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MASH TL-6 Evaluation of a 62-in. Tall, Single-Slope, Concrete Median Barrier

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Secretary for Research and Technology

MATC

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A Report on Research Performed by

Midwest Roadside Safety Facility
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16. Abstract

The *Manual for Assessing Safety Hardware* (MASH) specifies six test levels of increasing demand on roadside and median barrier systems. The most challenging impact conditions correspond to MASH Test Level 6 (TL-6), which consists of an 80,000-lb tractor-tank trailer vehicle impacting the barrier system at 50 mph and 15 degrees. Typically, tall barriers are used to contain and redirect tractor-tank trailer vehicles due to the elevated height of the liquid ballast compared to other commercial truck vehicles. Previous testing at the Texas A&M Transportation Institute (TTI-TAMU) showed satisfactory redirection of 80,000-lb tractor-tank trailer vehicles produced in the 1970s impacting at 50 mph and 15 degrees with 90-in. tall barrier systems. The Midwest Roadside Safety Facility (MwRSF) embarked to develop a lower-cost, lower-height barrier capable of containing and redirecting a tractor-tank trailer vehicle at MASH TL-6 impact conditions.

This study describes Phase IV of a multi-year development effort sponsored by the Mid-America Transportation Center (MATC). A 62-in. tall, 5.5-degree single-slope median barrier was designed to withstand a 300-kip design lateral load. The barrier system was impacted by an 80,026-lb 2010 Columbia 112 Freightliner tractor and 1997 LBT tank trailer at a speed of 51.1 mph and an angle of 15.5 degrees. The barrier successfully contained and redirected the tractor-tank trailer without barrier penetration or override. Upon exit, the vehicle rolled 90 degrees and slid on the concrete tarmac through 6.5 seconds. The vehicle with oval-shaped tank and sloshing liquid cargo traversed the concrete tarmac and began to roll another 180 degrees, whereby crush occurred to the truck's cab. Minimal damage occurred to the barrier system. Through 6.5 seconds, the MASH TL-6 barrier system contained and redirected the vehicle with roll onto its side and with all occupant risk criteria met. Further discussion is recommended to determine proper crash test expectations for TL-6 barriers under high-energy impact events with round-tank trailers.

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Uncertainty of Measurement Statement

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurements for several parameters involved in standard full-scale crash testing and non-standard testing of roadside safety features. Information regarding the uncertainty of measurements for critical parameters is available upon request by the sponsor and the Federal Highway Administration.

Independent Approving Authority

The Independent Approving Authority for the data contained herein was Mr. Scott Rosenbaugh.

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J. Oliver, Solidworks Drafting Coordinator
Undergraduate and Graduate Research Assistants

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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE & 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 yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	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 ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & 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.

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Chapter 1 Introduction

1.1 Background

Roadside and median barriers, including bridge rails, have commonly been used to prevent errant motorists from striking hazardous roadside fixed objects or geometric features during run-off-road (ROR) events, which can mitigate the severity of those crashes. For some situations, it is appropriate to only utilize barrier systems that are capable of safely containing and redirecting passenger vehicles. These barrier systems typically meet the Test Level 3 (TL-3) safety performance criteria published in either the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* [1], or the American Association of State Highway and Transportation Officials' (AASHTO) *Manual for Assessing Safety Hardware* (MASH) [2].

However, it may be necessary to use higher-performance vehicle containment barriers (i.e., TL-4 through TL-6) when the percentage of heavy vehicle and truck traffic is high and/or the consequences of vehicle penetration beyond the longitudinal barrier is significant. Historically, TL-4 and TL-5 barriers have been implemented to prevent catastrophic outcomes during impacts with heavy vehicles. These TL-4 and TL-5 barrier systems have been full-scale crash tested and evaluated using single-unit trucks and tractor-van trailers, respectively, but are likely structurally inadequate and lack sufficient height to safely contain and redirect tractor-tank trailer vehicles, which may transport hazardous or flammable chemicals through heavily populated communities. When the TL-4, TL-5, and TL-6 trucks are compared, as shown in Figures 1.1 and 1.2, it becomes clearer that the geometry of the tank-trailer vehicle is much different than that of the van-trailer and single-unit truck vehicles. Thus, current TL-4 and TL-5 systems may not be capable of safely containing and redirecting a tank-trailer vehicle.

Figure 1.1 TL-4 (22,000-lb), TL-5 (79,300-lb), and TL-6 (79,300-lb) Vehicle Side View [3]

Figure 1.2 TL-4 (20,000-lb), TL-5 (80,000-lb), and TL-6 (80,000-lb) Vehicle Rearview [3]

As noted by the Federal Highway Administration (FHWA) [4], “Crashes of heavy vehicles through or over traffic barriers that result in catastrophic consequences are rare but are of extreme public concern." Heavy vehicle crashes pose a serious risk to the drivers and passengers of involved vehicles, the drivers and passengers of vehicles in the general vicinity, and to adjacent structures. Due to the likelihood of these vehicles carrying hazardous material, it is important to understand how tractor-tank trailer accidents happen, and the consequences if an accident does occur.

On May 11, 1976, a tractor-tank trailer transporting 7,509 gal of anhydrous ammonia lost control and impacted the bridge rail on the ramp connecting Interstate 610 (I-610) to the Southwest Freeway (U.S. 59) in Houston, Texas [5]. This impact resulted in the tractor-tank trailer penetrating the bridge rail and leaving the ramp. As the vehicle fell, the tractor-tank trailer struck a support column of an adjacent overpass and came to rest 15 ft below the bridge on the Southwest Freeway. Due to the damage from the impact with the barrier, support column, and ground, the tank was damaged, which released anhydrous ammonia. As a result of the ammonia leak, six people were killed, 78 were hospitalized, and approximately an additional 100 people were treated for other related injuries. The National Transportation Safety Board (NTSB) determined the probable cause of the accident to be the excessive speed of the tractor-tank trailer, in addition to the lateral surge caused by the liquid in the partially-loaded truck. The NTSB also stated the severity of the accident was increased due to the failure of the bridge rail to contain or redirect the vehicle.

On January 13, 2004, a tractor-tank trailer carrying 8,800 gal of gasoline left the roadway in Elkridge, Maryland, and collided with the bridge rail of the ramp it was on, causing the tractor-tank trailer to roll over the top of the barrier [6]. The vehicle subsequently fell 30 ft onto the roadway below at which time it exploded and caught fire. The fire from the leaked gasoline destroyed five vehicles and caused four fatalities. The NTSB listed a few factors in the probable cause of the accident, which were: (1) the failure of the driver to maintain control of his vehicle,

(2) the narrow shoulder and the outdated design of the roadway, and (3) the outdated design of the guardrail to concrete parapet transition that caused the tanker to override and roll over the bridge rail.

On October 22, 2009, a 2006 Navistar International truck pulling a 1994 Mississippi Tank Company MC331 trailer hauling 9,001 gal of gasoline rolled over while traversing an at grade ramp connecting I-69 southbound to I-465 in Indianapolis, Indiana [7]. The rollover occurred when the truck driver overcorrected after drifting into the left lane from the right lane. This sudden overcorrection caused the tanker trailer to disconnect from the tractor and penetrate through a W-beam guardrail adjacent to the road. The tanker then collided with a nearby bridge pier column. The collision displaced the bridge pier column and punctured the tanker trailer, releasing the petroleum gasoline, which formed a vapor cloud and ignited, causing a fire. The fire caused injury to the truck driver and the driver of another car, which was in the adjacent lane during the crash. Three passengers of vehicles traveling on the I-465 bridge above the accident site were also injured. The NTSB concluded that the accident was a result of the excessive speed and rapid overcorrection by the truck driver as he drifted into the adjacent lane.

Crashes involving truck-tank trailer combination vehicles were reviewed, and a consistent theme in each of the crashes was that barriers installed at the locations in which the truck tank-trailer vehicle crashed were inadequate to contain and redirect the vehicle and prevent catastrophic outcomes. In each case, the catastrophic outcome was the direct impact of the tank trailer with another feature, or the vaulting and override of the barrier resulting in tumbling of the truck and trailer to a shielded location below. A TL-6 barrier utilized at these locations may mitigate some of these catastrophic events. However, the construction of barriers consistent with the current NCHRP Report No. 350-compliant TL-6 barrier [8] has not often occurred. As such, there exists a need to develop a new, cost-effective, structurally adequate, reduced-height vehicle containment system that is safe for motorists, capable of containing errant vehicle impacts with heavy tanker-truck vehicles, and prevents and/or mitigates the consequences of catastrophic crashes into high-risk facilities or highly-populated areas.

1.2 Objective

The objective of this research project was to develop a new, cost-effective, MASH TL-6 barrier [2]. This barrier should be able to safely redirect vehicles ranging from 2,420-lb small passenger cars to 79,300-lb tractor-tank trailers. This barrier was initially developed as a roadside barrier but will also have median and bridge rail configurations designed. This new barrier was intended to safely and stably contain and redirect large tractor-tank trailers while also limiting occupant risk measures in small cars and trucks. The TL-6 barrier needed to be aesthetically pleasing while also being economically competitive to current TL-5 barriers.

The Manual for Assessing Safety Hardware (MASH) specifies six test levels of increasing demand on roadside barrier systems. The most challenging impact conditions are consistent with test designation MASH TL-6, which consists of an 80,000-lb tractor-tank trailer vehicle impacting the barrier system at 50 mph and 15 degrees. The Texas A&M Transportation Institute successfully developed and tested a tall aesthetic bridge rail to contain and redirect tractor-tank trailer vehicles. Unfortunately, the strength requirements and material required to construct these barriers are cost-prohibitive for most locations. Therefore, the Midwest Roadside Safety Facility (MwRSF) embarked on developing a low-cost, low-height barrier capable of containing and redirecting a tractor-tank trailer vehicle at MASH TL-6 impact conditions.

A 62-in. tall, 5.5-deg single-slope median barrier was designed to withstand a transverse force of 300 kips. The barrier system was impacted at 51.1 mph and 15.5 degrees by a 80,026-lb 2010 Columbia 112 Freightliner tractor and 1997 LBT tank trailer. The vehicle was redirected by the barrier, but after redirection, the vehicle skidded and rolled 270 degrees before coming to rest. Minimal damage occurred to the barrier. The rollover violated occupant risk criteria, and the system was not successful according to MASH TL-6, but the barrier successfully contained and redirected the tank-truck vehicle at a significantly lower cost than existing protection systems.

1.3 Scope

The research objective was achieved through the completion of several tasks over the course of multiple phases. For the current phase, a recommended barrier shape and height were selected for the candidate TL-6 system based on a review of results in previous phases. The barrier was designed, including attachment to a rigid, unreinforced concrete foundation. One full-scale crash test was conducted on the TL-6 concrete barrier to meet the MASH test designation no. 6-12. The full-scale vehicle crash test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made pertaining to the safety performance of the TL-6 concrete barrier.

Chapter 2 Literature Review

2.1 Previously Tested and Real-World Systems

To date, only one TL-6 vehicle containment system has been successfully tested and evaluated according to NCHRP Report No. 230 [9] using a tractor-tank trailer vehicle [10]. Designed by the Texas A&M Transportation Institute (TTI) in 1984, the Roman Wall combination barrier system consisted of a lower, solid reinforced-concrete parapet with an upper beam-and-post reinforced-concrete railing system and measured 90 in. tall, as shown in Figure 3. Unfortunately, the cost, height, construction difficulty, and weight of this TL-6 barrier limited its implementation.

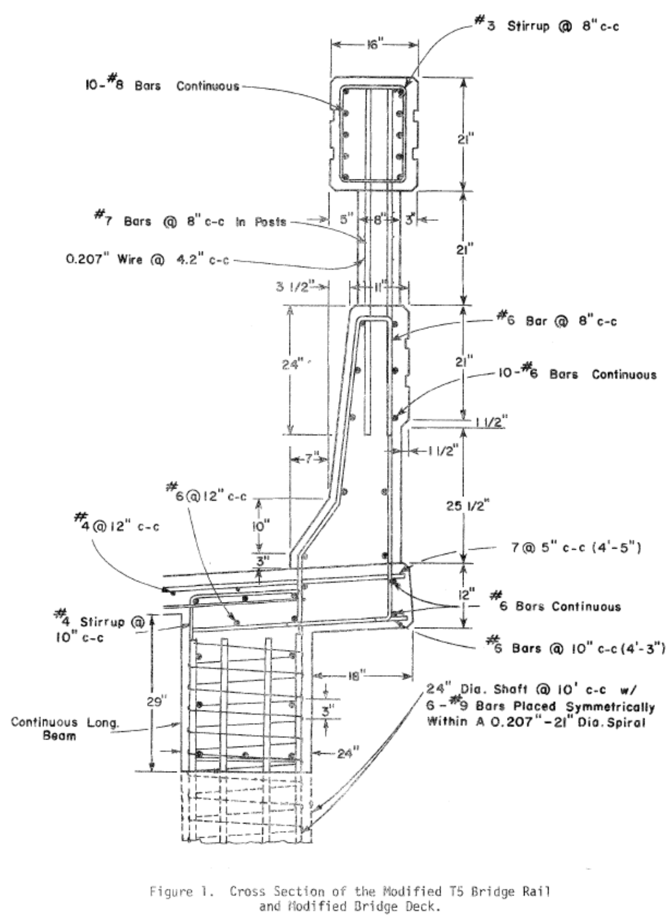


Figure 2.1 TTI TL-6 Roman Wall [10]

There are several known installations of a full-size, TTI Roman Wall barrier: one in San Antonio, Texas; one in Baton Rouge, Louisiana; and one in Cumberland, Maryland. The San Antonio barrier is installed on both sides of a flyover bridge connecting southbound I-10 to eastbound I-35 at exit 570. A Google Street View image of the San Antonio installation is shown in Figure 2.2. The Baton Rouge barrier is installed on the outer edge of a flyover bridge ramp connecting northbound I-10 to westbound I-10 at exit 155B, a street view image is shown in Figure 2.3.

Figure 2.2 TL-6 Barrier in San Antonio, Texas [3]

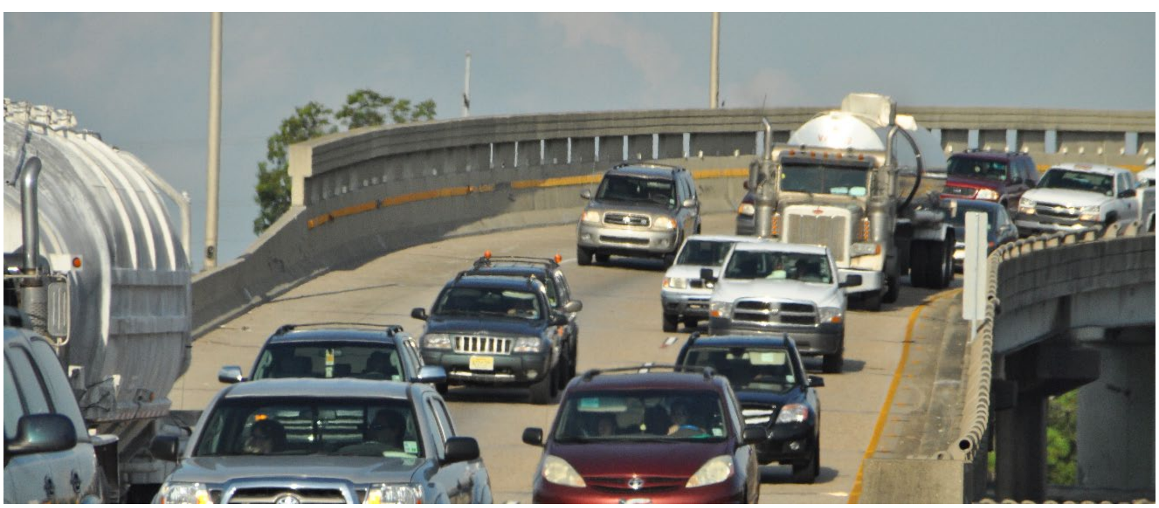


Figure 2.3 TL-6 Barrier in Baton Rouge, Louisiana [11]

Figure 2.4 TL-6 Barrier in Cumberland, Maryland [3]

In some locations, modified barriers which were not evaluated according to MASH TL-6 have been installed which may have TL-6 containment capabilities. The Virginia Department of Transportation (VDOT) currently uses a 90-in. tall wall design spanning between consecutive bridge piers. This barrier is used to help prevent damage to bridge piers resulting from trailer elements extending over the top surface of the barrier into the Zone of Intrusion (ZOI) and impacting the bridge piers.

The Utah DOT installed an 84-in. tall modification of the TTI Roman Wall in a narrow median on a large curve on Interstate 70, as shown in Figure 2.5. The Utah DOT has also utilized an 84-in. tall solid concrete wall, which was installed on the roadside to shield a railroad line adjacent to a curved highway, as shown in Figure 2.6.

Figure 2.5 Utah DOT 84-in. Tall Roman Wall Installation [3]

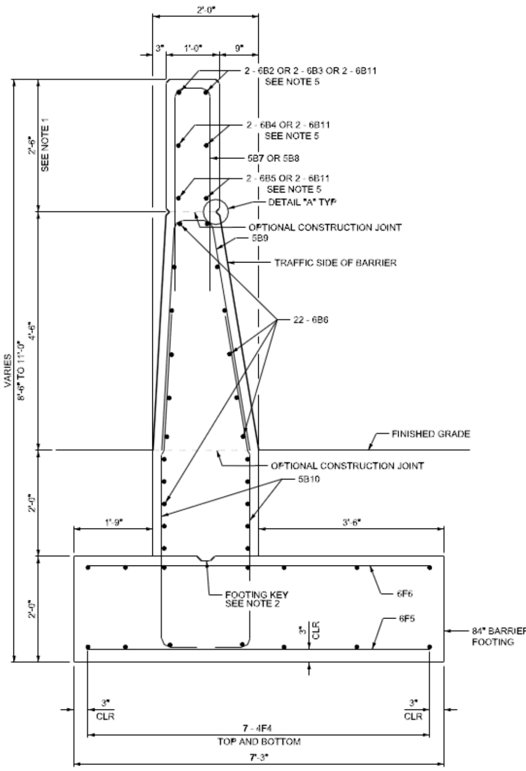


Figure 2.6 Utah DOT TL-5 Barrier [3]

State departments of transportation (DOTs) desire a TL-6 barrier option that is more economical, versatile, and easier to implement. Because only a few TL-6 barrier installations have been utilized in the real world thus far, there are numerous locations in which a TL-6 barrier may be warranted but not installed. These situations could include prevention and mitigation of:

(1) cross median, opposing-traffic vehicle crashes involving hazardous heavy tractor tank-trailer vehicles along urban freeways and interstates and (2) tractor tank-trailer vehicle penetration or override of existing TL-4 or TL-5 barriers located on bridges, elevated road structures, or high-volume roadways. These situations may create potentially catastrophic events near schools, malls, sports venues, concert arenas, military bases, international airports, critical government buildings, or other high-risk facilities. This research study was intended to evaluate a more cost-effective containment barrier for TL-6 applications.

2.2 Whitfield TL-6 Truck-Tank Trailer Combination Vehicle Modeling

Investigation of the tractor-tank trailer combination vehicle was completed in three phases. During the first phase, Whitfield investigated and developed new, cost-effective, MASH TL-6 concepts [12]. The author's research main objective was to design a barrier capable of containing and redirecting vehicles ranging from 2,420-lb small passenger cars to 79,300-lb tractor-tank trailers. This finding was achieved by investigating previous TL-6 and TL-5 barrier designs and estimating the cost of current TL-5 and TL-6 barriers. Barrier concepts were developed and evaluated based on their ability to meet the design criteria. A minimum barrier height study was conducted to determine a minimum barrier height for the concept designs. The barrier concepts were evaluated using Finite Element Analysis (FEA).

2.2.1 Initial Vehicle Model

Whitfield created a simplified TL-6 tractor-tank trailer vehicle model in LS-DYNA to evaluate barrier concepts. This tractor-tank trailer model was created by modifying an existing TL-5 tractor-van trailer model. The van trailer was removed, leaving the original tractor and rear tandem axle. The tank-trailer geometry was determined based on a vehicle dimension survey consisting of an elliptical cylinder 92 in. wide, 63 in. tall, and 488 in. long. The tank was attached to two C-channel rails with 4-in. wide flanges and an 8-in. tall web that was ½ in. thick.

Two 4-in. x 4-in. square tube spacer rails were also added between the C-channel rails and the rear tandem axle to suspend the tank at the correct height.

The fluid inside the tank-trailer was modeled with pure Lagrangian solid elements (ELFORM=1) with the properties of water at 20°C (72°F), with a density of 1.0E-6 kg/mm^3, Poisson's ratio of 0.2, and a bulk modulus of 2.15 GPa. The empty vehicle model had a weight of 25,050 lb. With the addition of 54,793 lb of water ballast into vehicle model, the resulting total weight was 79,843 lb.

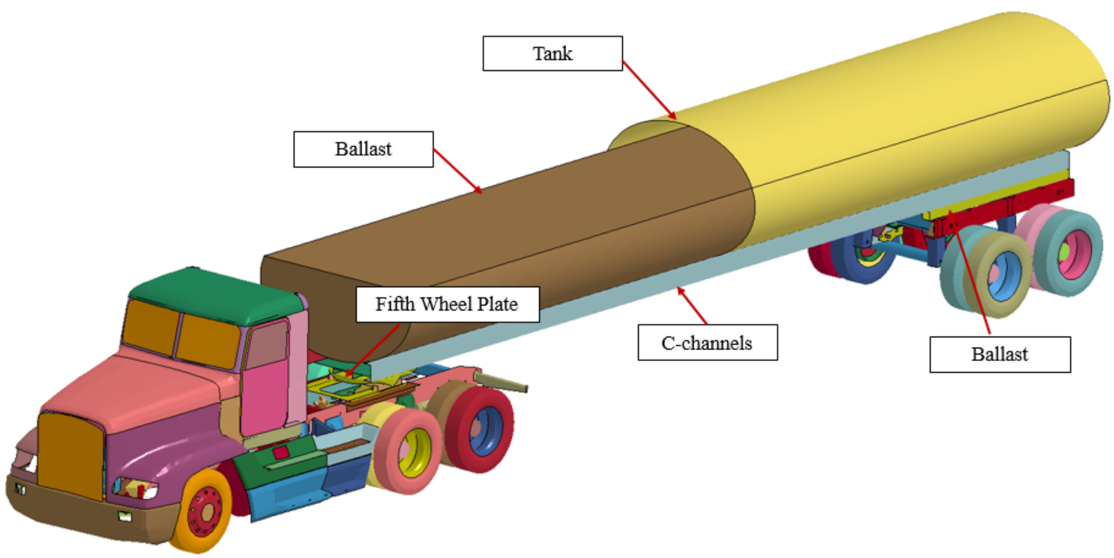


Figure 2.7 Whitfield's Vehicle Model [3]

2.2.2 Vehicle Model Validation

To validate TL-6 vehicle model, Whitfield created a simulation of an existing full-crash test using an instrumented wall, performed at TTI [13], to compare with the simulation results. The wall was segmented to measure load in discrete intervals. The truck model impacted the barrier model at 15 degrees and 50 mph at a point approximately 90 in. from the upstream edge of the barrier, which is similar to the impact conditions in the full-scale crash test.

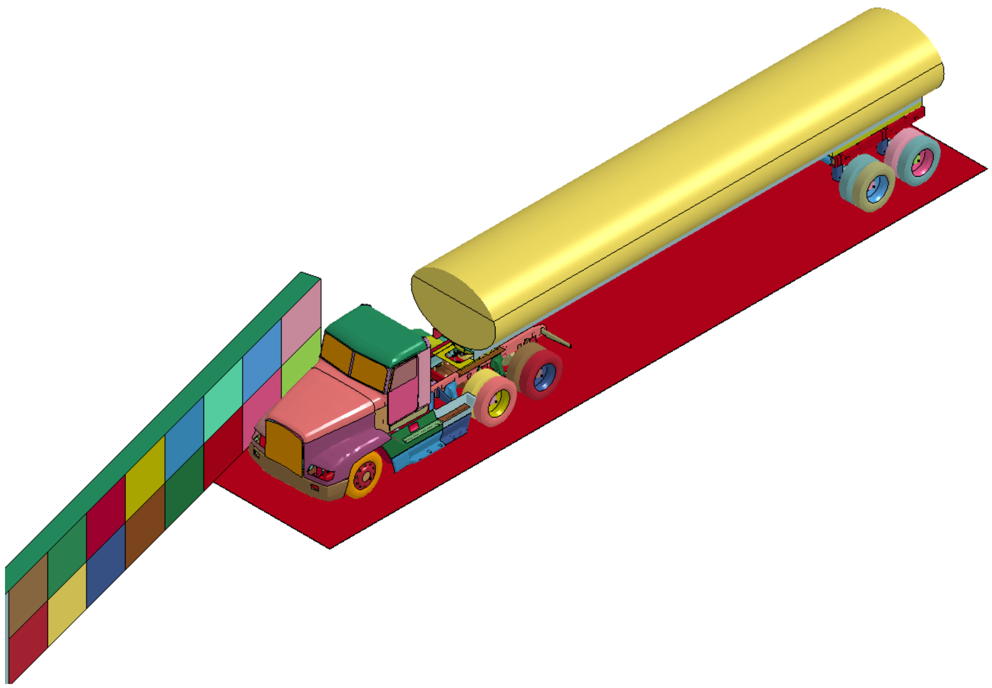


Figure 2.8 Instrumented Wall Simulation [3]

To validate the vehicle model, Whitfield compared the angular displacements from the full-crash test, which were recorded at the center of gravity (c.g.) of the tractor, with the angular displacements from the simulation. The author extracted x, y, and z rotational velocities from the simulation, and the Euler roll, pitch, and yaw were calculated. Angular displacements were compared, as shown in Figure 2.9. Using the angular displacement, the author concluded that since the initial roll was similar between the simulation and the test, the tractor impact into the barrier was representative of the full-scale crash test with the exception of the tank impact, which was less accurate.

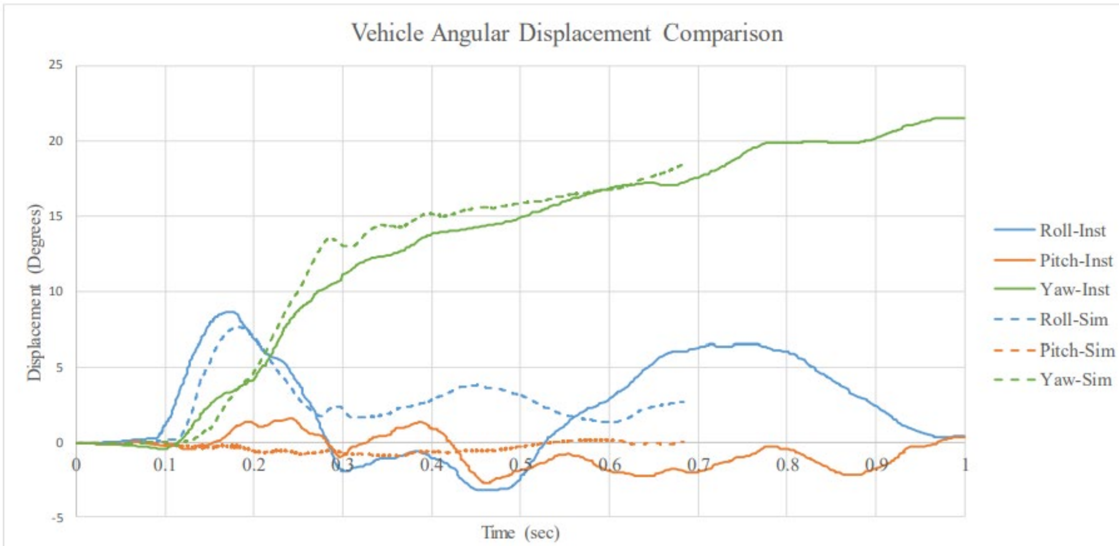


Figure 2.9 Angular Displacement Comparison [3]

The accelerations at the tractor model's c.g. were extracted and compared to the acceleration data from the instrumented wall crash test, which was located at the tractor's c.g. A 50-ms rolling average was applied to the resultant data, which was similar to the methods used when processing data from the instrumented wall test.

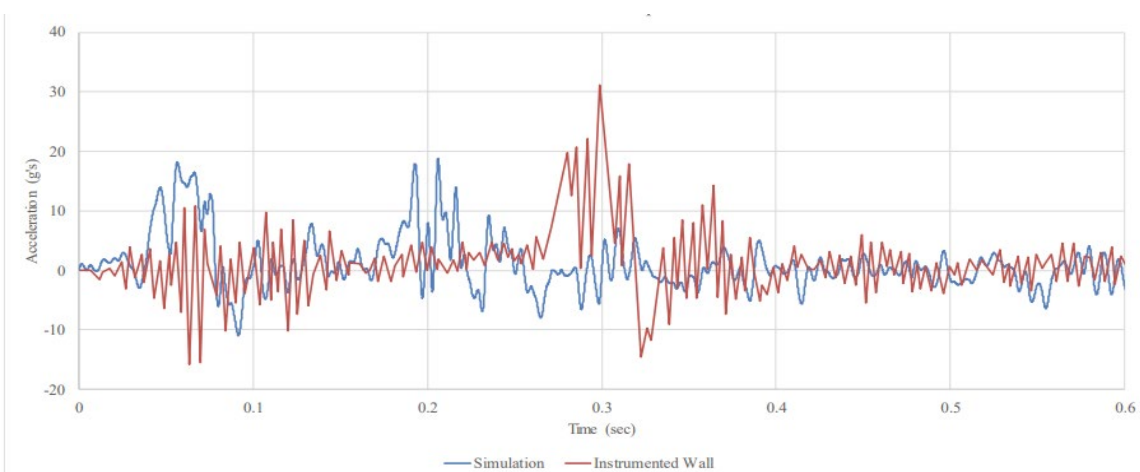


Figure 2.10 Lateral Acceleration Comparison [3]

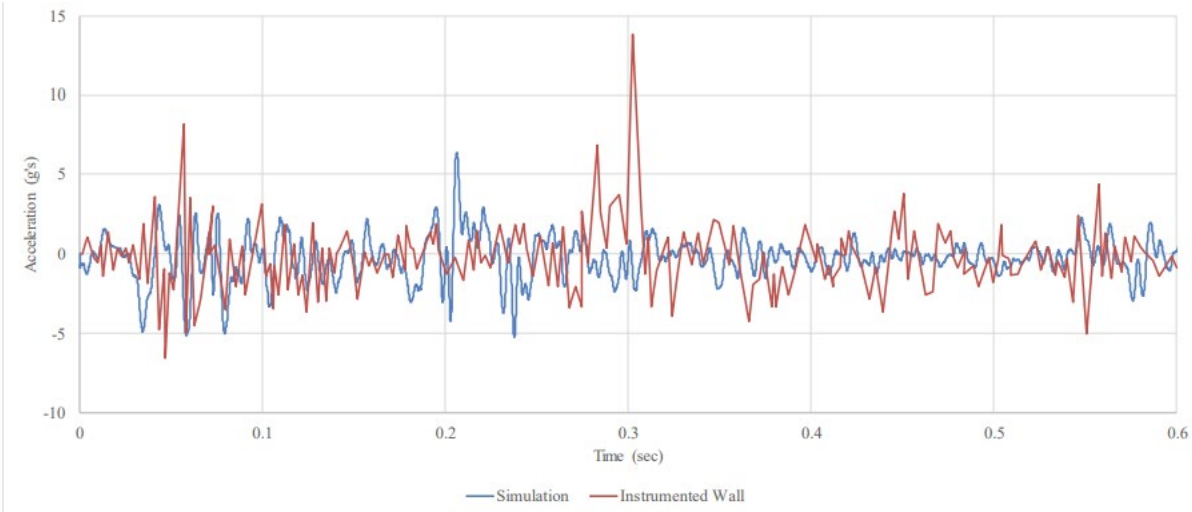


Figure 2.11 Longitudinal Acceleration Comparison [3]

As seen in the lateral acceleration comparison, the initial impact of the tractor (the first set of peaks) was larger in the simulation than the instrumented wall test. The largest 50-ms average in the instrumented wall test was reported as 12.3 g as compared to 8.7 g in the simulation. Overall, the general trend of the two tests was similar, but the magnitude and timing of major acceleration pulses varied.

Whitfield extracted the forces exerted on the barrier from the rigid walls and applied a 50-ms rolling average to match the filtering performed on the instrumented wall test data. The forces from all rigid walls were summed to obtain the resulting total load. The loads from the simulation and the instrumented wall test are shown in Figure 2.12. When comparing the forces, three distinct peaks were observed corresponding to three impact events: the impacting front-right bumper corner of the tractor, the truck tandem axle, and the trailer tandem axle in a phenomenon known as “tail slap.” The time at which these impacts occurred varied between the test and initial simulation model, however, the time between peaks was similar between the instrumented wall test and the simulation.

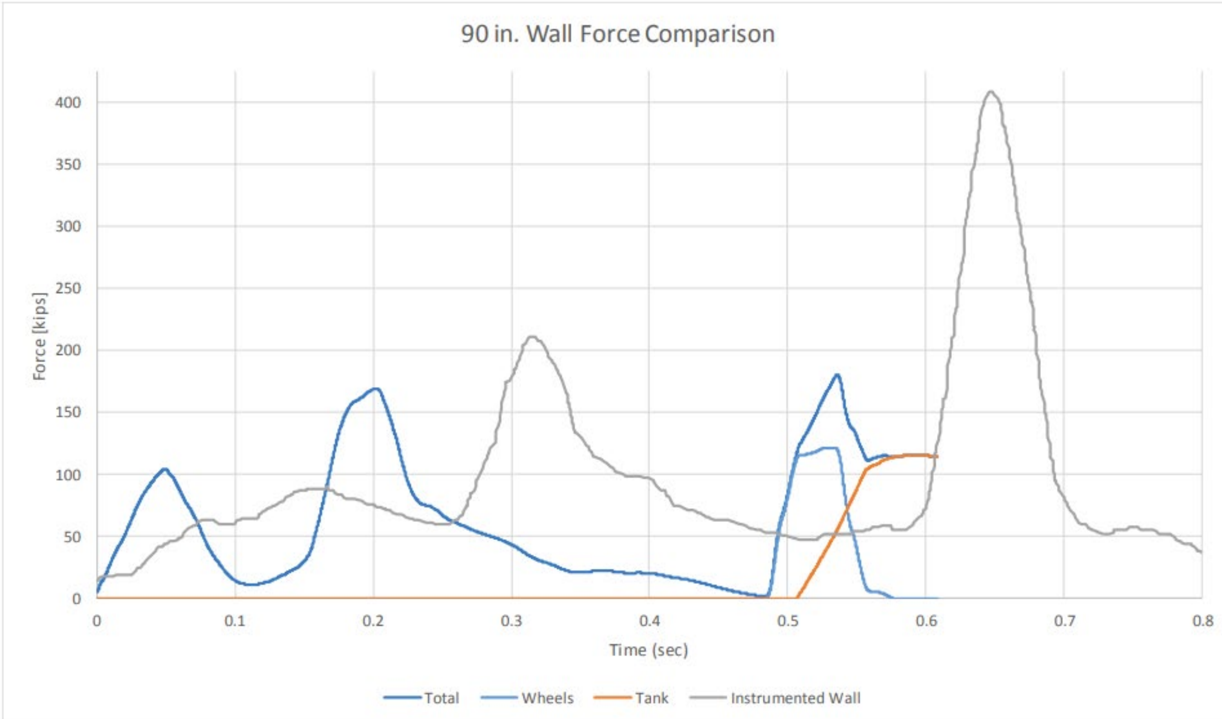


Figure 2.12 Wall Force Comparison [3]

Whitfield concluded that the preliminary TL-6 vehicle model did not accurately represent the impact loads and accelerations from the instrumented wall test. The author mentioned that the differences in the results may be due to the differences in the 1968 test vehicle and the preliminary vehicle model, which had a geometry based on newer tractor and trailer vehicles. The author listed several components that could be improved in the TL-6 vehicle model to enable more realistic behavior: (1) the fifth wheel plate; (2) the connection between the fifth wheel plate and the tank; (3) the support rails and lateral bracing; (4) the baffles and bulkheads inside the tank; (5) the rails in top of the tank; (6) many of the additional tubes and additional components located underneath the tank; and (7) the ballast inside the tank.

