FTA Report No. 0247

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

LRV Bumper Safety Technology Deployment

PREPARED BY

Applied Research Associates, Inc.

U.S. Department of Transportation
Federal Transit Administration

JUNE
2023

COVER PHOTO

Courtesy of Robert Bocchieri, ARA

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Applied Research Associates, Inc.
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Metric Conversion Table

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
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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14. ABSTRACT
This report summarizes findings from a project to design, build, and test a prototype LRV end enclosure, or bumper, as a retrofit to an existing LRV operated in the U.S. to reduce (1) potential for injury to automobile occupants, (2) damage to the LRV, and (3) costs to operators from crashes. The retrofit bumper design process consisted of geometric and mechanical design, design of hydraulics, envelope analysis, and nonlinear dynamic finite element crash analyses. Side and oblique impact simulations were performed for LRV impact speeds of 20 mph against a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). Injuries due to collisions were evaluated using a model of the ES-2re Side Impact Dummy (SID). Adding the bumper to the collision interface significantly reduced the potential for serious injuries in all the collision scenarios evaluated. Crash tests with automobiles resulted in minimal damage to the LRV enclosure, with no permanent deformation to the structure. A breakaway test to represent an LRV-LRV collision, was successful in allowing the front enclosure to push back beneath the anti-climber as designed. Additionally, findings from two case studies provide a lower bound estimate of the cost of automobile and pedestrian collisions and suggest that even a modest reduction in damage costs, loss of life, and injuries warrants the cost of retrofit.

15. SUBJECT TERMS
Light Rail Vehicle, LRV, Crash, Collision, Safety, Injury, Automobile, Crash Energy Management, CEM, Bumper

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Abstract

This report summarizes findings from a project to design, build, and test a prototype LRV end enclosure, or bumper, as a retrofit to an existing LRV operated in the U.S. to reduce (1) potential for injury to automobile occupants, (2) damage to the LRV, and (3) costs to operators from crashes. The retrofit bumper design process consisted of geometric and mechanical design, design of hydraulics, envelope analysis, and nonlinear dynamic finite element crash analyses. Side and oblique impact simulations were performed for LRV impact speeds of 20 mph against a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). Injuries due to collisions were evaluated using a model of the ES-2re Side Impact Dummy (SID). Adding the bumper to the collision interface significantly reduced the potential for serious injuries in all the collision scenarios evaluated. Crash tests with the automobiles resulted in minimal damage to the LRV enclosure, with no permanent deformation to the structure. A breakaway test to represent an LRV-LRV collision, was successful in allowing the front enclosure to push back beneath the anti-climber as designed. Additionally, findings from two case studies provide a lower bound estimate of the cost of automobile and pedestrian collisions and suggest that even a modest reduction in damage costs, loss of life, and injuries warrants the cost of retrofit.

Acknowledgments

We would like to acknowledge the collaboration and contributions provided by TriMet. We are also grateful for the support provided by Siemens and particularly the guidance provided by Glenn Gough. We are also grateful to the Los Angeles County Metropolitan Transportation Authority for input on design requirements and reviews, and to Sacramento Regional Transit for operational considerations. Finally, we would like to acknowledge Robert MacNeill's contributions to research and analysis in the development of this project. He also serves as the external technical reviewer.

Executive Summary

The majority of Light Rail Vehicle (LRV) crashes involve motor vehicles and cyclists/pedestrians. These crashes result in large crush intrusions into the automobile, causing injury and fatalities. When override occurs, automobile occupants may sustain more serious injuries and there is increased potential for extensive damage to the LRV. This greatly increases the repair costs and time before the vehicle is placed back in service. Therefore, there has been a recognized need to investigate methods for improving the crash safety in these collisions.

Recent research was conducted to evaluate the potential for mitigating injuries in crashes between LRVs and automobiles. The combined research showed marked improvements in automobile passenger safety for a variety of automobile types and collision scenarios. Following this research, the American Society of Mechanical Engineers (ASME) RT-1 Safety Standard for Structural Requirements for Light Rail Vehicles and Streetcars included crash safety design criteria for new LRVs requiring enclosed front ends, or bumpers. As a result, the inclusion of bumpers on new LRV designs is now common practice in the U.S. However, existing LRVs will continue to operate for decades without these crash safety features. The number and severity of injuries caused by continued operation of these vehicles, as well as the ongoing costs to vehicle operators from crashes, can be significantly reduced by retrofitting these vehicles with bumpers to be compliant with the current RT-1 standard.

The objective of this project is to design, build, and test a prototype LRV end enclosure, or bumper, as a retrofit to an existing LRV operated in the U.S. to reduce potential for injury to automobile occupants, damage to the LRV, and lower costs to operators from crashes. Three transit agencies provided significant contributions to the project and a complete prototype design was developed and tested for the Siemens SD660 operated by TriMet (Type 2 and Type 3 LRVs).

The project consisted of the following development steps: (1) retrofit design, (2) fabrication, (3) operational testing on LRVs, and (4) crashworthiness testing. To develop the design, Los Angeles County Metropolitan Transportation Authority (Metro) and TriMet provided substantial technical information on the end frame structures for the LRVs, as well as electrical and equipment details. They also helped to define the operational and maintenance requirements and performed design reviews. TriMet continued to support both the operational and crash test phases.

The retrofit bumper design process consisted of geometric and mechanical design, design of hydraulics, envelope analysis, and finally nonlinear dynamic finite element crash analyses. Side and oblique impact simulations were performed when impacting a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). Two crash conditions were considered: a normal (90˚) impact representative of a street crossing and an oblique (45˚) impact representing a car turning in front of a LRV. Both are the most common impact conditions. Injuries due to collisions were evaluated using a model of the ES-2re Side Impact Dummy (SID). Injuries were calculated for the head, chest, abdomen, and neck using the Abbreviated Injury Scale (AIS).

Simulations were performed for LRV impact speeds of 20 mph against the automobiles. For this speed, the bumper is designed to remain usable in service. Adding the bumper to the collision interface significantly reduced the potential for serious injuries in all the collision scenarios evaluated. For example, the 2003 Explorer injuries were reduced from an AIS3+ (serious) chest injury probability of 48.5 percent without bumper to 21.8 percent with the bumper when considering normal (90°) side impact. For the 2010 Yaris, injuries were reduced from 100 percent AIS6+ (fatal) injury probability, due to head impact against the LRV anti-climber, to 12.4 percent.

Table ES-1 *Probability of Occupant Injury with 90-degree Impacts at 20 mph*

Configuration	AIS 6+ (fatal) Injury to the Head 2010 Toyota Yaris	AIS3+ (serious) Injury to Chest 2003 Ford Explorer
Open End	100%	48.5%
With Enclosure	12.4%	21.8%

The bumper was also designed to be functional and remain in service for LRV-to-LRV crash speeds of 5 mph. To protect against LRV collisions at higher speeds, the bumper side panels break away at 11 mph, and the existing LRV crash energy management performance is unaffected.

Once a prototype was manufactured, operational testing was conducted with an enclosure mounted to a TriMet Type 3 (SD660) LRV. The objective of these tests was to demonstrate compatibility with operational vehicles, and to gather feedback from TriMet operators and maintenance staff. Testing of both powered and unpowered function was performed to raise and lower the front enclosure and coupling to another LRV. Operations went smoothly with no interference with car geometry. The operator noted that coupling was an easy process, not hindered by the raised enclosure. Moving operation was also performed in the Ruby Junction Rail Yard to demonstrate compatibility with trackside structures. No issues were noted by the operator and good clearance with track-side equipment was recorded with video.

Three crash tests of the front-end structure of the SD660 retrofit with an end enclosure were conducted at the Center for Advanced Product Evaluation (CAPE). The first two tests were designed to evaluate the enclosure performance when impacting a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). Two crash conditions were considered: a normal (90˚) impact and an oblique (45˚) impact. The last test was to evaluate the side panel breakaway behavior required for collisions between LRVs. The breakaway allows for the designed engagement of the LRV anti-climbers as is required in the RT-1 safety standard and to allow for the full design stroke of the coupler energy absorber. These functions must be maintained with any retrofit.

All three crash tests were successful in achieving the desired crash conditions. Both tests with the automobiles resulted in minimal damage to the enclosure, consisting only of scratches to the paint. There was no permanent deformation to the structure. The front enclosure was retracted and deployed after each crash test with no loss in function. In the breakaway test, the side panels sheared back as designed and the front enclosure pushed back beneath the anti-climber. In this way, the anti-climber is not obstructed for LRV-LRV collisions. Crash test results were consistent with pre-test crash simulations. In particular, the deformation of the automobiles compares well with measurements. This agreement provides a partial validation of the analysis methods used to determine the reduction in injuries predicted from the matrix of crash simulations.

Two case studies were considered to quantify the benefit of bringing existing LRVs up to current crash safety standards regarding automobile and pedestrian safety. There was not a complete dataset in either case, but the light rail collision analysis performed by Valley Metro in Phoenix, AZ provides what is believed to be a lower bound on the cost of automobile and pedestrian collisions. The following items were considered in the cost analysis: (1) repair costs to LRVs, (2) loss of LRV use, and (3) value of statistical life (VSL). Total annual costs (direct costs, loss of life, and value of preventing injuries) on an annual basis are summarized below for the years 2012 and 2022. The total cost to the city of Phoenix for these LRV crashes is approximately $16M in 2022 ($11M for 2012). Legal costs were not available or considered, so this is considered a lower bound estimate. Using these costs as a lower bound, even a modest reduction in damage costs, loss of life, and injuries warrants the cost of retrofit.

Table ES-2 *Total Annual Costs of LRV Collisions with Automobiles (Phoenix, AZ from 2009 to 2016)*

	2012 Cost	2022 Cost
Direct Cost to Transit Agency	$897,767	$1,233,571
Loss of Life - Auto	$2,582,125	$3,866,629
Loss of Life - Pedestrian	$955,500	$1,430,823
Injuries - Auto	$5,213,310	$7,713,924
Injuries - Pedestrian	$1,304,258	$1,953,073
Total Cost	**$10,952,960**	**$16,198,019**

This project demonstrates the feasibility of retrofitting existing LRVs with front enclosures, and the following potential benefits:

- Improves crash energy management (CEM) when impacting automobiles
- Reduces injury to automobile occupants
- Lowers risk of override and LRV derailment
- Reduces repair costs to LRV operators from automobile crashes
- Reduces system and equipment down times after a crash

Although the prototype bumper was designed specifically for the Siemens SD660 LRV in this study, the approach and structures were designed with the objective of being readily adapted for other LRV designs. There would likely be specific changes needed to attach the linkage mounts, for example, and/or front geometry changes to accommodate different front geometries. However, these changes would be more easily accomplished now that this prototype bumper has been designed and validated.

Section 1 Background

Historically, most crashes with a Light Rail Vehicle (LRV) occur with motor vehicles and cyclists/pedestrians [1]. Collisions where the LRV overrides an automobile are all too common, which can lead to negative consequences. First, the override behavior results in significantly greater crush intrusions into the automobile and greater injuries to the automobile occupants. Second, the override collision has the potential to produce much more extensive damage to the LRV and greatly increase the repair costs and time before the vehicle is placed back in service. Finally, the override collision has a much higher potential to derail the LRV or create higher crash decelerations that can result in higher injury potential to the LRV occupants. Therefore, there is a recognized need to investigate methods for improving the safety of passengers in motor vehicles when impacted by an LRV collision. These frequent crashes in shared right-of-way environments demonstrate that automobiles are disproportionately vulnerable in these scenarios.

Many of the past design specifications for LRVs in the U.S. included safety requirements for the LRV structure, passengers, and operators. However, in the early 2000s, there was a growing emphasis in the LRV safety community to extend safety measures to include protection for pedestrians and passengers of highway vehicles that may be struck by an LRV. In response, research was conducted to evaluate the potential for mitigation of these injuries [2,3,4,5]. The combined research showed marked improvements in automobile passenger safety for a variety of automobile types and collision scenarios. The results clearly show that careful selection of the front-end bumper profile can significantly reduce the probability of injuries to automobile occupants. A profile that is low enough to engage the door frame structures of small and light vehicles, with an adequate vertical height to engage the same structures on taller SUVs, provided the best overall performance.

Following this research, the ASME RT-1 Safety Standard for Structural Requirements for Light Rail Vehicles and Streetcars [6], introduced in 2009, included crash safety design criteria for new LRVs requiring enclosed front ends, or bumpers. As a result, the inclusion of bumpers on new LRV designs is now common practice in the U.S. However, some of the existing LRVs will continue to operate for decades without these crash safety features. The number and severity of injuries caused by continued operation of these vehicles, as well as the ongoing costs to vehicle operators from crashes, can be significantly reduced by retrofitting these vehicles with bumpers to be compliant with the current RT-1 standard [7].

Section 2

Project Description

The objective of this project is to design, build, and test a prototype LRV end enclosure, or bumper, as a retrofit to an existing LRV operated in the U.S. The criteria for LRVs with a need for retrofit are:

1. Shared-right-of-way operation with history of automobile crashes
2. Open front end with potential to override automobiles (typically high-floor or hybrid high/low floor)
3. Long remaining operational life

Three transit agencies provided significant contributions to the project: Sacramento Regional Transit (SacRT), Los Angeles County Metropolitan Transportation Authority (Metro), and TriMet in Portland, Oregon. All provided input on design requirements and operational considerations. Metro and TriMet both operate LRVs that meet the above criteria and have substantial remaining operation life, making them potentially worth the cost of retrofit. Both provided substantial technical information on their LRVs to develop preliminary designs for an end enclosure. Ultimately, a complete prototype design was developed and tested for the Siemens SD660 operated by TriMet (Type 2 and Type 3 LRVs).

