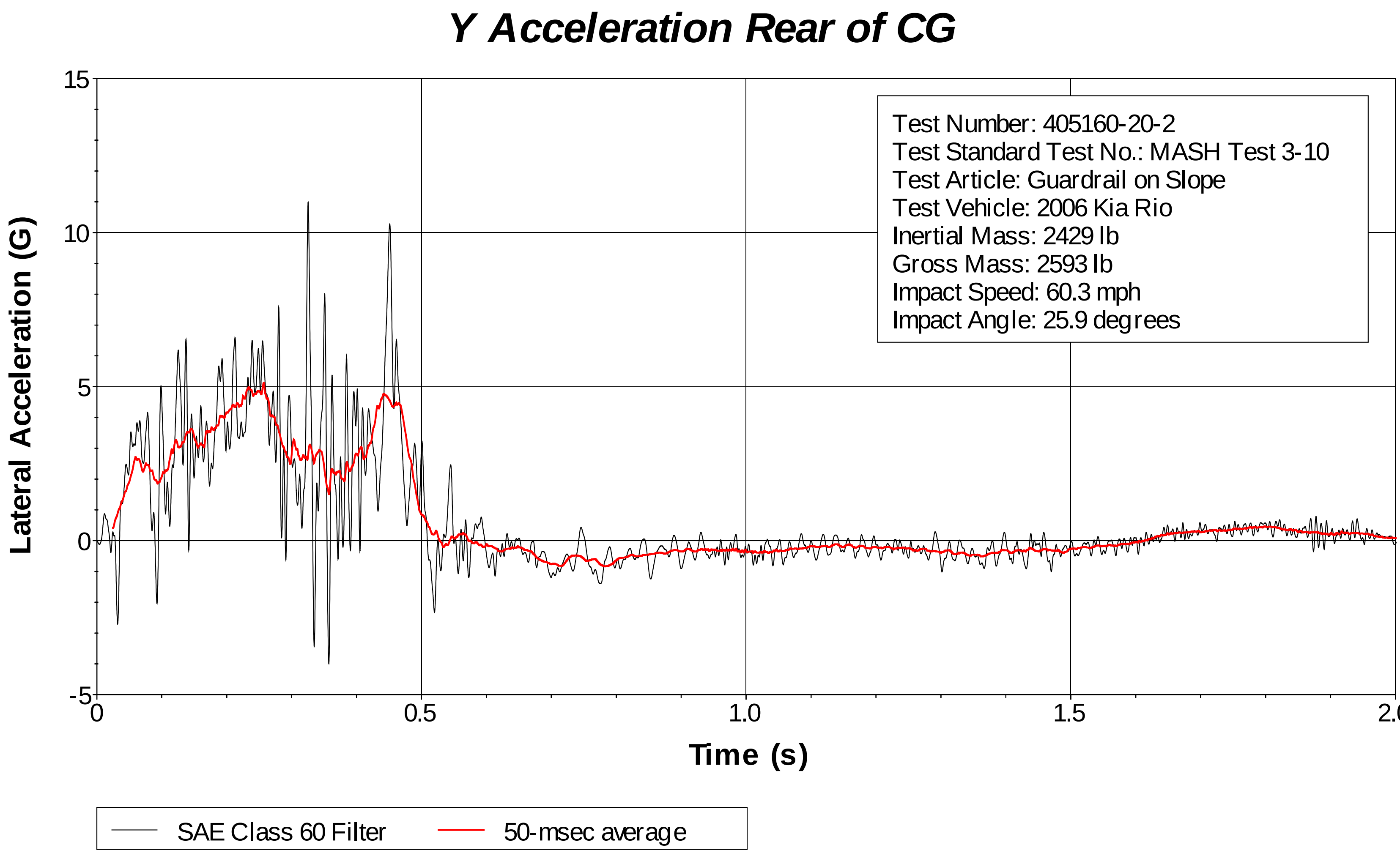


Figure E8. Vehicle lateral accelerometer trace for test 405160-20-2
(accelerometer located rear of center of gravity).