2.3 Vasquez's TL-6 Truck-Tank Modeling & Barrier Evaluation

Subsequent modeling was performed by Vasquez [14-15] using an updated model of a tank trailer. Design details of the Liquid & Bulk Tank, Inc. (LBT) BKZ 5949 trailer were modeled using FEA and calibrated using the TTI instrumented wall test [13]. The calibrated truck and trailer model were used to investigate barrier minimum capacities and heights to contain the truck.

2.3.1 Development of MASH Truck-Tank-Trailer FEA Model

The tractor-tank trailer model was developed by joining two different submodels together. The tractor model was extracted from an existing TL-5 tractor-van trailer truck model, originally developed by a research team at UT-Battelle's Oak Ridge National Laboratory and the University of Tennessee at Knoxville and modified by Dr. Chuck Plaxico of Roadsafe, LLC and Dr. John Reid of MwRSF. The tractor model was identical to the model used by Whitfield [3, 14].

The trailer model was developed using the geometry, bill of materials, and assembly and connection details of an LBT BKZ 4959, which was a 40-ft long tank trailer with four fluid compartments and an external jacket. The LBT tank structure is shown in Figure 2.13. Overall, the tank-trailer compartment had an approximate length of 42 ft – 5 in., as shown in Figure 2.14. The trailer volume capacity was about 9,500 gallons and was divided into four compartments, each with a capacity of 3,500; 1,000; 1,500; and 3,500 gallons, respectively, from front to rear.

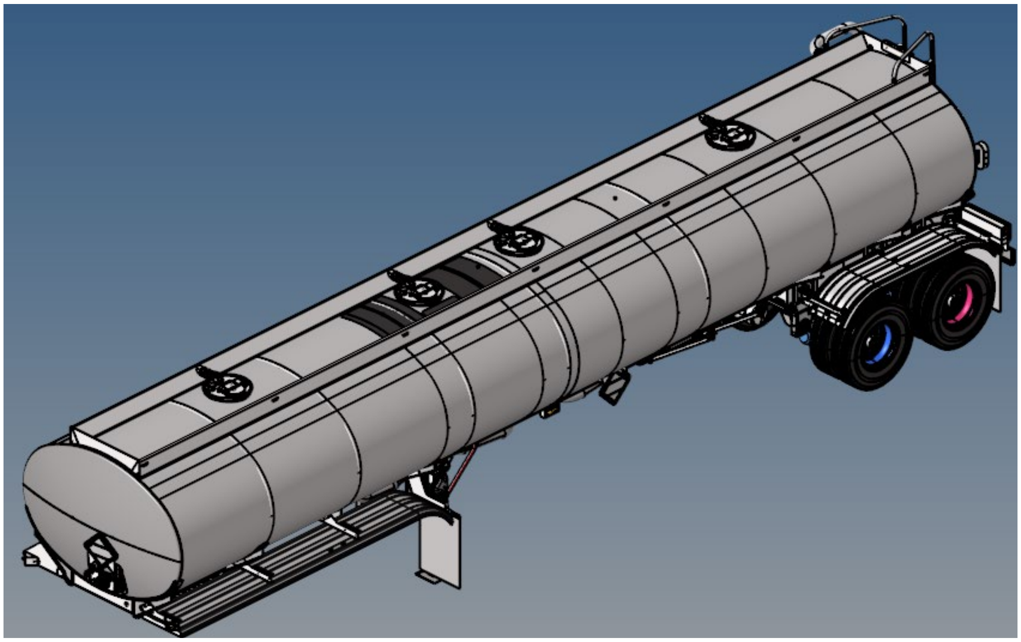


Figure 2.13 BKZ 5949 Trailer Model [14]

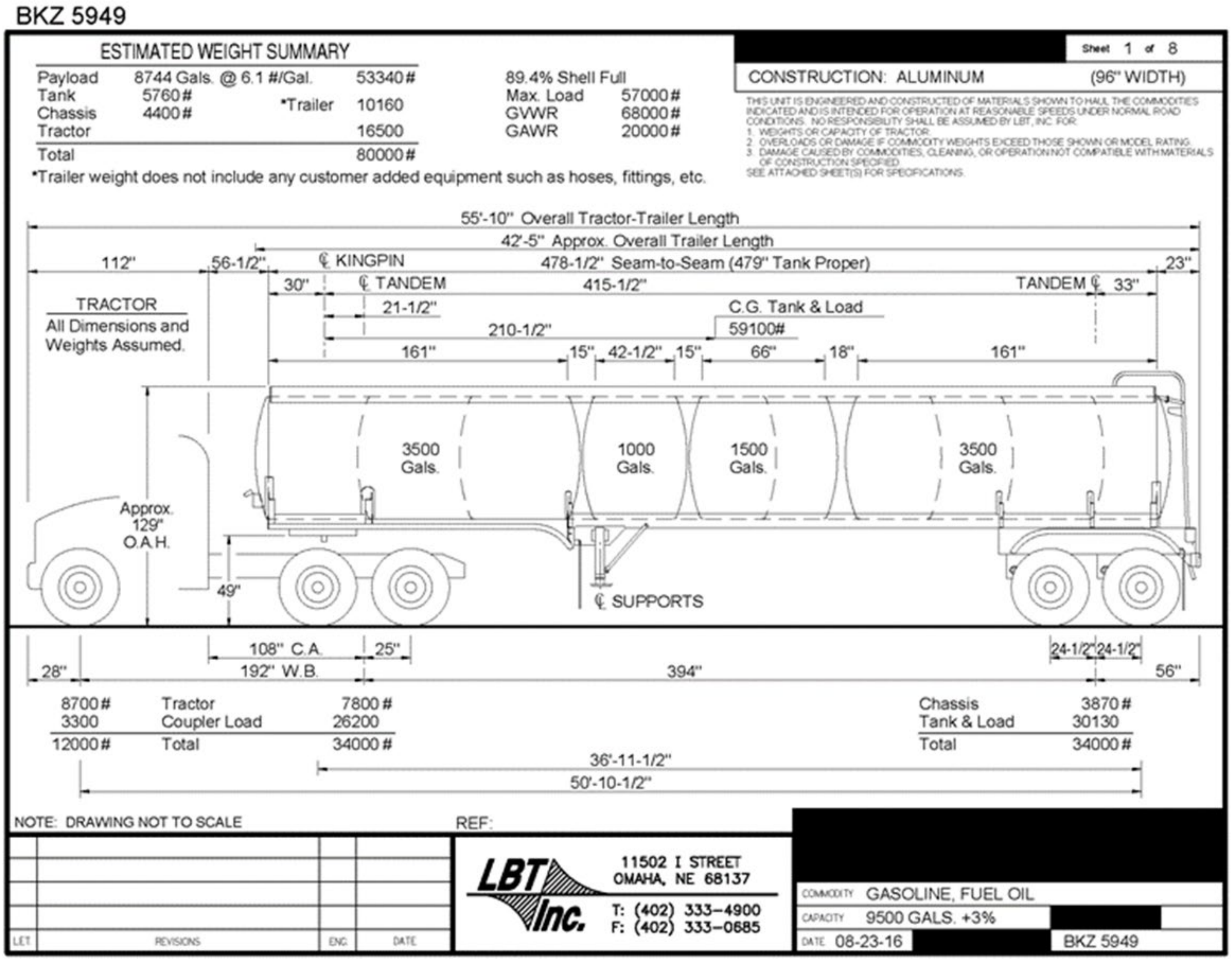


Figure 2.14 Standard Plan Drawings for Modeled Tank Trailer BKZ 5949 [14]

Most components from the chassis system were fully-integrated shell elements (ELFORM=16). Other components (lateral and longitudinal ribs) were defined as Belytschko-Tsay (B-T) shell elements (ELFORM=2). The only component formed from constant stressed solid elements (ELFORM= 1) was the fifth wheel pin. The fifth wheel shear pin was modeled with solid elements to secure to the rib, frame, and strut members of the fifth wheel box.

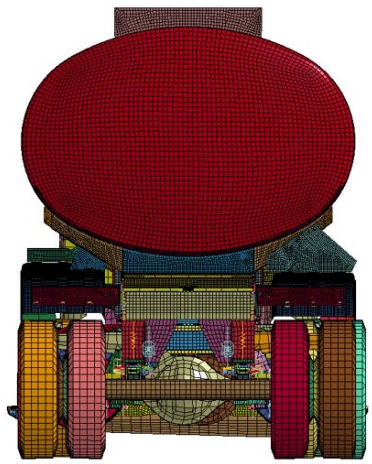


Figure 2.15 Whitfield's Model (Right) and Vasquez's Model (Left)

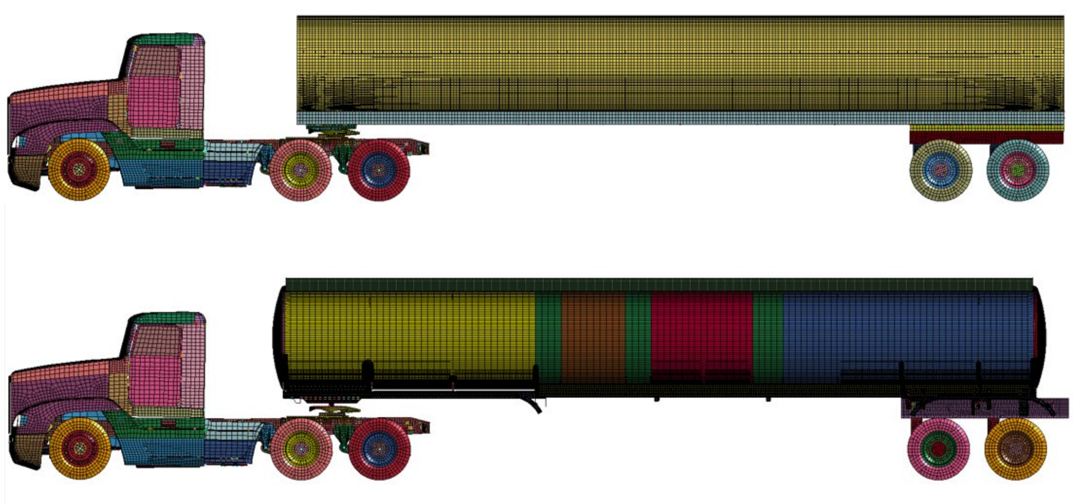


Figure 2.16 Whitfield's Model (Top) and Vasquez's Model (Bottom)

2.3.2 Fluid Model Selection

Vasquez et al. simulated different computational models of tanker fluid and their behaviors. In terms of visual representation, ALE provided a more fluid-like behavior following the tank's movement at high speeds, whereas the Lagrangian fluid model showed a gel-like behavior by resisting flow near the boundaries of the tank. Likewise, the movement of the water to the boundaries of the tank model, which pushes the air to the interior cavity, is believed to be a more realistic behavior than the Lagrangian "slime" result as it suggests the low viscosity and density of water relative to the fast tank movement.

Table 2.1 CPU-Time Comparison

Model	**Total Number**		**Time Frame (ms)**	**CPU Time (min)**	**No. CPU**
	Nodes	**Elements**			
Lagrangian	554,082	516,994	15	23	32
ALE	784,394	832,074	15	57	32

Despite these differences in fluid behavior, the overall load applied by the two fluid models were similar for the test setups. The computational efficiency afforded by the Lagrangian model led to its adoption by Vasquez. The TL-6 truck-tank trailer model was validated against the TTI instrumented wall test [13], and the model was determined to be satisfactory. Readers are referred to Vasquez's research for more complete calibration documentation.

2.3.3 Barrier Height Simulations

The validated truck-trailer simulation model was used to investigate vehicle stability and loading on rigid, vertical walls ranging in height from 50 to 90 in. The results from the simulations (roll, lateral and vertical intrusion, forces, general behavior of the vehicle, and others) were analyzed to evaluate the relationship between barrier height and impact loads. As barrier height increased, the roll angle of the cab and trailer both increased, but the shear, moment load, and barrier minimum capacities were reduced. The trailer's rear tandem axle roll angle is shown against barrier height in Figure 2.17.

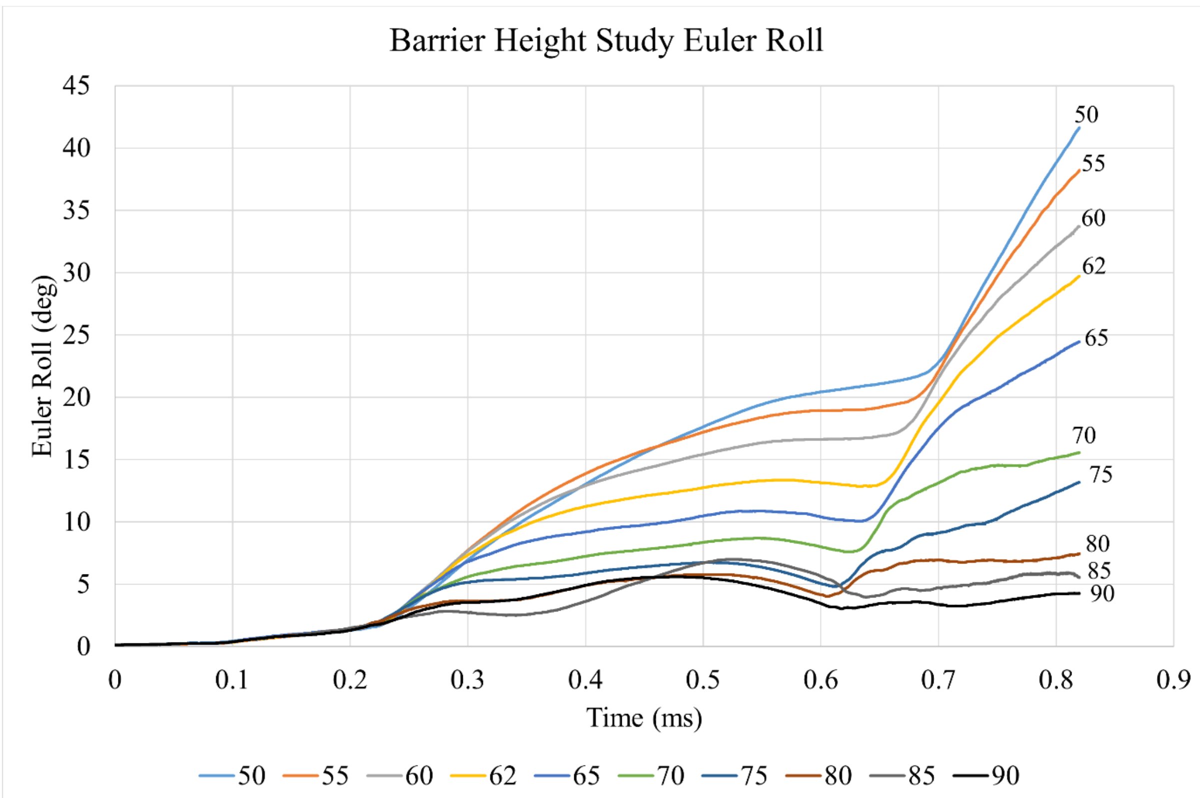


Figure 2.17 Roll Angle at Trailer Tandem Axle by Barrier Height

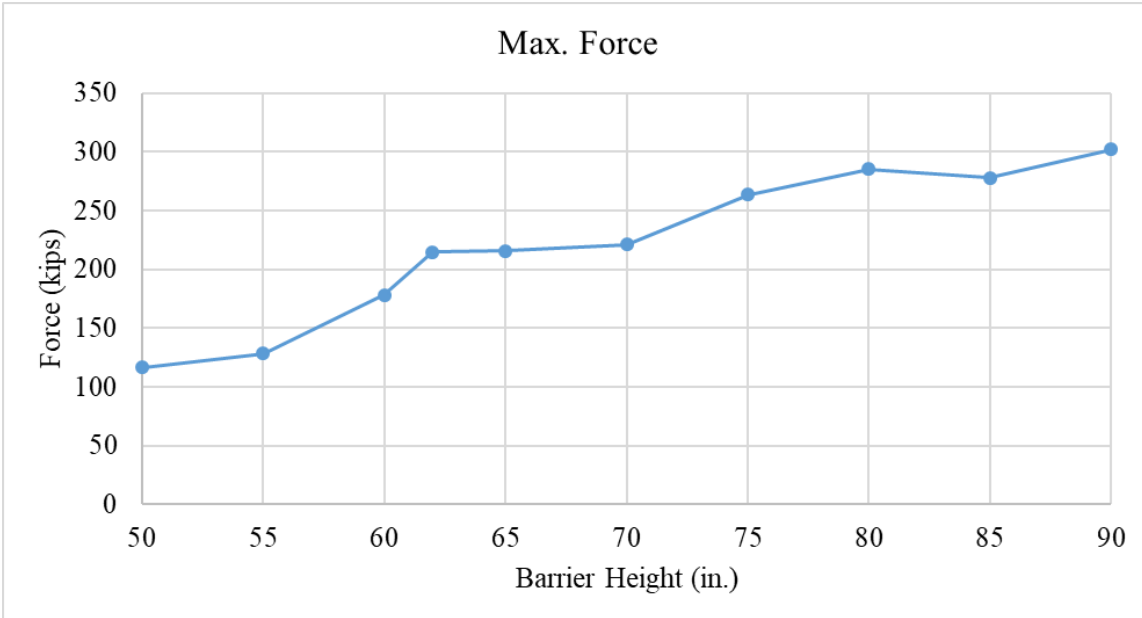


Figure 2.18 Peak Barrier Shear Forces by Barrier Height

Roll angles were also plotted by lateral intrusion of the vehicle over the top surface of the barrier, as measured at the front top edge of the barrier. In general, lateral intrusions (ZOI) were strongly correlated with roll angles in a nearly linear relationship, as shown in Figure 2.19.

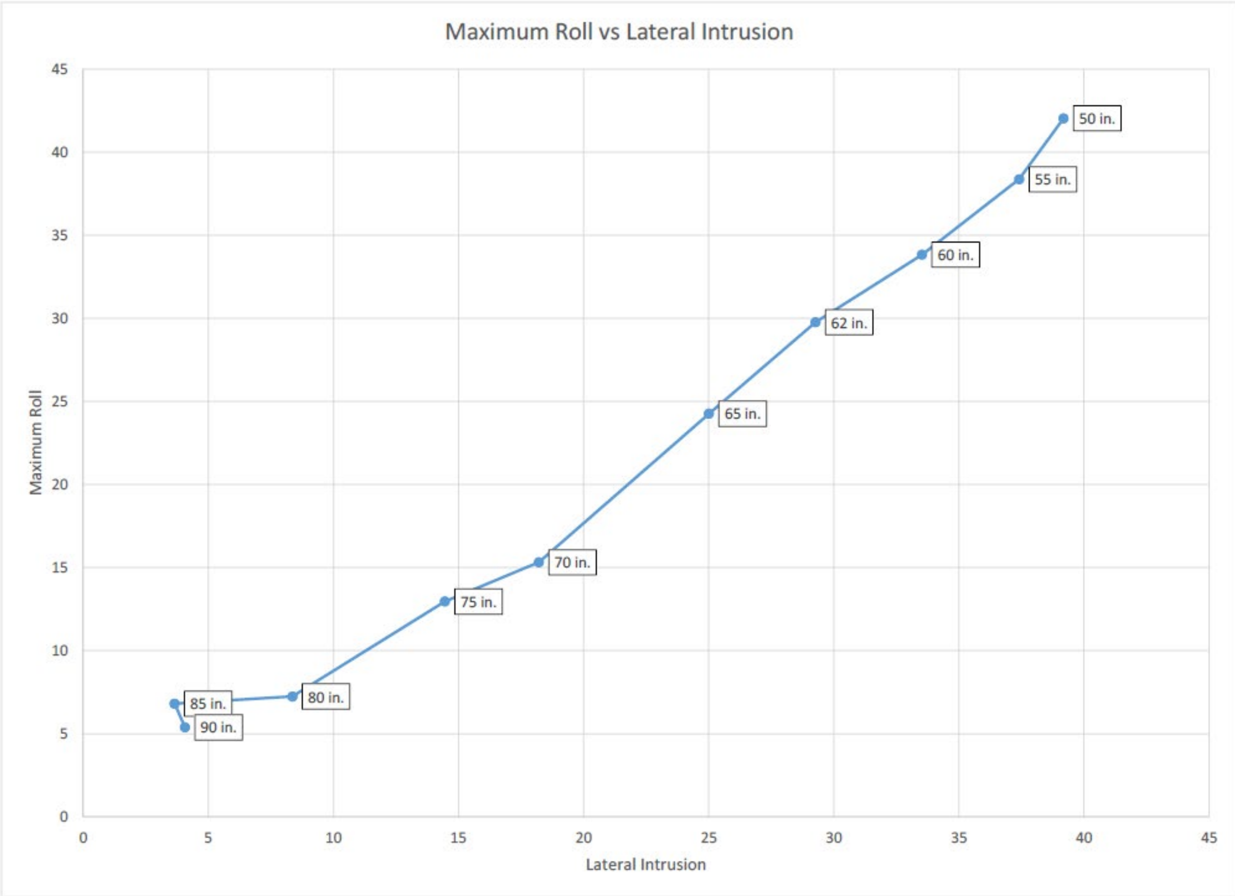


Figure 2.19 Maximum Roll vs. Lateral Intrusion

Based on computer simulation results, researchers made three critical observations:

- Barriers taller than 65 in. were associated with the tank partially deforming and protruding over the top surface of the barrier. Barriers shorter than 62 in. allowed the tank gussets and structure to extend over the top of the barrier. Thus, a critical transition region occurred at approximately 62 in. in which the tank gussets and the lower tank surface engaged the barrier, but the trailer would partially roll onto the top of the barrier and impart a vertical load onto the foundation.
- When the vehicle was able to partially roll on top of the barrier, the vehicle roll angles were increased but the lateral loads imparted to the barrier were

significantly decreased. This is because the impulse and collision time were extended when the vehicle partially rolled on top of the barrier.

- Tractor-tank trailer simulations may have extensive vehicle-to-barrier interaction times. Simulations typically initialized over the first 50 ms and then involved vehicle engagement with the barrier spanning 850 to 900 ms before numerical instabilities terminated data collection. Although the lateral vehicle velocity at 900 ms was approximately zero and the roll behavior toward the barrier was declining, indicating the vehicle was fully contained by the barrier, the post-impact rebound and vehicle stability and response are not known.

2.4 Conclusions

Research performed during Years 1 through 3 of this MATC research effort were utilized to select a critical height for the new barrier system. Based on stability and capture simulations, load estimation, and simulation parameters, researchers believed a critical height threshold of 62 in. was applicable for the new, optimized TL-6 barrier. The height of 62 in. represented a transition in roll, stability, and capture for the new barrier. It was believed that barriers shorter than 62 in. may not capture the impacting truck, whereas barriers above 62 in. were likely to be able to capture the impacting truck with reduced roll and instability.

The purpose of this study was to design, install, and evaluate an aggressive and efficient barrier section. Therefore, the 62-in. top barrier height was selected. The barrier strength and design were subsequently determined and are described in Chapter 3.

Chapter 3 Selection of Barrier Design Strength

3.1 Barrier Geometry

In order to make a cost-competitive TL-6 traffic barrier, the height of the barrier had to be optimized. The 90-in. tall Roman Wall was likely too costly to construct for most roadway agencies. A shorter barrier that was closer in height to other TL-5 barriers would be expected to have installation costs similar to those of a TL-5 barrier, making the new TL-6 system more feasible. On the other hand, the barrier needed to be tall enough to contain and redirect a tractor-tank trailer, thereby preventing the tank from rolling over the barrier. Thus, the barrier was to be designed with the minimum height required to redirect the TL-6 vehicle to limit installation costs.

The initial design goal for the barrier was a footprint not larger than 24 in. wide for a roadside configuration and not larger than 36 in. wide for a median configuration. As described previously, simulations conducted on barrier heights less than 60 in. showed continuing vehicle roll when the simulation prematurely terminated. Thus, there was a substantial risk of the vehicle rolling over the barrier at these low heights. Simulations on barrier heights from 60 in. to 70 in. showed significant roll angles, but the vehicles stabilized and began to return to an upright position. However, there were concerns with roll angles above 30 degrees as the fluid in the tanks would slosh around and could result in vehicle instabilities. Therefore, the 62-in. barrier height, which limited the roll angle to 30 degrees, was believed to be the optimum barrier height for capturing a MASH 36000T vehicle.

The shape of a concrete barrier can greatly affect the trajectory and stability of an impacting vehicle. Multiple studies have shown that vehicle stability is maximized for barriers with flat, vertical walls [16-18]. Accordingly, a vertical barrier face was considered ideal for the new barrier. However, vertical barrier walls cannot be easily slipformed, a construction process that significantly reduces installation costs by eliminating traditional forms. Most barrier installers prefer a sloped face of at least 12V:1H for barrier walls. For a 12H:1V slope, the top of a 62-in. tall barrier would be set back 5.2 in. from the toe of the barrier. To create a round number and still satisfy the 12V:1H requirement, the top was set back 6 in. for the new TL-6 barrier. The barrier cross section for a median configuration has a top width of 10 in. and is shown in Figure 3.1.

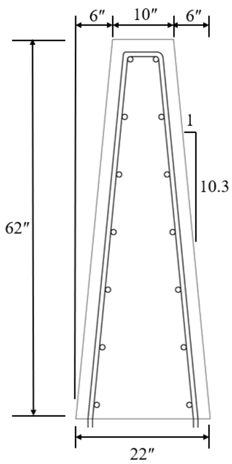


Figure 3.1 MwRSF TL-6 Barrier Design Geometry

3.2 Design Load

The 2012 *AASHTO LRFD Bridge Design Specifications* [19] provides design loads for traffic barriers based on test level. In Section A13.2-1, a transverse load of 175-kips applied at the top of the barrier is specified for a TL-6 barrier. However, this design load was determined for the TL-6 impact conditions specified by NCHRP Report 350, and Section 13 of *AASHTO LRFD Bridge Design Specifications* has not been revised to include design loads for MASH barriers. Due to the increases in MASH vehicle weight and speed as compared to NCHRP Report 350 conditions, MASH TL-6 design loads were expected to be higher than those listed in

AASHTO LRFD Bridge Design Specifications. This failure pattern is shown in Figure 3.2 and its associated strength calculation equations are shown below:

$$L_c = L_t + \sqrt{\frac{8M_w H_1}{M_{c,ave}}} \tag{3.1}$$

$$R_w = \left(\frac{H_1}{H_e}\right)\left[M_{c,base}\left(\frac{L_t}{H_1}\right) + M_{c,avg}\left(\frac{L_c - L_t}{H_1}\right) + M_w\left(\frac{8}{L_c - L_t}\right)\right] \tag{3.2}$$

where L_c = critical length of the failure pattern

L_t = length of the applied load

H_1 = height of the barrier

H_e = effective height of the applied load

M_w = Moment capacity of the wall about a vertical plane

$M_{c,base}$ = Overturning moment capacity at the base of the barrier

$M_{c,ave}$ = Average overturning moment capacity of the barrier

F_f = magnitude of the applied load

R_w = Strength capacity of the barrier

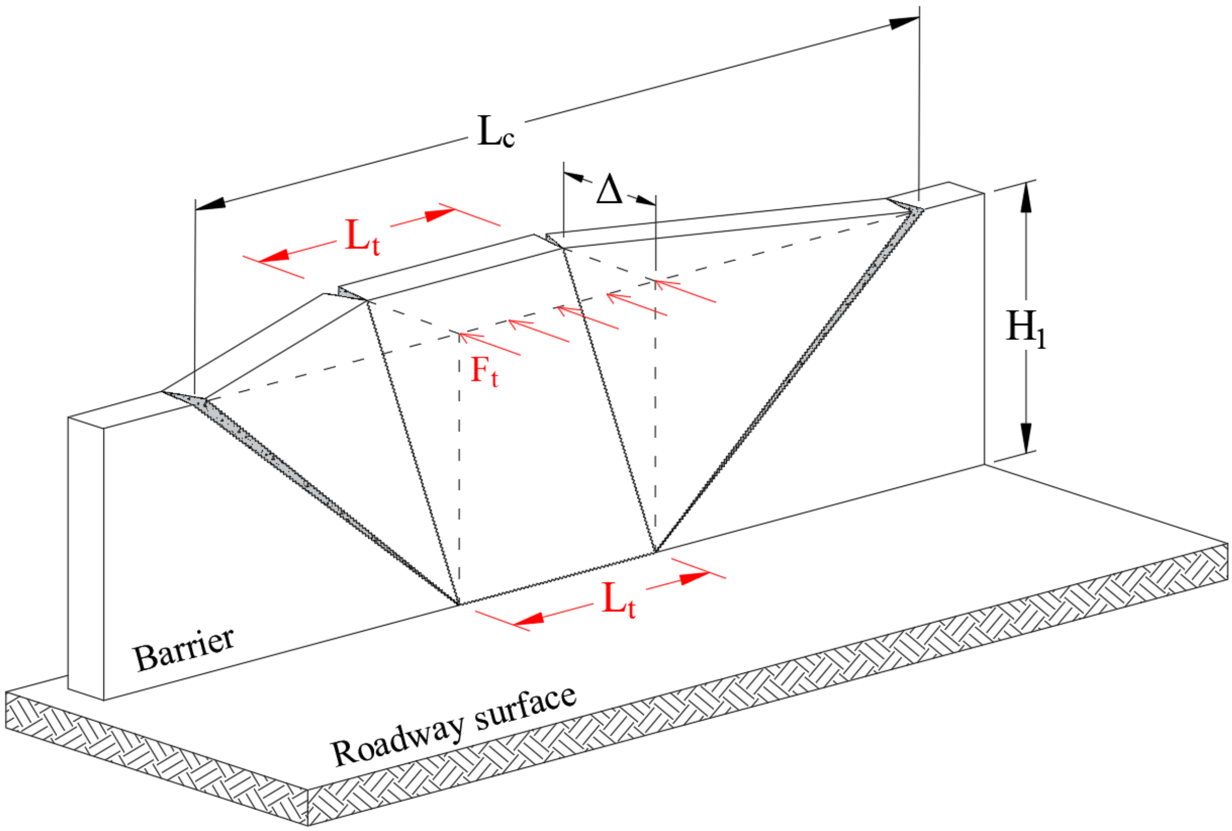


Figure 3.2 Trapezoidal Failure Pattern for Yield Line Theory Analysis [20]

As previously discussed in Section 1.1, test no. 7046-4 of the 1988 TTI instrumented wall involved a 1971 Peterbilt tractor with a 1968 Fruehauf tank-trailer weighing 79,900 lb impacting an instrumented wall at 54.8 mph and an angle of 16 degrees. The maximum load recorded by the wall load cells was 408 kips at an effective height of 56 in. In the previous phase of this research effort, MwRSF researchers evaluated TL-6 barrier design loads using LS-DYNA simulation with an uncalibrated tractor-tank trailer vehicle model. Barrier heights ranged from 50 in. to 90 in. at 5-in. increments, and the peak force from the simulation was estimated to be approximately 300 kip. The non-conservative maximum force estimate was potentially concerning for barrier strength. To ensure the barrier would be adequate to capture the vehicle, the maximum force predicted in the simulation was increased to accommodate the difference between the 90-in. tall vertical wall full-scale test and the simulation test. Using a top barrier height of 62 in., a conservative strength for the barrier capacity of 300 kip was used.

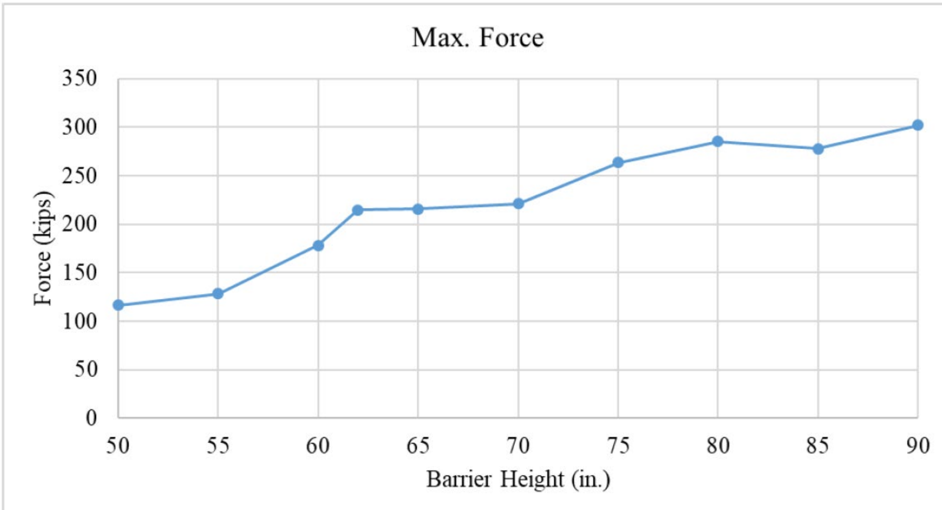


Figure 3.3 Maximum Force during Uncalibrated Vehicle Simulations with Different Wall Heights [15]

The simulated TL-6 impacts also showed two distinct load application heights. The tank applied high magnitude impact loads near the top of the simulated barriers, while the wheels applied significant load to the lower portion of the barrier. Further, the load applied at the top of the barrier by the tank typically accounted for about two-thirds of the total impact load. Therefore, the design loads for the new barrier were determined as 200 kips at the top of the barrier and 100 kips applied at the height of the center of the rear tandem axle, which was estimated to be 22 in. The length of the applied load, L_t, for a tractor-tank trailer was estimated to be 10 ft. Because the design loads were applied at two different heights, a weighted average was used to calculate an effective height of 48.7 in. The design loads are shown in Figure 3.4.

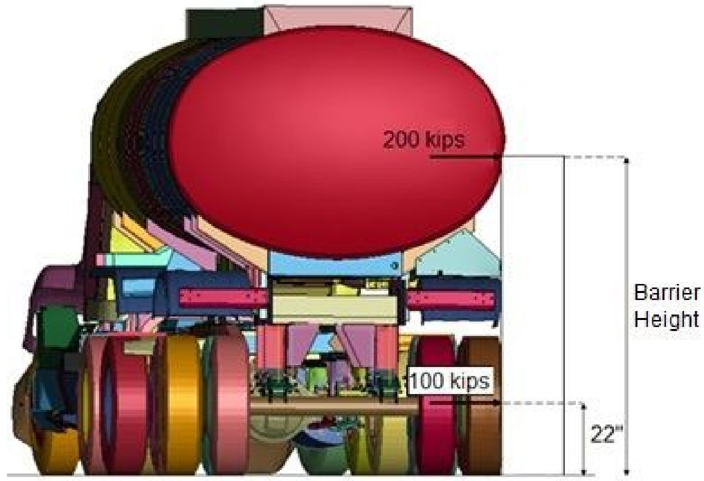


Figure 3.4 Barrier Design Loads

3.3 Barrier Reinforcement

Variables within the general design configuration included size and number of longitudinal bars, and size and spacing of stirrup bars. Both longitudinal and transverse steel bar size options included #4, #5, and #6 reinforcement. Longitudinal bar quantities included eight, ten, twelve, and fourteen, with the bars split evenly between the front and back faces of the TL-6 barrier. A 2-in. clear cover was required for all reinforcements.