The front end of Metro's Kinkisharyo (KI) P3010 is shown in Figure 2-1. The open-ended design with the coupler protruding well ahead of the anti-climber makes the P3010 well suited for retrofit. Metro has 235 open-ended KI vehicles that have all been built since 2014. These vehicles represent a significant percentage of the Metro fleet and are newer vehicles that will remain in service for a long time. The Siemens SD660 Type 3 LRV operated by TriMet is shown in Figure 2-2. These vehicles are also operated in a shared right-of-way environment on the Blue and Yellow lines in Portland, Oregon, as shown in Figure 2-3. TriMet operates almost 62 miles of light rail service in the

Figure 2-1 *Metro P3010 Front End*

Portland metropolitan area with a fleet of 145 light rail vehicles. In this fleet, there are 79 open-end Siemens SD660 vehicles that may benefit from a retrofit with a similar end enclosure.

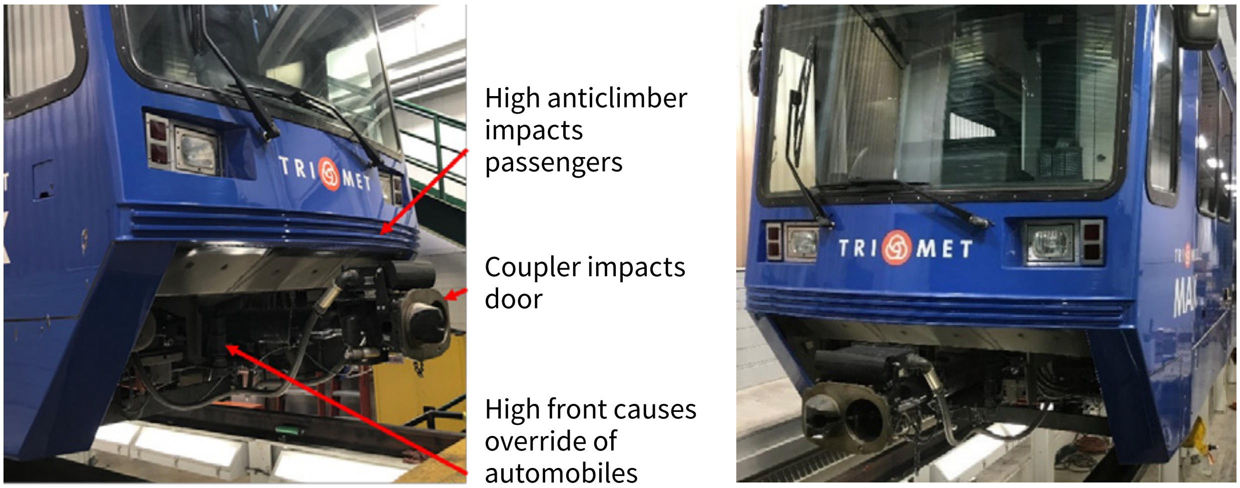


Figure 2-2 *TriMet Type 3 Siemens SD660 Front End*

Figure 2-3 *Portland SD660 Operating on Shared Right-of-Way (photographed by Steve Morgan)*

These are fixed (non-retracting/folding) coupler LRVs with an open front end that has an aggressive profile when impacting automobiles. The high anti-climber and vertically sloping front-end profile have a significant potential to override automobiles in frontal collisions, as shown for other vehicles in Figure 2-4. The high anti-climber can also directly impact the automobile passengers. The fixed coupler impacts the door of the automobile in side-on crashes.

Figure 2-4 *Example Collisions between LRV and Automobiles [6]*

The project consisted of the following development steps: (1) retrofit design, (2) fabrication, (3) operational testing on LRVs, and (4) crashworthiness testing. To perform design, Metro and TriMet provided substantial technical information on the end-frame structures for the LRVs as well as electrical and equipment details. They also helped to define the operational and maintenance requirements and performed design reviews. TriMet continued to support both the operational and crash test phases.

Several overall design approaches were considered in this project. The first approach considered was the final product of the FTA Cooperative Agreement No. FTA-CA-26-7007.2010.1 [6]. This prototype design has a segmented LRV Crash Energy Management (CEM) bumper system that attaches to the coupler. It showed a marked improvement in automobile passenger safety in collisions for a variety of automobile types. This design was initially evaluated in this project for retrofit applications in coordination with coupler manufacturers. However, it was determined not to be a cost-effective solution for retrofitting LRVs within the scope of this project, but could be a viable option for new LRV designs.

Therefore, this project focused on designs that are fixed to the carbody when deployed and can be raised to couple LRV cars. This approach is easier to retrofit to existing vehicles and still provides significant safety benefits. A flexible design approach was adapted as a retrofit to two different manufacturers' car designs. The design was developed for both Metro's Kinkisharyo P3010 LRVs (Appendix B) and TriMet's Siemens SD660 LRVs. The design approach is applicable to most, if not all, open-ended high-cab LRVs operating in North America on shared rights of way.

Full 3D CAD models of the LRV end frames and surrounding equipment were constructed to perform mechanical and structural design and analysis, as well as analyses of the operational envelope. Structural analysis was then performed using nonlinear dynamic finite element analysis (FEA). Detailed FEA of LRVs impacting automobiles were performed on the LRV design, both with and without the bumper, to assess and optimize overall bumper design and crash performance. Evaluation of injury reductions to occupants was also performed using FEA models of the side impact Anthropomorphic Test Devices (ATD) commonly used in automotive crash testing.

Once a prototype was manufactured, operational testing was conducted with an enclosure mounted to a TriMet Type 3 (SD660) LRV. The objective of these tests was to demonstrate compatibility with operational vehicles and to gather feedback from TriMet operators and maintenance staff. Testing of both powered and unpowered function was performed to raise and lower the front enclosure and coupling to another LRV. Moving operation was also performed in the Ruby Junction Rail Yard to demonstrate compatibility with trackside structures.

Three crash tests of the front-end structure of the SD660 retrofit with an end enclosure were conducted at the Center for Advanced Product Evaluation (CAPE). The first two tests were designed to evaluate the enclosure performance when impacting a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). Two crash conditions were considered: a normal (90˚) impact representative of a street crossing and an oblique (45˚) impact representing a car turning in front of an LRV. Both are the most common impact conditions that LRV operators experience. The last test was designed to evaluate the side panel breakaway behavior required for collisions between LRVs. The breakaway allows for the designed engagement of the LRV anti-climbers as is required in the RT-1 safety standard and to allow for the full design stroke of the coupler energy absorber. These functions must be maintained with any retrofit.

Section 3

Design and Analysis

The first step in designing the enclosure was to hold conceptual design meetings with transit agencies to develop design requirements. The following technical specifications were developed through these discussions:

1. Enclosure shall NOT interfere with anti-climber engagement for LRV-LRV collisions.
2. Enclosure shall allow for full stroke of the coupler for LRV-LRV collisions.
3. Enclosure shall have both powered and manual operation.
4. Enclosure shall be easy to operate manually and conform to the standard ergonomics for both male and female operators.
5. Enclosure shall function within the existing operational envelope when deployed or retracted.
6. Enclosure shall be largely reusable to relative crash speeds of 20 mph without damage to the LRV structure.
7. All equipment and components used for the enclosure shall be made to exist in a transit environment and meet all federal and local regulatory standards for transit equipment.
8. Enclosure shall be able to “lock” in its final positions.
9. Enclosure shall be designed to minimize maintenance requirements and be highly reliable.

The first two requirements are to maintain current ASME RT-1 crash standards for LRV-LRV collisions. Any front enclosure therefore needs to deform backward in such a way to allow the anti-climbers to engage unobstructed and not reduce the full stroke of the fixed couplers. Both manual and powered operation are desirable for ease of use. Manual operation is particularly desirable if there is a loss of power and the front enclosure needs to be raised.

The 20-mph design speed for the front enclosure is particularly important. First, it is at these speeds that serious to fatal injuries occur. As discussed in Section 6, TriMet also identified several recent crashes where speeds were sufficient to cause damage to the LRV. These had relative vehicle speeds from 18 to 25 mph. Structures that deform significantly at these speeds will not work well with a fixed coupler design since the rigid coupler would still intrude into the struck vehicle. They also lead to significant replacement/repair costs in use [8]. To avoid these ongoing costs, reusability at these speeds is important to minimize maintenance requirements and maximize reliability.

Finally, the enclosure needs to “lock” in its final positions (deployed or retracted) to prevent excess noise and manage wind buffeting loads. This is needed to minimize potential vibrations of the front enclosure. TriMet operates

LRVs above 50 mph and can have crosswinds exceeding 65 mph. These requirements were considered in the development of designs as described in the following sections.

Design Engineering

This section provides details on the end enclosure design, including mechanical, geometric, and structural design considerations. The major objective of the mechanical and geometric design was to develop a profile that tightly conforms to the end profile of the existing LRV to stay within the operational envelope while in the deployed and retracted state, as well as managing the crash loads delivered to a variety of automobile types while deployed. The objective for the structural design was to have an enclosure that experiences only minor damage during automobile collisions up to relative speeds of 20 mph, while being light weight, and not damaging the LRV underframe during normal operation or when transferring crash loads. It also needed to deform during LRV-LRV collisions in such a way to meet existing LRV safety requirements.

Mechanical and Structural Design

A low rounded front enclosure shown in Figure 3-1 was designed primarily to spread crash loads over a large engagement area into the automobile and prevent override. It has a profile that is low enough to engage the underframe structures of small and light vehicles and with an adequate vertical height to engage the same structures on taller SUVs. Since this is a retrofit, however, the geometry could not be completely driven by the goal of reducing injuries. The shape is largely dictated by the operational envelope, as described in the next section, and the need to retract the front enclosure tightly to the front of the car to lock it in place.

A coupler cutout was included in the front enclosure to allow couplers to engage and fully stroke during LRV-to-LRV crash scenarios. This cutout was geometrically designed to gather the coupler from off-center positions when the front enclosure is deployed. Linkage and hydraulic actuators were designed to raise the front enclosure to a retracted configuration, shown in Figure 3-2. The design is capable of meeting all the above system requirements. Note that a final facia design would blend with the existing carbody to improve aesthetics.