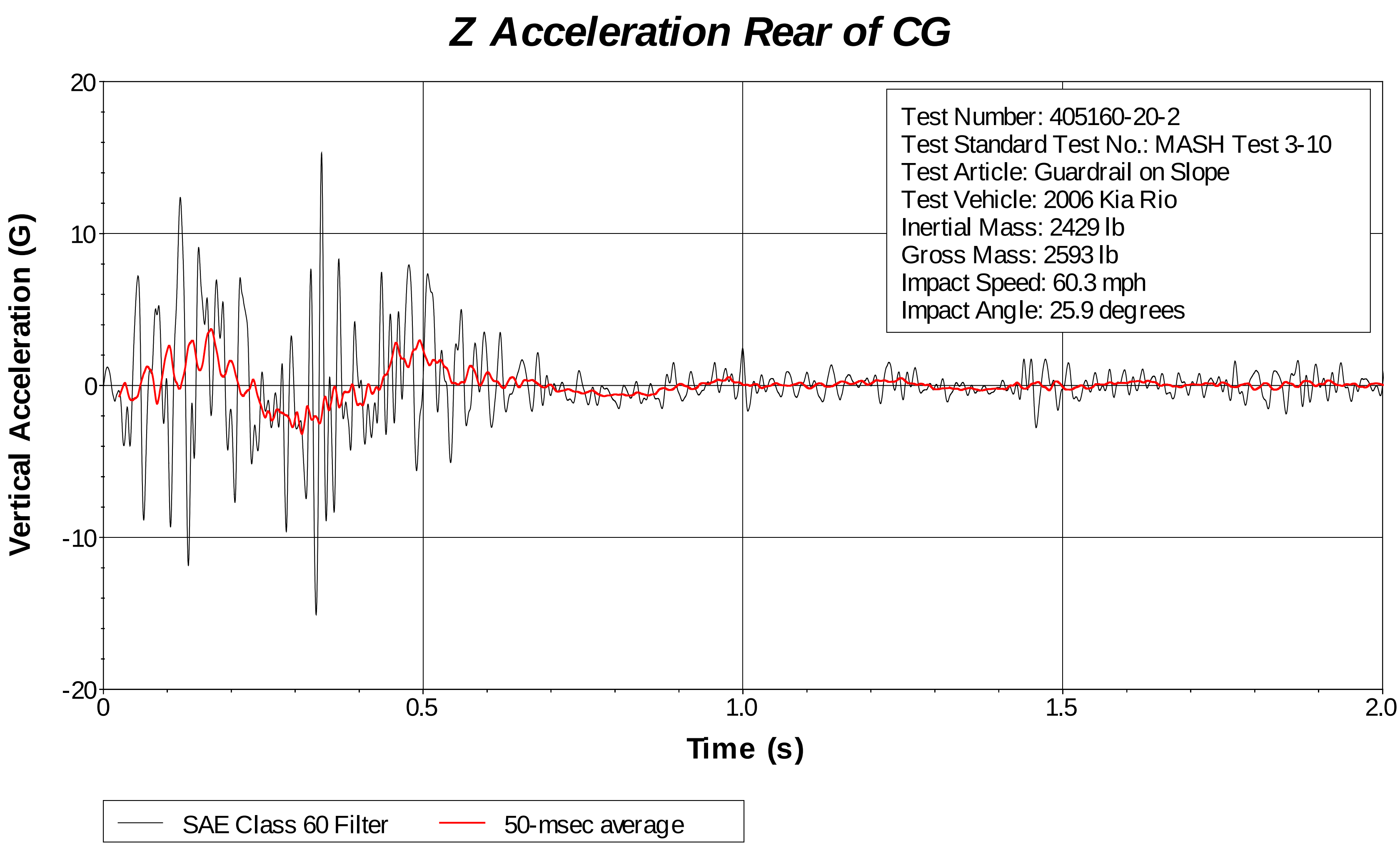


Figure E9. Vehicle vertical accelerometer trace for test 405160-20-2
(accelerometer located rear of center of gravity).