The strength of each barrier configuration was calculated using modified yield-line equations, in which altering the current yield-line equations to account for the effective load height of an impact event results in the modified barrier strength, $R_{w\text{-}eff}$, being equal to the standard yield-line strength, R_w, multiplied by the ratio of the barrier height, H, over the effective load height, H_e. The relationship is shown in Equation 3.3.

$$R_{w-eff} = R_w \left(\frac{H}{H_e}\right) \tag{3.3}$$

Each design configuration was checked for punching shear failure along the top of the barrier, in which a block of concrete fails with diagonal tension breakout around the impact region. The punching shear capacity, V_n, was estimated via Equation 3.4, which is consistent with Equation 5.12.8.6.3-1 in *AASHTO LRFD Bridge Design Specifications*, as follows:

$$V_n = 0.125\lambda\sqrt{f_c'}b_0 d \tag{3.4}$$

Both flexural and punching shear capacities had to satisfy the 300-kip design load for a design configuration to be considered a viable option. Additionally, each design configuration was checked for separated cantilever bending strength, which separated the longitudinal-axis bending strength of the barrier M_c into a weighted average value above the base, $M_{c,avg}$, and the value at the horizontal yield-line, $M_{c,base}$, to better represent the physical mechanism during the impact events. The barrier strength can be calculated using Equations 3.5a and 3.5b.

$$R_{w,int.} = M_{c,base}\left(\frac{L_t}{H_1}\right) + M_{c,avg}\left(\frac{L_c - L_t}{H_1}\right) + M_w\left(\frac{8}{L_c - L_t}\right) \tag{3.5a}$$

$$L_{c,int.} = L_t + \sqrt{\frac{8M_wH_1}{M_{c,avg}}} \tag{3.5a}$$

All strength calculations were conducted on the double-sided configuration, as shown in Figure 3.1. Thus, the barrier design configuration, which consisted of a 10-in. top width, fourteen #6 longitudinal bars, and a #5 stirrup spaced at 12 in. on-center, satisfied the strength criteria and was selected for the new TL-6 concrete barrier. The barrier capacity for interior sections of this design was calculated to be 313 kips.

3.4 Barrier End Region Design

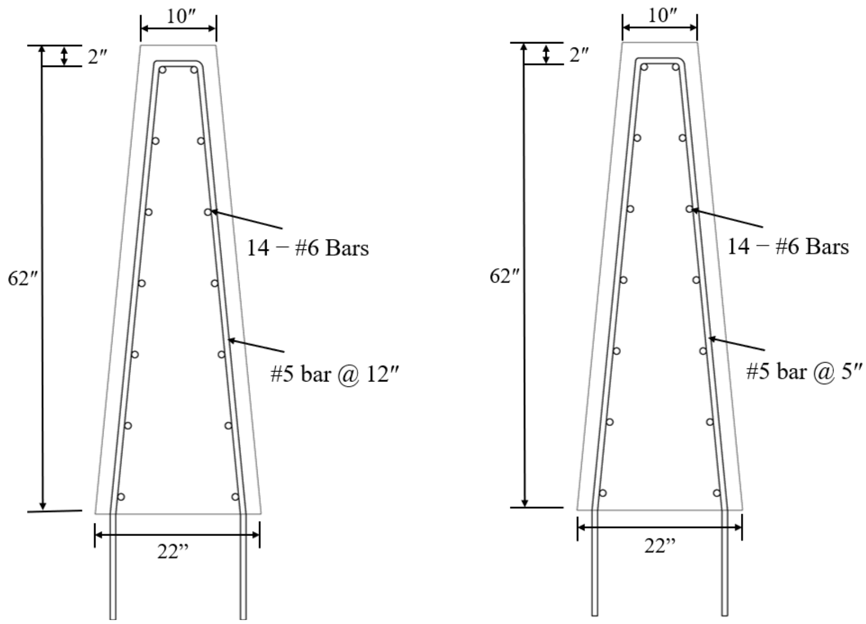
Barrier system end regions are found adjacent to discontinuities like expansion joints and at the ends of installations. Since the impact loads cannot be transferred across the open joint, end regions are susceptible to failure during impact events. The barrier end regions need additional reinforcement, additional width, or another mechanism to transfer loads.

The TL-6 barrier end region configuration was designed using the same methodology as the interior regions. The yield-line analysis equations for the end region calculations were used for the TL-6 barrier. The end configuration was checked for punching shear failure and separated cantilever bending strength, which can be estimated via Equations 3.6a and 3.6b.

$$R_{w,end} = \left[3 + \frac{L_c - L_t}{L_c - 0.5L_t}\right]^{-1} \left[8M_w \frac{1}{L_c - 0.5L_t} + 4M_{c,avg} \frac{L_c - 0.5L_t}{H} + 2M_{c,base} \frac{L_t}{H}\right] \quad (3.6a)$$

$$L_{c,end} = \frac{1}{8M_{c,avg}} \left[5M_{c,avg}L_t + \sqrt{M_{c,avg}\left(M_{c,avg}L_t^2 + 4M_{c,base}L_t^2 + 128HM_w\right)}\right] \quad (3.6a)$$

Additionally, the barrier width and longitudinal steel pattern were desired to remain the same for construction purposes. In this design, the stirrup spacing was varied to increase the barrier strength. Thus, the optimal barrier end region design configuration consisted of a 10-in. top width, fourteen #6 longitudinal bars, and a #5 stirrup spaced at 5 in. on-center, which provided a capacity of 308.8 kips. The calculated critical length of the end section was 14.3 ft. Cross sections for both the interior and end regions of the new TL-6 barrier are shown in Figure 3.5.



Interior region *End region, L_{cr} = 14.3 ft*

Figure 3.5 Cross Sections for TL-6 Concrete Barrier Design

3.5 Final Barrier Design Details

The test installation for the TL-6 median barrier was 187 ft – 6 in. long and consisted of an upstream and a downstream section of barrier separated by a ¾-in. wide expansion joint. The upstream section of the installation was approximately 37 ft – 6 in. long, and the downstream section was approximately 150 ft long. The system layouts are shown in Figures 3.6 through 3.11, and photographs of the test installation are shown in Figures 3.12 and 3.13. Material specifications, mill certifications, and certificates of conformity for the system materials are shown in Appendix A. The target impact location for the MTL6-1 full-scale crash test was at the expansion joint to maximize loading on the barrier and the potential for the tank trailer structure to contact and snag on the expansion joint gap between the upstream and downstream barrier sections.

The reinforced concrete barrier was 62 in. tall and had a single-slope front face that was 5.5 degrees from vertical on the front and back sides, as shown in Figure 3.8. The barrier system was specified with a concrete compressive strength of 5,000 psi; the actual test-day compressive strength averaged 4,613 psi. The bottom of the barrier was 22 in. wide, and the top of the barrier was approximately 10 in. wide with ¾-in. chamfers on both top edges.

The barrier was designed such that no load was exchanged between the upstream and downstream barrier segments across the ¾-in. wide expansion joint. To accomplish this objective, the barrier was designed with end sections and interior sections, as shown in Figure 3.6. The interior sections were designed to resist the design load as described in Chapter 3. The end sections were designed in accordance with yield-line theory, as recommended by the *AASHTO LRFD Bridge Design Specifications,* and measured approximately 14 ft – 4 in. long.

All steel rebar had a minimum yield strength of 60 ksi. The barrier was reinforced with seven equally-spaced #6 longitudinal bars on both the front and back sides of the barrier located $9^3/_{16}$ in. on center, with the bottom bar located at $3^3/_{16}$ in. and the upper bar located at $58^3/_{16}$ in., as shown in Figure 3.7. Vertical stirrup reinforcement consisted of two lapped and bent #5 stirrup bars embedded in MwRSF's existing concrete tarmac to a depth of 10 in. using Hilti HIT-RE 500 V3 epoxy anchor adhesive to develop the full strength of the bars. The stirrups were spaced 5 in. apart in the barrier end sections and 12 in. apart in the interior sections. A 2-in. clear cover was used around all concrete reinforcement.

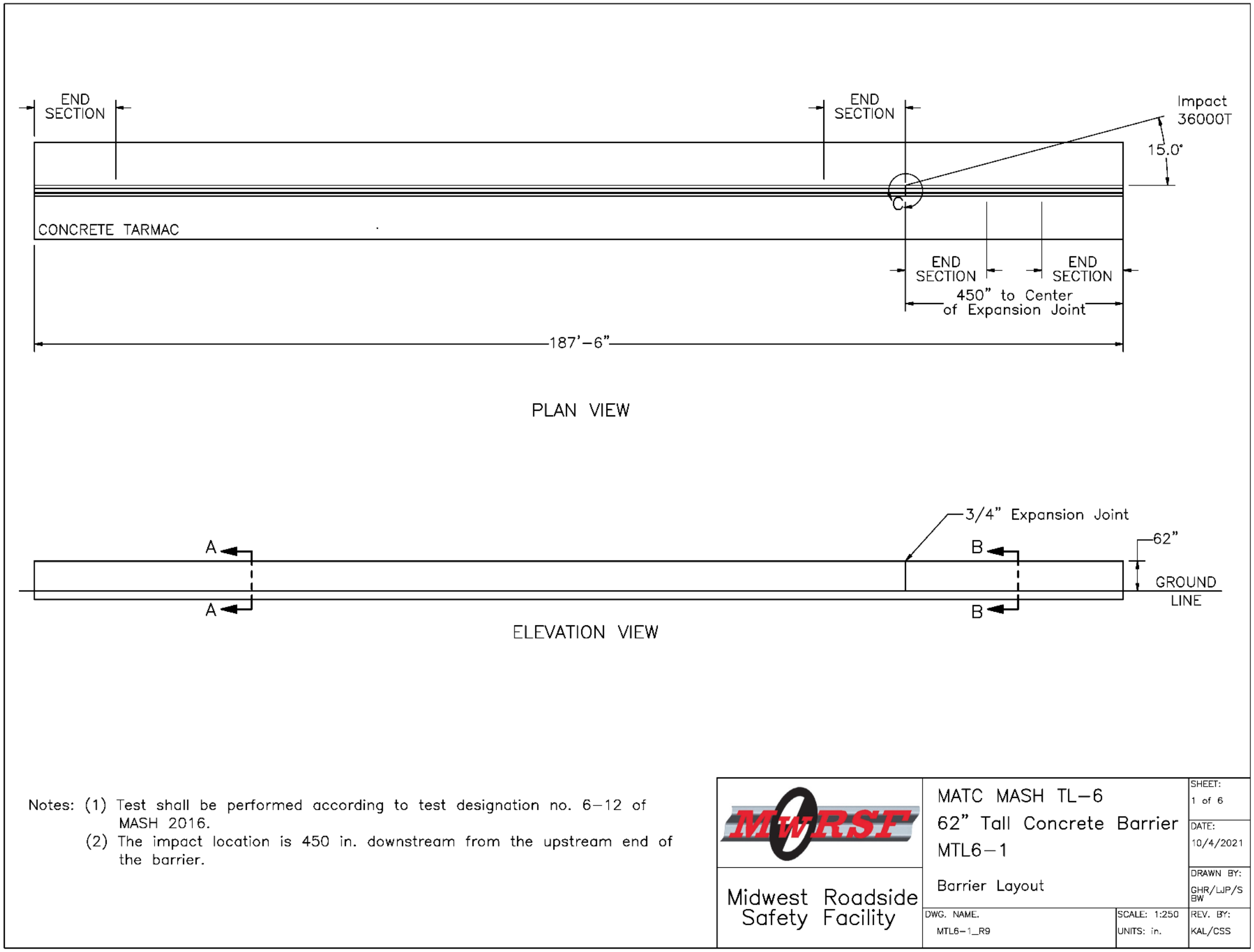


Figure 3.6 Barrier Layout, Test No. MTL6-1

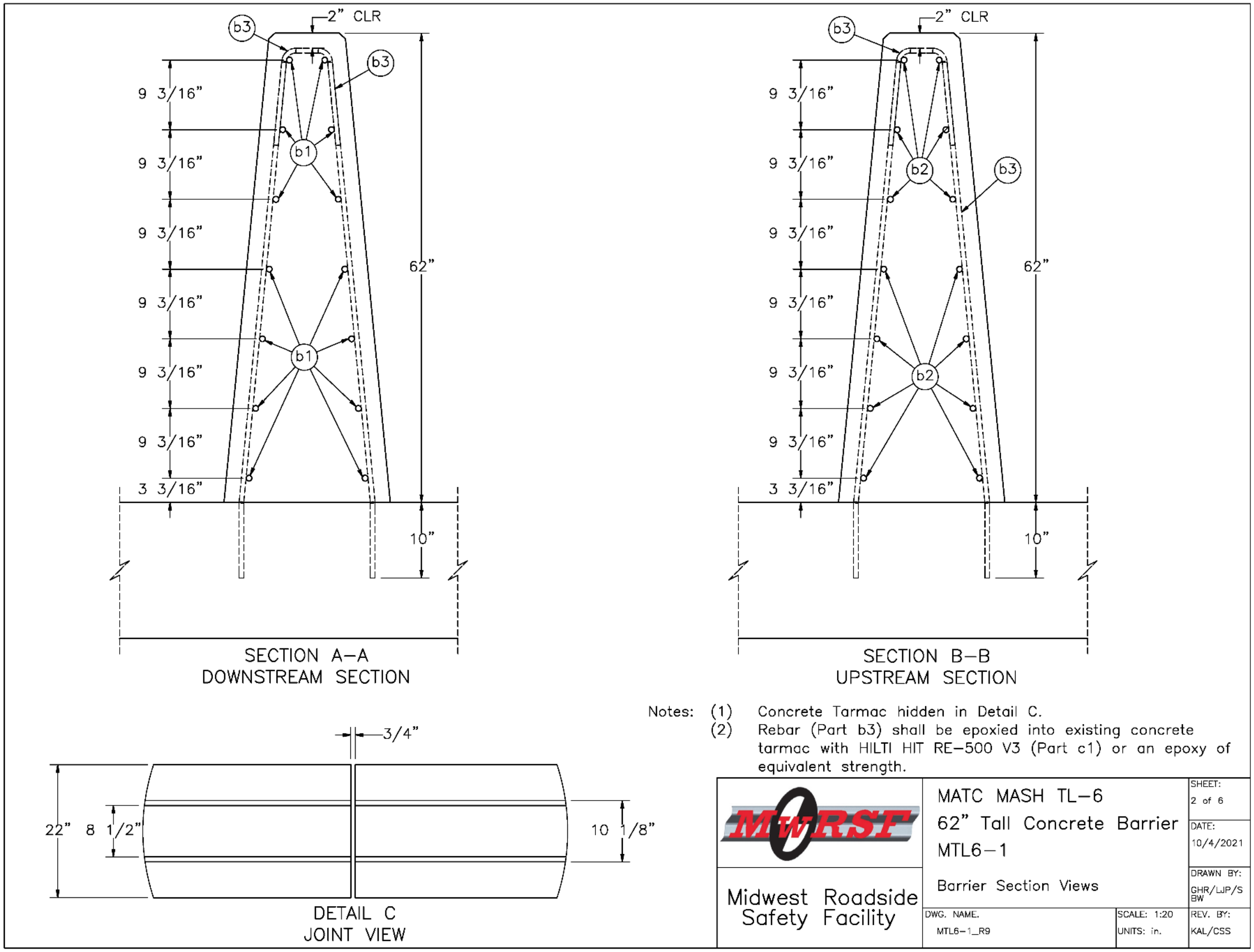


Figure 3.7 Barrier Section Views, Test No. MTL6 1

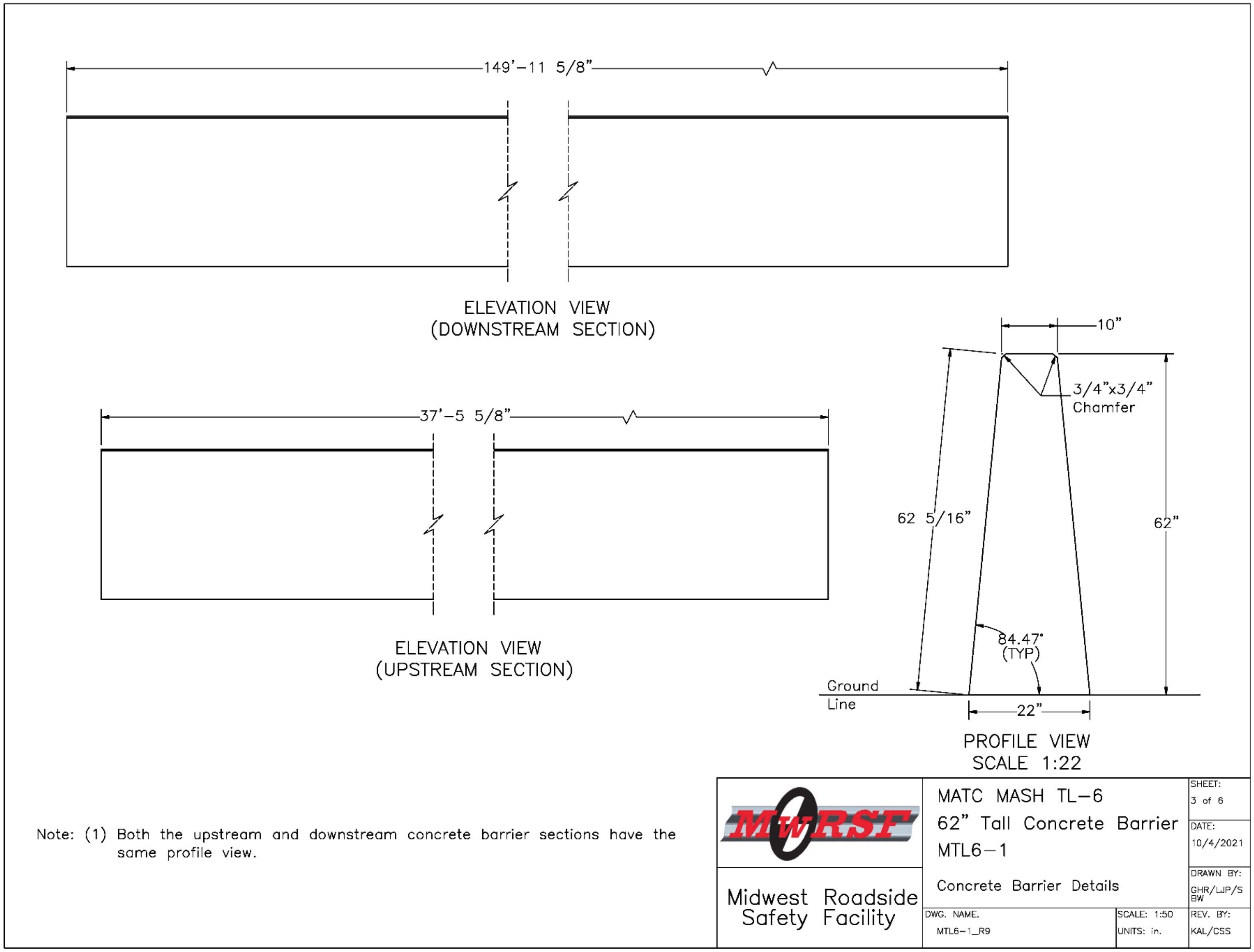


Figure 3.8 Concrete Barrier Details, Test No. MTL6 1

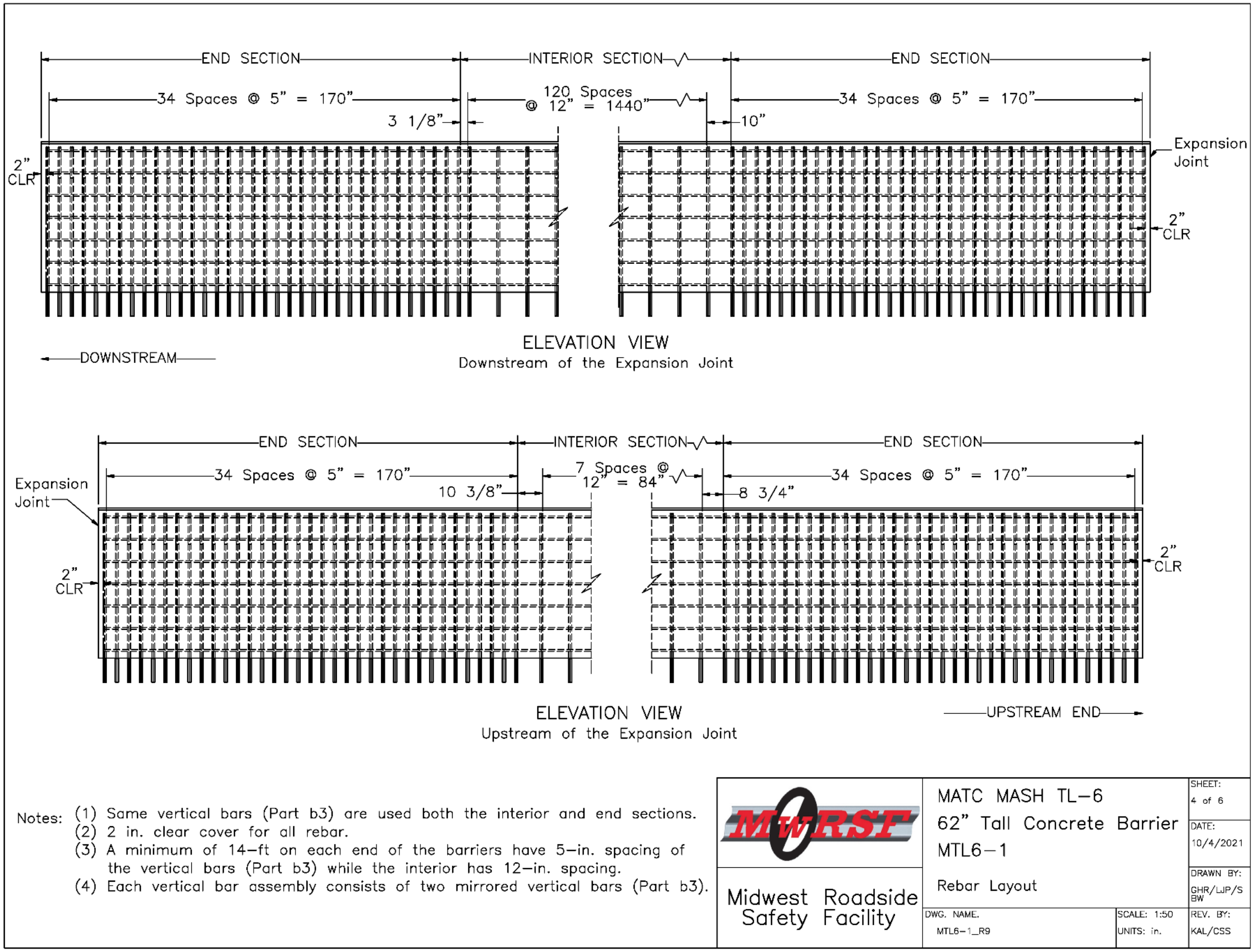
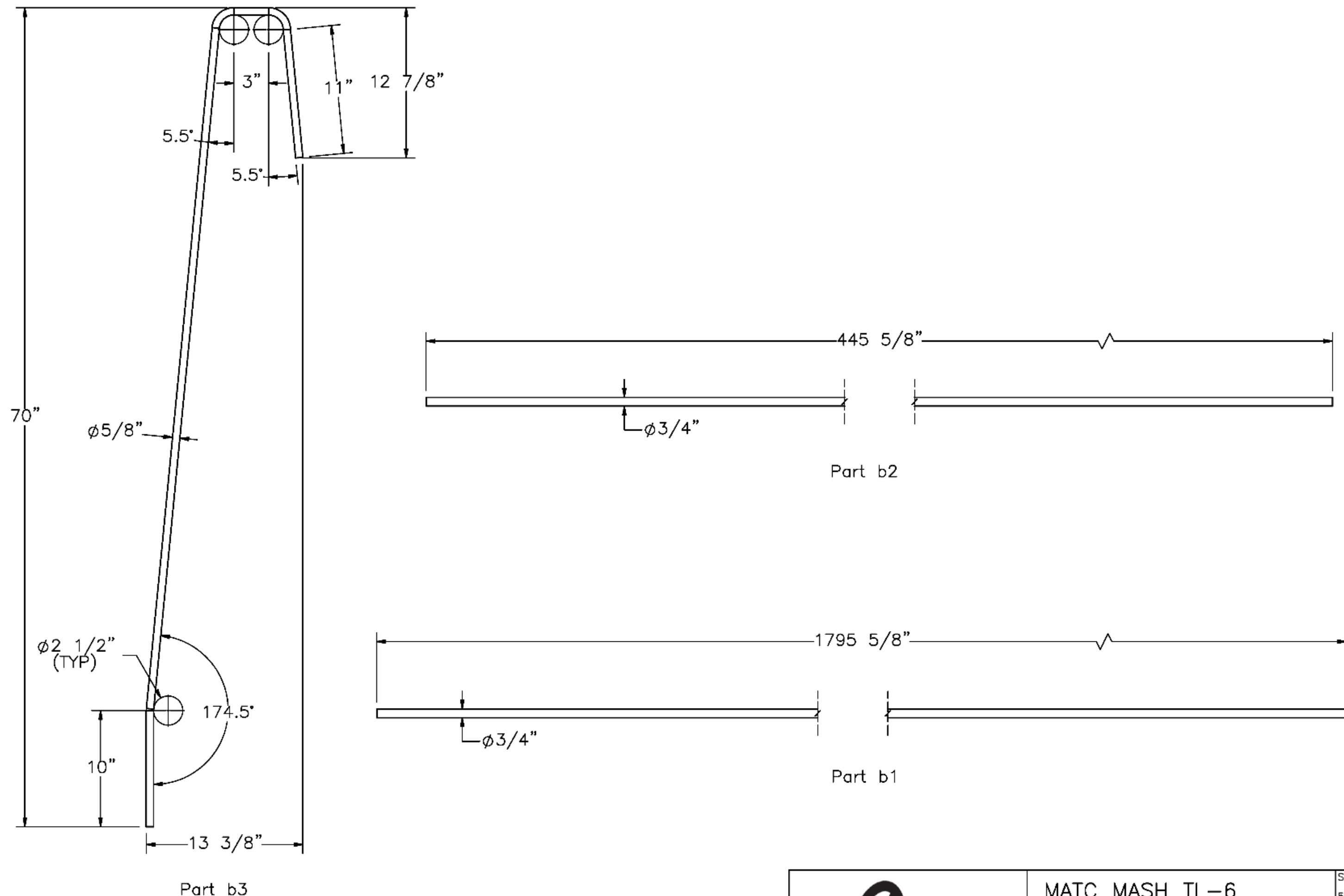


Figure 3.9 Rebar Layout, Test No. MTL6 1



BILL OF BARS

Item No.	QTY.	Size	Lap Length	Total Length	Material Specification
b1	14	#6	36"	1,795 5/8"	ASTM A615 Gr. 60
b2	14	#6	36"	445 5/8"	ASTM A615 Gr. 60
b3	538	#5	–	87 3/8"	ASTM A615 Gr. 60

MwRSF
Midwest Roadside Safety Facility

MATC MASH TL–6
62" Tall Concrete Barrier
MTL6–1

Rebar Details

SHEET: 5 of 6
DATE: 10/4/2021
DRAWN BY: GHR/LJP/SBW
DWG. NAME. MTL6–1_R9
SCALE: 1:12
UNITS: in.
REV. BY: KAL/CSS

Figure 3.10 Rebar Details, Test No. MTL6 1

Item No.	QTY.	Description	Material Specification	Treatment Specification	Hardware Guide
a1	–	Concrete	Min. f'c = 5.0 ksi	–	–
b1	14	#6 Rebar, 1,795 5/8" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b2	14	#6 Rebar, 445 5/8" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b3	538	#5 Rebar, 87 3/8" Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A394)	–
c1	–	Epoxy Adhesive	HILTI HIT RE-500 V3 or Equivalent	–	–

Midwest Roadside Safety Facility

MATC MASH TL-6
62" Tall Concrete Barrier
MTL6-1

Bill of Materials

SHEET: 6 of 6	DATE: 10/4/2021	DRAWN BY: GHR/LJP/SBW	REV. BY: KAL/CSS
DWG. NAME. MTL6-1_R9	SCALE: None	UNITS: in.	

Figure 3.11 Bill of Materials, Test No. MTL6 1

(a)

(b)

Figure 3.12 Rebar Configuration in (a) Interior Section (b) End Section, Test No. MTL6-1

Figure 3.13 Test Article Construction, Test No. MTL6-1

Figure 3.14 MwRSF Optimized TL-6 Single-Slope Barrier Installation, Test No. MTL6-1

Chapter 4 Test Requirements and Evaluation Criteria

4.1 Test Requirements

Longitudinal barriers must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the FHWA for use on the National Highway System. For new hardware, these safety standards consist of the guidelines and procedures published in MASH [2]. According to TL-6 of MASH, longitudinal barrier systems must be subjected to three full-scale vehicle crash tests, as summarized in Table 4.1. However, only the 36000T crash test was deemed necessary, as prior research and crash testing have demonstrated that single-slope concrete barriers with heights of greater than or equal to 36 in. were crashworthy to MASH TL-4 [21-24].

Table 4.1 MASH TL-6 Crash Test Conditions for Longitudinal Barriers

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight lb	Impact Conditions		Evaluation Criteria [1]
				Speed mph	Angle deg.	
Longitudinal Barrier	6-10	1100C	2,420	62	25	A,D,F,H,I
	6-11	2270P	5,000	62	25	A,D,F,H,I
	6-12	36000T	79,300	50	15	A, D, G

1 Evaluation criteria explained in Table 4.2.

4.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three factors: (1) structural adequacy; (2) occupant risk, and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the barrier to contain and redirect impacting vehicles. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 4.2 and defined in greater detail in MASH. The full-scale vehicle crash test was conducted and reported in accordance with the procedures provided in MASH [2].

In addition to the standard occupant risk measures, the Post-Impact Head Deceleration (PHD), the Theoretical Head Impact Velocity (THIV), and the Acceleration Severity Index (ASI) were determined and reported. Additional discussion on PHD, THIV and ASI is provided in MASH [2]. Note that PHD, THIV, and ASI are not associated with MASH evaluation criteria for test designation 6-12.

Table 4.2 MASH Evaluation Criteria for Longitudinal Barrier

<table>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">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.</td></tr>
<tr><td rowspan="12">Occupant Risk</td><td>D.</td><td colspan="3">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. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td>G.</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s</td><td>40 ft/s</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
</table>

Chapter 5 Test Conditions

5.1 Test Facility

The Outdoor Test Site is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles northwest of the University of Nebraska-Lincoln.

5.2 Vehicle Tow and Guidance System

A ⅜-in. diameter, reverse-cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicles were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the barrier system. A digital speedometer on the tow vehicle increased the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch [25], was used to steer the test vehicle. Two tow vehicles were connected using a rigid tow bar between the chassis of the trailing truck and the tow hitch of the leading truck. A guide flag, attached to the right-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. diameter guide cable was tensioned to approximately 3,500 lb and supported both laterally and vertically every 100 ft by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide flag struck and knocked each stanchion to the ground. The vehicle was guided through a protective “chute” formed using portable concrete barriers to assist with capture and containment of the vehicle in the event of a guidance system disruption, as shown in Figure 5.1. The tow cable attachment to the vehicle is shown in Figure 5.2.

Figure 5.1 Guidance Chute, Test No. MTL6-1

Figure 5.2 Test Vehicle Guidance System, Test No. MTL6-1

5.3 Test Vehicle

For test no. MTL6-1, a 2010 Columbia 112 Freightliner tractor and 1996 Fruehauf (LBT) BKZ 4466 tank trailer was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 25,614 lb, 79,864 lb, and 80,026 lb, respectively. The test vehicle is shown in Figures 5.3 through 5.5. The vehicle dimensions are shown in Figure 5.6 and trailer dimensions are shown in Figure 5.7.

The test vehicle consisted of two separate entities: the truck and trailer, which were connected with a pinned bracket connection known as the “fifth wheel.” The truck was less than 12 years old as specified by MASH requirements for heavy trucks. The trailer consisted of a 1996 Fruehauf (LBT) BKZ 4466 trailer. Note that although MASH provides a recommended 12-year maximum age of the test vehicle, no guidance was provided for recommended age of the trailer. Thus, the research team selected a trailer which was consistent with the dimensions shown in MASH, with construction similar to in-production models of trailers, and which was similar to the model used in computer simulations. The trailer had a payload capacity of 9,500 gallons distributed in four tanks. The four tanks had capacities of 4,000 gal, 1,200 gal, 1,500 gal, and 2,800 gal from front to back, respectively. The rear tandem to the fifth wheel connection was 34 ft – 9 in. long, and 32 ft – 11½ in. measured from the center of the rear tandem axle to the estimated center of the truck tandem rear axle. The overall trailer length was 42 ft – 6 in. The trailer tank jacket, bulkheads, baffles, and pipe connections were constructed from aluminum alloy structural materials consistent with modern liquid petroleum transport tank specifications.

The truck was connected to the trailer using an SAF Holland Group FW35 SAF Holland Fifth Wheel with an 8-in. integrated plate mount. The specifications for the fifth wheel are shown in Figures 5.8 and 5.9. Images of the fifth wheel connection are shown in Figures 5.10 and 5.11.

Prior to the test, the test vehicle consisting of the tractor, tank trailer, and fifth wheel assembly were mapped to a colorized point cloud using a FARO Focus X130 with an accuracy of 0.1 in. and a resolution of ±0.02 in. Scans were collected for pre-test and post-test geometry and the final resting position of the vehicle relative to the point of impact. The pre-test scan of the test vehicle is shown in Figure 5.12.

The c.g. for the 36000T vehicle was not determined, but the longitudinal and vertical locations of the ballast c.g. were calculated. For each compartment, the top fill height from the bottom of the jacket to the top of the jacket was approximately 65½ in. The ballast heights recorded for tanks 1, 2, 3, and 4, as measured from the fifth wheel toward the rear tandem axle, were 37 in., 59⅜ in., 46½ in., and 39½ in., respectively. Although it is generally recommended that tank-trailer vehicles increase the payload fill in the front and rear tanks, leaving the middle two tanks filled to the lowest fill levels, the as-tested configuration was necessary to meet the ballast and weight distribution requirements. The final ballast configuration is shown in Figure 5.13. Ballast information and data used to calculate the location of the c.g. are shown in Appendix B.