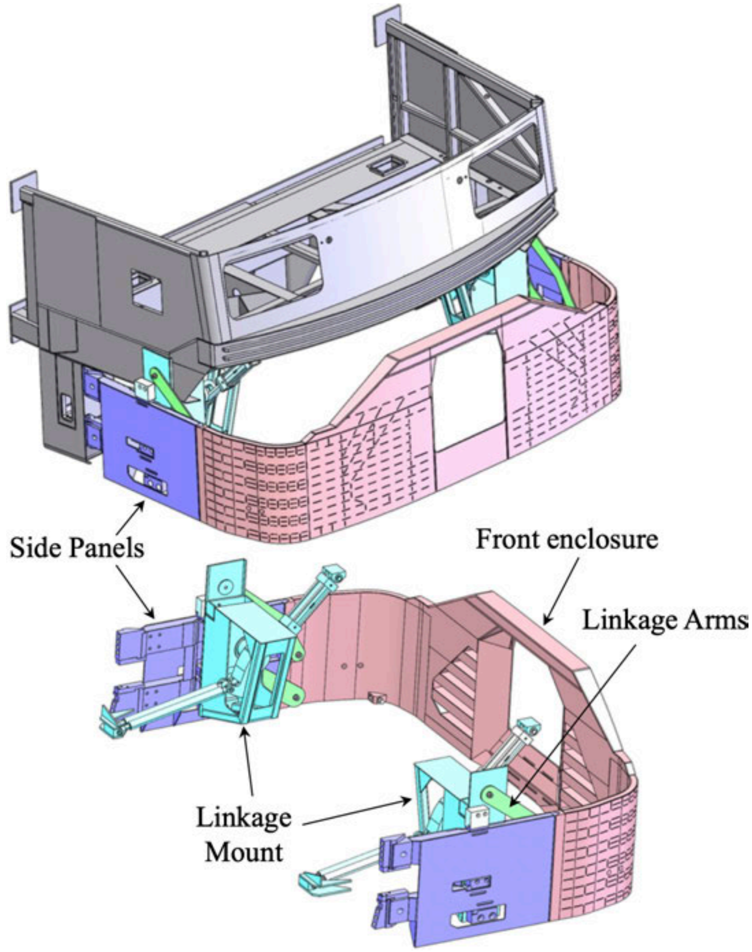


Figure 3-1 *Full Enclosure CAD Geometry*

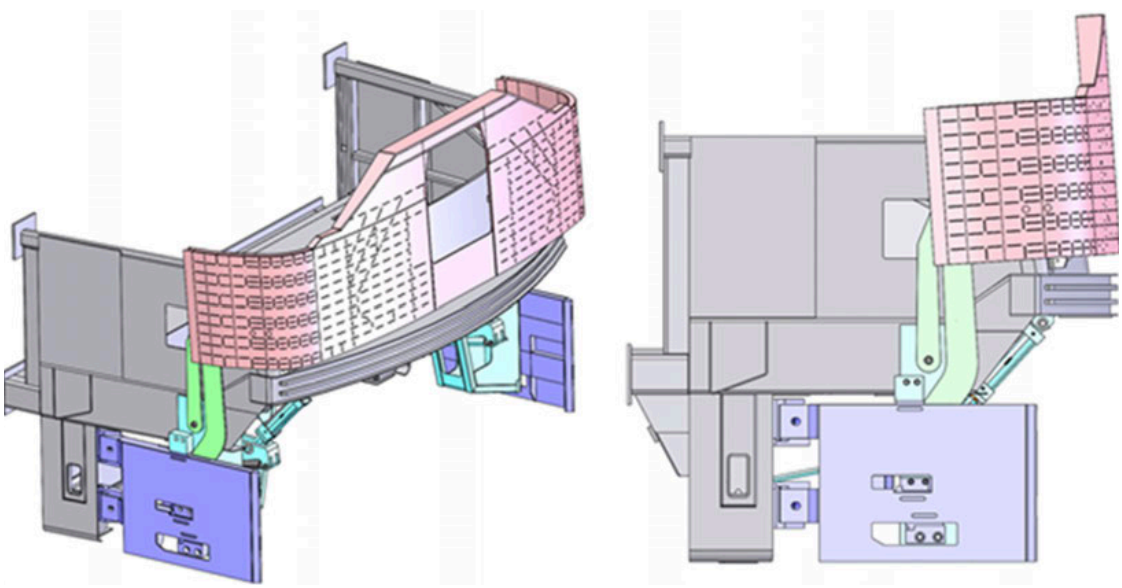
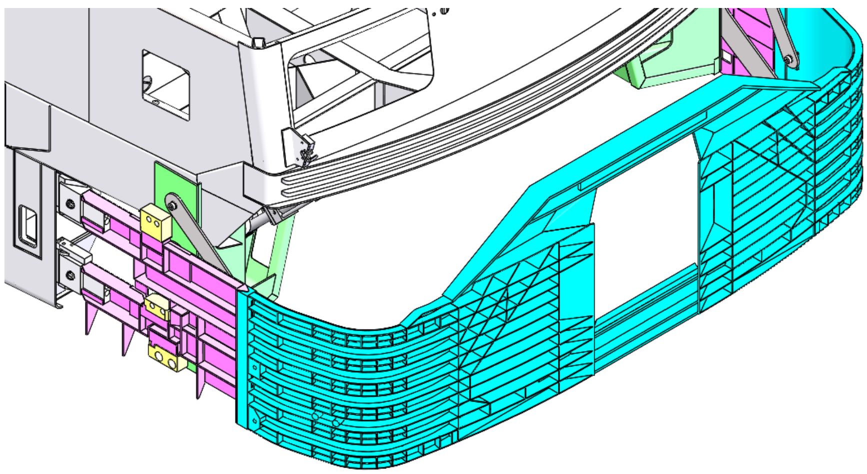


Figure 3-2 *Enclosure Geometry in Retracted Position*

The front enclosure and side panels were weight optimized to manage the dynamic crash loads. They are composed of high-strength 100 ksi (700 MPa) sheets and bar steel. Light-weight internal stiffeners are welded throughout the structure, as shown in Figure 3-3. These are used, in particular, to transfer loads around the coupler cutout and to resist plate buckling around the corners.

The geometric design for gathering the coupler from off-center positions is shown in Figure 3-4. The coupler has its own gathering mechanism that restricts lateral and vertical swing motion, so that the coupler is roughly aligned with the carbody centerline. This geometry was designed to gather within that range and align the coupler to be centered in the coupler cutout.



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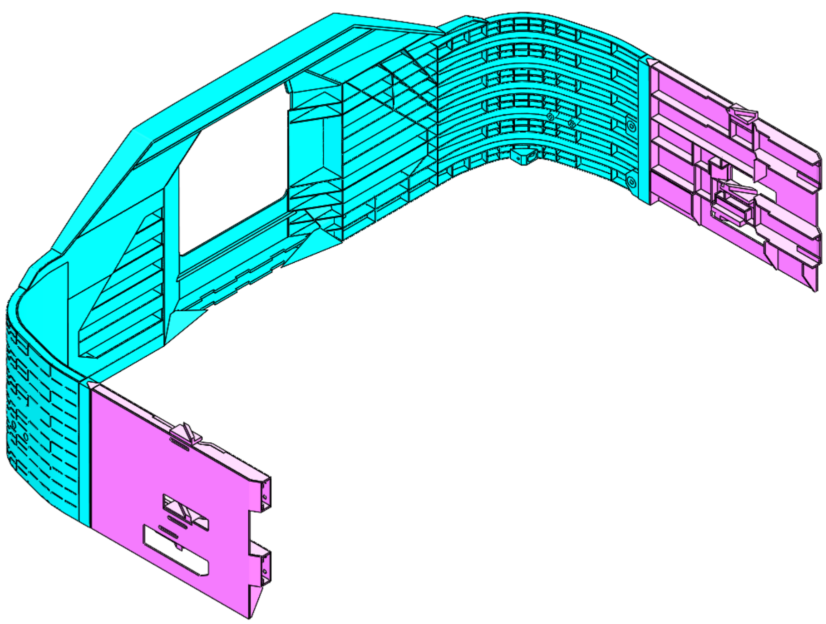

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Figure 3-3 *Enclosure Structural Design*

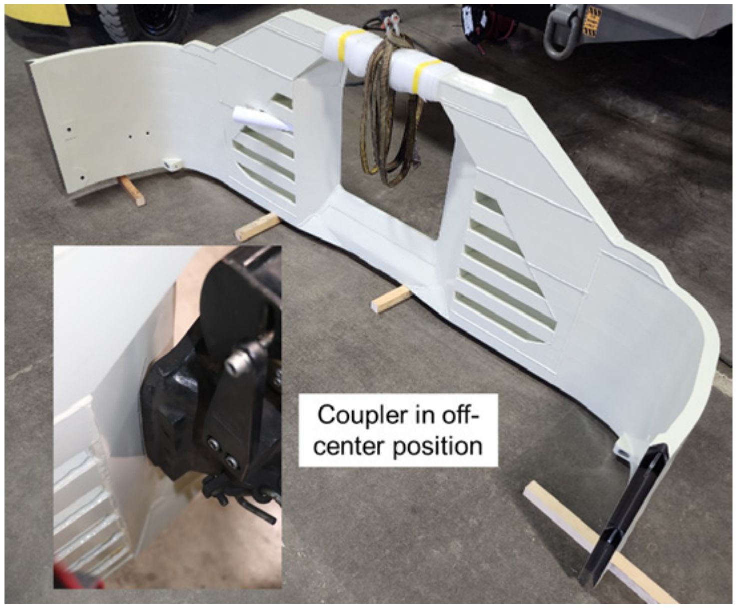


Figure 3-4 *Coupler Cutout Geometry*

The final design installed for operational testing (discussed in the next section) is shown in Figure 3-5 to Figure 3-8. Permanent retrofit components are painted white and temporary attachments are painted black. Installation only requires removal of the side skirts, shown in Figure 3-7 without the enclosure installed, which are easily unbolted in the Type 3 vehicles.

The system can be actuated from the deployed to the retracted position either hydraulically or in free-float mode. Under power, a hydraulic pump provides the pressure to the hydraulic cylinders to rotate the swing arms, shown in Figure 3-8. The enclosure can then be lowered using the same hydraulics. If there is a loss of power, or if it is desired, the enclosure can also be raised manually. The gas springs, also shown in in Figure 3-8, are pressurized for a variable lifting load from zero (i.e., the front enclosure lifts on its own when in free float mode) to 35 lb. Hydraulic pressure is maintained with our without power to the hydraulic power unit (HPU), so the free float mode only occurs when intentionally applied. The weights of the main components (Figure 3-6) are provided in Table 3-1.

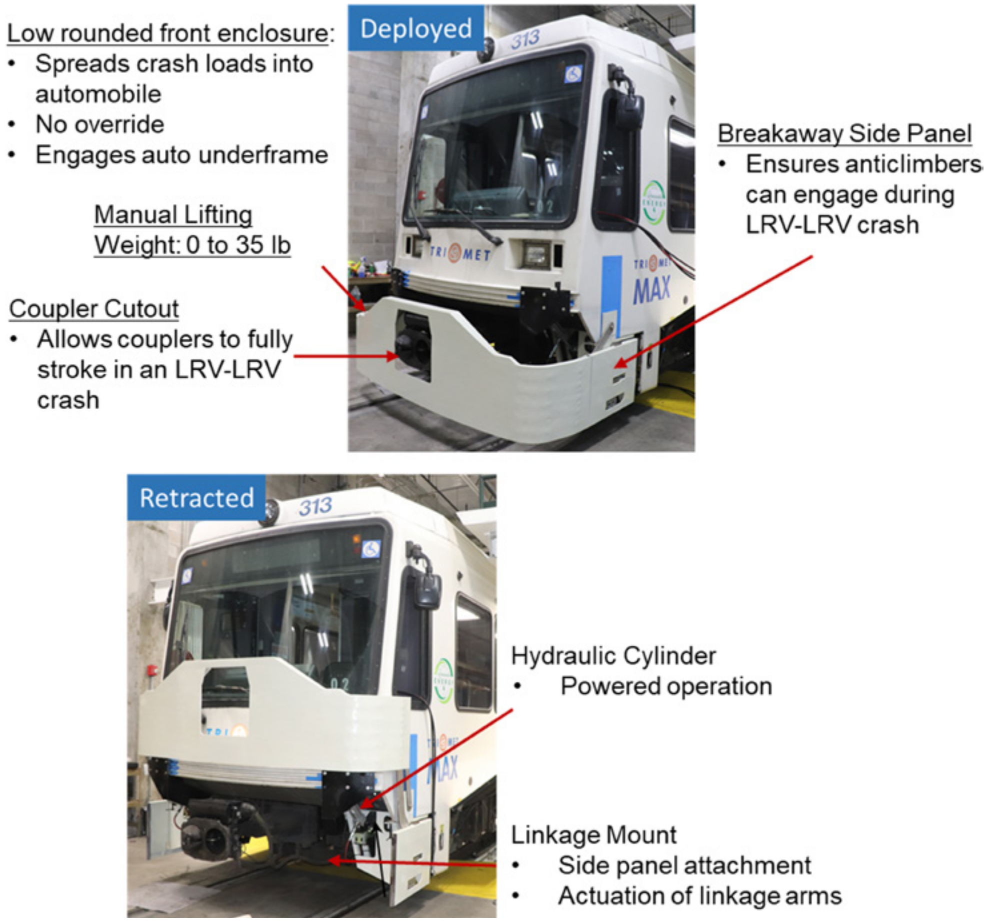


Figure 3-5 *Temporary End Enclosure Retrofit to the Type 3 LRV*

Table 3-1 *Weigth Summary of End Enclosure Components*

ID	Description	Weight (lb)
1	Front Enclosure	600
2	Side Panels	230
3	Linkage Mounts	176
4	Top & Bottom Linkage Arms	78
5	Pivot Linkages	58
6	Anti-climber Hydraulic Clevis Mounts	6
7	Jacking Post Gas Strut Mounts	16
8	Side Panel Slider Blocks	82
9	Jacking Post Slider Blocks	38
	Total	1284

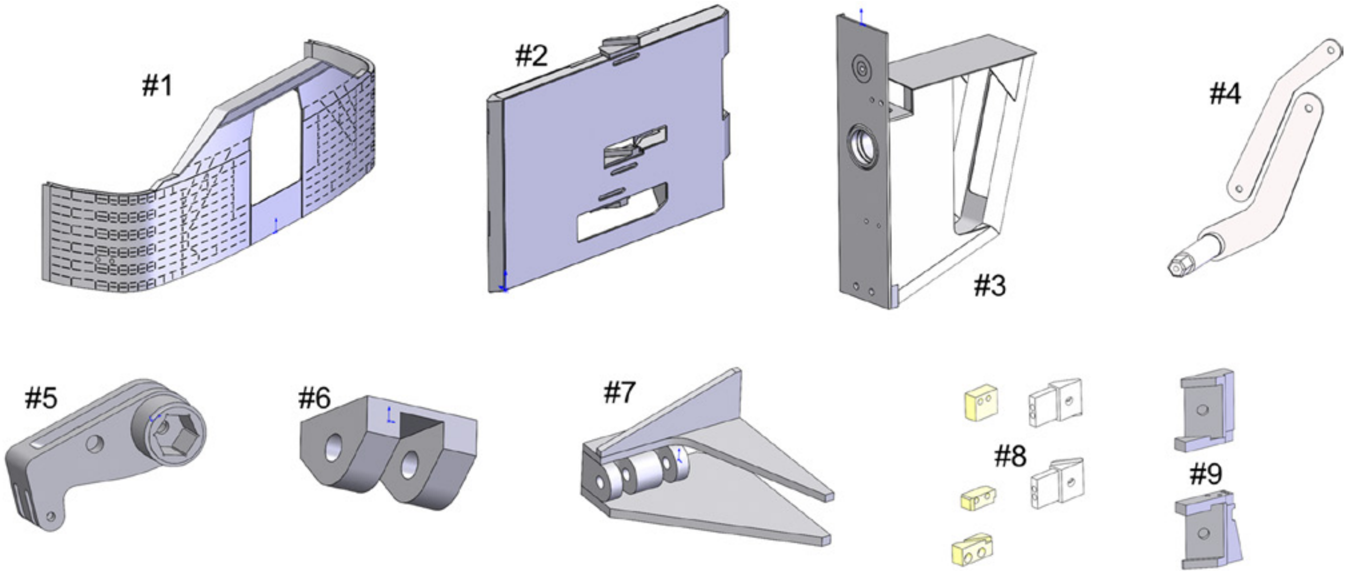
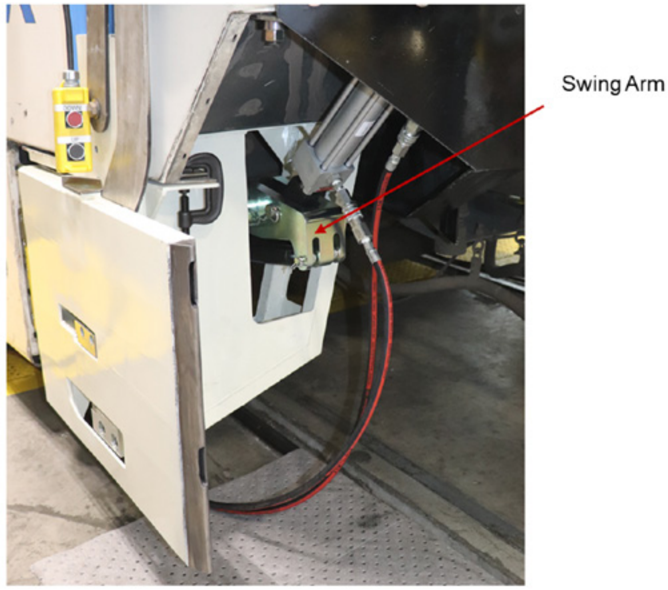


Figure 3-6 *End Enclosure Component Items*

Figure 3-7 *Type 3 LRV with and without Front Enclosure*



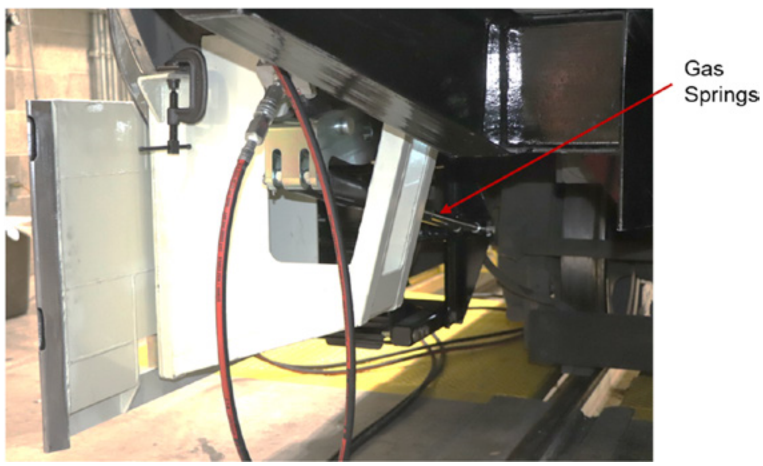


Figure 3-8 *Temporary End Enclosure Retrofit to the Type 3 LRV*

The enclosure needs to "lock" in its final positions (deployed or retracted) to prevent excess noise and manage wind buffeting loads. This is needed to minimize potential vibrations of the front enclosure. When deployed, it is naturally held in place by the geometric design of the side panels where they mate to the front enclosure. This design was driven by the crashworthiness design, but also serves the same function in mechanically locking the front enclosure when deployed. When mated, the triangular shape of the leading edge of the side panel restricts motion laterally. The tongues on the front enclosure fit inside the grooves in the side panel to restrict motion downward. Vertical lifting is locked by the hydraulics through the linkage arms as well as the natural weight of the front enclosure.

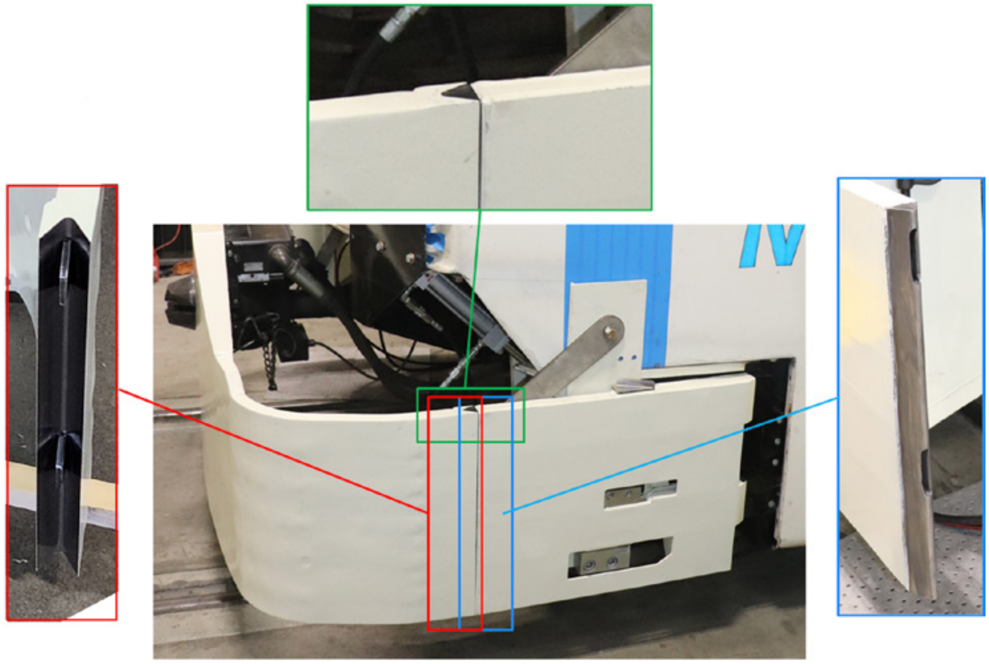


Figure 3-9 *Side Panel and Front Enclosure Geometric Interface*

The hydraulics lock the linkage arms in place at any position, but additional approaches were used to lock the front enclosure in place when retracted. This is needed to minimize potential vibrations of the front enclosure when held just by the linkage arms and buffeting loads from high winds. A mechanical latch is used to restrict motion longitudinally, as shown in Figure 3-10. The latch is attached to the front of the corner posts and can be manually released or released with an electronic switch from inside the cab. A pin is positioned on the inside of the front enclosure to mate with the latch when retracted. Lateral motion of the front enclosure is restricted with rubber stops affixed to the inside of the front enclosure, as shown in Figure 3-11. These rest on the corner posts when retracted.

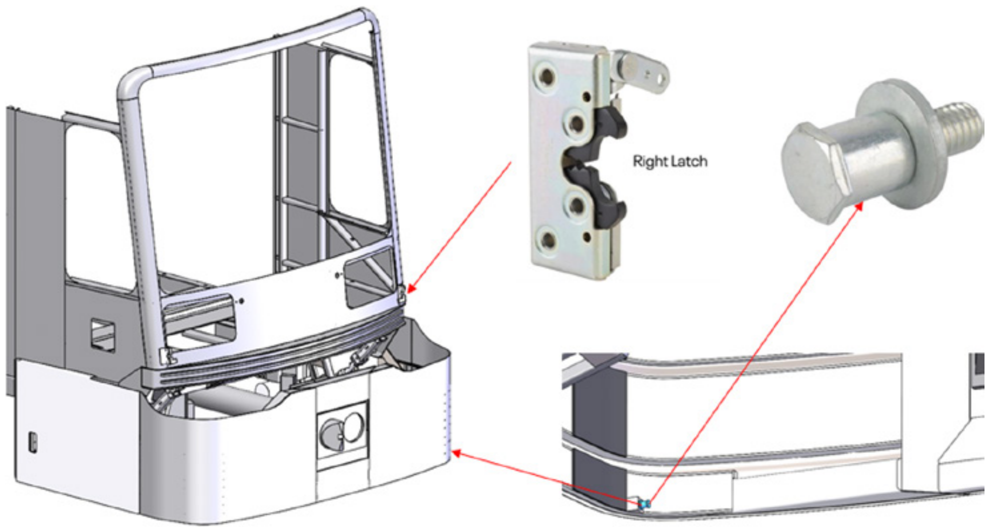


Figure 3-10 *Mechanical Latch for Locking the Front Enclosure When Retracted*

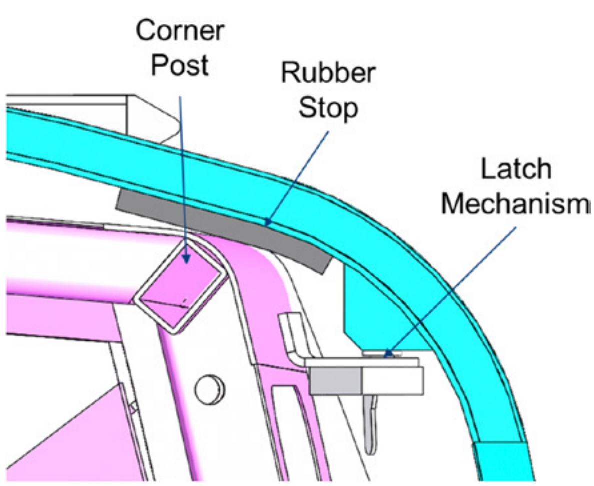


Figure 3-11 *Rubber Stop and Latch Mechanism on the Front Enclosure (top view)*

Geometric Design and Envelope Analysis

The width of the front enclosure retrofit is the same as the existing SD660. However, the lateral clearance is dictated by the smallest diameter curve in operation. The required lateral clearance for the enclosure was calculated based on navigating an 82-ft curve, as required by TriMet. The required static envelope for navigating this curve was calculated from the dynamic envelope provided in drawings from Siemens. The dynamic envelope is more stringent than static because it accounts for movement of the car on its suspension as it navigates the track. The geometry of the enclosure was then designed to stay within this envelope. A top view of the end frame of the LRV with the enclosure geometry attached is shown in Figure 3-12. The 82-ft curvature and static envelope of the enclosure in this curve are also shown.

The required clearance above rail is determined from the minimum vertical curve radius, sag of 350 m as required in the technical specification for the SD660 and the maximum pitch/roll of the LRV. The maximum pitch geometry is shown relative to the 350 m radius sag in Figure 3-14. This pitch geometry was calculated by the maximum dynamic envelope calculated by Siemens (i.e., maximum pitch angle). The clearance at the forwardmost point of the enclosure is 78 mm. Roll reduces this clearance to 74 mm.

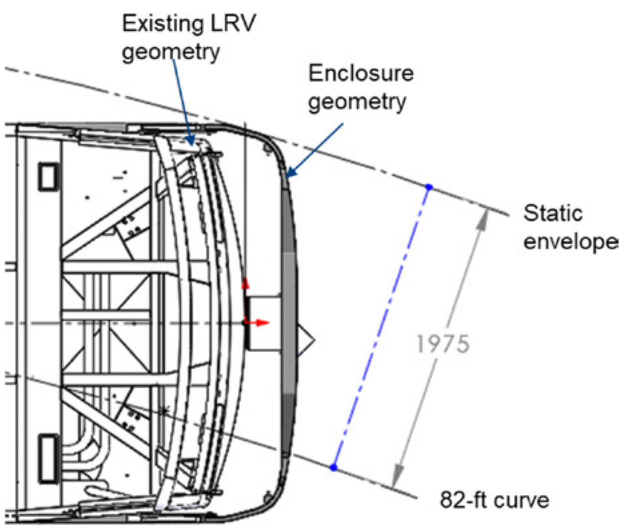


Figure 3-12 *Operational Envelope with the Front Enclosure in an 82-ft Curve [mm]*

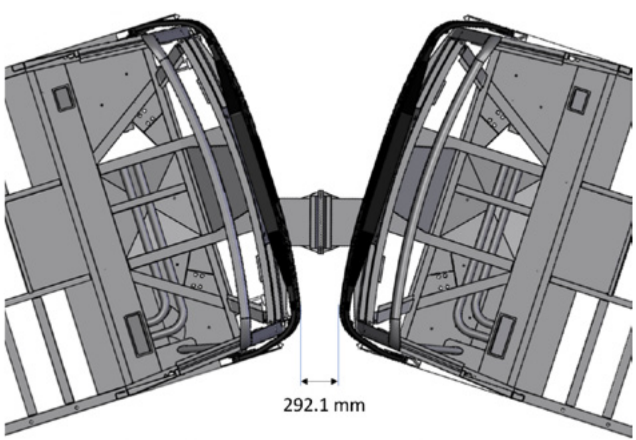


Figure 3-13 *Clearance between Coupled Cars with Retracted Front Enclosures in an 82-ft Curve*

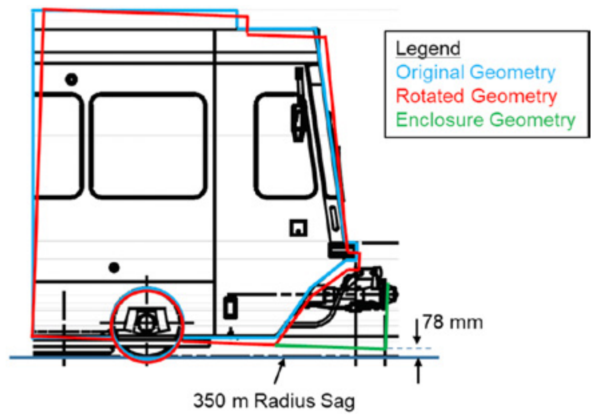


Figure 3-14 *Minimum Enclosure Height above Rail*

Geometric design of the front enclosure did not specifically consider pedestrian safety since it was out of scope of the project. Shapes that minimize injury are also an open topic of research [9]. There is also a technical guide for tramways developed by STRMTG that provides some general guidelines [10]. The main conclusion from these documents is that pedestrian safety is improved with a low protruding section of the tram or LRV front, not just an enclosed front, that will hit the pedestrian below the thorax first. This causes the body to be accelerated before the head or thorax is impacted, reducing the impact speed to these body regions where more serious injuries can occur.

A comparison of the existing front-end geometry of the SD660 and the front enclosure geometry is shown in Figure 3-15. The 50 percent male Total HUman Model for Safety (THUMS) is shown for reference [11]. The existing SD660 geometry would impact the anti-climber directly into the thorax with little room before the head would impact the front of the LRV. The pedestrian would then easily fall beneath the LRV, likely causing even more severe injuries or death. The front enclosure designed in this project obviously encloses the front end in a way that greatly reduces the possibility of a pedestrian falling beneath the vehicle.