Figure 5.3 Test Vehicle, Test No. MTL6-1

Figure 5.4 Pre-Test Photos of Truck on Impact Side, Test No. MTL6-1

Figure 5.5 Test Vehicle, Test No. MTL6-1

Test Name: MTL6-1

Tractor:

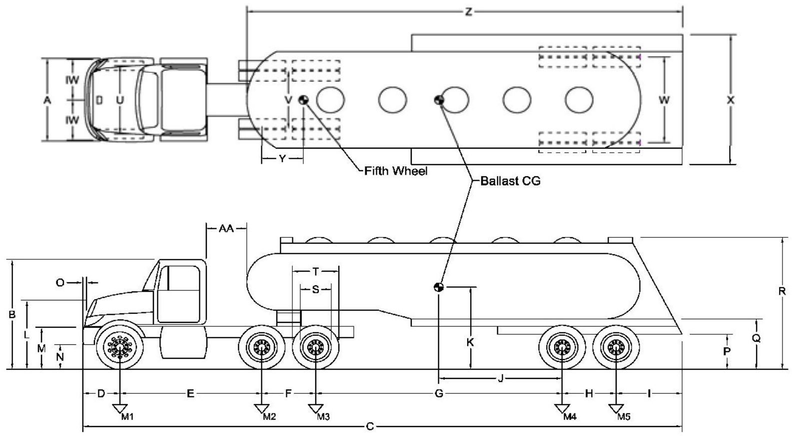
Model Year:	Make:	Model:	VIN No.:
2010	Freightliner	Columbia 112	1FUJFOCV2ADAV1130

Odometer: 503917.9

Trailer:

Model Year:	Make:	Model:	VIN No.:
1996	Fruehauf Trailer Co.	Tanker Trailer	8VT 001601

Vehicle Geometry - in. (mm)
Target Ranges listed below



A: 94 3/4 (2407 mm)				
B: 108 3/4 (2762 mm)				
C: 701 (17805 mm) Max: 780 (19850)				
D: 50 1/4 (1276 mm)				
E: 155 (3937 mm)				
F: 51 1/4 (1302 mm)				
G: 362 1/4 (9201 mm)				
H: 49 (1245 mm)				
I: 33 1/4 (845 mm) Max: 73 (1850)	M: 31 1/4 (794 mm)	Q: 45 1/2 (1156 mm)	U: 84 1/8 (2137 mm)	Y: 16 (406 mm)
J: 282 3/16 (7168 mm)	N: 12 (305 mm)	R: 120 1/2 (3061 mm)	V: 75 5/8 (1921 mm)	Z: 481 (12217 mm)
K: 77 1/8 (1959 mm) 81±4 (2050±100)	O: 2 (51 mm)	S: 28 3/8 (721 mm)	W: 73 1/4 (1861 mm)	AA: 75 3/4 (1924 mm)
L: 63 1/4 (1607 mm)	P: 35 (889 mm)	T: 39 1/2 (1003 mm)	X: 98 (2489 mm)	IW: 44 3/8 (1127 mm)

Weights - lb (kg)

	Curb	Test Inertial	Gross Static
M1:	8,562 (3,884 kg)	10,145 (4,602 kg)	10,145 (4,602 kg)
M2:	4,760 (2,159 kg)	17,544 (7,958 kg)	17,544 (7,958 kg)
M3:	4,412 (2,001 kg)	16,625 (7,541 kg)	16,625 (7,541 kg)
M4:	3,220 (1,461 kg)	15,300 (6,940 kg)	15,300 (6,940 kg)
M5:	4,660 (2,114 kg)	20,250 (9,185 kg)	20,250 (9,185 kg)
Total:	25,614 (11,618 kg) 29,000±3,100 (13,200±1,400)	79,864 (36,226 kg) 79,300±1,100 (36,000±500)	79,864 (36,226 kg)

Tractor Wheel Base: 180 5/8 (4588 mm) Max: 200 (5100)

Longitudinal C.G.: 342 7/16 (8698 mm)

Ballast Weight - lb (kg): 55,111 (24,998 kg)

Vertical C.G. not measured or recorded

Wheel Center Height M1:	19 (483 mm)
Wheel Center Height M2:	19 5/8 (498 mm)
Wheel Center Height M3:	19 5/8 (498 mm)
Wheel Center Height M4:	20 (508 mm)
Wheel Center Height M5:	19 1/2 (495 mm)

Surrogate Occupant Data

Type: Hybrid II
Mass: 161 lb
Seat Position: Left/Driver

Engine Type: Diesel
Engine Size: 12.8L I6
Transmission Type: Manual
Drive Type: RWD

Note any damage prior to test: No significant damage, scrapes, dings only.

Figure 5.6 Vehicle Dimensions, Test No. MTL6-1

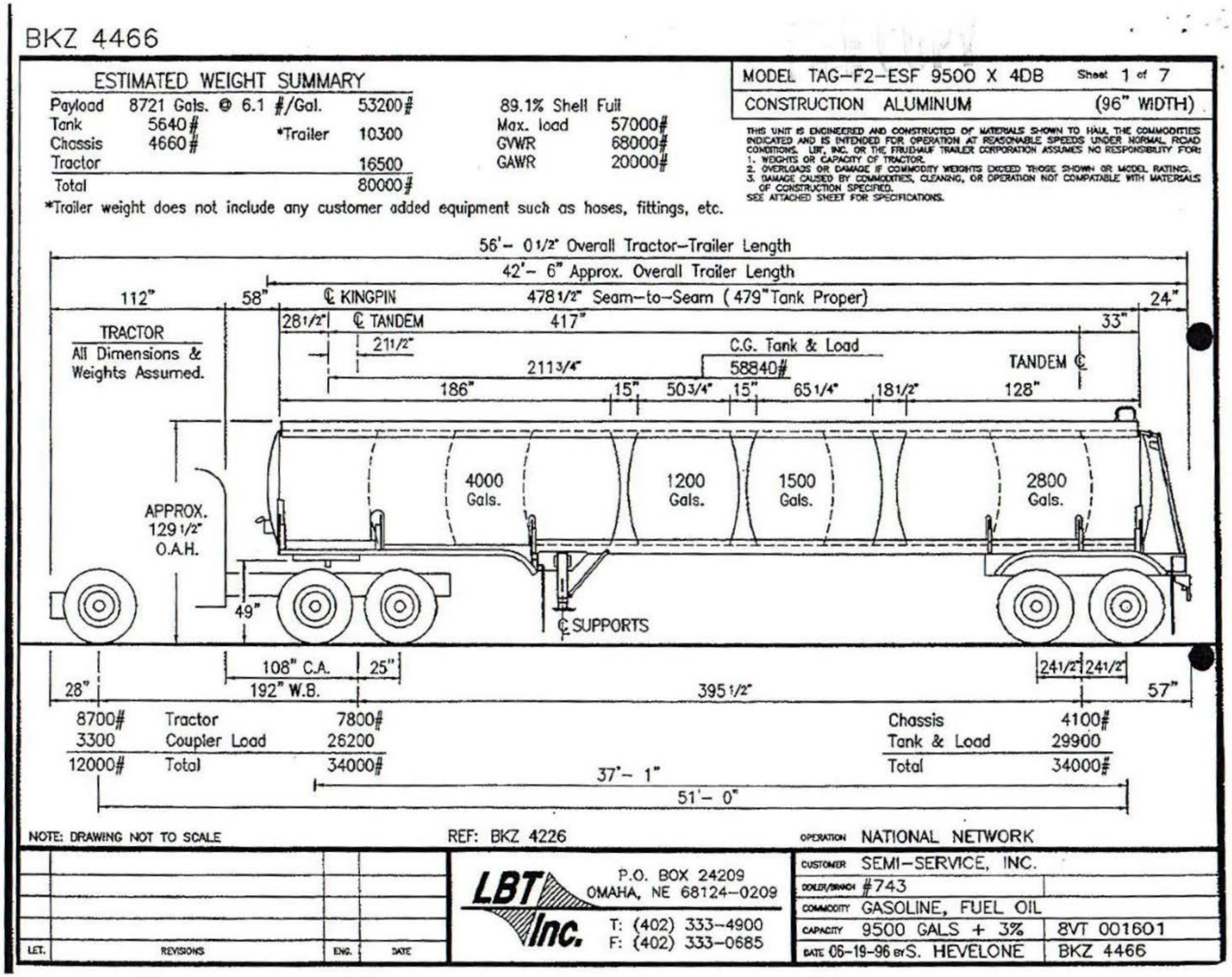
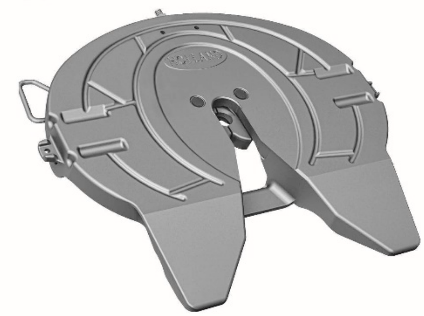


Figure 5.7 Trailer Dimensions, Test No. MTL6-1

FW35



Capacity

55,000 lbs. Maximum Vertical Load
150,000 lbs. Maximum Drawbar Pull

Applications

Standard, Moderate, and Severe Duty
(Refer to Applications Guidelines (pages 6-8) for limitations and restrictions.)

Features

- Cast Steel Construction
- Forged, Machined, Heat-Treated Steel Lock Jaw
- Visible Lock Indicator
- Easy Infinite Lock Adjustment
- Automatic Secondary Lock
- Closed Loop Drop Handle
- NoLube™ Pocket Inserts
- Cast-In Grease Grooves

Warranty

- 6 Year/600,000 Mile Materials and Workmanship
- 6 Year/600,000 Mile Performance Guarantee

Options Available

- Right Hand Release Handle
- Air Release (Left Hand Release Only)
- Drilled and Tapped for Auto Lube
- Dolly Release Handle
- No-TILT
- ELI-te™ (For ELI-te™ Option Codes, see Page 10)

Top Plate Part Numbers

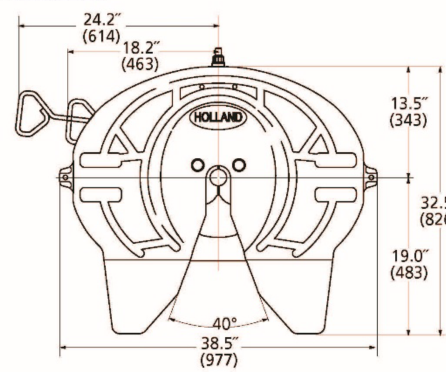
DESCRIPTION	PART NUMBER	WEIGHT
Left Hand Release	XA-351-A-L-P	226 lbs.
Right Hand Release	XA-351-A-P	226 lbs.
For options, insert one of the following codes after the 6th digit. Example: XA-351-A-86-L-P. For multiple option combinations, please contact Customer Service for applicable Option Code.		
Air Release – OEM Installation		Code 80
Air Release – Aftermarket Retrofit		Code 86
Drilled and Tapped for Auto Lube		Code 24
Dolly Release Handle (LH Only)		Code 28
No-Tilt Stationary		Code 06
No-Tilt Slider – Change "A-" to "A1-"		Code 06

Mounting Systems Available

For Complete Assembly Part Numbers refer to "Mounting System" pages.
NOTE: Height and Travel data is given in INCHES

STATIONARY STYLES	HEIGHTS	
STANDARD BASES		
Foot Mount	6, 7, 8, 9	
Integrated Plate Mount		
Brackets Only		
NO-TILT BASES		
Outboard Mount	8, 9	
Inboard for Angle Mounting	8	
KOMPENSATOR® BASES		
Outboard Plate Mount	10, 12, 13	
SLIDING STYLES	**HEIGHTS**	**TRAVELS**
STANDARD BASES		
ILS Outboard Mount	7, 8, 9, 10	12, 24, 36, 48
ILS Inboard Mount		
NO-TILT BASES		
ILS Outboard Mount	9	6, 18, 30, 42
ILS Inboard Mount		
KOMPENSATOR® BASES		
SDS Inboard	13	12, 24, 36, 48, 60, 72
SDS Outboard		

Dimensions

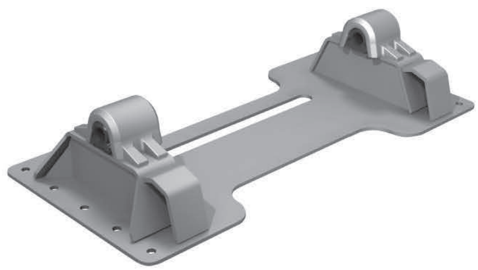


Rebuild and Replacement Kits

DESCRIPTION	RELEASE	PART NUMBER
Rebuild-Standard	LH	RK-351-A-L
Rebuild-Standard	RH	RK-351-A
Rebuild-w/Manual Secondary Release	LH	RK-351-A-02-L
Rebuild-w/Manual Secondary Release	RH	RK-351-A-02
Rebuild-w/Air Release	LH	RK-351-A-80-L
Lock Replacement Kit		RK-351-07296
Release Handle Replacement Kit	LH/RH	RK-08415-1
Pocket Inserts - Pair		RK-PKT-2

Figure 5.8 Holland FW35 Fixed Fifth Wheel Mount, Test No. MTL6-1 [26]

Integrated Plate Mount



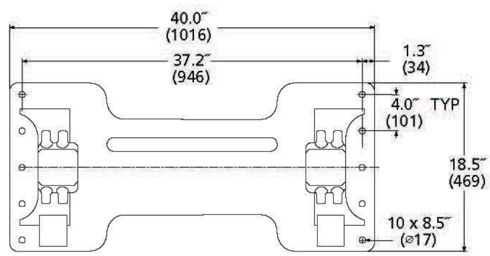
Applications

Bolt-On Outboard Angle Applications
Fifth Wheels: FW17, FW31, FW33, FW35, FWAL

Features

- Lightweight 5/16″ Plate Base
- Fabricated Steel Construction
- Forged Steel Cap
- Nylon Lined "Up-Shock" Bushing

Dimensions



Part Numbers

FIFTH WHEEL ASSEMBLY MODEL NUMBER (1) (2) (3)	HEIGHT	WEIGHT (4)
FW__Z600XL00	6″	243 lbs.
FW__Z700XL00	7″	251 lbs.
FW__Z800XL00	8″	258 lbs.
FW__Z900XL00	9″	254 lbs.

(1) __ = One of the following two digit top plate model numbers: 17, 31, 33, 35, AL.

(2) For Right Hand (curb-side) Release Handle, replace L (10th digit) in part number with R. Right hand release available on FW31, FW33 and FW35.

(3) For options, replace the 00 at the end of the part number with the appropriate two digit code. For multiple option combinations, please contact Customer Service for the applicable Option Code.

- **Air Release** – Available on FW17, FW31, FW33, FW35 and FWAL – ***Option Code-80***
- **Drilled and Tapped for Auto Lube** – Available on FW35 – ***Option Code-24***
- **Left Hand Dolly Release Handle** – Available on FW33 and FW35 – ***Option Code-28***
- **For ELI-te™ Option Code, see page 10**

(4) Weights shown are for FWAL (add 6 lbs. for air release). Add the following based on top plate model:

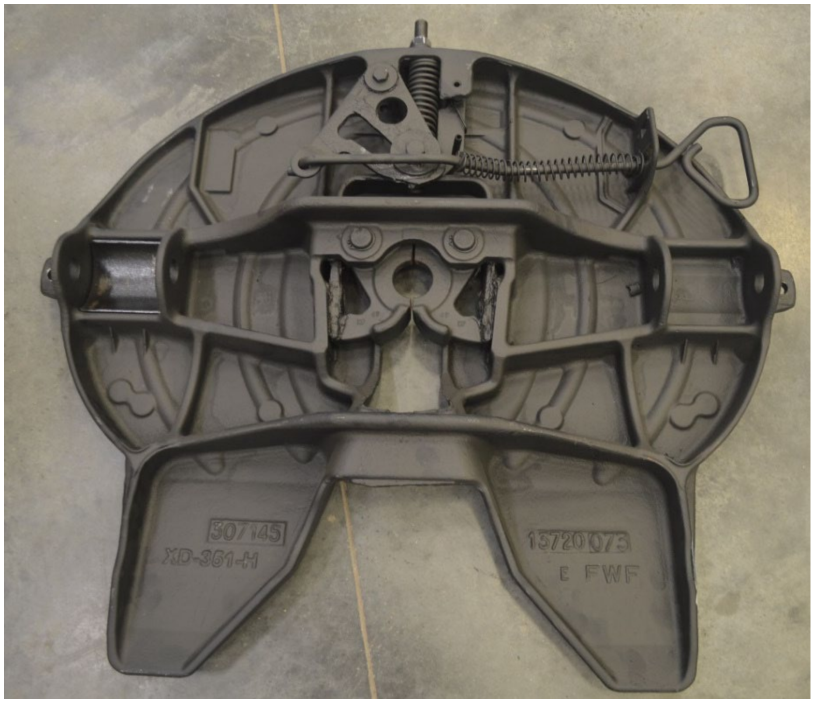
FIFTH WHEEL MODEL	MANUAL RELEASE	AIR RELEASE
FW17	45 lbs.	51 lbs.
FW31	94 lbs.	98 lbs.
FW33	94 lbs.	98 lbs.
FW35	69 lbs.	73 lbs.

Figure 5.9 Bracket-to-Frame Attachment, Holland Fixed Fifth Wheel Mount, Test No. MTL6-1 [26]

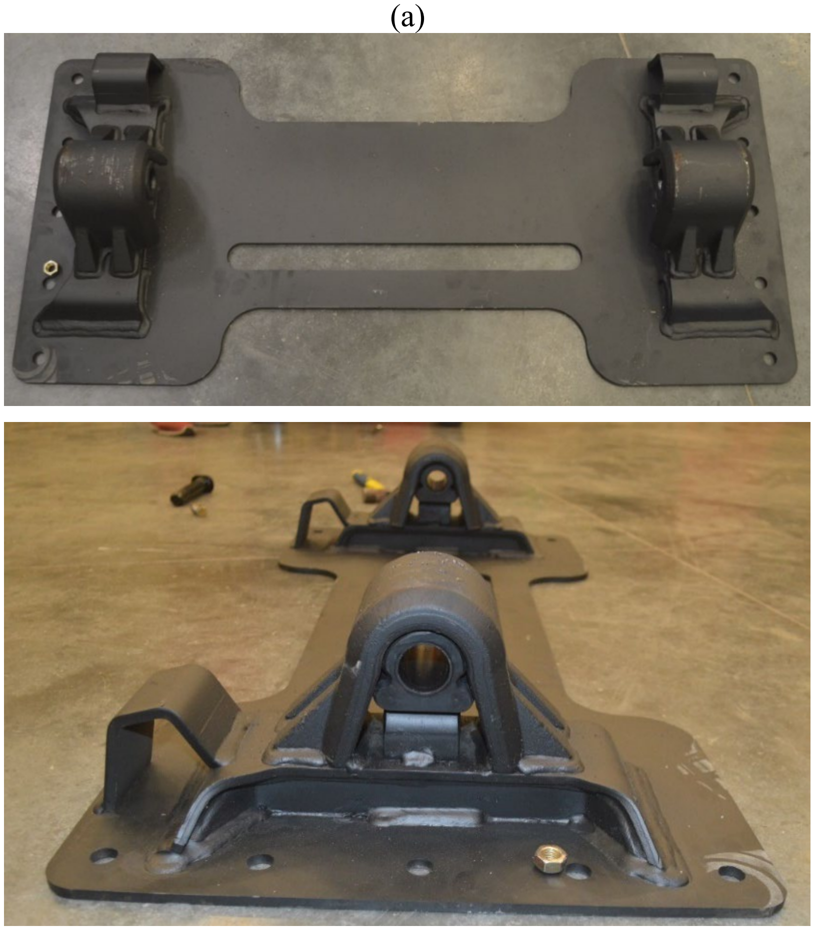
(a)

(b)

Figure 5.10 Fifth Wheel Installation: (a) Sliding Fifth Wheel on Truck As-Received and (b) Holland FW-35 Model Fifth Wheel Installed on Truck, Test No. MTL6-1



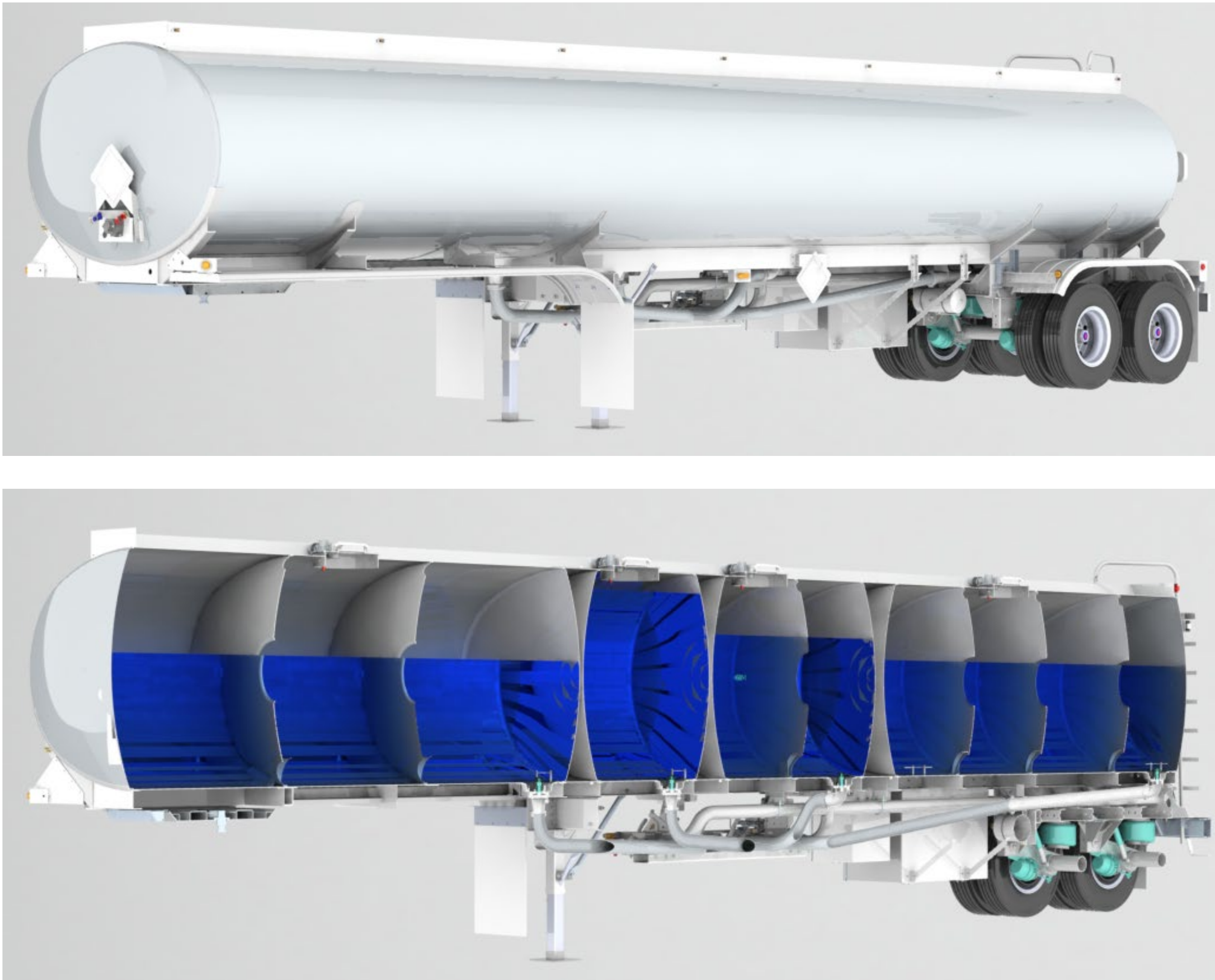
(a)



(b)

Figure 5.11 Holland FW-35 Fifth Wheel Details: (a) Top Plate and (b) Bracket, Test No. MTL6-1

Figure 5.12 Images of 3D Point Clouds of Test Vehicle, Test No. MTL6-1



Note: Trailer model shown is BKZ 5949, although tested trailer was BKZ 4466.

Figure 5.13 Ballast Fill Heights, Test No. MTL6-1

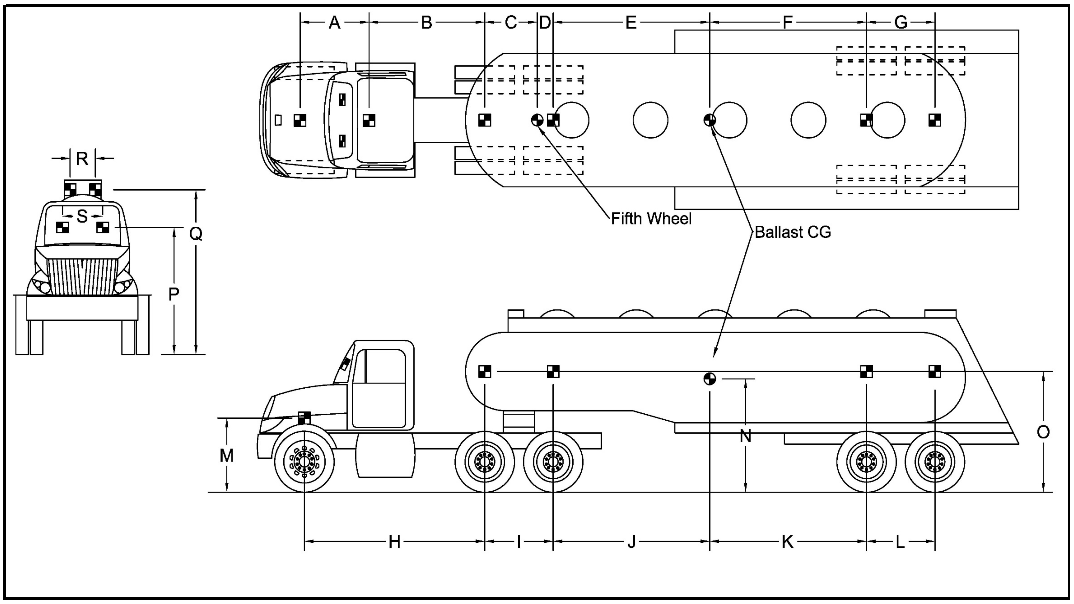
Square, checkered targets were placed on the vehicle, as shown in Figure 5.14, to serve as a reference in the high-speed digital video and aid in the video analysis. Round, checkered targets were placed on the sides and roof of the tank to mark the location of the ballast c.g. An additional round, checkered target was placed on the roof of the tank to mark the c.g. location of the fifth wheel.

The front wheels of the test vehicle were aligned to vehicle standards except the toe-in value was adjusted to zero such that the vehicle would track properly along the guide cable. A

5B flash bulb was mounted under the vehicle's left-side windshield wiper and was fired by a pressure tape switch mounted at the impact corner of the bumper. The flash bulb was fired upon initial impact with the test article to create a visual indicator of the precise time of impact on the high-speed digital videos. A radio-controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

Test Name: MTL6 **VIN:** 1FUJFOCV2ADAV1130

Model Year: 2010 **Make:** Freightliner **Model:** Columbia 112



TARGET GEOMETRY-- in. (mm)

A: 62 7/16 (1586)	G: 38 1/4 (972)	N: 77 1/8 (1959)
B: 114 1/4 (2902)	H: 155 5/8 (3953)	O: 90 (2286)
C: 16 (406)	I: 51 1/4 (1302)	P: 90 (2286)
D: 38 5/16 (973)	J: 152 7/8 (3883)	Q: 123 (3124)
E: 144 15/16 (3681)	K: 208 1/16 (5285)	R: 32 (813)
F: 221 1/2 (5626)	L: 152 7/8 (3883)	S: 42 1/2 (1080)
	M: 47 3/4 (1213)	

Figure 5.14 Target Geometry, Test No. MTL6-1

5.4 Data Acquisition Systems

5.4.1 Accelerometers and Rate Transducers

Three environmental shock and vibration sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. The first two systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. The acceleration sensors were mounted inside the bodies of custom-built SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software programs and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The third accelerometer system, DTS, was a two-arm piezoresistive accelerometer system manufactured by Endevco of San Juan Capistrano, California. Five independent accelerometers were used to measure the longitudinal (2), lateral (2), and vertical accelerations at a sample rate of 10,000 Hz. The accelerometers were configured and controlled using a system developed and manufactured by DTS. More specifically, data was collected using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M. The SIM was configured with 16 MB SRAM and 8 sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack. The module rack was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. Both the SIM and module rack were crashworthy. The "DTS TDAS Control" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data. The electronic accelerometer data obtained from all accelerometers was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [27].

Each of the accelerometer systems was placed at a different location along the vehicle. The SLICE-1 unit was mounted inside the cab, while the SLICE-2 unit was mounted directly above the fifth wheel, and the TDAS unit was mounted at the rear tandem axle. Locations of the accelerometers are shown in Figure 5.15.

Figure 5.15 Accelerometer Mounting Locations, Test No. MTL6-1

5.4.2 Retroreflective Optic Speed Trap

A retroreflective optic speed trap was used to determine the speed of the test vehicle before impact. Five retroreflective targets, spaced at approximately 18-in. intervals, were applied to the side of the vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the data acquisition computer, recording at 10,000 Hz, as well as the external LED box activating the LED flashes. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are used as a backup if vehicle speeds cannot be determined from the electronic data.

5.4.3 Linear Transducers and Strain Gauges

Eight linear potentiometers were installed on the back side of the barrier near the top, as seen in Figure 5.16. Two were placed downstream from the expansion joint and six were placed upstream. Strain gauges were placed on reinforcing bars both upstream and downstream from the expansion joint, as illustrated in Figure 5.17. Each linear potentiometer had a 0.90-in. diameter cross-section with an operational temperature range between -40 and 190°F and up to 95 percent humidity, was rated to IP64 (dust and water resistant), and utilized rod end joints for increased mounting flexibility. The strain gauges were single-axis GOBLET F-series foil strain gauges with a 5-mm gauge length and 350 Ohm gauge resistance. During testing, output voltage signals were sent from the transducers to a National Instruments PCI-6071E data acquisition board, acquired with LabView software, and stored on a personal computer at a sample rate of 10,000 Hz. Specifications for the foil strain gauges are shown in Figures 5.18 and 5.19.

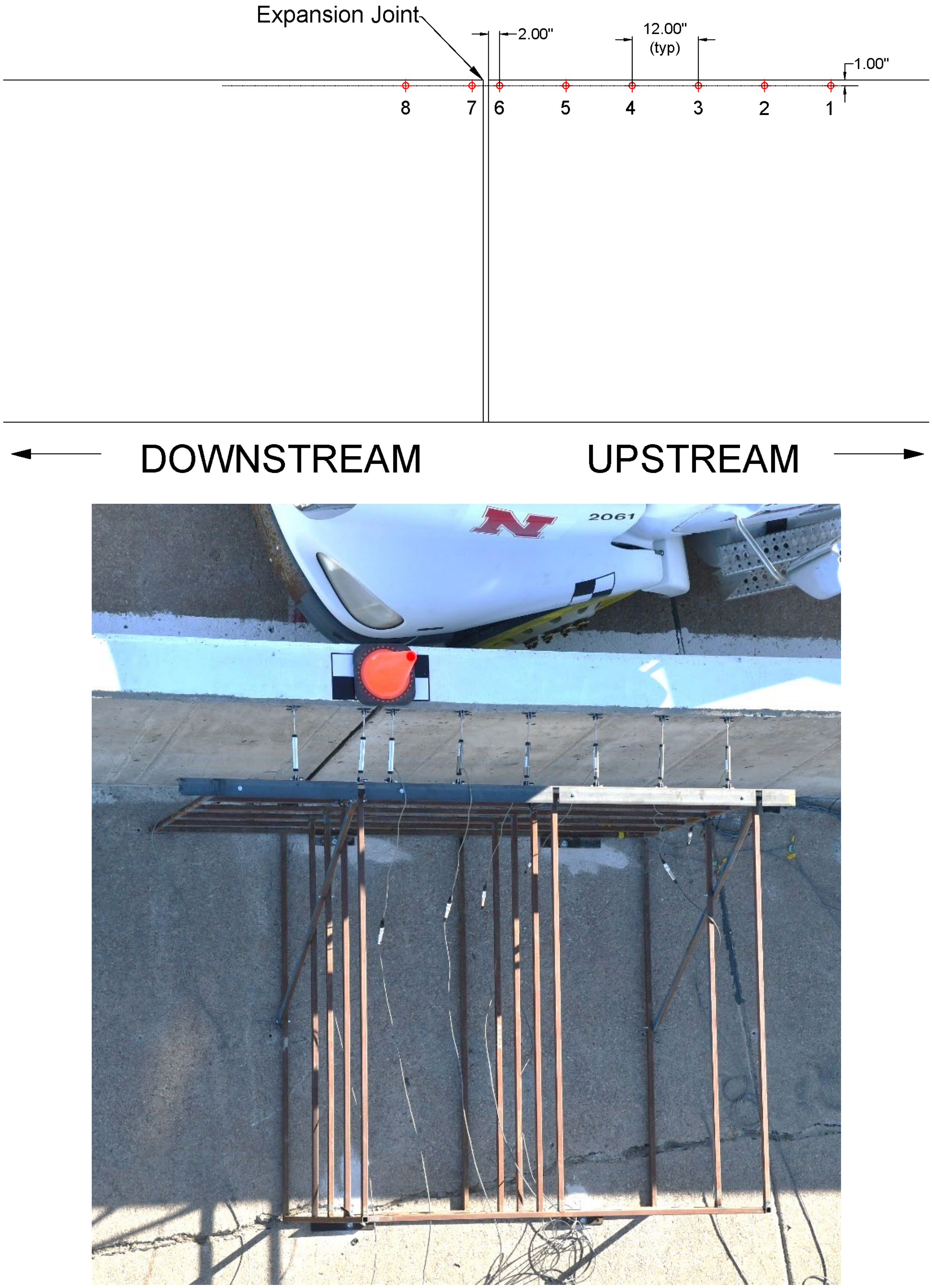


Figure 5.16 Location of Linear Potentiometers, Test No. MTL6-1

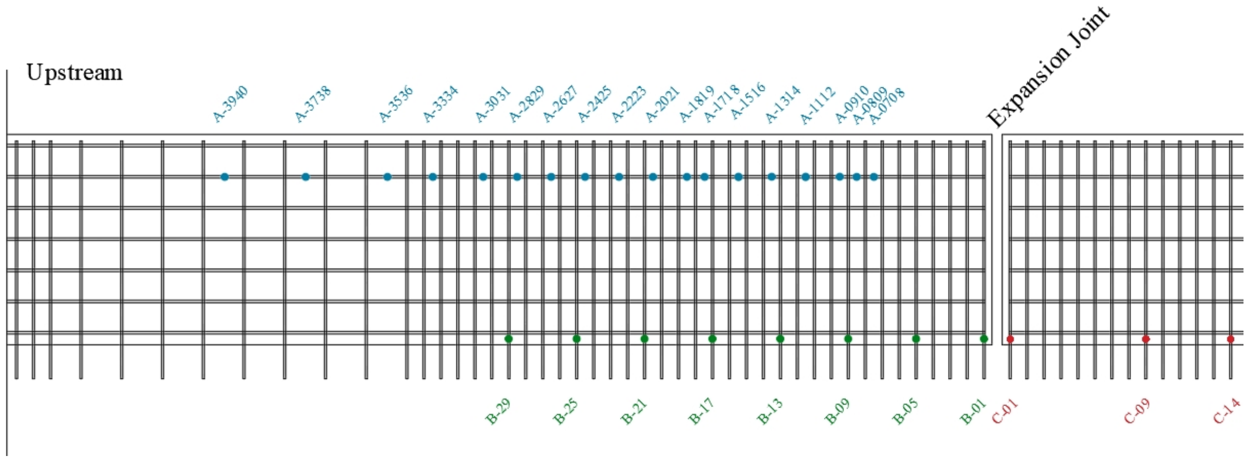


Figure 5.17 Location of Strain Gauges, Test No. MTL6-1

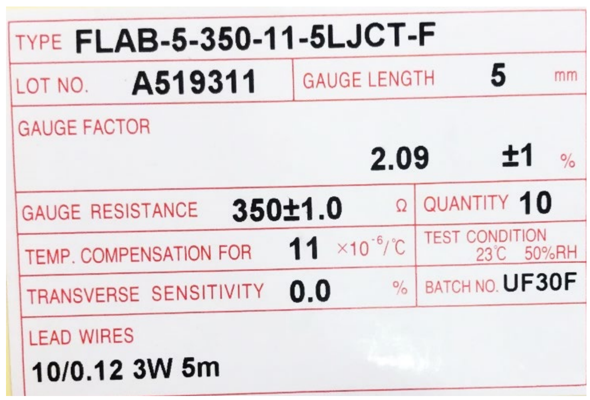


Figure 5.18 Strain Gauge Specifications, Test No. MTL6-1

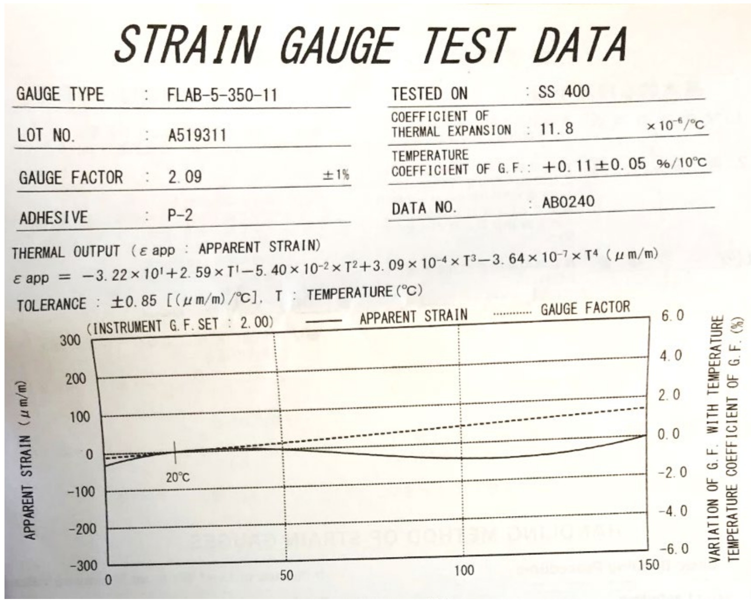


Figure 5.19 Strain Gauge Specifications, Test No. MTL6-1

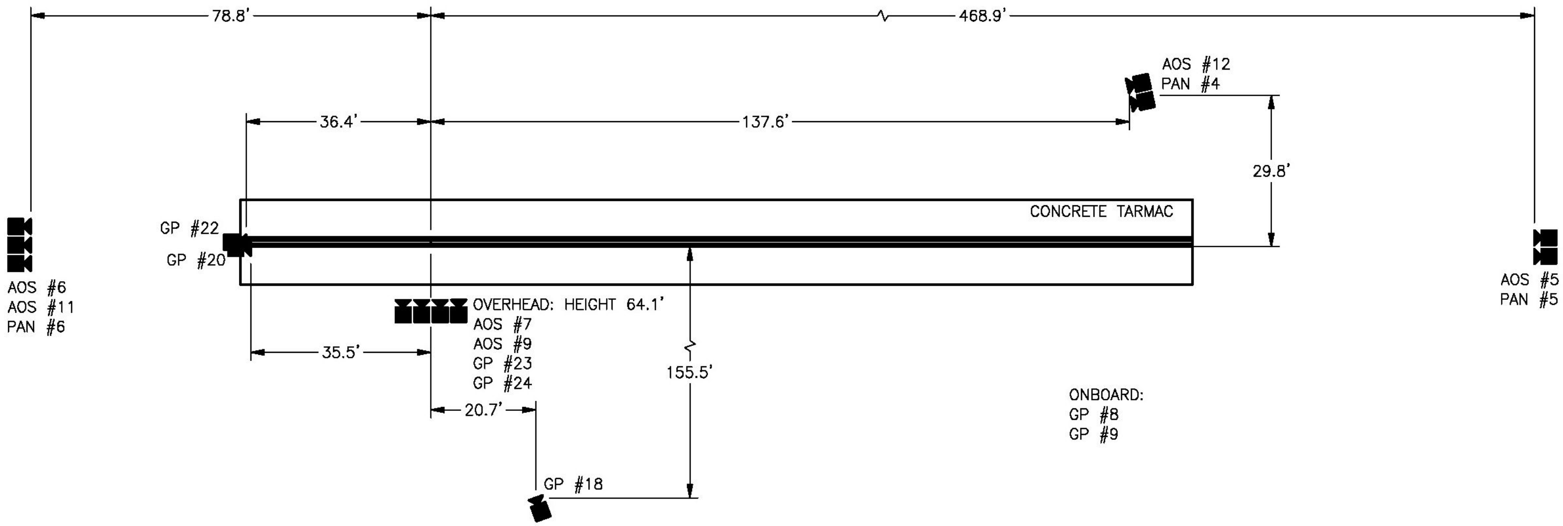
5.4.4 3D Measurement and Imaging

MwRSF acquired and utilizes a GPS-assisted LiDAR scene digitizer with photographic overlay, the FARO Focus 3D X130. The FARO FOCUS generates a spatially-accurate representation of a scene using line-of-site digitation, recording a scene with point accuracy of 0.1 in. and a polar resolution of ¼ in. at a distance of 100 ft. The FARO Focus is used to provide highly-accurate, digitized models of the test vehicle, the barrier system, and the vehicle's post-impact trajectory prior to and following the crash test.