The enclosure geometry also has many similarities to that recommended by Weber 2015 [9]. The forwardmost part of the front enclosure is of a similar height (varying from 77 to 105 cm). In this way, the first impact occurs below the thorax. Both geometries protrude in front of the windshield about the same amount, which allows time for the head to decelerate before hitting the front of the vehicle, or not hitting at all. When retrofitted, additional shaping of the front end will be performed with facia attached to the carbody, further improving the compatibility with pedestrians.

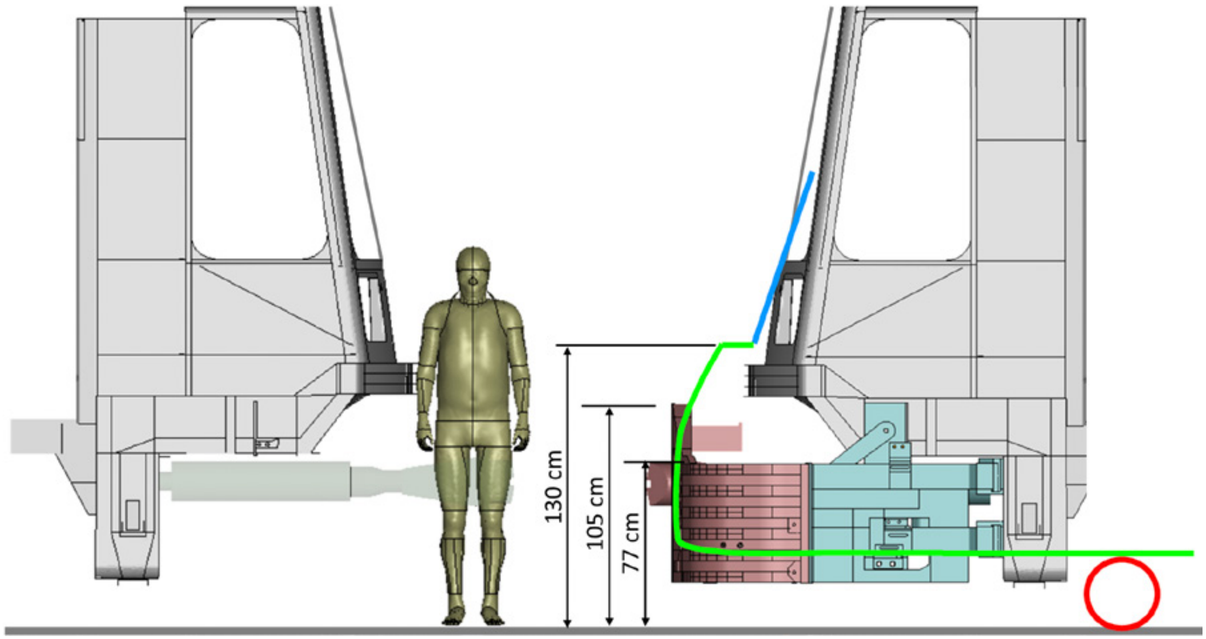


Figure 3-15 *Front-End Geometry Comparison with Recommended Geometry from Weber 2015 [9]*

Finite Element Analysis

The detailed 3-D crash analyses were performed using the LS-DYNA finite element (FE) code (Version 12.1). LS-DYNA is a nonlinear dynamic finite element code, developed and supported by Ansys/Livermore Software Technology (LST), that is ideally suited to performing crash, impact, and puncture analyses [12]. Finite element model development and meshing was performed using a combination of LS-Prepost, Hypermesh, and TrueGrid [13].

The finite element models of the Yaris, Explorer, and side impact dummy (SID) used in the analyses are shown in Figure 3-16. They include sufficient fidelity, as does the LRV and bumper model, to asess nonlinear response to the deformable structures. It should be noted that the automobile models were not validated for side impact. However, they are suitable for this comparative study with and without the front enclosure to demonstrate relative performance.

The SID model closely represents its real-life analog with head, neck, chest, and other sensors to relate to tested crash injury metrics. The SID model was developed by LSTC [14]. The Explorer and Yaris models were developed by the George Washington University National Crash Analysis Center and are available from the National Highway Traffic Safety Administration (NHTSA) website [15]. The SID was belted in the driver position using a pretensioned, retractable belt. No airbag models were used in the analyses.

A detailed FEA model of the end frame of the SD660 was built from the original mechanical drawings of the LRV for this project. To be conservative, ASTM minimum yield values were used for all steels in the model. The SD660 end frame and most of the front enclosure is modeled with Belytschko-Tsay shell elements with four integration points through the thickness. Typical element size is 6 to 8 mm, which is comparable to that used in the automobile FEA models. All structures are modeled with piecewise liner plasticity constitutive models for the steel used.

Collisions were simulated for various LRV-to-automobile scenarios as well as LRV-to-LRV collisions to support the bumper design efforts and evaluate the resulting design. The collision scenarios with automobiles include both normal and oblique impact conditions shown in Figure 3-17. LRV-to-LRV impact was also assessed as shown in Figure 3-18. In the normal impact, the automobile is oriented perpendicular to the LRV for a side-impact. In the oblique impact, the automobile is oriented at a 45° angle from the LRV with the driver facing away from the LRV. Automobile collisions were simulated with the LRV moving initially at 20 mph, while the vehicles were stationary. LRV-to-LRV collisions were evaluated at 5 mph and 11 mph to test the bumper performance at low-speed bumps and breakaway of the side panels for higher speed collisions. In these LRV-to-LRV scenarios, one train is moving at the initial speed while the other is stationary. The six primary collision scenarios are summarized in Table 3-2.

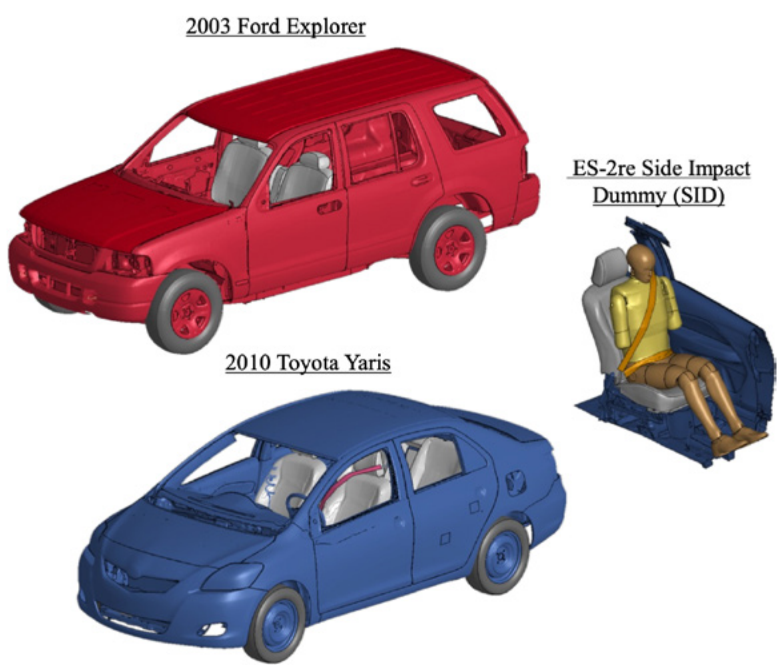


Figure 3-16 *Finite Element Models for 2003 Ford Explorer, 2010 Toyota Yaris, and ES-2re SID*

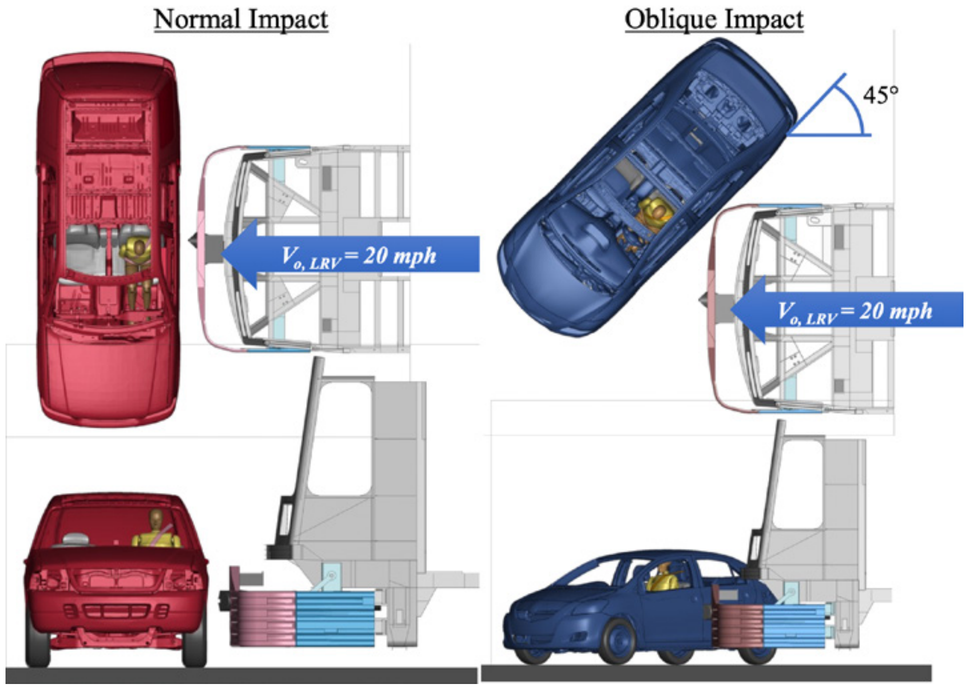


Figure 3-17 *Normal (90°) and Oblique (45°) Impact Scenarios (top and side views)*

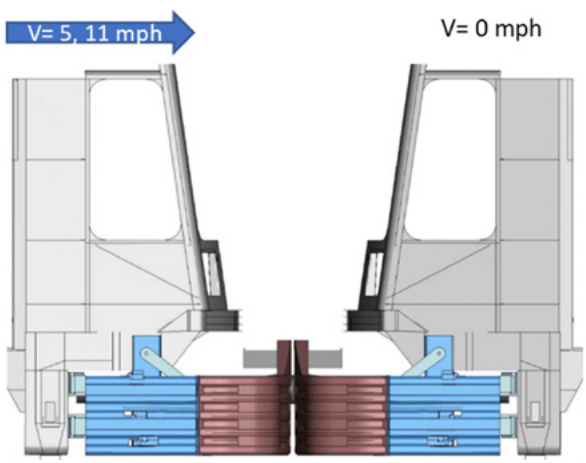


Figure 3-18 *LRV-to-LRV Impact Scenario (side view)*

Table 3-2 *Scenarios for Crash Simulations*

Scenario #	Colliding Vehicle	LRV Angle (deg)	LRV Speed (mph)
1	Explorer	45	20
2		90	
3	Yaris	45	
4		90	
5	LRV	90	5
6			11

LRV-to-Automobile Crash Analysis

LRV-to-Explorer simulations were performed, at an impact speed of 20 mph, with and without the bumper, for normal impact, shown in Figure 3-19. The simulation without the bumper shows localized intrusion of the coupler head into the door and impact with the chest of the SID. The corresponding simulations that include the bumper show a better distribution of loads, as the bumper engages a large area of the struck car, which reduces intrusion, chest deflection, and injury severity.

Similar LRV-to-Yaris simulations were also performed with and without the bumper, shown in Figure 3-20. As with the Explorer, the enclosure better distributes impact loads and reduces body loads. Yaris simulations for the oblique impact scenario were also performed, as shown in Figure 3-21. The use of the bumper eliminates override tendency for both the Explorer and Yaris, as shown from a side view in Figure 3-22. These comparisons demonstrate that the bumper significantly improves the crash compatibility of the LRV front end with automobiles.

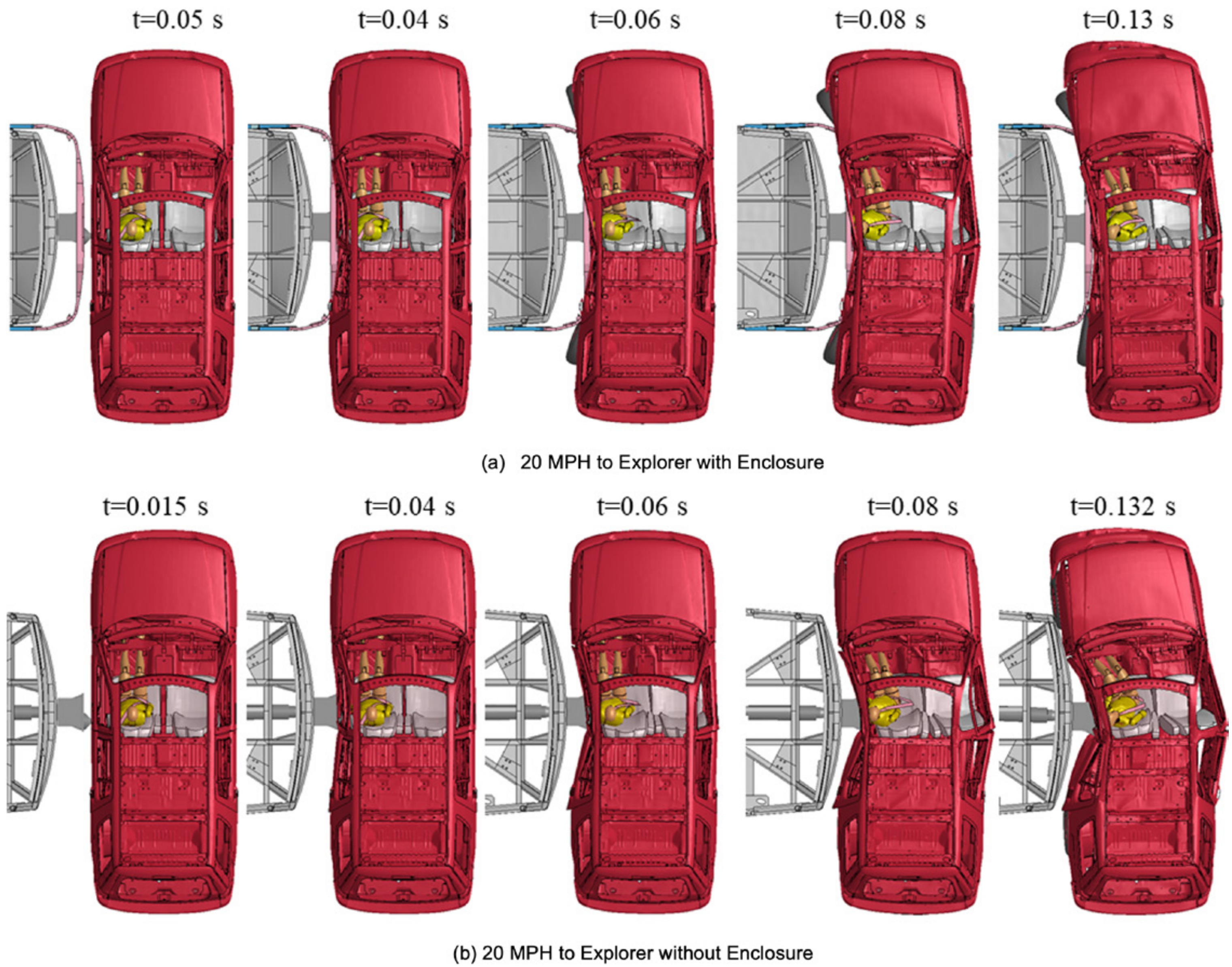


Figure 3-19 *Normal Impact on Explorer with and without Enclosure*

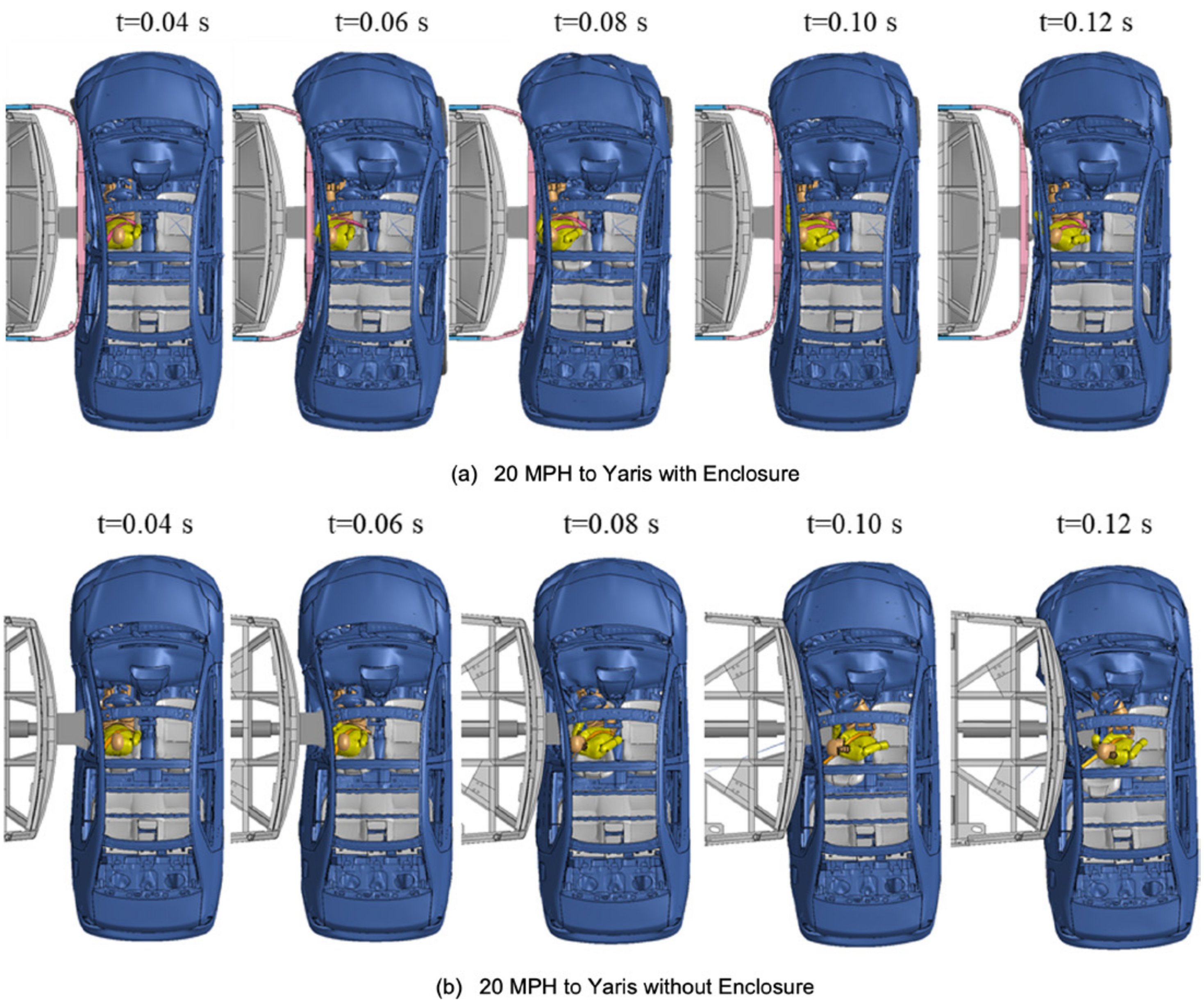


Figure 3-20 *Normal Impact on Yaris with and without Enclosure*

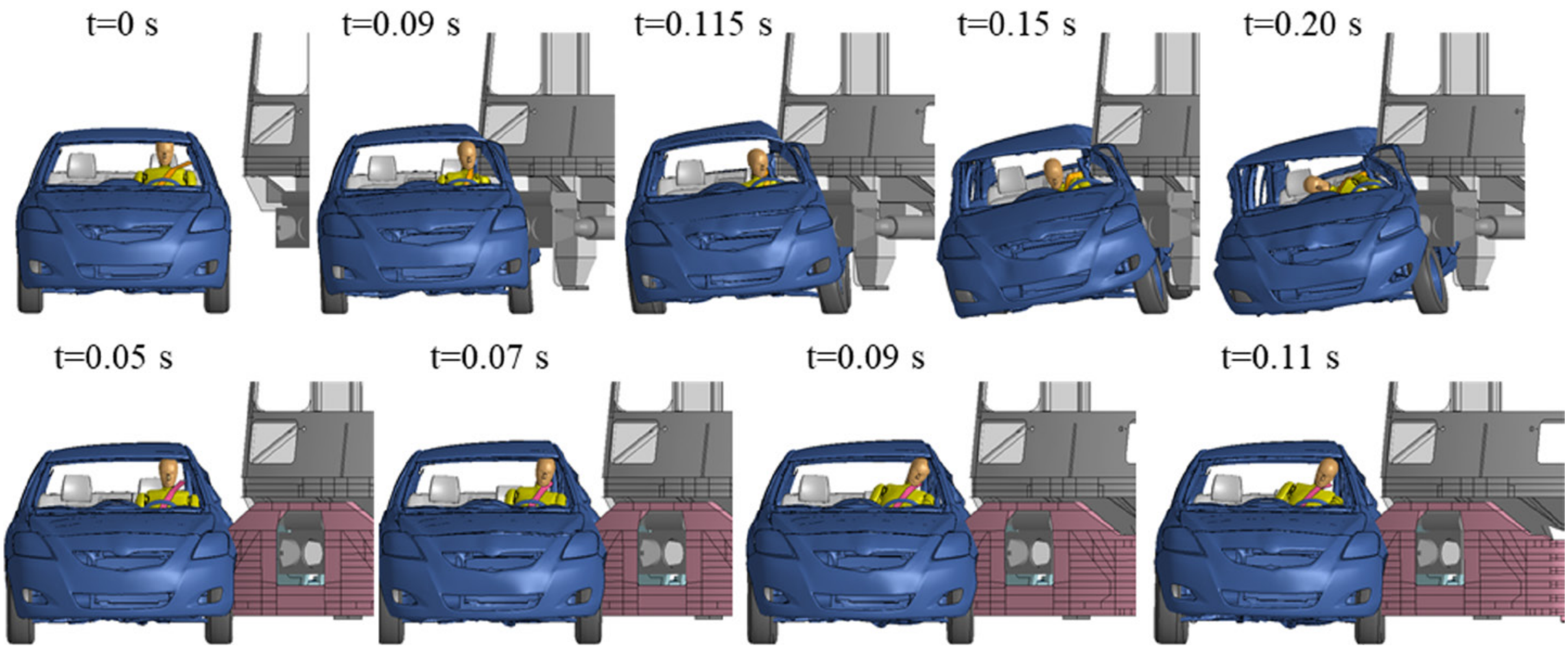


Figure 3-21 *Oblique (45°) Impact at 20 mph on Yaris with and without Enclosure*

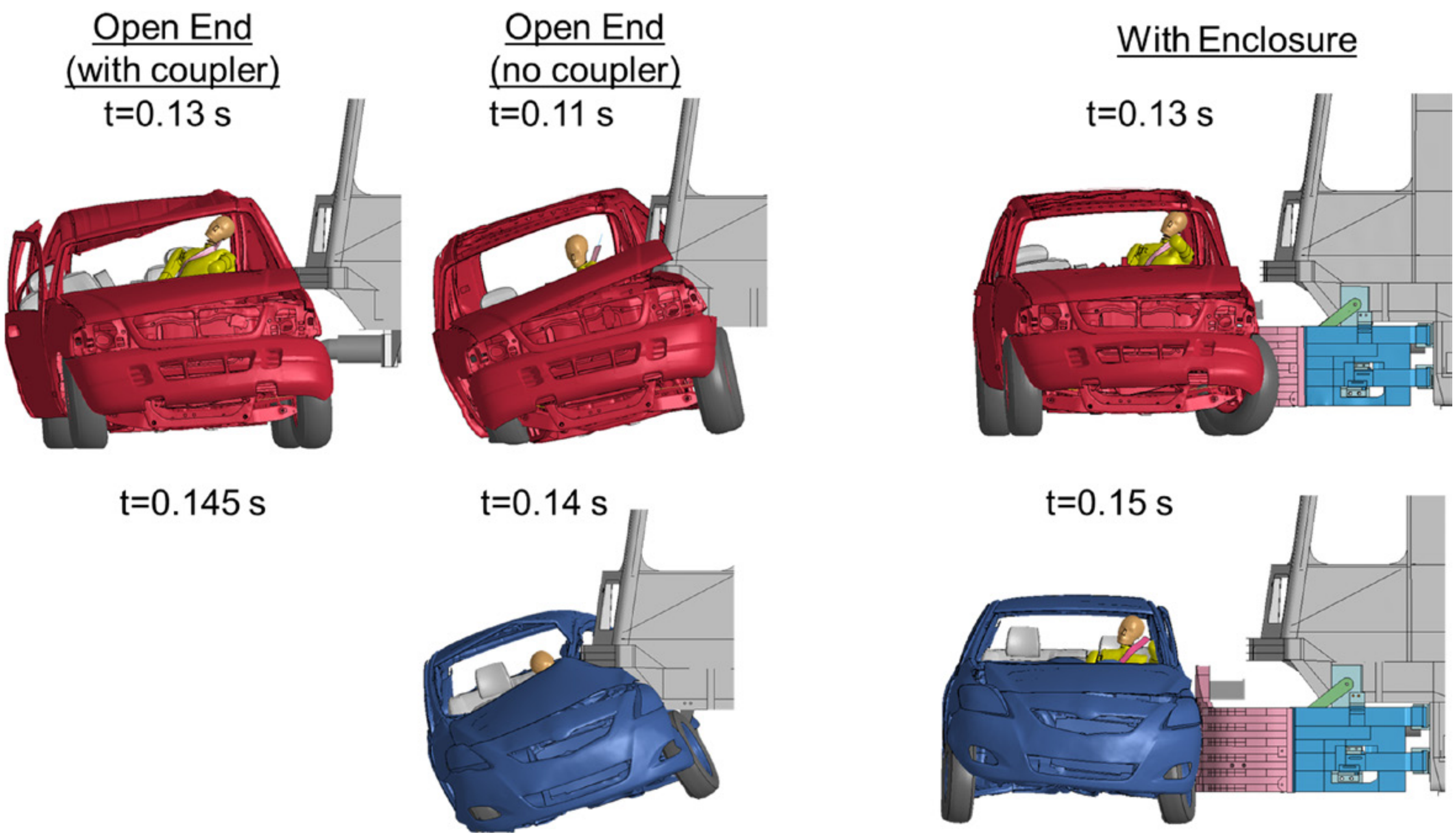
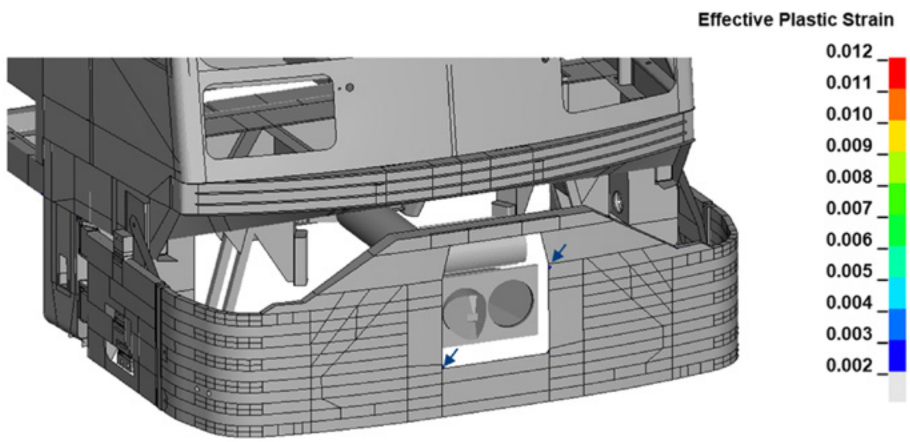