5.4.5 Digital Photography

Six AOS high-speed digital video cameras, seven GoPro digital video cameras, and three Panasonic digital video cameras were utilized to film test no. MTL6-1. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figure 5.20. The camera mounting location on the fifth wheel is shown in Figure 5.21. Due to technical difficulties, cameras GP-18 and GP-20 did not record the impact event.

The high-speed videos were analyzed using TEMA Motion and Redlake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A digital still camera was also used to document pre- and post-test conditions for the test.



No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-5	AOS X-PRI Gigabit	500	100mm	-
AOS-6	AOS X-PRI Gigabit	500	50mm	-
AOS-7	AOS X-PRI Gigabit	500	Kowa 16mm	-
AOS-9	AOS TRI-VIT 2236	1000	Kowa 12mm	-
AOS-10	AOS J-PRI	500	Sigma 24-135	135
AOS-11	AOS J-PRI	500	28-70	28
GP-8	GoPro Hero 4	120		
GP-9	GoPro Hero 4	120		
GP-18*	GoPro Hero 6	240		
GP-20*	GoPro Hero 6	120		
GP-22	GoPro Hero 7	240		
GP-23	GoPro Hero 7	240		
GP-24	GoPro Hero 7	240		
PAN-4	Panasonic HC-V770	120		
PAN-5	Panasonic HC-VX981	120		
PAN-6	Panasonic HC-VX981	120		

*Camera did not record impact event due to technical difficulties.

Figure 5.20 Camera Locations, Speeds, and Lens Settings, Test No. MTL6-1

Figure 5.21 Fifth Wheel Camera Mounting Details, Test No. MTL6-1

Chapter 6 Full-Scale Crash Test No. MTL6-1

6.1 Weather Conditions

Test no. MTL6-1 was conducted on December 8, 2021, at approximately 1:45 p.m. The weather conditions as reported by the National Oceanic and Atmospheric Administration (station 14939/KLNK) are shown in Table 6.1.

Table 6.1 Weather Conditions, Test No. MTL6-1

Temperature	49°F
Humidity	35%
Wind Speed	9 mph
Wind Direction	140° from True North
Sky Conditions	Clear
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.00 in.
Previous 7-Day Precipitation	0.00 in.

6.2 Test Description

Initial vehicle impact was to occur at the centerline of the expansion joint, 450 in. downstream from the upstream end of the barrier, as shown in Figure 6.1. The impact point was selected using LS-DYNA analysis to maximize loading on and deflection of the upstream joint to maximize risk of snagging the tank on an exposed surface at the top of the barrier. The 79,864-lb tractor-tank trailer impacted the concrete barrier at a speed of 51.1 mph and at an angle of 15.7 degrees. The actual point of impact was at the centerline of the expansion joint or 450 in. downstream from the upstream end of the barrier. After exiting the system, the vehicle rolled and came to rest on its left side, 310 ft downstream from impact and 14 ft behind the barrier.

A detailed description of the sequential impact events is contained in Table 6.2. Sequential photographs are shown in Figures 6.2 through 6.5. Documentary photographs of the crash test are shown in Figures 6.6 through 6.8. The vehicle trajectory and final position are shown in Figure 6.9.

Figure 6.1 Target Impact Location, Test No. MTL6-1

Table 6.2 Sequential Description of Impact Events, Test No. MTL6-1

Time (sec)	Event
0.000	Tractor’s left-front bumper corner contacted barrier 450 in. downstream from upstream end of barrier.
0.004	Tractor’s left-front wheel contacted concrete barrier.
0.018	Tractor's hood contacted barrier.
0.028	Tractor’s left-front wheel lifted off the tarmac and climbed front face of barrier.
0.098	Tractor’s left-front wheel engaged tarmac.
0.100	Tractor’s right-front wheel lost disengaged from tarmac.
0.124	Tractor's left side mirror contacted the top surface of the barrier.
0.244	Tractor’s left-rear tandem wheels contacted the barrier.
0.306	Left-front trailer rib below tank contacted impact side of barrier.
0.312	Tractor’s right-rear tires lost contact with tarmac.
0.348	Trailer’s right tandem lost contact with the tarmac. Tractor’s body lost contact with barrier.
0.416	Left-front surface of tanker-trailer jacket near front baffle contacted top traffic-side edge of barrier.
0.424	Tractor’s right-front tire regained contact with tarmac.
0.668	Trailer’s left-rear bulkhead seam at back of trailer contacted top, traffic-side edge of barrier.
0.716	Trailer’s rear-most left rib contacted impact side of barrier.
0.734	Tractor’s front right tire disengaged from the tarmac.
0.790	All left side trailer ribs disengaged from barrier surface, only tank jacket, left trailer tandem, and left rear wheel guards in contact with barrier.
0.802	Trailer left tandem wheels and wheel guard disengaged from barrier.
1.256	Maximum trailer lateral ZOI.
1.652	Left-front edge of trailer disengaged from barrier.
1.680	Left-rear side of the trailer disengaged from barrier.
1.774	Tractor’s right-front tire contacted tarmac.
1.840	Tractor’s front bumper’s right corner contacted tarmac.
2.278	Trailer’s right-rear wheels contacted tarmac.
2.750	Trailer’s left-rear tires disengaged from tarmac.
3.750	Trailer right side rolled 90 degrees and contacted tarmac.

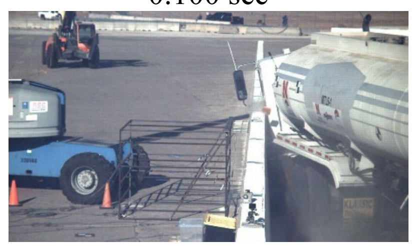
0.000 sec

0.000 sec

0.100 sec

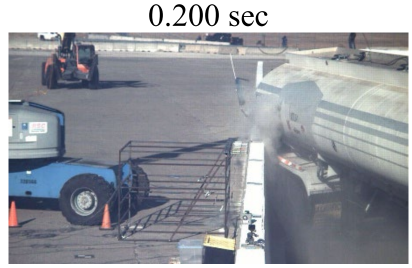
0.100 sec

0.200 sec



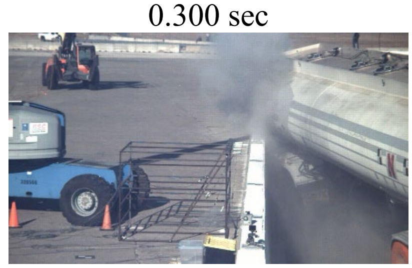
0.200 sec

0.300 sec



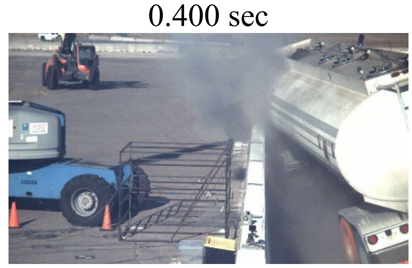
0.300 sec

0.400 sec



0.400 sec

0.500 sec



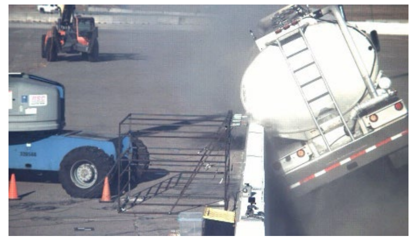
0.500 sec

Figure 6.2 Sequential Photographs, Test No. MTL6-1

0.600 sec

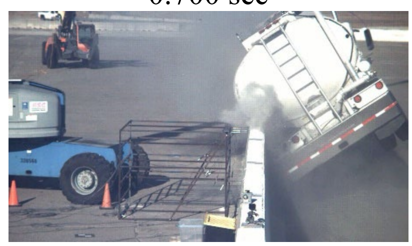
0.600 sec

0.700 sec



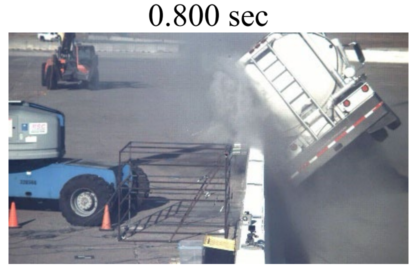
0.700 sec

0.800 sec



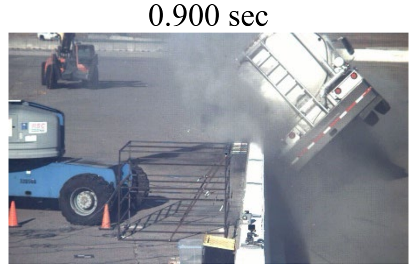
0.800 sec

0.900 sec



0.900 sec

1.000 sec



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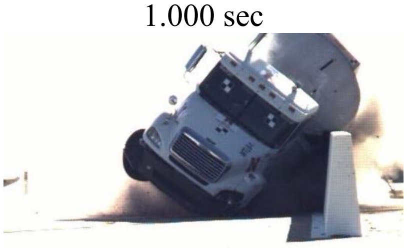

1.100 sec

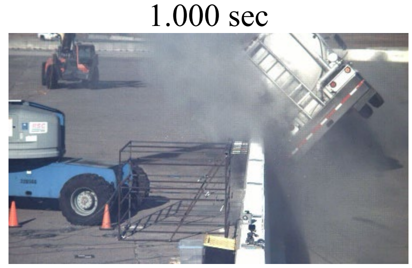

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Figure 6.3 Sequential Photographs, Test No. MTL6 1

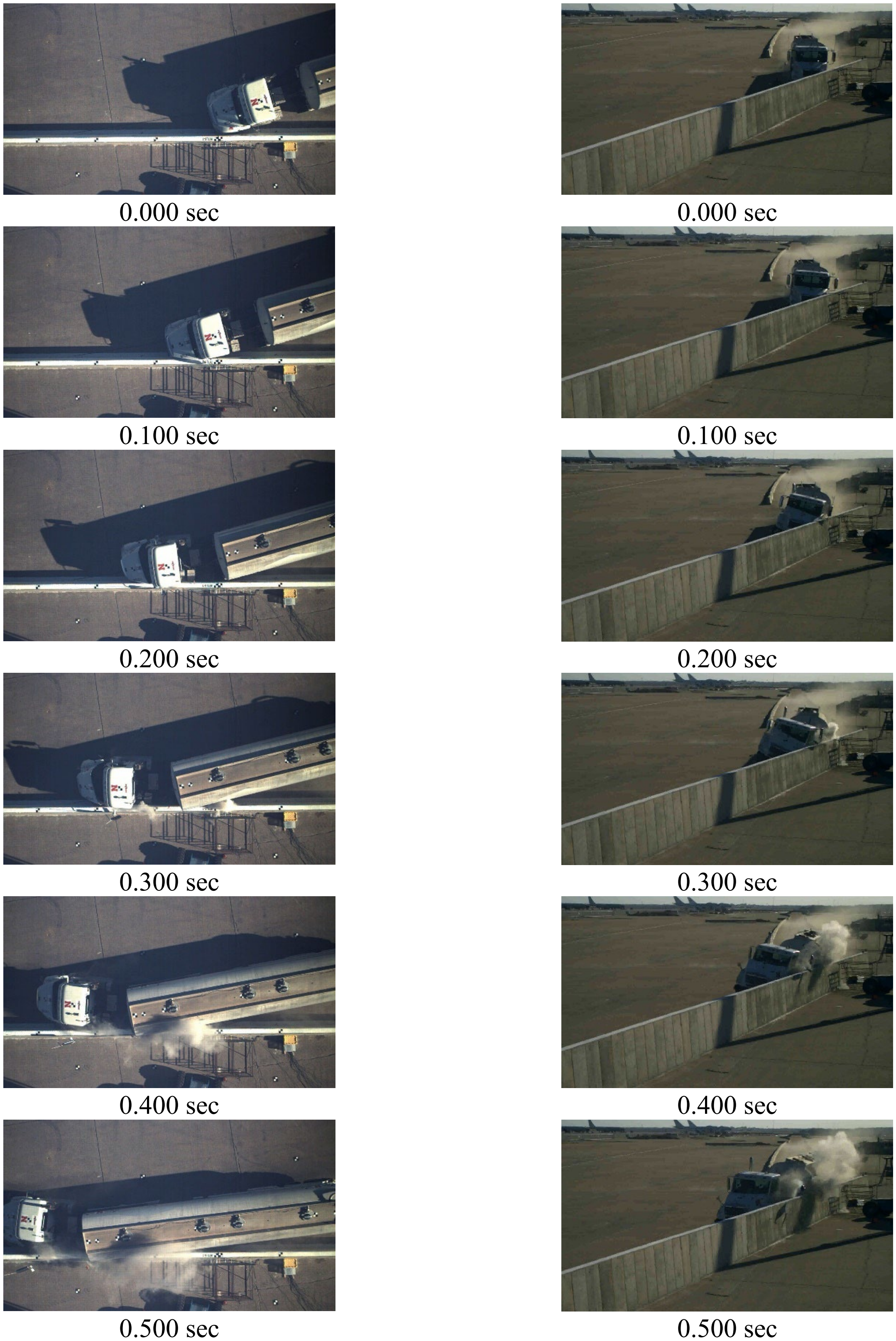
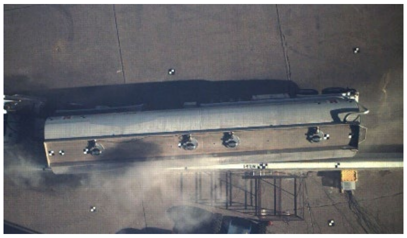


Figure 6.4 Sequential Photographs, Test No. MTL6 1



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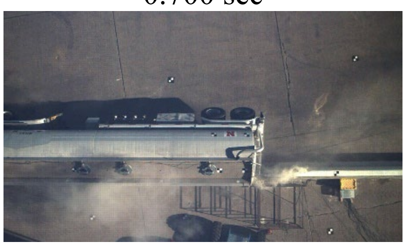

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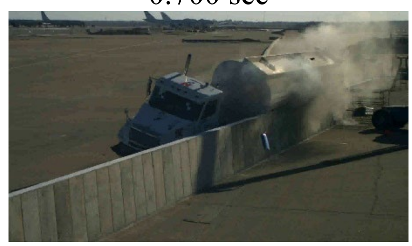

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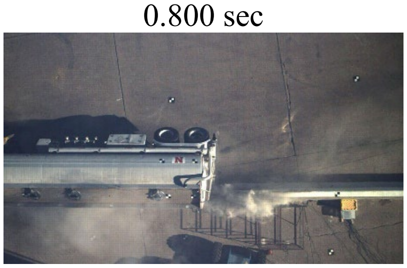

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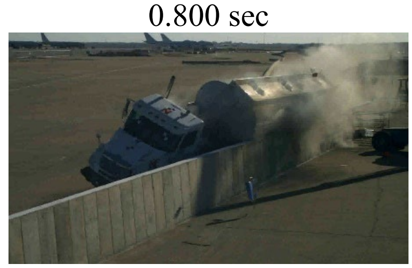

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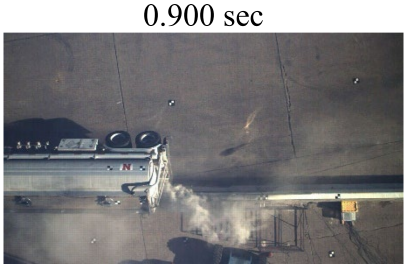

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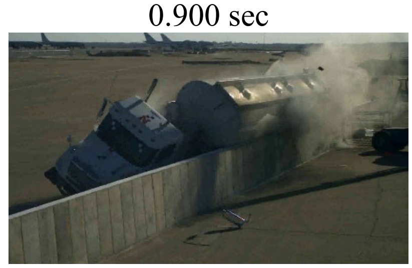

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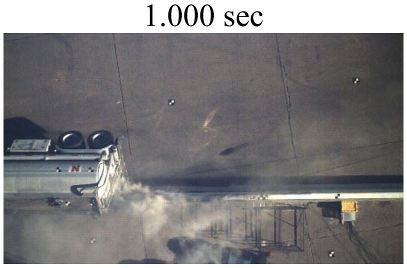

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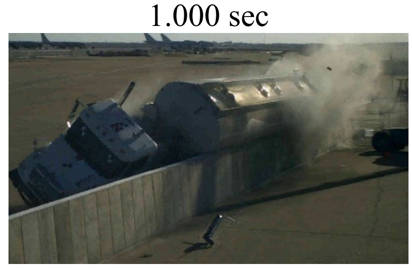

1.100 sec

Figure 6.5 Sequential Photographs, Test No. MTL6 1

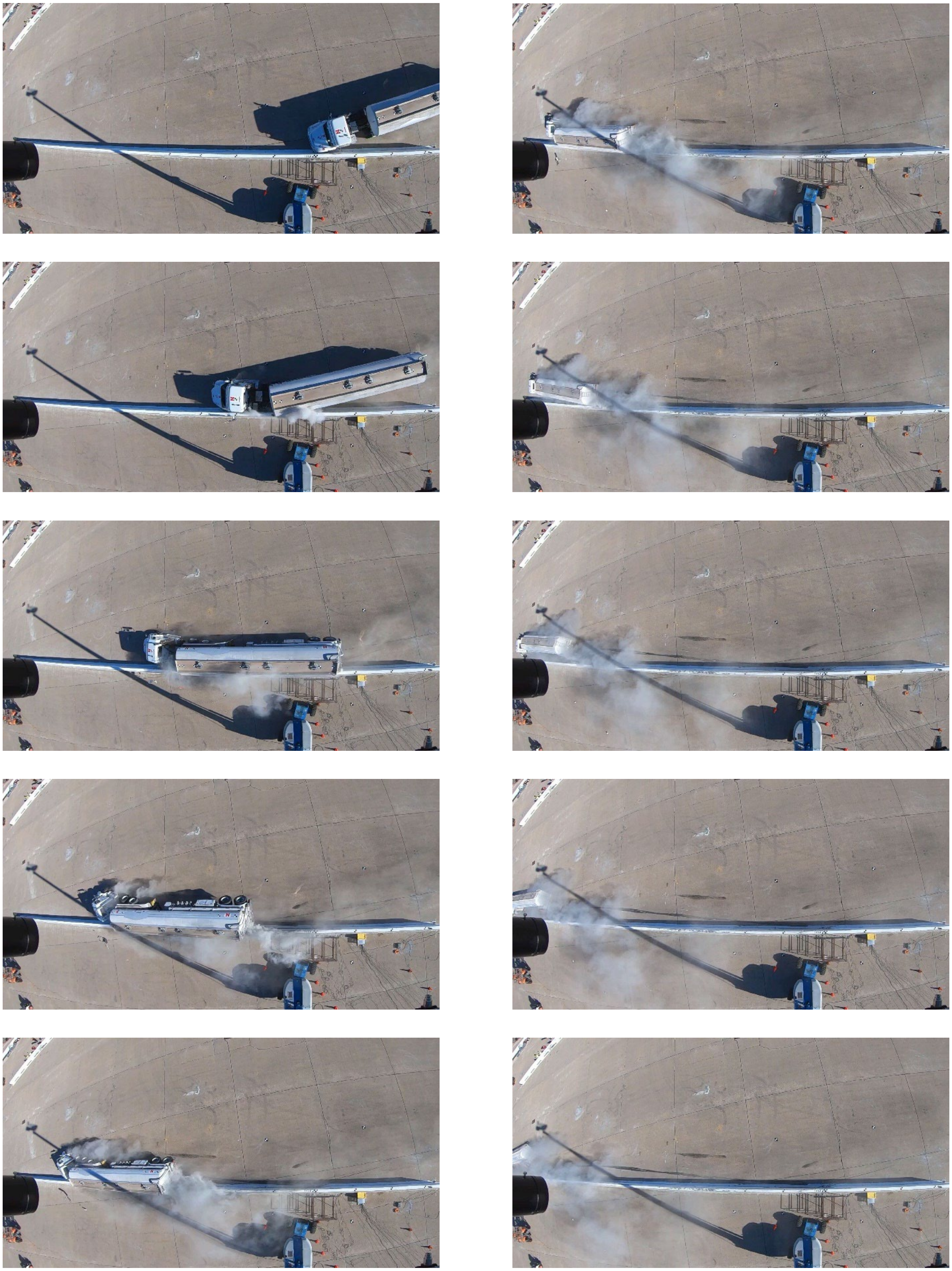

Figure 6.6 Documentary Photographs, Test No. MTL6 1

Figure 6.7 Documentary Photographs, Test No. MTL6 1

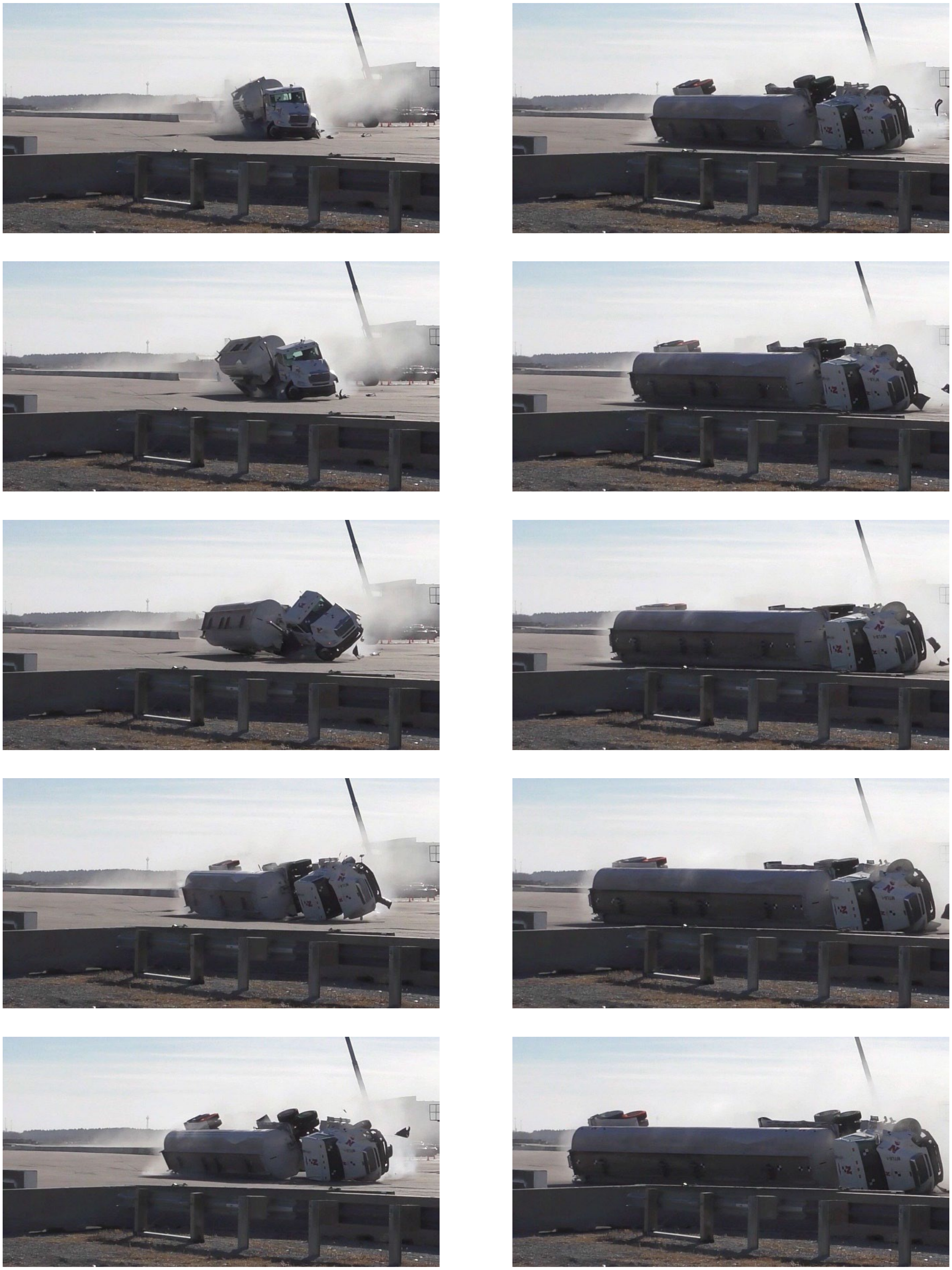

Figure 6.8 Documentary Photographs, Test No. MTL6 1

Figure 6.9 Vehicle Final Position and Trajectory Marks, Test No. MTL6-1

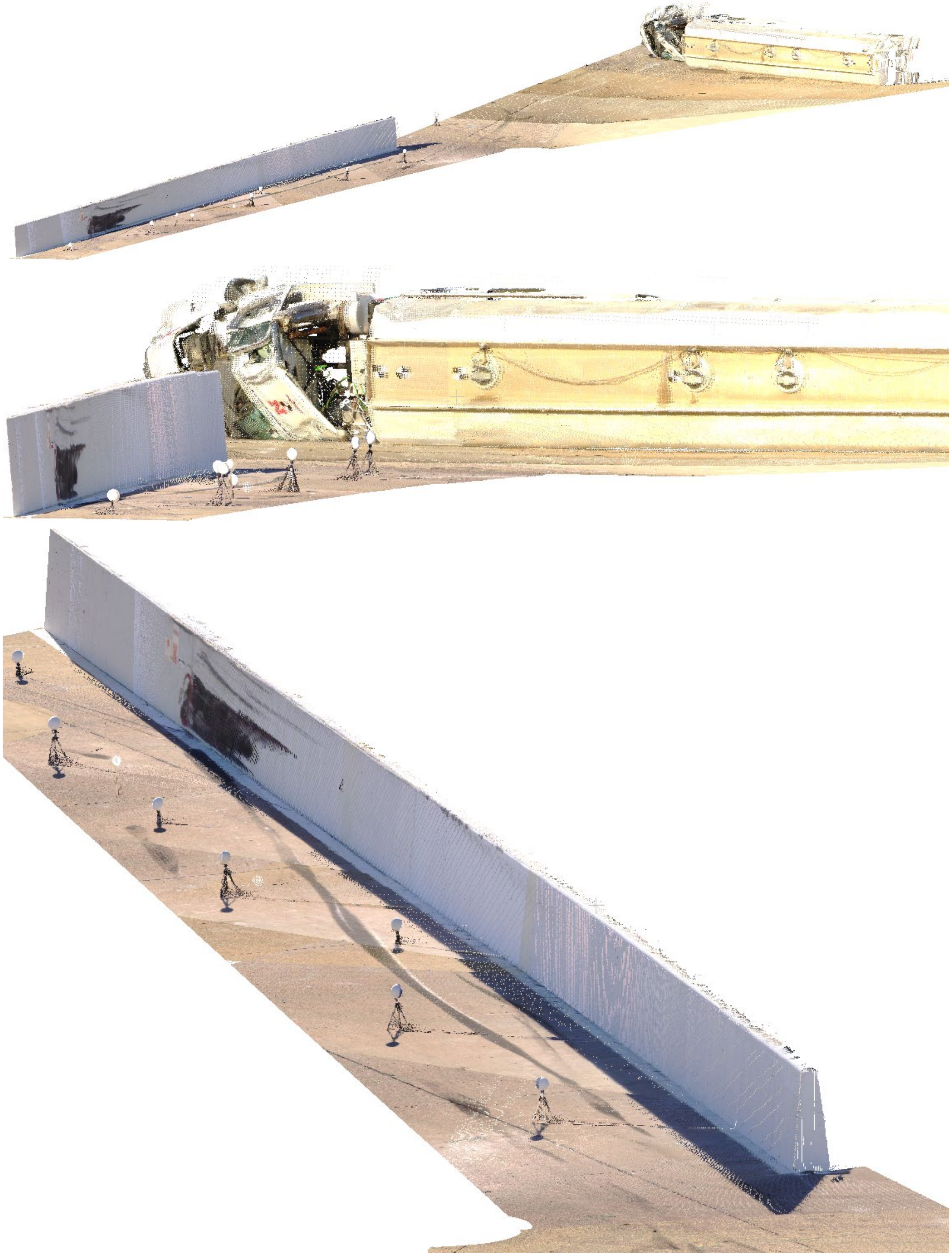

Figure 6.10 3D Scans of Vehicle Trajectory and Final Rest, Test No. MTL6-1

6.3 Barrier Damage

Damage to the barrier was minimal, as shown in Figures 6.11 and 6.14. Barrier damage consisted of contact marks on the front face of the barrier, minor concrete chipping and grinding, and chipping around the top and impact-side surfaces of the expansion joint. The length of vehicle contact along the barrier was approximately 90 ft – 6 in., beginning 6 ft – 10 in. upstream from the centerline of the expansion joint.

Tire contact marks on the front face of the barrier began 6 ft – 10 in. upstream from the expansion joint and ended approximately 26 ft downstream from the expansion joint. The overall width of the tire contact marks varied, but the highest point was 38.5 in. above the tarmac. Contact marks from other portions of the vehicle were observed up to the top of the barrier and gouging or spalling occurred along the top-front edge of the barrier from 6 ft – 10 in. upstream from the expansion joint to approximately 77 ft – 8 in. downstream from the expansion joint. Additional intermittent gouging and chipping along the top-front edge of the barrier extended through the end of vehicle contact.

Additional gouging and chipping were observed on the front face of the barrier, in the 3 ft to either side of the expansion joint. At the expansion joint location, the top-front corners of the barrier segments were broken off to a depth of approximately ½ in. as was 13 in. of the upstream front edge, beginning 5 in. above the tarmac. No reinforcing bars were exposed by this damage.

Figure 6.11 System Damage, Test No. MTL6-1

Figure 6.12 System Damage, Test No. MTL6-1

Figure 6.13 System Damage Near Expansion Joint, Test No. MTL6-1

Figure 6.14 System Damage Near Expansion Joint, Test No. MTL6-1

Figure 6.15 Scraping Damage along Top Impact-Side Edge of Barrier, Test No. MTL6-1

No permanent set was observed for test no. MTL6-1. Some deflections were observed from linear potentiometers mounted on the back side of the single-slope barrier, but due to technical difficulties data was not collected through the end of the impact event. A maximum dynamic deflection of 0.4 in. was measured using high-speed video analysis. After the test, survey of the test article control points indicated that all deflections were within the margin of error of the surveying equipment, and no cracks nor signs of foundation damage were observed on the front side of the barrier. The working width of the barrier was approximately 37.2 in. as measured using high-speed video analysis, which was associated with the trailer body extending over the top of the barrier system. The barrier deflection and working width are shown schematically in Figure 6.16.

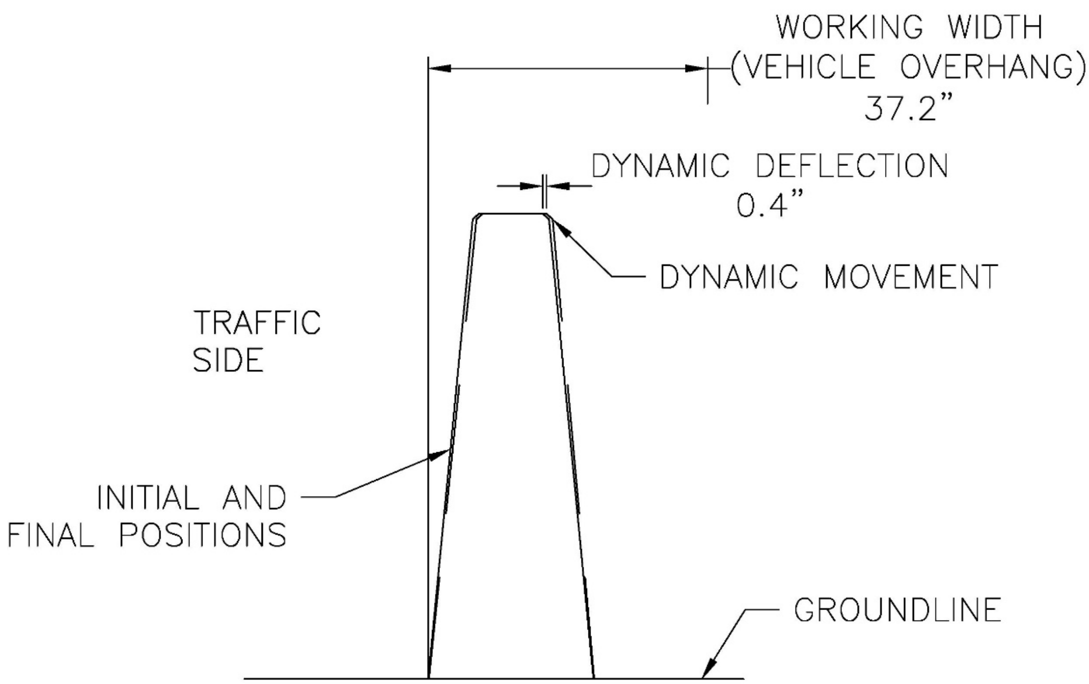

Figure 6.16 Barrier Damage, Test No. MTL6-1

6.4 Vehicle Damage

The damage to the vehicle was severe, as shown in Figures 6.17 through 6.30. The maximum occupant compartment intrusions were not collected after the test due to extensive occupant compartment deformations. MASH defines intrusion or deformation as the occupant compartment being deformed and reduced in size with no observed penetration. The secondary rollover event at the end of the crash sequence resulted in roof crush and damage to A-pillars which exceeded MASH occupant compartment deformation limits.

The tractor experienced extensive damage from impact and the subsequent rollover. The cab, windshield, roof, and both side doors were crushed inward. The cab frame experienced tears which caused the roof and door structures to collapse inward when the vehicle was uprighted after the test. The left-front bumper corner, fender, and foot ramp were damaged from impact with the concrete barrier. A crease was observed at the approximate height of the concrete barrier across the left-side door and cab frame. The hood was disengaged from the left rear mount and displaced to the right side, and extensive engine frame and console frame damage occurred including buckling, twisting, and crushing.

The trailer experienced extensive damage to the left, top, and right sides. Scraping, minor gouging, and some peeling of the aluminum jacket were observed near interior baffle locations. Scrub marks were observed on the left side of the trailer at the impact height of the barrier, and two large dents were observed at the same height: one in the front, and one in the back. The left-side wheel hubs were scraped and gouged. The right side of the trailer experienced extensive scraping in the vertical direction corresponding to sliding on the concrete tarmac, with multiple small tears and holes observed in the aluminum jacket especially near the internal baffles. The right side was flattened and crushed inward along the entire middle section where the vehicle rolled and skidded, and several tears were observed in the jacket measuring between 2 and 3 in.

long. The top of the trailer was scraped, and the longitudinal safety rails were slightly deformed. One tear was observed in the undercarriage of the tank. The suspension, wheels, frame, and undercarriage of the trailer were not damaged.

Figure 6.17 Vehicle Damage and Final Rest, Test No. MTL6-1

Figure 6.18 Tractor Damage, Test No. MTL6-1

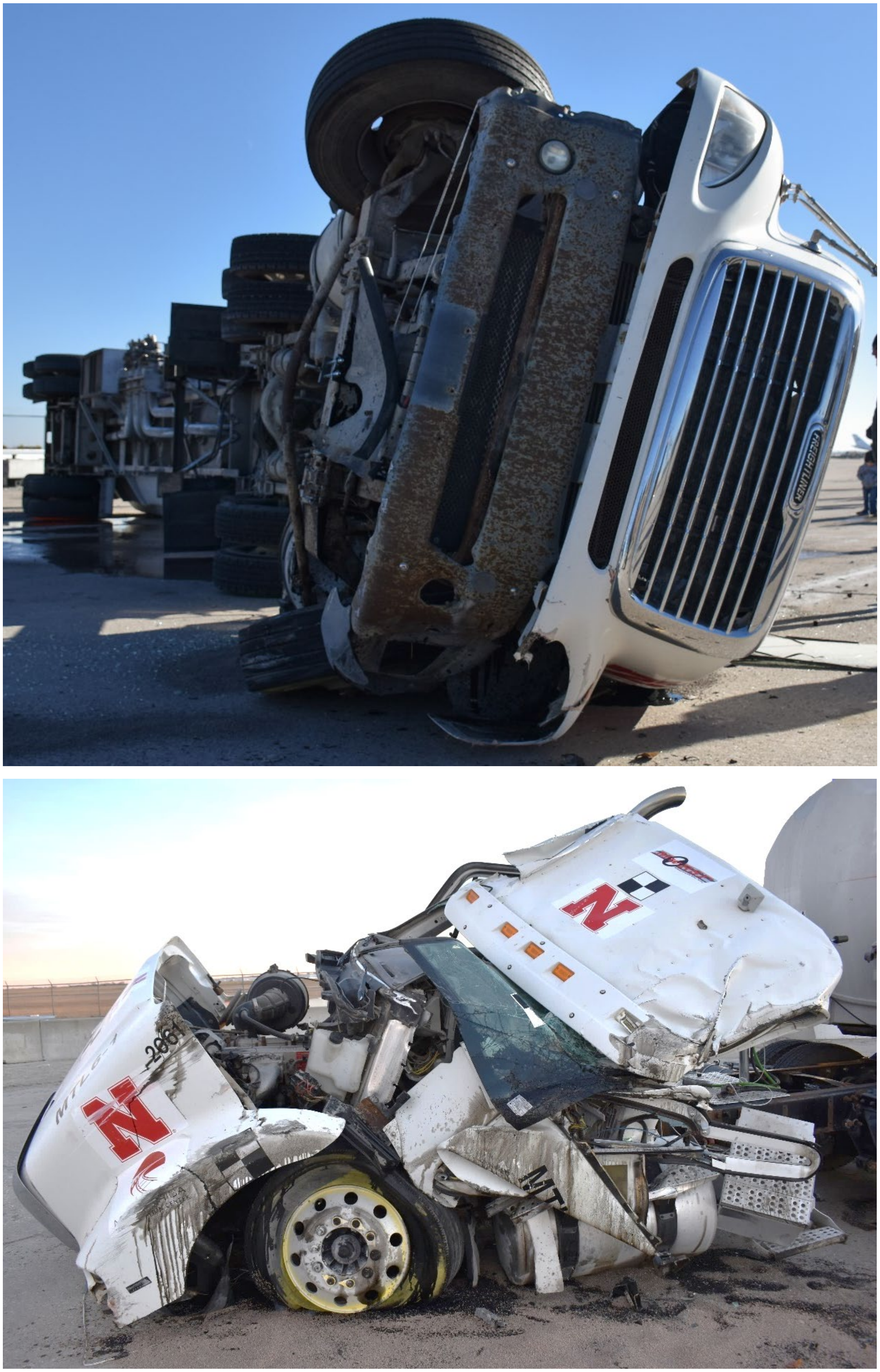

Figure 6.19 Tractor Damage, Test No. MTL6-1

Figure 6.20 Tractor Undercarriage Chassis Damage, Test No. MTL6-1

Figure 6.21 Tractor Suspension Damage, Test No. MTL6-1

Figure 6.22 Trailer Damage, Test No. MTL6-1

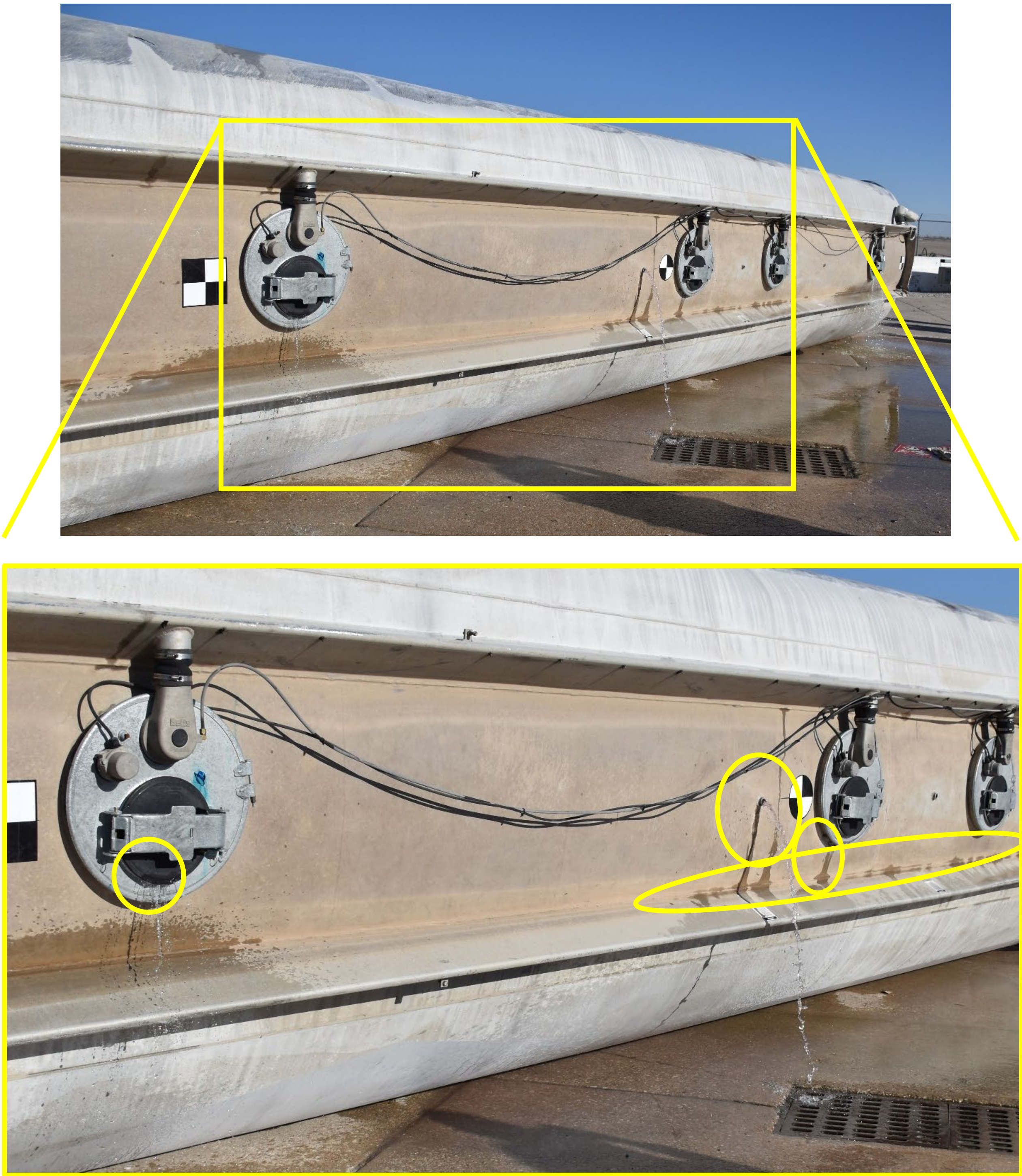

Figure 6.23 Locations of Trailer Leaks, Test No. MTL6-1

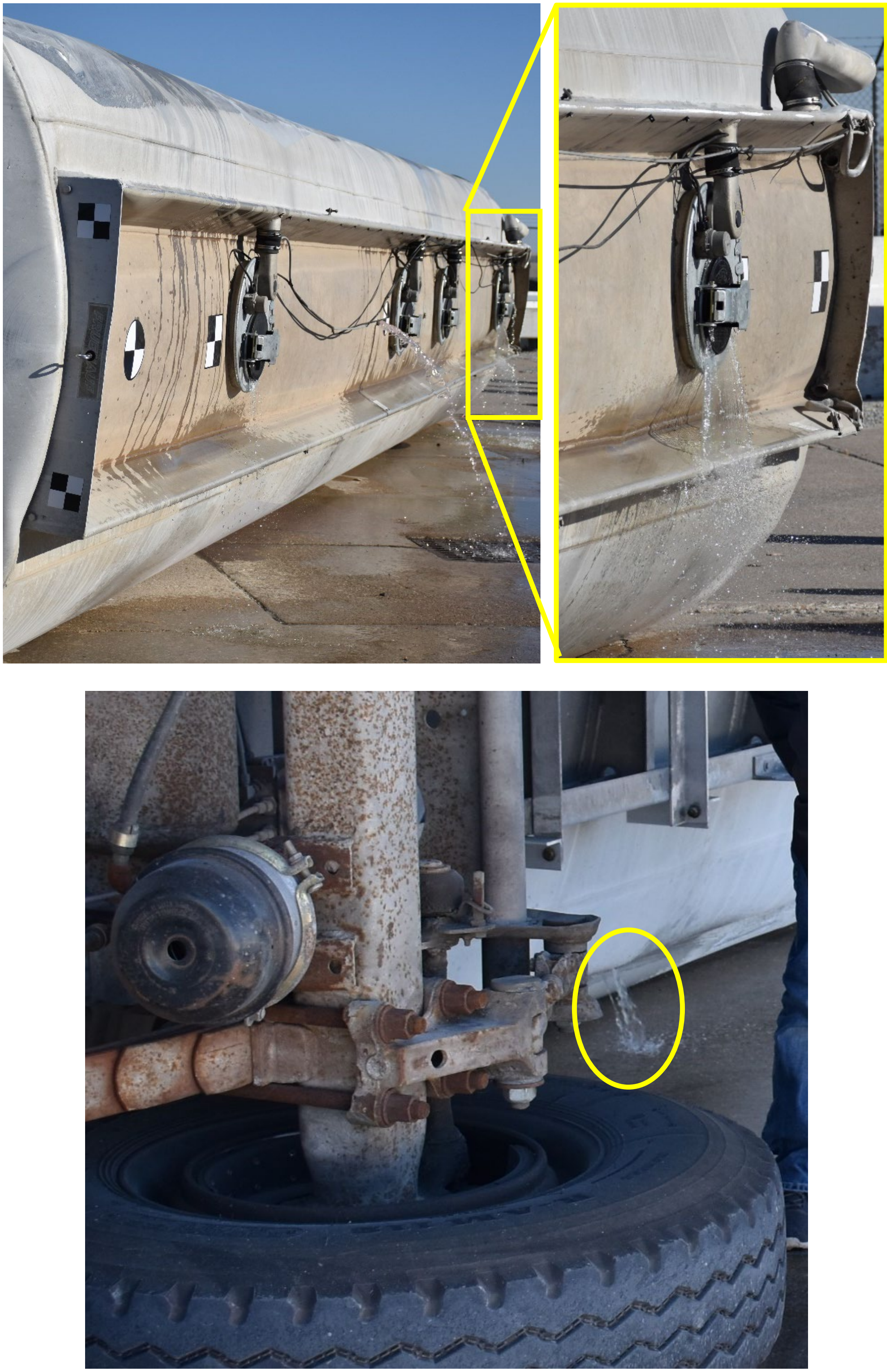

Figure 6.24 Locations of Trailer Leaks, Test No. MTL6-1

Figure 6.25 Trailer Damage After Uprighting, Test No. MTL6-1

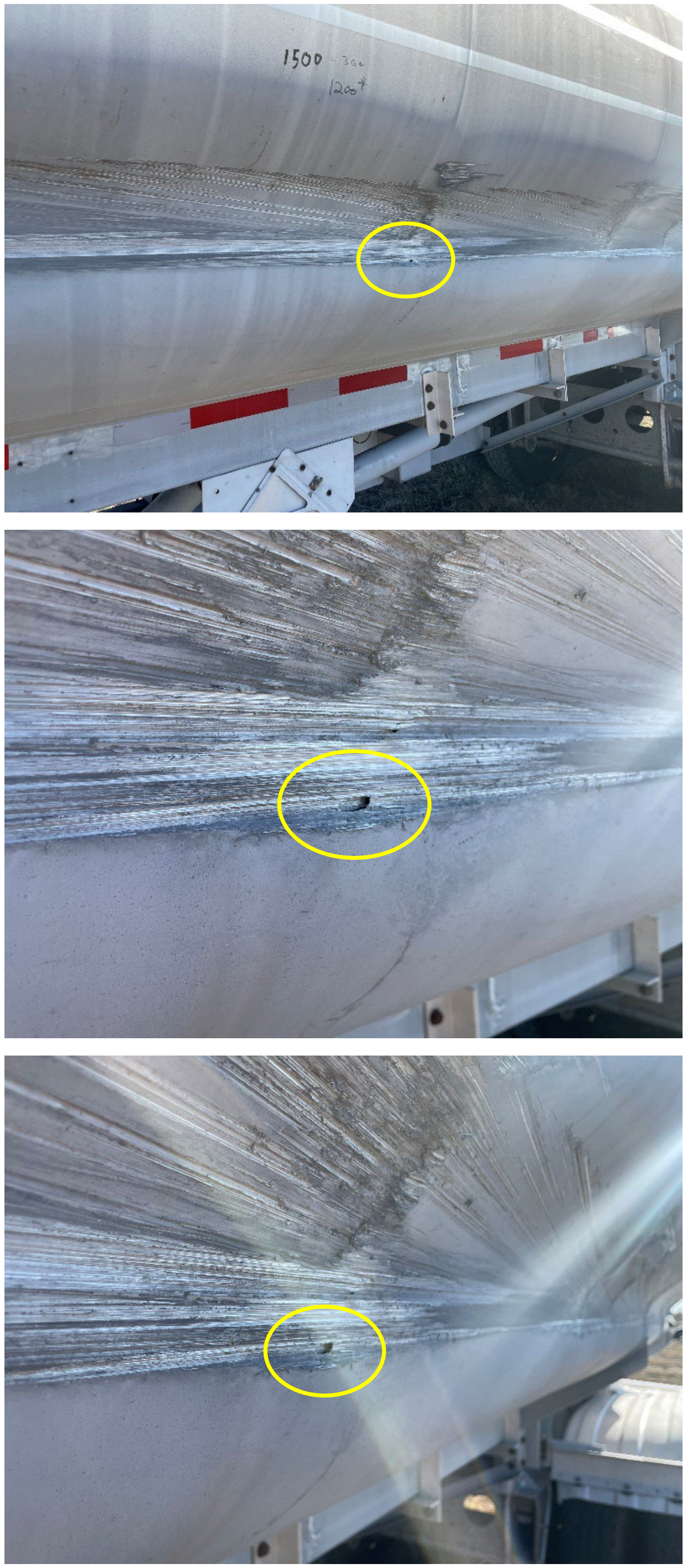

Figure 6.26 Pinhole Damage in Trailer After Being Uprighted, Test No. MTL6-1

Figure 6.27 Trailer Damage on Impact Side After Being Uprighted, Test No. MTL6-1

Figure 6.28 Trailer Damage on Non-Impact Side After Being Uprighted, Test No. MTL6-1

Figure 6.29 Tears in Trailer Jacket on Non-Impact Side, Test No. MTL6-1

Figure 6.30 Fifth Wheel Damage, Test No. MTL6-1

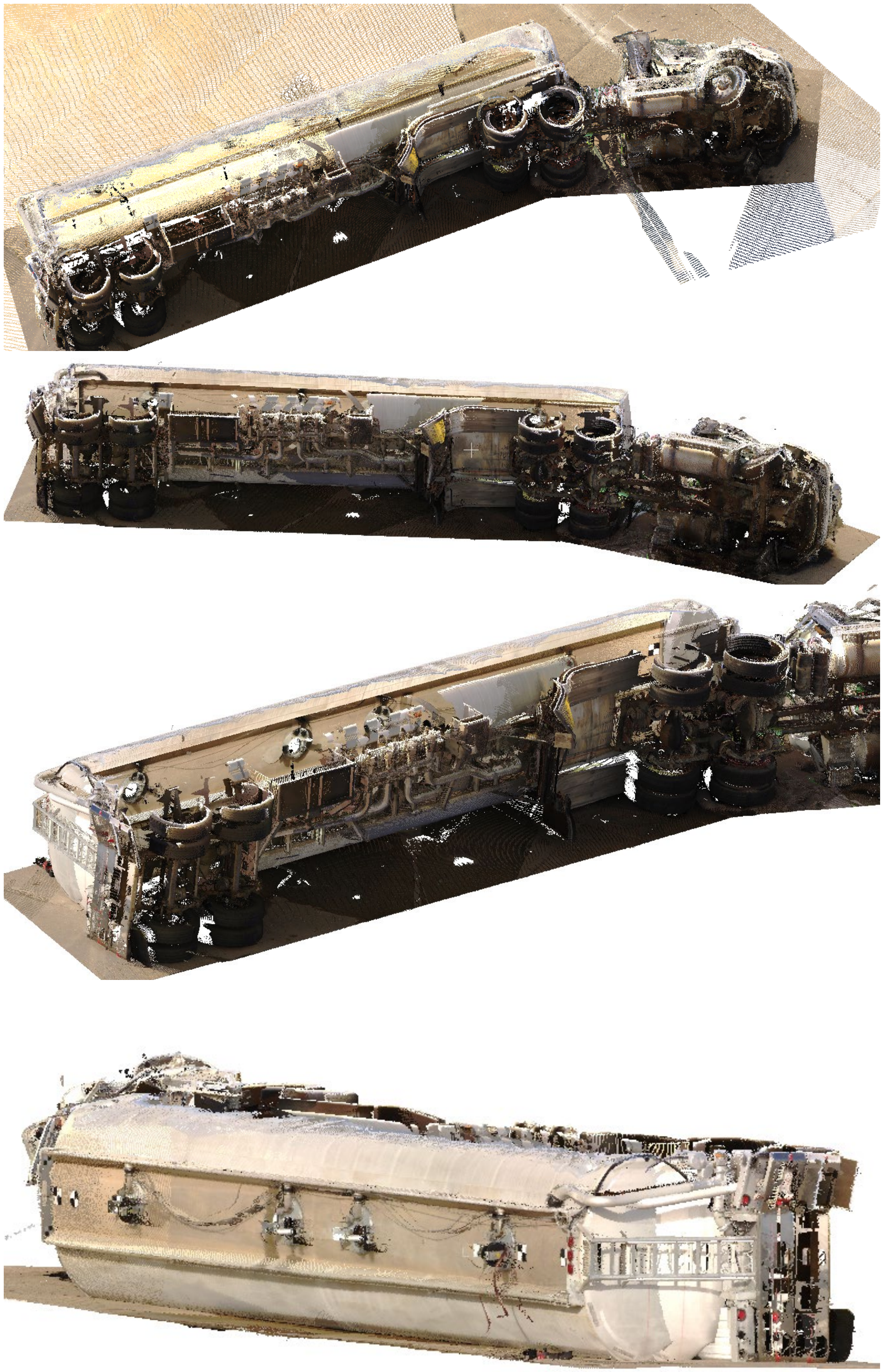

Figure 6.31 Vehicle Scan Results, Tanker Damage, Test No. MTL6-1

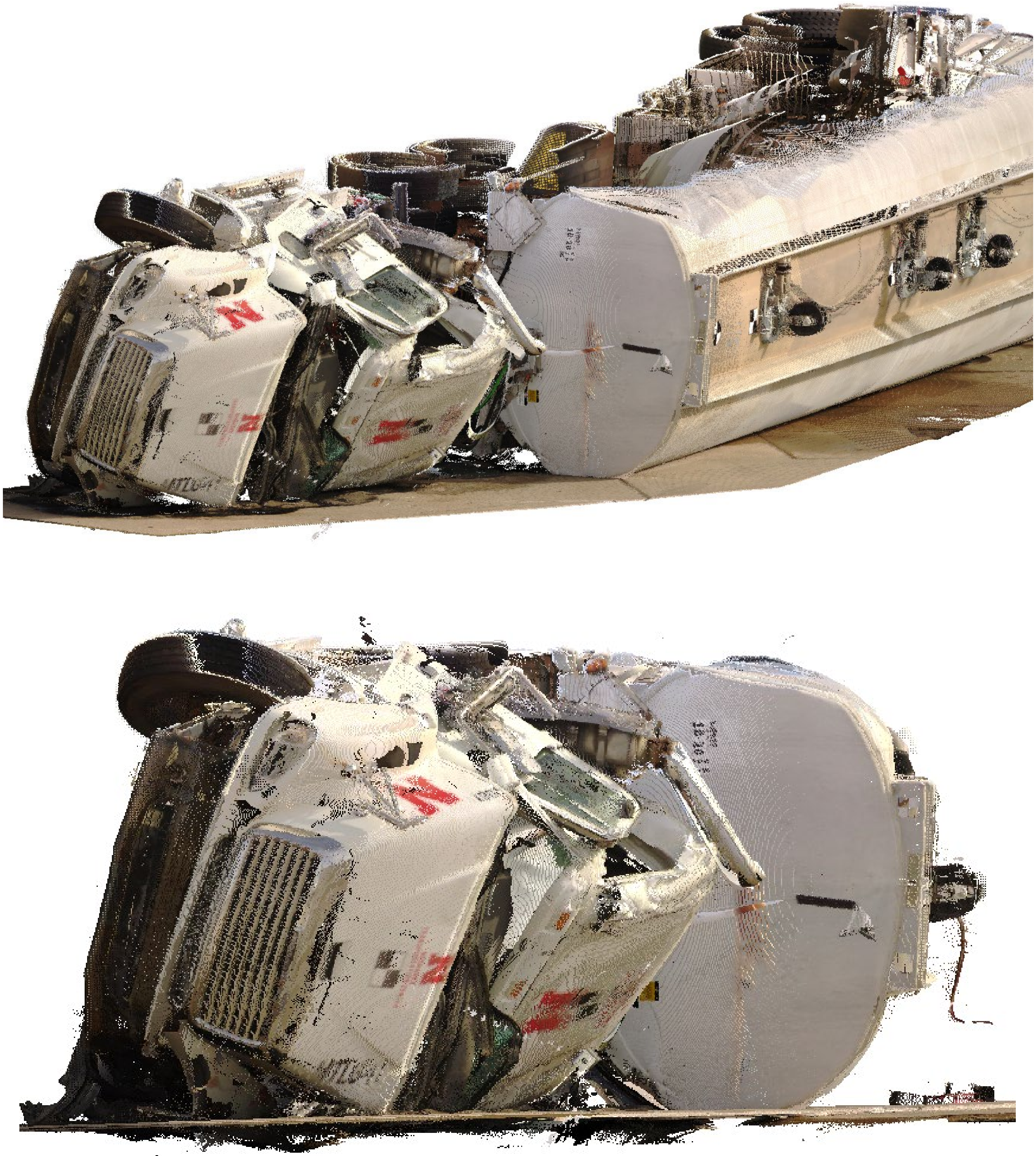

Figure 6.32 Vehicle Scan Results, Tractor Damage, Test No. MTL6-1

6.5 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec average occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions, as determined from the accelerometer data, are shown in Table 6.3. These values are reported for completeness, but OIV and ORA are not included in the evaluation criteria for MASH test designation no. 6-12. The calculated THIV, PHD, and ASI values are also shown in Table 6.3. The recorded data from the accelerometers and the rate transducers is shown graphically in Appendix C.

Table 6.3 Summary of Occupant Risk Values, Test No. MTL6-1

Evaluation Criteria		Transducer			MASH Limits
		SLICE-1 (in-cab)	SLICE-2 (rear-axle)	TDS (truck-rear)	
OIV ft/s	Longitudinal	-3.36	-4.44	16.21	not required
	Lateral	13.70	4.71	24.90	
ORA g's	Longitudinal	3.67	-5.00	43.37	
	Lateral	7.36	15.73	28.08	
Maximum Angular Displacement deg.	Roll	265.2	276.0	-	¼ roll
	Pitch	11.12	2.15	-	not required
	Yaw	33.57	-29.38	-	
THIV – ft/s		35.18	20.46	-	
PHD – g's		7.36	16.01	-	
ASI		0.71	1.21	2.58	

6.6 Linear Transducers and Strain Gauges

Due to technical difficulties, the linear potentiometers and strain gauge data were not recovered for the impact event and are not included in this report.

6.7 Discussion

Test results indicated that the vehicle was contained and redirected, but the momentum of the vehicle roll of the tank trailer and lateral movement of the fluid ballast caused the vehicle to roll 90 degrees onto its right side after exiting the barrier. Subsequently, while sliding to a stop, the rocking motion of the fluid in the interior tanks, the vehicle orientation on its side, and potential uneven surfaces on the test site tarmac contributed to a secondary 180-degree rollover event near the point of final rest. The rotational motion of the tractor and tanker trailer during the impact are shown in Figure 6.33. Review of the tractor-tank trailer vehicle roll motion shows that the initial rollover of the vehicle onto its right side was consistent with the roll of the vehicle as it exited the barrier. After the tractor-tank trailer vehicle rolled onto its right side, the vehicle slid downstream for approximately 2.5 seconds prior to the final roll motion of the vehicle. This relatively long period of stable vehicle translation downstream may suggest that factors such as fluid sloshing and the unevenness of tarmac surface may have led to the secondary roll motion, as mentioned previously.

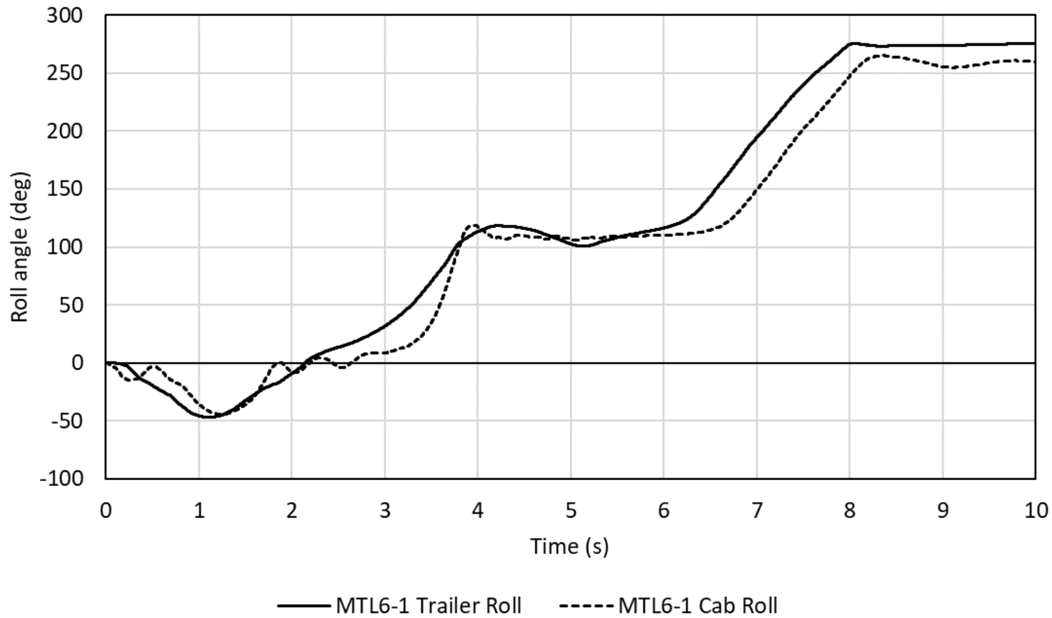

Figure 6.33 Vehicle Roll Angles, Test No. MTL6-1

The analysis of the test results for test no. MTL6-1 showed that the system contained and redirected the 36000T vehicle with controlled lateral displacements of the barrier, but the vehicle did not remain upright following impact. A summary of the test results and sequential photographs are shown in Figure 6.34. Detached elements, fragments, or other debris from the test article did not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or work-zone personnel. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury occurred during the secondary rollover event at the conclusion of the vehicle's post-impact trajectory. The test vehicle did not penetrate nor ride over the barrier and exited the barrier at an angle of approximately 5 degrees. After exiting the system, the vehicle rolled onto its right side, slid for approximately 100 ft downstream, then subsequently rolled an additional half rotation and came to rest on its left side. MASH criteria for test designation no. 6-12 permits a vehicle to roll one quarter turn, but the rotation of the vehicle cannot exceed 90 degrees. As a result, the test condition is not considered acceptable according to MASH criteria. However, the primary purpose of a TL-6 barrier system is not to prevent vehicle rollover nor serious injury, rather, the primary function of such a barrier is to contain and redirect the most extreme vehicle impacts on the highway system and prevent potential catastrophic outcomes associated with tractor-tank trailer vehicles proceeding behind or over these barriers. As such, it was believed that the barrier evaluated herein was successful in meeting the primary function of MASH TL-6 vehicle containment.

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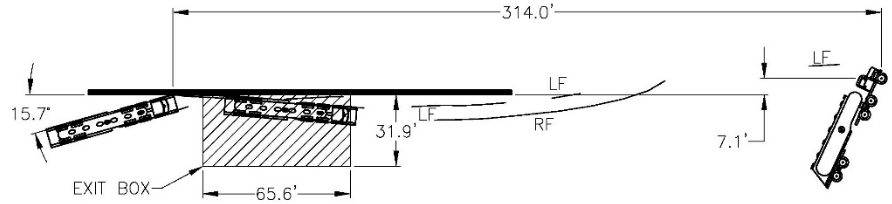

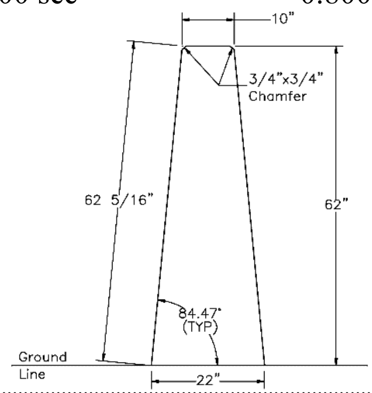

- Test Agency .... MwRSF
- Test Number........ MTL6-1
- Date........ 12/8/2021
- MASH Test Designation No. 6-12
- Test Article........ MASH TL-6 Concrete Barrier
- Total Length .... 187 ft – 6 in.
- Key Component – Concrete Barrier
  - Length .... 187 ft – 6 in.
  - Height........ 62 in. from top of tarmac
- Soil Type........ Coarse, crushed limestone (well-graded gravel)
- Vehicle Make /Model........ Freightliner Columbia 112 with Fruehauf Tanker Trailer
  - Curb........ 25,614 lb
  - Test Inertial........ 79,864 lb (MASH 2016 Limit 79,300 ± 1,100 lb)
  - Gross Static........ 80,026 lb
- Impact Conditions
  - Speed........ 51.1 mph (MASH Limit 50 ± 2.5 mph)
  - Angle........ 15.6 deg (MASH Limit 15 ± 1.5 deg)
  - Impact Location........ 450 in. downstream from the upstream end of the barrier
- Impact Severity .... 498.2 kip-ft > 404 kip-ft MASH 2016 limit
- Exit Conditions
  - Speed........ 36.5 mph
  - Angle .... 5 deg. (approximately)
- Exit Box Criterion........ N/A
- Vehicle Stability........
- Vehicle Stopping Distance........ 310 ft downstream, 14 ft laterally behind
- Vehicle Damage........ Severe
  - VDS........ N/A
  - CDC........ N/A
  - Maximum Interior Deformation .... N/A
- Test Article Damage .... Minimal
- Maximum Test Article Deflections
  - Permanent Set........ N/A
  - Dynamic .... 0.4 in.
  - Working Width........ 37.2 in.
- Transducer Data

Evaluation Criteria		Transducer			MASH Limits
		SLICE-1 (in cab)	SLICE-2 (rear axle)	TDS (truck rear)	
OIV ft/s	Longitudinal	-3.36	-4.44	16.21	not required
	Lateral	13.70	4.71	24.90	
ORA g's	Longitudinal	3.67	-5.00	43.37	
	Lateral	7.36	15.73	28.08	
Maximum Angular Displacement deg.	Roll	265.2	276.0	-	¼ roll
	Pitch	11.12	2.15	-	not required
	Yaw	33.57	-29.38	-	
THIV – ft/s		35.18	20.46	-	
PHD – g's		7.36	16.01	-	
ASI		0.71	1.21	2.58	

Figure 6.34 Summary of Test Results and Sequential Photographs, Test No. MTL6-1

Chapter 7 Summary and Conclusions

Vehicle models were developed and calibrated as best as reasonably possible for simulating tractor-tank trailer vehicle crashes into tall, high-performance, barrier systems. Simulation results were used to select a reduced-height barrier for containing and redirecting tractor-tank trailer vehicles under high-energy impact events under MASH TL-6 impact conditions.

A 62-in. tall, concrete barrier system was configured using yield-line analysis procedures in combination with a 300-kip design lateral load, 200 kips at the top and 100 kips at center wheel location. The 187-ft 6-in. long barrier system incorporated top and bottom widths of 10 in. and 22 in., respectively, and utilized a ¾-in. wide expansion gap downstream from the upstream end. One crash test was performed on the barrier system using a Columbia 112 Freightliner and LBT tank trailer with a gross static weight of 80,026 lb and impacting at 51.1 mph and 15.6 degrees under MASH test designation no. 6-12. The barrier successfully contained and redirected the tractor-tank trailer without barrier penetration and override. Minimal damage occurred to the reinforced-concrete barrier system.

Test no. MTL6-1 was conducted on a 62-in. tall, reinforced concrete single-slope barrier according to MASH test designation no. 6-12. A summary of the test evaluation is shown in Table 7.1.

In test no. MTL6-1, the 79,864-lb tractor-tank trailer impacted the TL-6 concrete barrier 450 in. upstream from the centerline of the expansion joint at a speed of 51.1 mph and an angle of 15.6 degrees, resulting in an impact severity of 498.2 kip-ft. After impacting the barrier system, the vehicle exited the system at a speed of 36.5 mph and an angle of approximately 5 degrees. The vehicle was contained and redirected with minimal damage to the barrier system and severe damage to the vehicle. Upon exit, the vehicle eventually rolled 90 degrees and slid on the concrete tarmac through 6.5 sec after impact. After 6.5 sec, the vehicle with an oval-shaped tank and sloshing liquid cargo began to roll another 180 degrees, whereby crush occurred to the truck's cab. While this post-impact vehicular response is not ideal, the vehicle was contained and remained on the impact side of the barrier. The impact event itself did not result in any unacceptable outcomes for occupant compartment damage, driver survivability, or ballast depletion. The elliptical shape of the tank trailer provided little to no resistance to unstable rollovers, and once a rollover was initiated, only vehicle inertia or terrain adjacent to the vehicle could prevent further roll. Through the first 6.5 sec of the impact event, the MASH TL-6 barrier system contained and redirected the heavy vehicle with roll onto its side and with all occupant risk criteria met.

While this post-impact vehicular response is not ideal, the vehicle was contained and remained on the impact side of the barrier. The impact event itself did not result in any unacceptable outcomes for occupant compartment damage, driver survivability, or ballast depletion. The elliptical shape of the tank trailer provided little to no resistance to unstable rollovers, and once a rollover was initiated, only vehicle inertia or terrain adjacent to the vehicle could prevent further roll. The unique shape of the vehicle and nature of unstable ballast render MASH TL-6 tests unlike test vehicles utilized in MASH Test Levels 4 or 5. Single-unit trucks (SUTs) and tractor-van trailer vehicles would rarely, if ever, be subjected to roll angles exceeding 90 degrees because of the nature of the box and trailer sides, respectively. Subjecting the vehicle to additional evaluation criteria which have no comparable contribution during MASH TL-5 or TL-4 evaluations would be an abrogation of consistency. As such, it is justifiable that the MTL6 barrier be deemed acceptable as a MASH TL-4 and TL-5 barrier. Further discussions are recommended to determine proper crash test expectations for MASH TL-6 barriers subjected to high-energy impact events with round- or oval-shaped tank-trailers.

Note that the crash test described herein successfully demonstrated that a barrier system with a top height much lower than 90 in. would contain and redirect tractor-tank trailer vehicles under MASH TL-6 impact conditions. Crash tests with 1100C (test designation no. 6-10) and 2270P (test designation no. 6-11) vehicles were deemed unnecessary due to prior successful crash tests on tall, vertical-shape, concrete barriers [28]. Further, the barrier system can be used in roadside, median, and bridge applications where mitigation of catastrophic risks associated with tractor-tank trailer vehicles crashes is desired.

Computer simulations demonstrated that the vehicle’s maximum roll angle was reduced from 30 degrees to approximately 17 degrees with a barrier height increase from 62 in. to 70 in. For situations where it is desirable to reduce the vehicle’s risk of roll onto its side, the barrier could reasonably be constructed with 70-in. top height and a 5.5-degree slope away from vertical without the need for additional crash testing.

Finally, further discussions are recommended to determine reasonable crash test expectations for MASH TL-6 barriers subjected to high-energy impact events with round- or oval-shaped tank-trailers.

Further evaluation of the barrier system along with details concerning the project background, design methodology, and system installation recommendations will be published in an overall project summary report upon completion of the entire research study.

Table 7.1 Summary of Safety Performance Evaluation

Evaluation Factors	Evaluation Criteria	Test No. MTL6-1
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.	S
Occupant Risk	D. 1. 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. 2. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.	S U
	G. It is preferable, although not essential, that the vehicle remain upright during and after collision.	S
MASH Test Designation No.		6-12
Final Evaluation (Pass or Fail)		Disputed*

S – Satisfactory U – Unsatisfactory N/A – Not Applicable

*Note: Per criteria described in MASH, test no. MTL6-1 would not be considered a pass according to MASH evaluation criteria for vehicle stability and occupant compartment deformation. Vehicle shapes utilized in MASH 4-12 and 5-12 impact conditions are not conducive to rollovers greater than 90 degrees, whereas tank body trailers may accentuate the risk of rollovers exceeding 90 degrees. The requirement that the vehicle remain upright may represent an undue burden for accepting crash test results, and could result in fewer TL-6-approved systems being installed on the roadway, thereby potentially increasing risk that crashes involving truck-tank trailer vehicles may not be contained. Researchers recommend revising the language of MASH for Test Level 6 evaluation criteria denote that it is desirable but not required for vehicles to remain upright and experience roll angles of less than 90 degrees, and that occupant compartment damage resulting from rollover is not included in test article evaluation criteria.

Chapter 8 Recommendations

The development and evaluation of the new MASH TL-6 median barrier provided insight into several further research needs. First, the TL-6 barrier evaluated herein was a standalone barrier system anchored into an existing concrete tarmac. Real-world barrier installations will require the development of dedicated foundation designs to accommodate the loads associated with potential impacts into this barrier, and geometric transition designs will need to be developed between the TL-6 median barrier and existing concrete barrier sections. Second, while the use the tractor-tank trailer vehicle simulation model developed in this research effort was integral in the design of the barrier geometry, it was noted that there were several areas for improvement to the vehicle model, including refinement of the tanker structure and connections, refinement of the tractor-tank trailer suspension, improvement of the fifth wheel connection, updates to the tanker material models, and improved fluid and baffle structure modeling. Finally, review of the damage to the tractor-tank trailer in the full-scale crash test noted holes in both sides of the tanker structure due to contact with the barrier and the concrete tarmac and leaking of newly installed tank lids seals. As tractor-tank trailers are often tasked with transporting hazardous materials, it may be desirable to further study the damage observed in this test and conduct further research into improving the structural integrity and reinforcement of the tanker to prevent dangerous spilling of their contents.

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Appendices

Appendix A Material Specifications

Table A.1 Bill of Materials, MTL6-1

Item No.	Description	Material Specification	Reference
a1	Concrete	Min. f'c = 5.0 ksi	R#22-149 Ticket#1272151 #1272153, #1272149 R#22-156 Ticket #1273373 #1273376, #1273378
b1	#6 Rebar, 1,795 $^5/_8$” Total Length	ASTM A615 Gr. 60	H#58047458, H#58047453, H#58047181
b2	#6 Rebar, 445 $^5/_8$” Total Length	ASTM A615 Gr. 60	H#58047458, H#58047453, H#58047181
b3	#6 Rebar, 87 $^5/_8$” Unbent Length	ASTM A615 Gr. 60	H#8011403 H#7015596 H#7014721 H#3600019353
c1	Epoxy Adhesive	HILTI HIT RE-500 V3 or Equivalent	COC

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ____________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	056	056	62461		NTE	H42	10/26/21	10:34 AM	1272149

Customer	Delivery Address	Special Instructions
UNL-MIDWEST ROADSIDE SAFETY	4630 NW 36TH ST	AIRPARK / NW 31ST STREET & W CUMING ST & EAST / NORTH OF OLD GOODYEAR HANGERS / PUMPED

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
9.00	9.00	27.00	QL324504	LNK47B1PF4000HW	yd	$132.50	$1,192.50

Water Added On Job At Customer's Request:	SLUMP	Notes:		
	4.00 in		TICKET SUBTOTAL	$1,192.50
			SALES TAX	$0.00
			TICKET TOTAL	**$1,192.50**
			PREVIOUS TOTAL	
			GRAND TOTAL	**$1,192.50**

CAUTION FRESH CONCRETE
KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.1 Concrete, Test No. MTL6-1 (Item No. a1)

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ______________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	284	8520	62461		NTE	H42	10/26/21	10:59 AM	1272153

Customer	Delivery Address	Special Instructions
UNL-MIDWEST ROADSIDE SAFETY	4630 NW 36TH ST	AIRPARK / NW 31ST STREET & W CUMING ST & EAST / NORTH OF OLD GOODYEAR HANGERS / PUMPED

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
9.00	27.00	27.00	QL324504	LNK47B1PF4000HW	yd	$132.50	$1,192.50

Water Added On Job At Customer's Request:	SLUMP	Notes:		
	4.00 in		TICKET SUBTOTAL	$1,192.50
			SALES TAX	$0.00
			TICKET TOTAL	**$1,192.50**
			PREVIOUS TOTAL	$2,385.00
			GRAND TOTAL	**$3,577.50**

CAUTION FRESH CONCRETE
KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.2 Concrete, Test No. MTL6-1 (Item No. a1)

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ______________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	233	6907	62461		NTE	H42	10/26/21	10:48 AM	1272151

Customer	Delivery Address	Special Instructions
UNL-MIDWEST ROADSIDE SAFETY	4630 NW 36TH ST	AIRPARK / NW 31ST STREET & W CUMING ST & EAST / NORTH OF OLD GOODYEAR HANGERS / PUMPED

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
9.00	18.00	27.00	QL324504	LNK47B1PF4000HW	yd	$132.50	$1,192.50

Water Added On Job At Customer's Request:	SLUMP	Notes:		
	4.00 in		TICKET SUBTOTAL	$1,192.50
			SALES TAX	$0.00
			TICKET TOTAL	**$1,192.50**
			PREVIOUS TOTAL	$1,192.50
			GRAND TOTAL	**$2,385.00**

CAUTION FRESH CONCRETE
KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.3 Concrete, Test No. MTL6-1 (Item No. a1)

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ______________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	128	9463	62461		N01	TL-6	11/23/21	10:39 AM	1273373

Customer
UNL-MIDWEST ROADSIDE SAFETY

Delivery Address
4630 NW 36TH STREET

Special Instructions
HWY 34 & NW 31ST ST & SOUTH / WEST ON CUMING ST / NORTH OF GOODYEAR HANGERS PUMP

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
10.00	10.00	30.00	QL31E403	LNK47BTYPE15500h	yd	$146.25	$1 462.50
				WINTER SERVICE			$60.00

Water Added On Job At Customer's Request: ______

SLUMP: 4.00 in

Notes:

TICKET SUBTOTAL	$1,522.50
SALES TAX	$0.00
TICKET TOTAL	$1,522.50
PREVIOUS TOTAL	
GRAND TOTAL	$1,522.50

CAUTION FRESH CONCRETE
KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.4 Concrete, Test No. MTL6-1 (Item No. a1)

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ______________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	148	7709	62461		N01	TL-6	11/23/21	10:54 AM	1273376

Customer
UNL-MIDWEST ROADSIDE SAFETY

Delivery Address
4630 NW 36TH STREET

Special Instructions
HWY 34 & NW 31ST ST & SOUTH / WEST ON CUMING ST / NORTH OF GOODYEAR HANGERS PUMP

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
10.00	20.00	30.00	QL31E403	LNK47BTYPE15500h	yd	$146.25	$1,462.50
				WINTER SERVICE			$60.00

Water Added On Job At Customer's Request: ________

SLUMP: 4.00 in

Notes:

TICKET SUBTOTAL	$1,522.50
SALES TAX	$0.00
TICKET TOTAL	**$1,522.50**
PREVIOUS TOTAL	$1,522.50
GRAND TOTAL	**$3,045.00**

CAUTION FRESH CONCRETE
KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.5 Concrete, Test No. MTL6-1 (Item No. a1)

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ____________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
1	184	8508	62461		N01	TL-6	11/23/21	11:05 AM	1273378

Customer	Delivery Address	Special Instructions
UNL-MIDWEST ROADSIDE SAFETY	4630 NW 36TH STREET	HWY 34 & NW 31ST ST & SOUTH / WEST ON CUMING ST / NORTH OF GOODYEAR HANGERS PUMP

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
10.00	30.00	30.00	QL31E403	LNK47BTYPE15500h	yd	$146.25	$1,462.50
				WINTER SERVICE			$60.00

Water Added On Job At Customer's Request:

SLUMP: 4.00 in

Notes:

TICKET SUBTOTAL	$1,522.50
SALES TAX	$0.00
TICKET TOTAL	$1,522.50
PREVIOUS TOTAL	$3,045.00
GRAND TOTAL	$4,567.50

CAUTION FRESH CONCRETE

KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

Figure A.6 Concrete, Test No. MTL6-1 (Item No. a1)

Cert ID 13444

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

Page 1 / 1

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID
ADELPHIA METALS LLC 801 DIVISION ST SIOUX CITY,IA 51105-2644 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000628754

LENGTH	WEIGHT	HEAT / BATCH
60'00"	5,407 LB	58047458/05

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
10614101/000070		ASTM A615/A615M-20

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
836119	1327-0000425195	06/11/2021

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.41	1.04	0.010	0.040	0.33	0.25	0.09	0.16	0.029	0.004	0.024	0.000	0.001	0.61

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
66698	460	102514	707	8.000	200.0	15.40	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

BHASKAR YALAMANCHILI
QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

WADE LUMPKINS
QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Heat 58047458

Figure A.7 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

Cert ID 13443

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

Page 1 / 1

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA METALS LLC 801 DIVISION ST SIOUX CITY,IA 51105-2644 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000628753

LENGTH	WEIGHT	HEAT / BATCH
60'00"	5,407 LB	58047453/05

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
10614101/000070		ASTM A615/A615M-20

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
836119	1327-0000425195	06/11/2021

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.39	0.90	0.011	0.034	0.19	0.26	0.08	0.17	0.026	0.005	0.002	0.019	0.001	0.56

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
74551	514	109489	755	8.000	200.0	13.20	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

BHASKAR YALAMANCHILI
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Heat 58047453

Figure A.8 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

Cert ID 13441

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

Page 1 / 1

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA METALS LLC 801 DIVISION ST SIOUX CITY,IA 51105-2644 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000628751

LENGTH	WEIGHT	HEAT / BATCH
60'00"	149,956 LB	58047181/02

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
10614101/000070		ASTM A615/A615M-20

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
836119	1327-0000425195	06/11/2021

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqvA706 (%)
0.39	1.33	0.040	0.026	0.40	0.33	0.09	0.07	0.031	0.005	0.026	0.000	0.001	0.61

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
82100	566	115564	797	8.000	200.0	12.40	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

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Heat 58047181

Figure A.9 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

Page: 4
Document: bol
Sales Order: 278758
Comments:

CMC

CMC STEEL NEW JERSEY
1 Crossman Road North
Sayreville NJ 08872-1402

CERTIFIED MILL TEST REPORT
For additional copies call

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Joseph T Homic
Quality Assurance Manager

HEAT NO.:8011403 SECTION: REBAR 13MM (#4) 60'0" 420/60 GRADE: ROLL DATE: 04/21/2021 MELT DATE: 04/20/2021 Cert. No.: 83447323 / 011403M265	S O L D T O	Adelphia Metals LLC 1930 Marlton Pike E Cherry Hill NJ US 08003-2150 8569888889 9527589323	S H I P T O	CPU Chicago Depot 13535 S Torrence Ave Chicago IL US 60633-2164 7736466363	Delivery#: 83447323 BOL#: 2078140 CUST PO#: 835985 CUST P/N: DLVRY LBS / HEAT: 39640.000 LB DLVRY PCS / HEAT: 989 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.44%	Tensile to Yield ratio test1	1.48		
Mn	0.68%	Elongation Gage Lgth 1(metri	200mm		
P	0.017%	Bend Test 1	Passed		
S	0.033%	Rebar Deformation Avg. Spaci	0.334IN		
Si	0.23%	Rebar Deformation Avg. Heigh	0.029IN		
Cu	0.53%	Rebar Deformation Max. Gap	0.085IN		
Cr	0.11%				
Ni	0.18%				
Mo	0.060%				
V	0.012%				
Cb	0.004%				
Sn	0.013%				
Al	0.001%				
Yield Strength test 1	71.4ksi				
Yield Strength test 1 (metri	492MPa				
Tensile Strength test 1	105.8ksi				
Tensile Strength 1 (metric)	729MPa				
Elongation test 1	13%				
Elongation Gage Lgth test 1	8IN				

The Following is true of the material represented by this MTR:
*Material is fully killed
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

REMARKS :

Page 1 OF 1 05/05/2021 09:23:55

Figure A.10 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

Page: 10

Document: bol

Sales Order: 278758

Comments:

CMC

CMC STEEL TENNESSEE
1919 Tennessee Avenue
Knoxville TN 37921-2686

CERTIFIED MILL TEST REPORT
For additional copies call

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Jim Hall
Quality Assurance Manager

HEAT NO.:7015596 SECTION: REBAR 13MM (#4) 60'0" 420/60 GRADE: ROLL DATE: 02/15/2021 MELT DATE: 02/12/2021 Cert. No.: 83447322 / 015596L265	SOLD TO	Adelphia Metals LLC 1930 Marlton Pike E Cherry Hill NJ US 08003-2150 8569888889 9527589323	SHIP TO	CPU Chicago Depot 13535 S Torrence Ave Chicago IL US 60633-2164 7736466363	Delivery#: 83447322 BOL#: 2078139 CUST PO#: 835985 CUST P/N: DLVRY LBS / HEAT: 24048.000 LB DLVRY PCS / HEAT: 600 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.30%	Rebar Deformation Avg. Spaci	0.325IN		
Mn	0.69%	Rebar Deformation Avg. Heigh	0.033IN		
P	0.018%	Rebar Deformation Max. Gap	0.121IN		
S	0.061%				
Si	0.19%				
Cu	0.37%				
Cr	0.18%				
Ni	0.10%				
Mo	0.015%				
V	0.005%				
Sn	0.005%				
Yield Strength test 1	89.7ksi				
Yield Strength test 1 (metri	618MPa				
Tensile Strength test 1	104.7ksi				
Tensile Strength 1 (metric)	722MPa				
Elongation test 1	11%				
Elongation Gage Lgth test 1	8IN				
Elongation Gage Lgth 1(metri	200mm				
Bend Test 1	Passed				

The Following is true of the material represented by this MTR:
*Material is fully killed
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

REMARKS :

Page 1 OF 1 04/30/2021 15:44:33

Figure A.11 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

Page: 11

Document: bol

Sales Order: 278758

Comments:

CMC

CMC STEEL TENNESSEE
1919 Tennessee Avenue
Knoxville TN 37921-2686

CERTIFIED MILL TEST REPORT
For additional copies call

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Jim Hall
Quality Assurance Manager

HEAT NO.:7014721 SECTION: REBAR 13MM (#4) 60'0" 420/60 GRADE: ROLL DATE: 02/15/2021 MELT DATE: 01/07/2021 Cert. No.: 83447322 / 014721L265	SOLD TO	Adelphia Metals LLC 1930 Marlton Pike E Cherry Hill NJ US 08003-2150 8569888889 9527589323	SHIP TO	CPU Chicago Depot 13535 S Torrence Ave Chicago IL US 60633-2164 7736466363	Delivery#: 83447322 BOL#: 2078139 CUST PO#: 835985 CUST P/N: DLVRY LBS / HEAT: 12024.000 LB DLVRY PCS / HEAT: 300 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.32%	Rebar Deformation Avg. Spaci	0.323IN		
Mn	0.77%	Rebar Deformation Avg. Heigh	0.035IN		
P	0.017%	Rebar Deformation Max. Gap	0.138IN		
S	0.050%				
Si	0.24%				
Cu	0.46%				
Cr	0.23%				
Ni	0.16%				
Mo	0.026%				
V	0.004%				
Sn	0.009%				
Yield Strength test 1	91.9ksi				
Yield Strength test 1 (metri	634MPa				
Tensile Strength test 1	107.7ksi				
Tensile Strength 1 (metric)	743MPa				
Elongation test 1	13%				
Elongation Gage Lgth test 1	8IN				
Elongation Gage Lgth 1(metri	200mm				
Bend Test 1	Passed				

The Following is true of the material represented by this MTR:
*Material is fully killed
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

REMARKS :

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Figure A.12 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

NUCOR

Mill Certification
04/16/2021

MTR#:670919-3
Lot #:360001935320
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: ADELPHIA METALS I LLC
411 MAIN ST E
NEW PRAGUE, MN 56071 US

Ship To: ADELPHIA METALS LLC
411 MAIN ST E
NEW PRAGUE, MN 56071 US

Customer PO	834399	Sales Order #	36018898 - 8.5
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	360001935320
Size	#5	Heat #	3600019353
BOL #	BOL-749133	Load #	670919
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	03/19/2021	Qty Shipped LBS	15020
Product Country Of Origin	United States	Qty Shipped EA	360
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States Melting Date: 03/16/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.35	0.89	0.017	0.039	0.177	0.22	0.23	0.07	0.37	0.010	0.001

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.036	Pass

Tensile testing

	Elongation in 8" (%)	Tensile (PSI)	Yield (PSI)
(1)	13.3	103800	66900

Other Test Results
Weight Percent Variance (%) : -3.90

Comments:
All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Zachary Sprintz, Chief Metallurgist

Page 1 of 1

Comments:

Figure A.13 #6 Rebar, Test No. MTL6-1 (Item Nos. b1 through b3)

P.O. Box 21148
Tulsa, OK 74121
Phone (918) 252-6000
Fax No. (918) 252-6520

Certified Quality and Environmental Systems
SQS
ISO 9001 / ISO 14001
Reg. No. 12455-03

Date: 12/13/2016

Subject: Certificate of Conformance

Product: HIT RE-500 V3 Adhesive

To Whom it May Concern:

This is to certify that the HIT-RE 500 V3 is a high-strength, slow cure two-part epoxy adhesive contained in two cartridges separating the resin from the hardener.

Additionally, this certifies that the product has been seismically and cracked concrete qualified as represented in ICC-ES report ESR- 3814.

Sincerely,

Hilti, Inc.

5400 South 122 East Avenue

Tulsa, Oklahoma 74146

800-879-8000

800-879-7000 fax

US-Sales@hilti.com

Figure A.14 Epoxy Adhesive, Test No. MTL6-1 (Item No. c1)

Appendix B Vehicle Center of Gravity Determination

	Test Name: MTL6	VIN:	1FUJFOCV2ADAV1130
Model Year: 2010	Make: Freightliner	Model:	Columbia 112

Vehicle CG Determination

Vehicle Equipment		Weight (lb)	Vertical CG (in.)	Vertical M (lb-in.)
	Unbalasted Vehicle (Curb)	25614	0	0
+	Guidance Hub	43	19.0	817.0
+	Tow Pin Plate	9	12.25	110.25
+	Pnumatic Tank (Nitrogen)	30	52.5	1575.0
+	Strobe/Brake Battery	5	52.0	260.0
+	Brake receivers/wires	5	92.0	460.0
+	Brake Actuator Frame	7	51.5	360.5
+	Cab DAQ & Mounting Plate	4	48.625	194.5
+	DTS Unit	0	0	0
+	Front Trailer DAQ & Mount	0	0	0
+	Rear Trailer DAQ & Mount	20	27.75	555.0
+	Rear Truck DAQ & Mount	16	31.0	496.0
-	Interior	-177	62.0	-10974.0
-	Washer fluid	-12	57.0	-684.0
-	Fuel	-117	14.0	-1638.0
				0
				0
BALLAST +	From Ballast Page	55110.72	77.137	#########
+				0
+				0
				0
				4242617.9

Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle

Estimated Total Weight (lb) 80557.72

Total Ballast Weight (lb) 55110.72
Ballast Vertical CG Location (in.) 76.984

Vehicle Dimensions for C.G. Calculations

Tractor Front to Front Tandem:	155.0 in.	Front Tractor Track Width:	73.25 in.
Tractor Front to Rear Tandem:	51.25 in.	Rear Tractor Track Width:	98.0 in.
Tractor Rear to Trailer Front Tandem:	362.25 in.	Trailer Track Width:	44.375 in.
Trailer Front to Rear:	49.0 in.		

Center of Gravity	36000T MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb)	79300 ± 1100	79864	564.0
Longitudinal CG (in.)	NA	342.465	NA
Lateral CG (in.)	NA	0.336	NA
Ballast Vertical CG (in.)	81 ± 4	76.984	-4.01647

Note: Long. CG is measured from front axle of test vehicle
Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

Vehicle Weights

	Curb Weight (lb)			Test Inertial Weight (lb)		
	Left	Right	Total Axle	Left	Right	Total Axle
Tractor Front Axle	4190	4372	8562	4981	5164	10145
Tractor Tandem Front	2416	2344	4760	8910	8634	17544
Tractor Tandem Rear	2274	2138	4412	8098	8527	16625
Trailer Front Axle	1490	1730	3220	7520	7780	15300
Trailer Rear Axle	2060	2600	4660	10050	10200	20250
		Total Curb Weight	25614		Total Test Inertial Weight	79864

Figure B.1 Vehicle Mass Distribution, Test No. MTL6-1

	Test Name:	MTL6-1	VIN:	1FUJFOCV2ADAV1130
Year: 2010	Make:	Freightliner	Model:	Columbia 112

Vehicle CG Determination

		Vehicle Equipment	Long CG (in.)	Lat CG (in.)	Long M (lb-in.)	Lat M (lb-in.)
		Unbalasted Vehicle (Curb)	248.141	1.058	6355895.0	27096.875
	+	Guidance Hub	0	50.5	0	2171.5
	+	Tow Pin Plate	0	0	0	0
	+	Pnumatic Tank (Nitrogen)	53.25	23.0	1597.5	690.0
	+	Strobe/Brake Battery	59.0	0.5	295.0	2.5
	+	Brake receivers/wires	65.25	0	326.25	0
	+	Brake Actuator Frame	25.25	-19.5	176.75	-136.5
	+	Cab DAQ & Mounting Plate	50.5	0	202.0	0
	+	DTS Unit	0	0	0	0
	+	Front Trailer DAQ & Mount	0	0	0	0
	+	Rear Trailer DAQ & Mount	569.0	0	11380.0	0
	+	Rear Truck DAQ & Mount	233.5	0	3736.0	0
	-	Interior	42.0	0	-7434.0	0
	-	Washer fluid	-0.75	-32.0	9.0	384.0
	-	Fuel	53.5	-32.0	-6259.5	3744.0
					0	0
					0	0
BALLAST	+	From Ballast Page	286.34	0	########	0
	+				0	0
	+				0	0
					0	0
		Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle			########	33952.375

Estimated Total CG Location (in.)	274.838	0.421
Ballast CG Location (in.)	286.34	0

Calibrated Scales Used

Equipment Type	Manufacturer	Serial #	Capacity
Pad Scale	Pennsylvania Scale	95-228908	5000 lb
Pad Scale	Pennsylvania Scale	95-228909	5000 lb
Yellow aircraft scales	Intercomp	25702547	10000
Yellow aircraft scales	Intercomp	25702541	10000
Yellow aircraft scales	Intercomp	25702546	10000
Yellow aircraft scales	Intercomp	25702549	10000
Gray pad scale	Intercomp	0601AK21009	10000
Gray pad scale	Intercomp	0601AK21013	10000

Vehicle Weights

	Gross Static Weight (lb) Left	Right	Total Axle
Tractor Front Axle	4981	5164	10145
Tractor Tandem Front	8910	8634	17544
Tractor Tandem Rear	8098	8527	16625
Trailer Front Axle	7520	7780	15300
Trailer Rear Axle	10050	10200	20250
	Total Gross Static Weight		79864

Notes:

Surrogate Occupant was not used for this test.

Figure B.2 Vehicle Mass Distribution, Test No. MTL6-1

Appendix C Accelerometer and Rate Transducer Data Plots

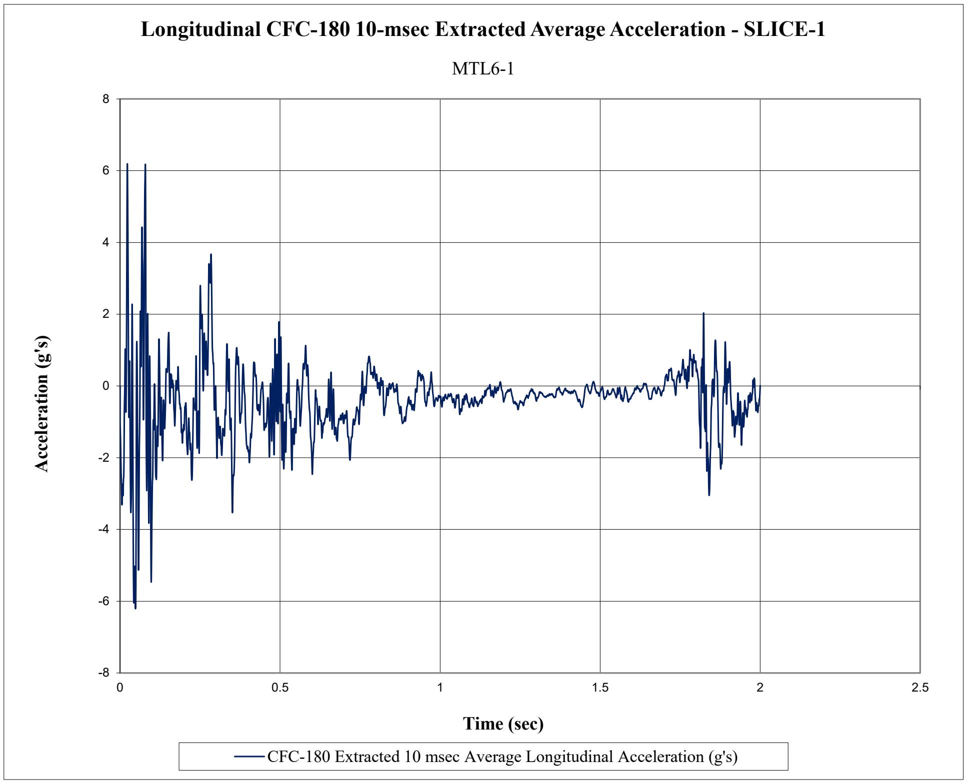

Figure C.1 10-ms Average Longitudinal Acceleration (SLICE-1), Test No. MTL6-1

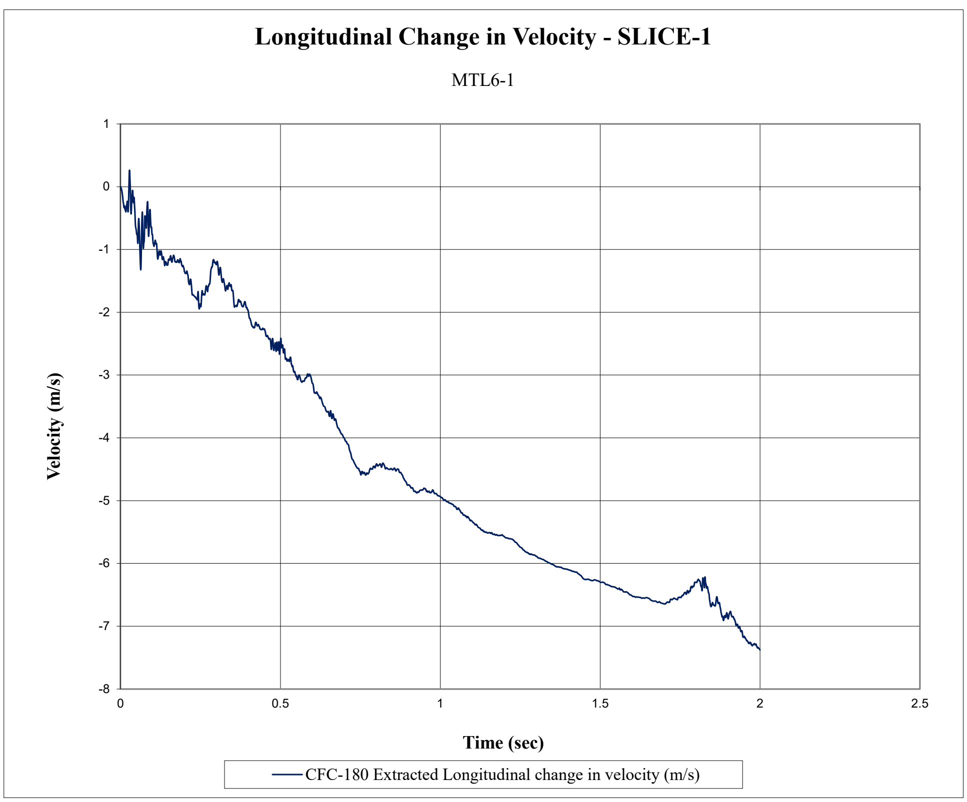

Figure C.2 Longitudinal Occupant Impact Velocity (SLICE-1), Test No. MTL6-1

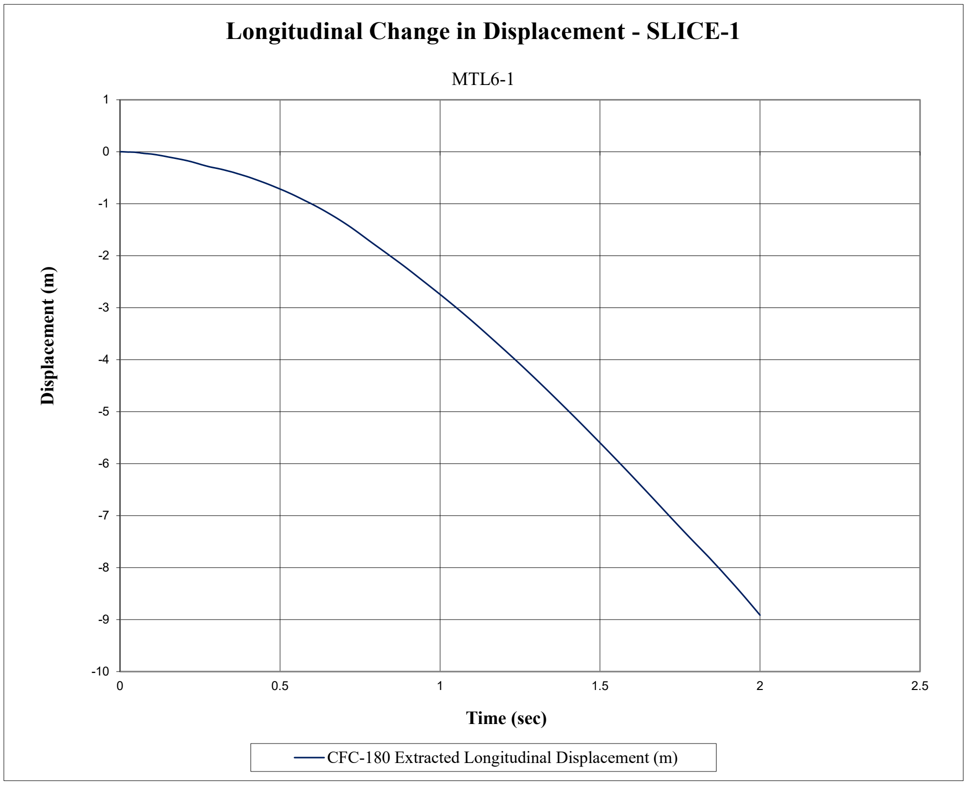

Figure C.3 Longitudinal Occupant Displacement (SLICE-1), Test No. MTL6-1

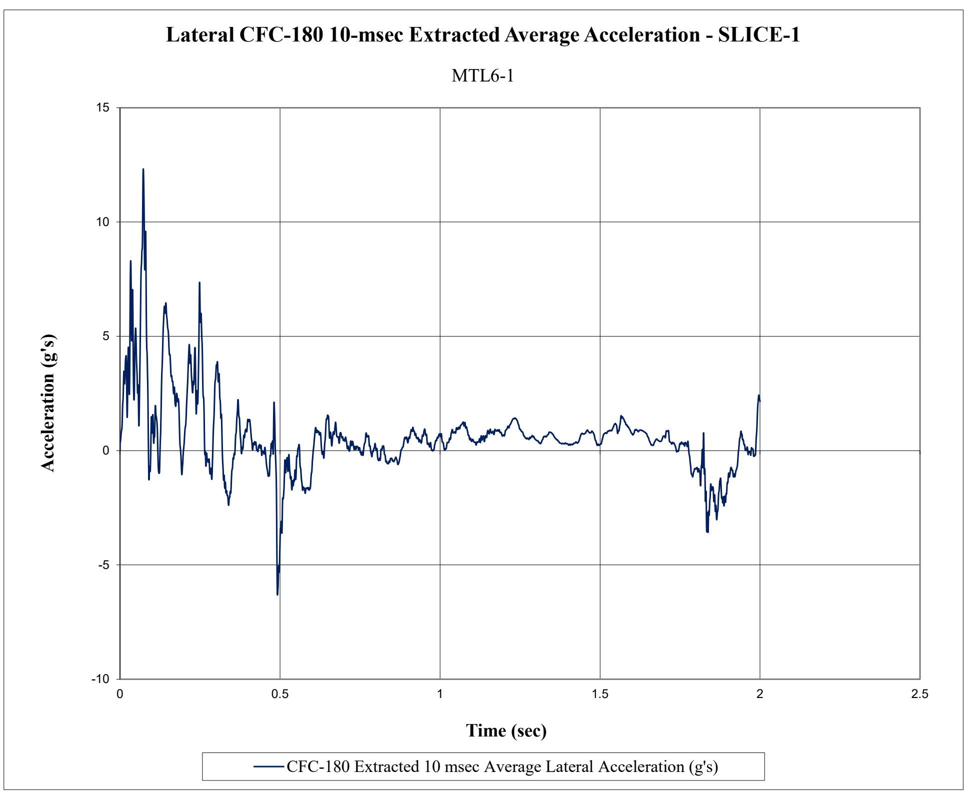

Figure C.4 10-ms Average Lateral Acceleration (SLICE-1), Test No. MTL6-1

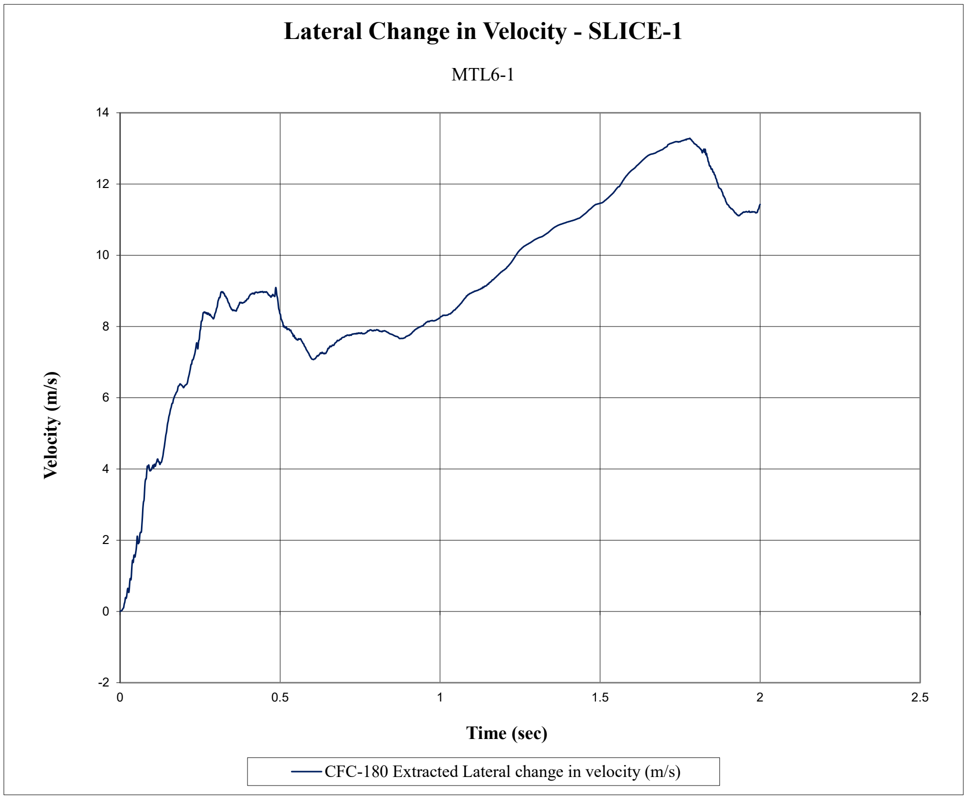

Figure C.5 Lateral Occupant Impact Velocity (SLICE-1), Test No. MTL6-1

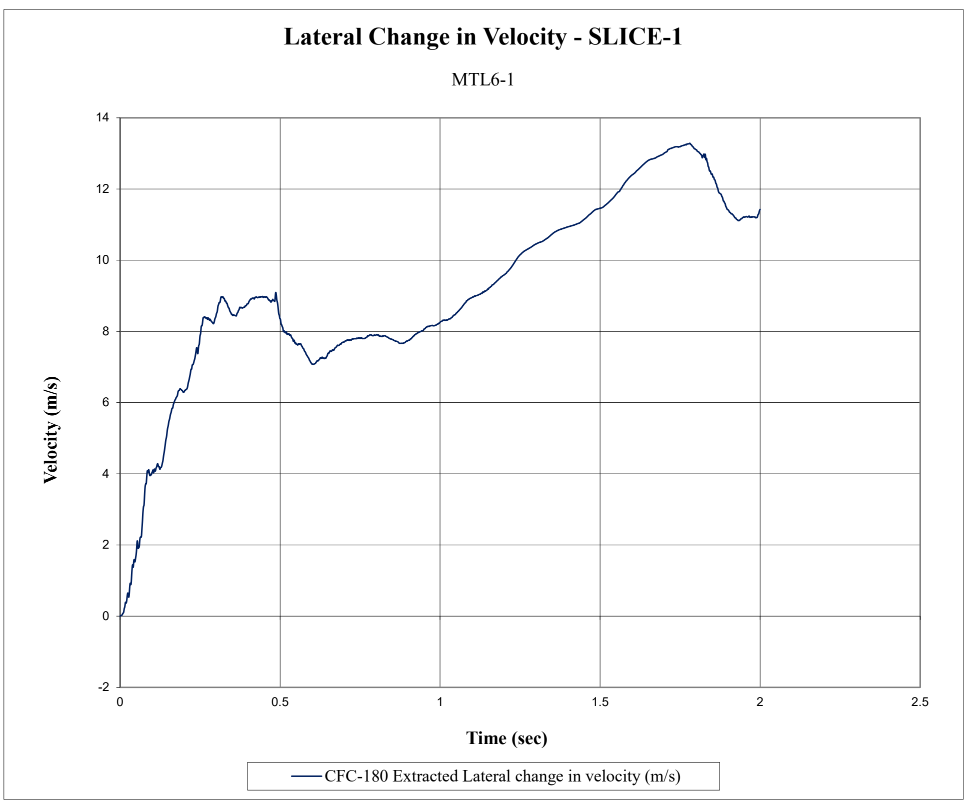

Figure C.6 Lateral Occupant Displacement (SLICE-1), Test No. MTL6-1

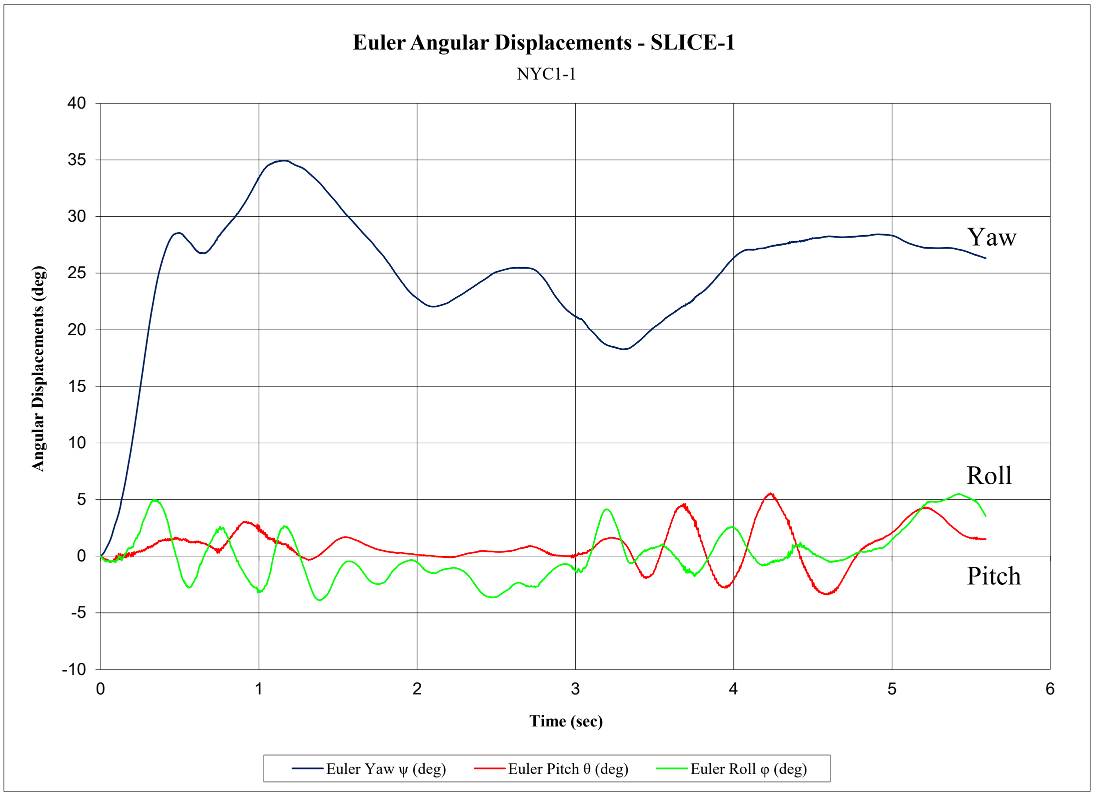

Figure C.7 Vehicle Angular Displacements (SLICE-1), Test No. MTL6-1

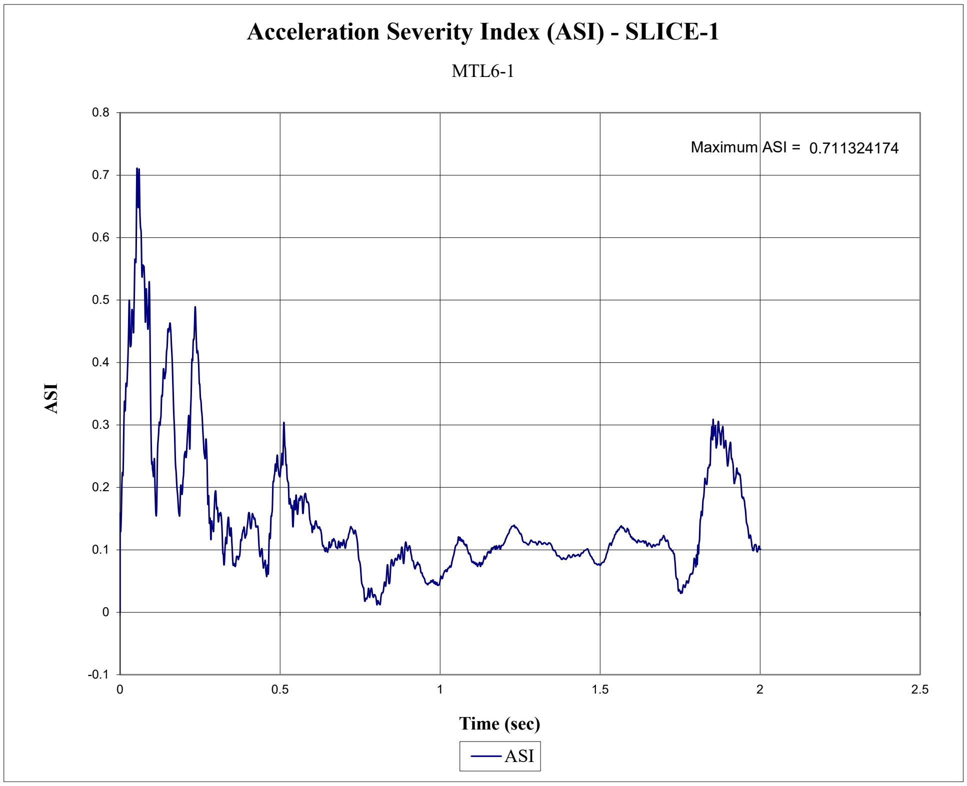

Figure C.8 Acceleration Severity Index (SLICE-1), Test No. MTL6-1

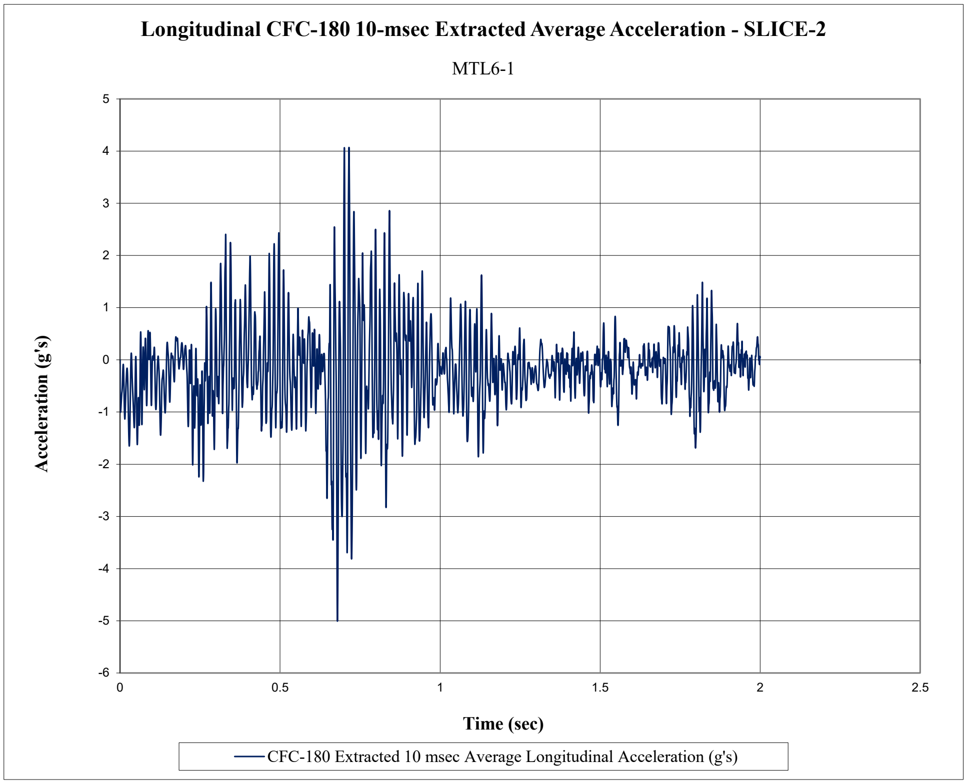

Figure C.9 10-ms Average Longitudinal Acceleration (SLICE-2), Test No. MTL6-1

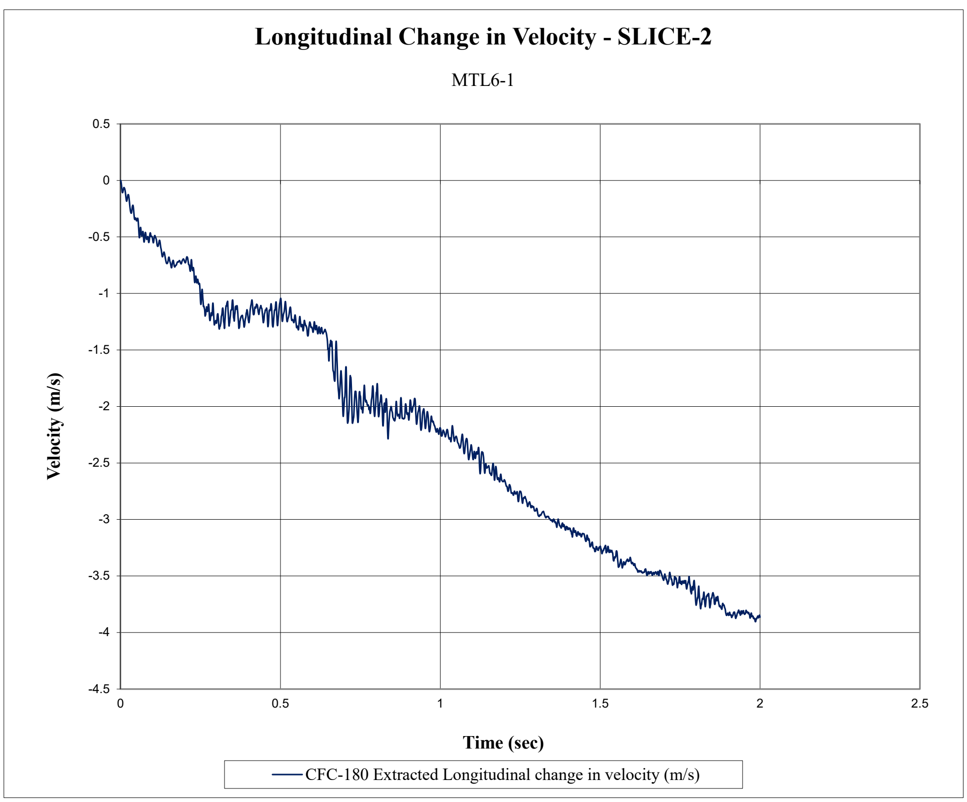

Figure C.10 Longitudinal Occupant Impact Velocity (SLICE-2), Test No. MTL6-1

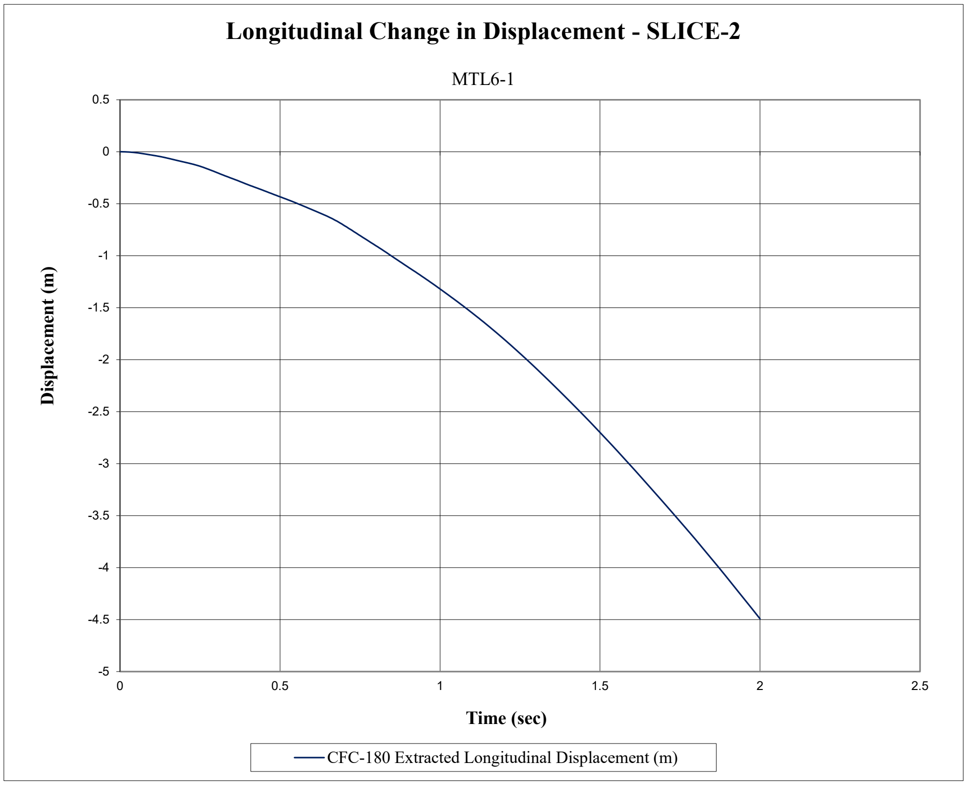

Figure C.11 Longitudinal Occupant Displacement (SLICE-2), Test No. MTL6-1

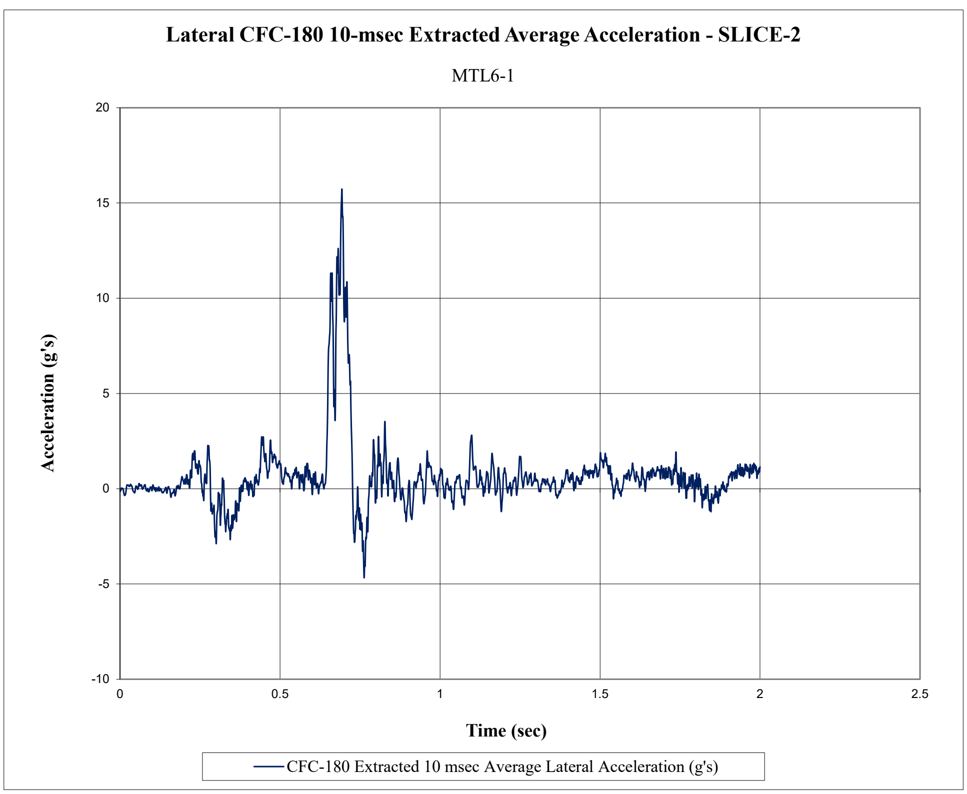

Figure C.12 10-ms Average Lateral Acceleration (SLICE-2), Test No. MTL6-1

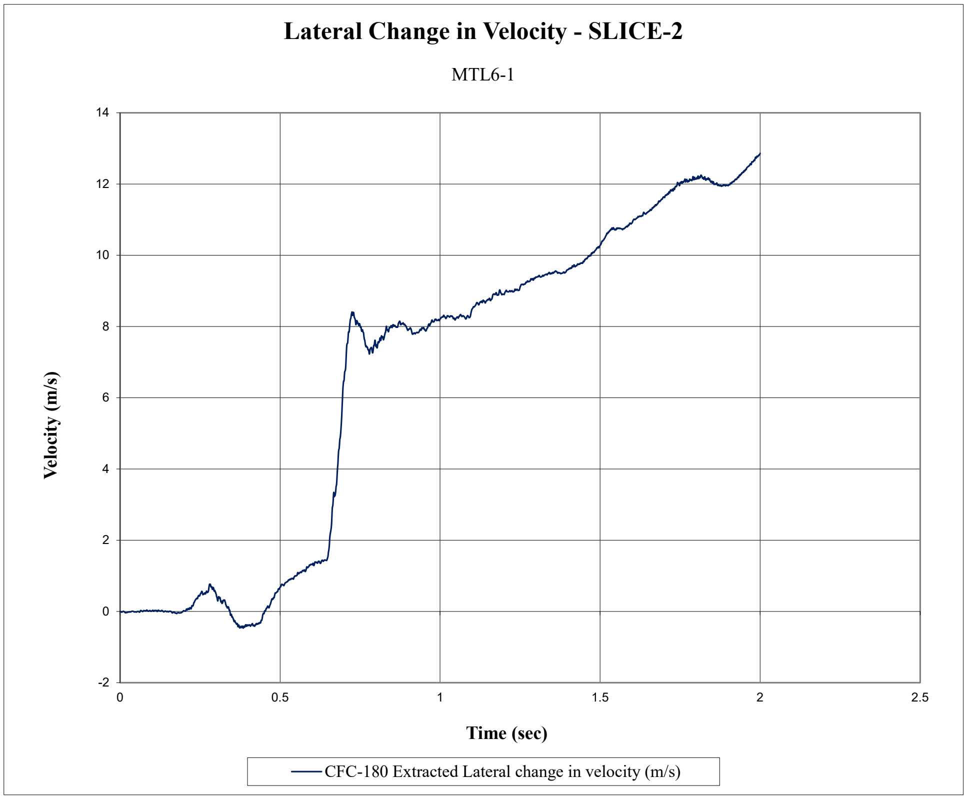

Figure C.13 Lateral Occupant Impact Velocity (SLICE-2), Test No. MTL6-1

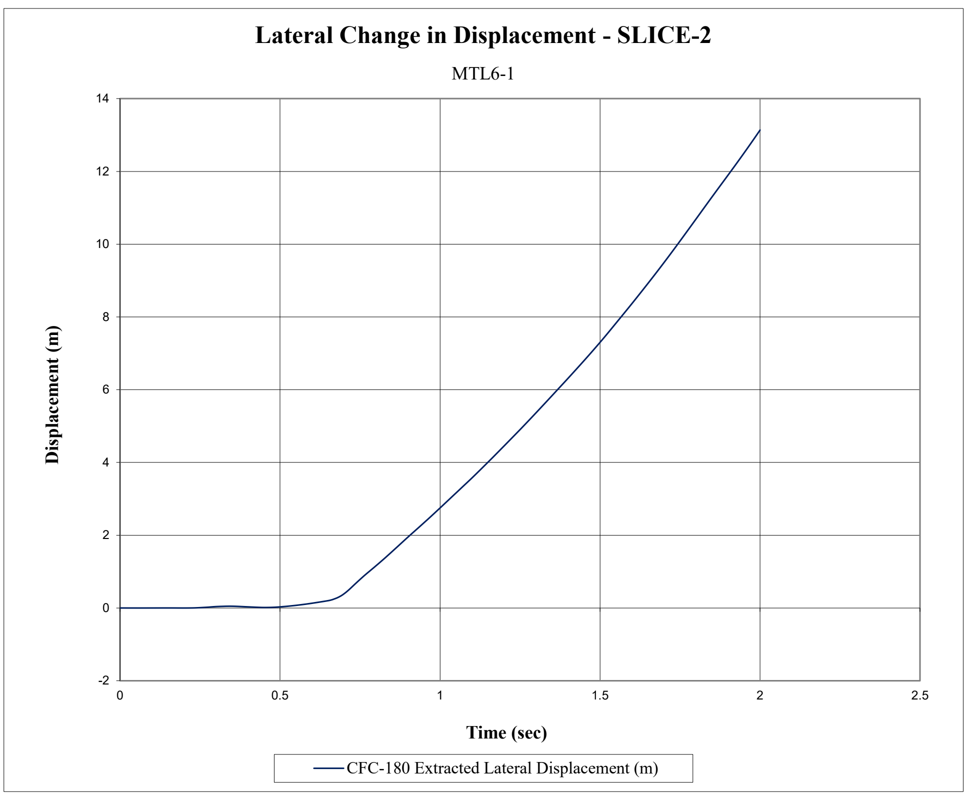

Figure C.14 Lateral Occupant Displacement (SLICE-2), Test No. MTL6-1

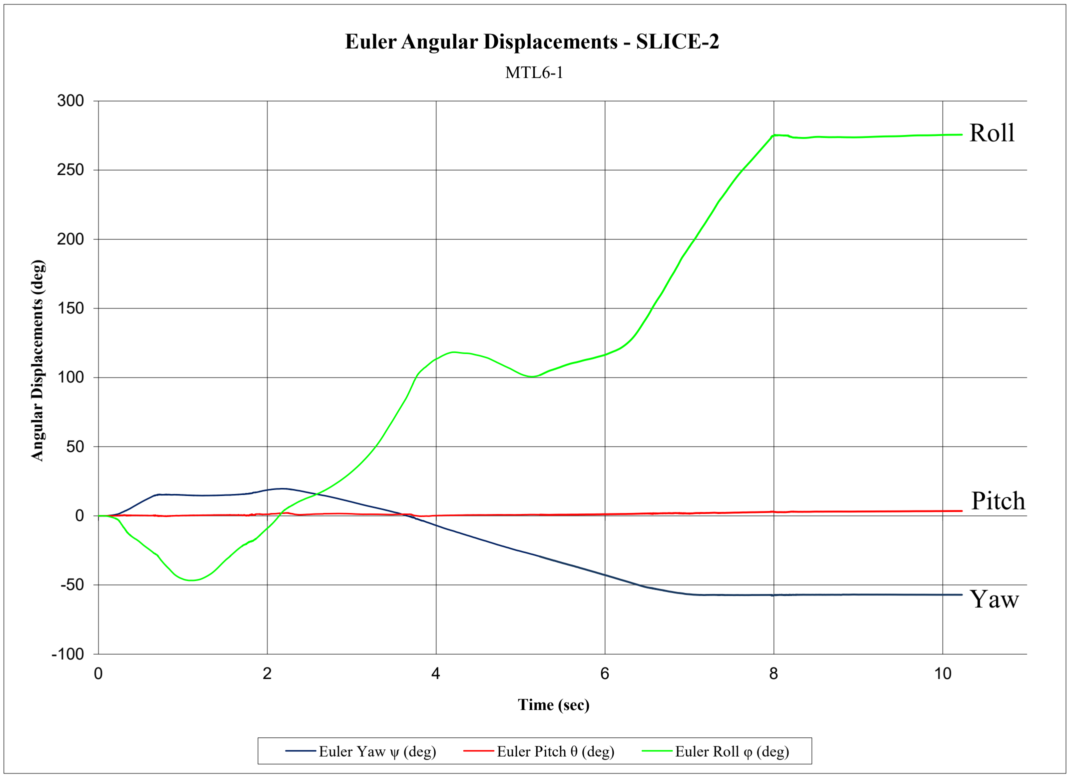

Figure C.15 Vehicle Angular Displacements (SLICE-2), Test No. MTL6-1

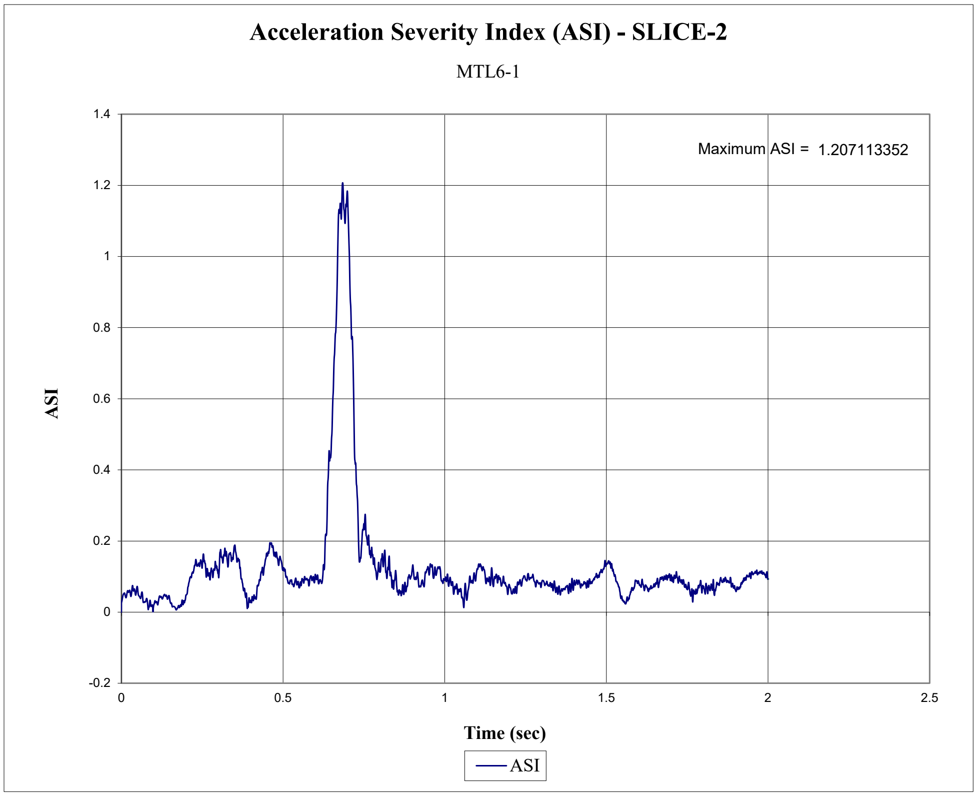

Figure C.16 Acceleration Severity Index (SLICE-2), Test No. MTL6-1