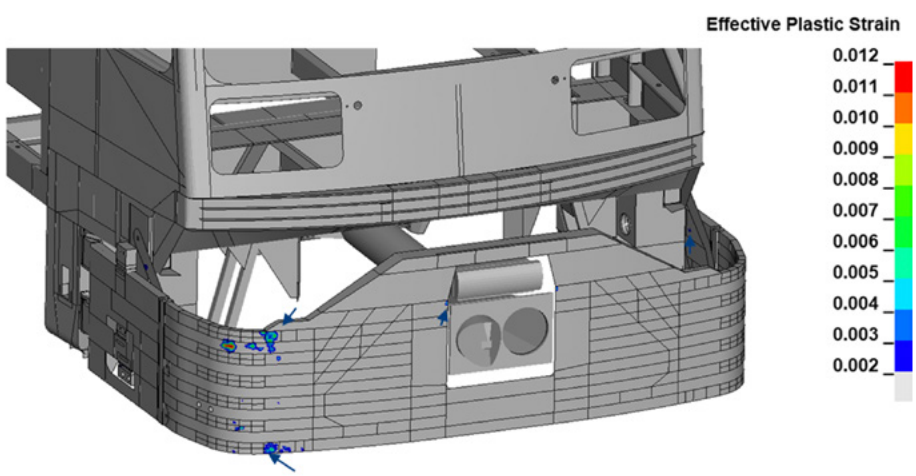
Figure 3-22 *Vehicle Override with and without Enclosure*

Enclosure Damage

Only small, localized damage occurs to the bumper enclosure at crash speeds up to 20 mph, making it completely reusable for many collision scenarios. To make the enclosure more robust for shearing loads caused by a moving automobile, the Yaris was also impacted at 90° while moving at 10 mph. Equivalent plastic strain plots for a 20 mph impact with the Explorer at 45° and 90° show small, localized plastic strains near the corner of the enclosure as shown in Figure 3-23. Similarly small strains are seen for the LRV impact with a moving Yaris at 10 mph, shown in Figure 3-24. The level of plastic deformation observed in these collision analyses would not result in a significant change in geometry or loss of integrity in a subsequent impact. This level of damage is primarily cosmetic, and the enclosure could continue to be used in operation safely. It should be noted that ASTM specified minimum properties were used to model the SD660 structural steel in the dynamic analysis for conservatism.

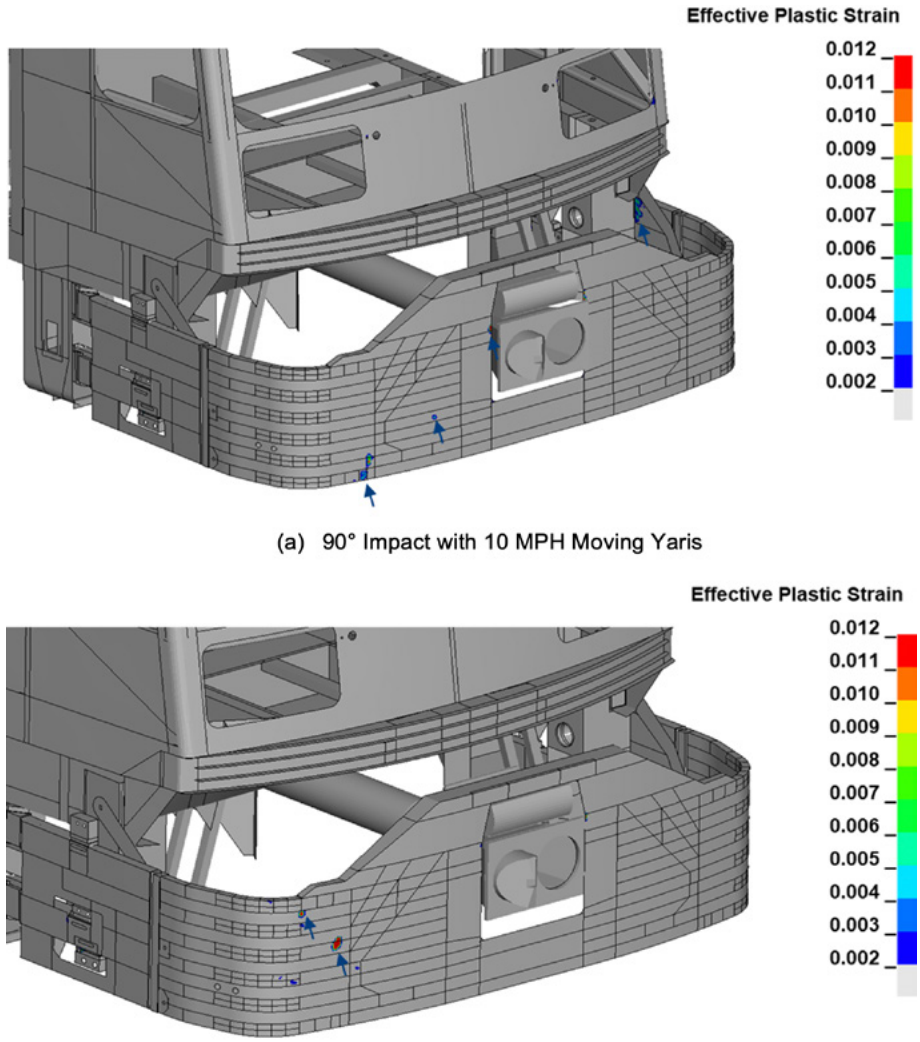


(a) 90° Impact with Explorer



(b) 45° Impact with Explorer

Figure 3-23 *Effective Plastic Strains from 20-mph LRV Impacting Stationary Explorer*



(a) 90° Impact with 10 MPH Moving Yaris

(b) 45° Impact with Stationary Yaris

Figure 3-24 *Effective Plastic Strains from 20-mph LRV Impacting the Yaris*

Injury Results

Injury metrics from the collision scenarios were calculated to compare the risk both with and without the bumper. A summary of the injury assessment is provided in Table 3-3. Calculations include injury probabilities for the Abbreviated Injury Scale (AIS) as specified by the Association for the Advancement of Automotive Medicine (AAAM) [16] at AIS3+ (serious) injury for the head, chest, and abdomen. Values were calculated as described in reference [17]. The neck injury criterion results were also included and show reductions in neck injury for both automobiles when adding the front enclosure.

Major improvements in injury reduction are found in all scenarios when the bumper is added to the front end of the LRV. The largest reductions in the taller SUV are in the chest. The lighter and smaller Yaris has higher injury probabilities overall, with large reductions in the head, chest, and abdomen. Adding the bumper to the collision interface significantly reduced the potential for serious injuries in all the collision scenarios evaluated. For the 2003 Explorer, injuries were reduced from an AIS3+ (serious) chest injury probability of 48.5 percent without bumper to 21.8 percent with the bumper when considering normal (90°) side impact.

For the Yaris 90° impact scenario, there is still a high probability of a serious head injury with the bumper (with no side airbag deployed). However, when we further evaluate the critical to fatal head injuries, we again find that the bumper is providing a significant level of injury protection in this collision scenario, as shown in Table 3-4. For the 2010 Yaris, injuries were reduced from 100 percent AIS6+ (fatal) injury probability without an enclosure, due to head impact against the LRV anti-climber, to 12.4 percent with the enclosure.

Table 3-3 *Occupant Injury Summary with LRV Traveling at 20 mph*

Vehicle	Angle (deg)	Configuration	FMVSS No 214 Injury Criterion AIS3+ (serious) Injury Probability (%)			Neck Injury Criterion (%)
			Head	Chest	Abdominal	
Explorer	45	Open End	1.7	34.2	0.9	60.0
		With Enclosure	2.1	18.0	0.4	40.0
	90	Open End	13.3	48.5	4.2	74.0
		With Enclosure	4.8	21.8	1.1	43.0
Yaris	45	Open End	99.8	37.7	0.5	66.0
		With Enclosure	6.6	22.0	0.7	37.0
	90	Open End	100.0	55.5	70.0	96.0
		With Enclosure	96.7	37.8	31.6	77.0

Table 3-4 *Head Injury Probability*

Vehicle	Angle (deg)	Configuration	Head Injury Probability (%)		
			AIS4+	AIS5+	AIS6+
			Severe	Critical	Fatal
Explorer	45	Open End	0.4	0.0	0.0
		With Enclosure	0.5	0.0	0.0
	90	Open End	2.9	0.2	0.0
		With Enclosure	1.0	0.1	0.0
Yaris	45	Open End	98.3	95.9	90.2
		With Enclosure	1.4	0.1	0.0
	90	Open End	100.0	100.0	100.0
		With Enclosure	81.0	49.2	12.4

LRV-to-LRV Crash Analysis

Crash analyses were performed for LRV-to-LRV impacts at 5 mph and 11 mph. The 5 mph impact scenario was used to design against enclosure damage for a hard coupling impact event. The calculated response for the 5-mph collision is shown in Figure 3-25. The bumper structure successfully withstands the loads resulting from the 5-mph collision without breaking away at the side panels. The bumper enclosure does not suffer any significant damage that would render it unusable or degrade the integrity for future collisions.

The 11-mph impact scenario was used to evaluate the side panel breakaway behavior required for more severe collisions. A time sequence of side panel breakaway for the 11-mph impact scenario is shown in Figure 3-26.The breakaway of the side panels allows for the designed engagement of the LRV anti-climbers and the resulting performance of the vehicle crash energy management would not be modified by the addition of the bumper. The panels are designed to divert away from the vehicle, so they do not interfere with pushback and/or go beneath the LRV and cause a derailment. They are captured by cables, so they do not pose a risk to surrounding vehicles and pedestrians when released.

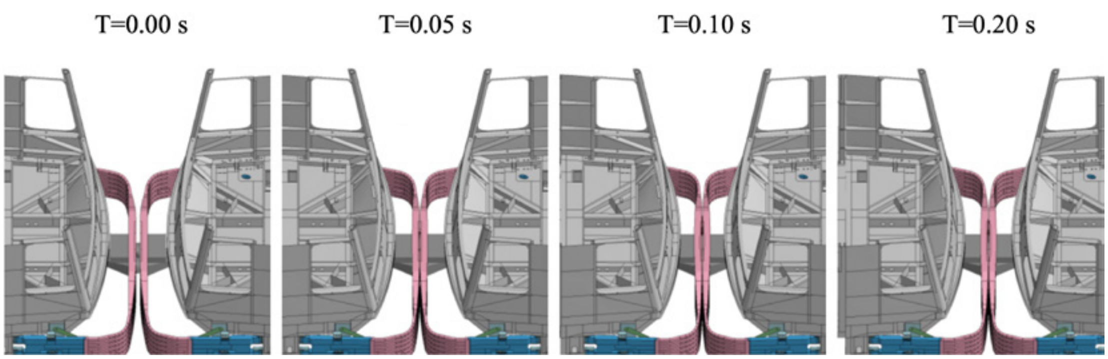


Figure 3-25 *Time Sequence of LRV-to-LRV 5-mph Impact*

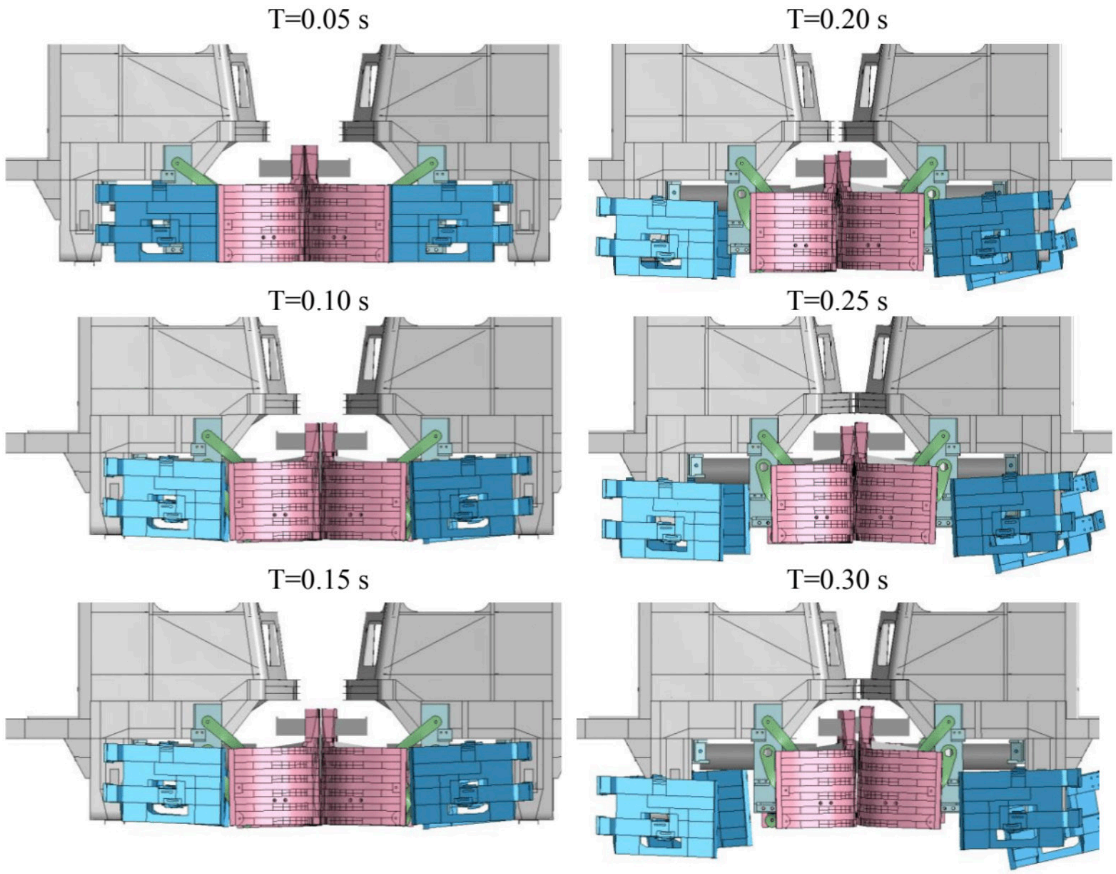


Figure 3-26 *Time Sequence of Side Panel Breakaway for 11-mph LRV-to-LRV Impact*

Section 4

System Testing in Operational Environment

Operational testing consisted of three main phases as follows:

1. Installation
2. Testing of powered and unpowered function
3. Operation in the Ruby Junction Rail Yard

TriMet requested that installation of the prototype enclosure use non-permanent procedures (i.e., no welding and/or modification to the existing structure). To this end, temporary attachments were designed that only required removal of the bolted side skirts and coupler stops. The final design for attaching the end enclosure without permanently modifying the Type 3 is shown in Figure 4-1. The jacking post clamp, side panel attachment, and anti-climber mount were designed only for this temporary installation and would not be part of a retrofit. The linkage mount is almost identical to the design for a retrofit except for a bolting location that attaches to the coupler stop locations and an extended flange under the side sill. To accommodate the temporary installation, the breakaway side skirt hardware was not included. However, the full bumper width is represented. Breakaway hardware and function were evaluated during crash testing, which is described in the next section. The installed bumper enclosure is shown in Figure 3-5 to Figure 3-8.

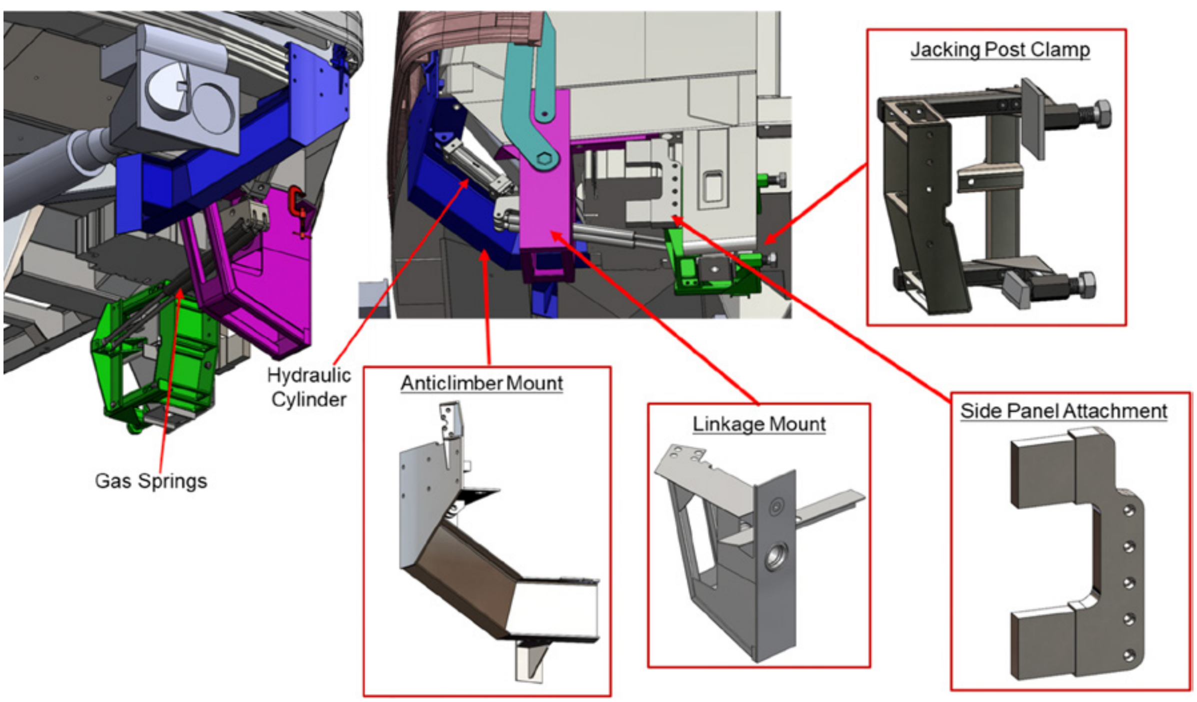


Figure 4-1 *Temporary Attachment Components for the Type 3 LRV*

Powered actuation of the front enclosure was tested using an external hydraulic power unit (HPU). Enclosure positions at various points during the test are shown in Figure 4-2. There was no interference with car geometry. Some additional tuning of the hydraulics will be needed to maintain good side-to-side control in production, but the enclosure raised and lowered well, seated into the side panels during deployment, and retracted without incident. Retracting the enclosure takes approximately 11 seconds and deploying the enclosure about 5 seconds. This timing can be tuned by controlling hydraulic flow as desired.

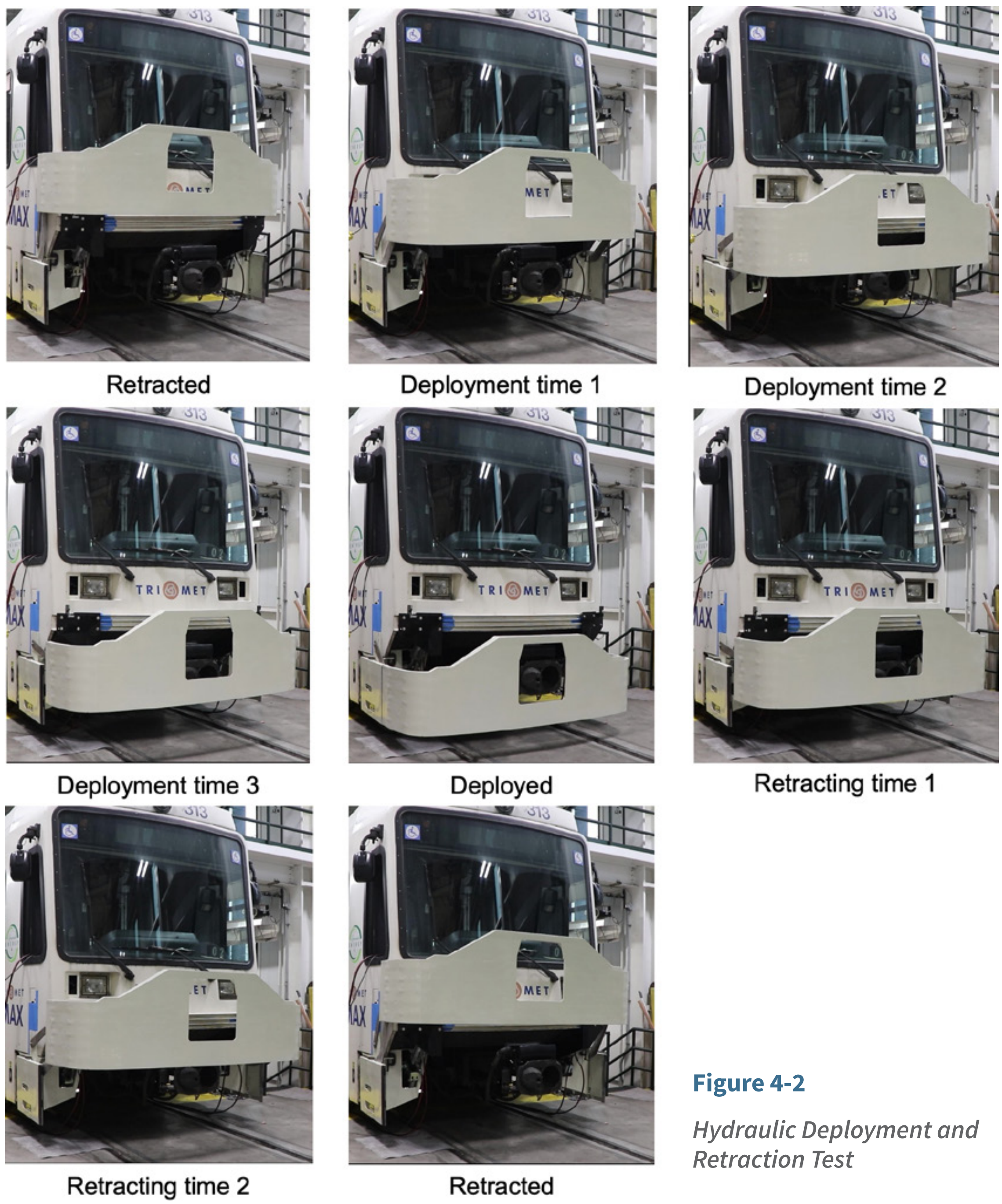


Figure 4-2

Hydraulic Deployment and Retraction Test

Float mode (i.e., without hydraulics powered and the float valve opened), was then tested, as shown in Figure 4-3. For this test, the gas springs were pressurized to raise the enclosure without any manual lifting. The enclosure rises slowly over approximately 20 seconds. This time would be reduced if lifted manually as well.

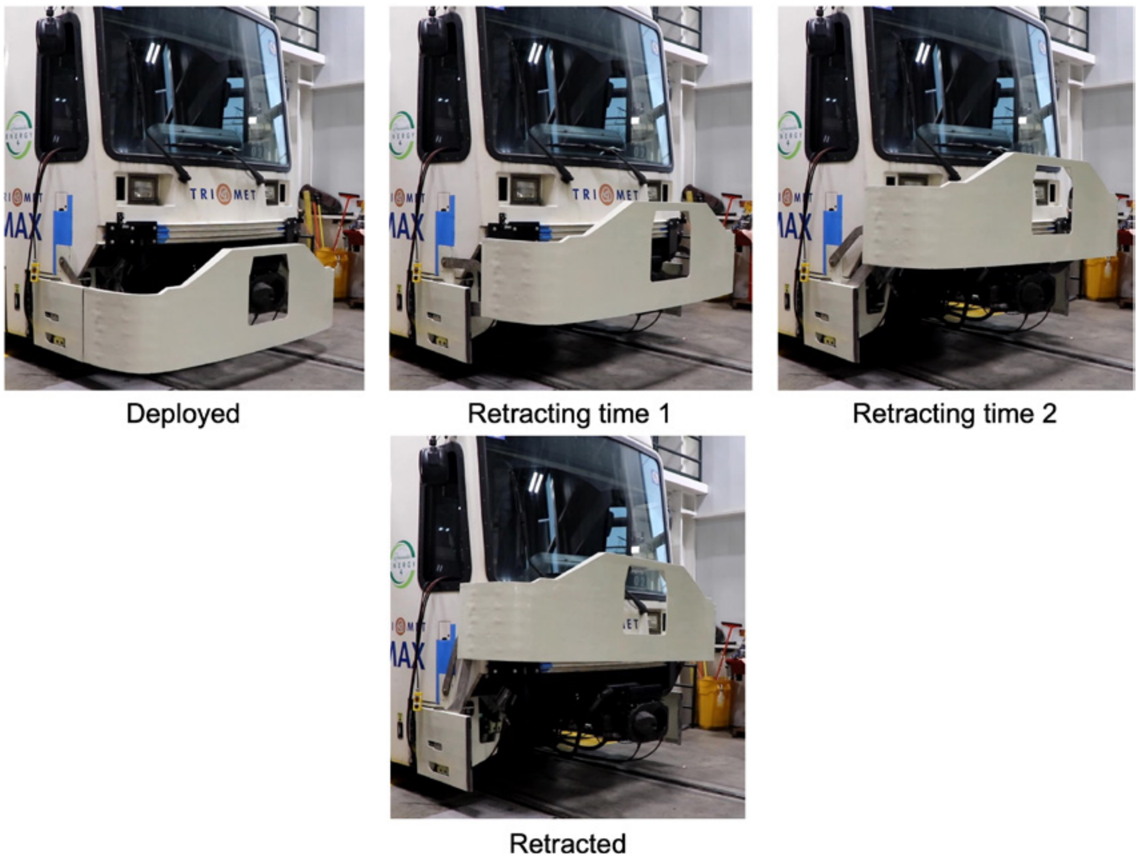


Figure 4-3 *Retraction Test in Float Mode*

A coupling test was then performed with a second LRV, as shown in Figure 4-4. The operator in the retrofitted car noted that coupling was an easy process, and their view was not hindered by the raised enclosure. Note that the coupler cutout, needed so couplers can actuate fully during hard coupling events, also serves to provide good visibility for the operator of the coupling faces.

Finally, a ride test was performed at the Ruby Junction Rail Yard. The LRV was driven through the yard at slow speeds (5 mph), as shown in Figure 4-5. No issues were noted by the operator and good clearance with track-side equipment was recorded with video cameras attached to the LRV.

(a) coupled clearance

(b) operator view when coupling

Figure 4-4 *Coupled Type 3 LRVs with a Temporary Front Enclosure Retrofit*

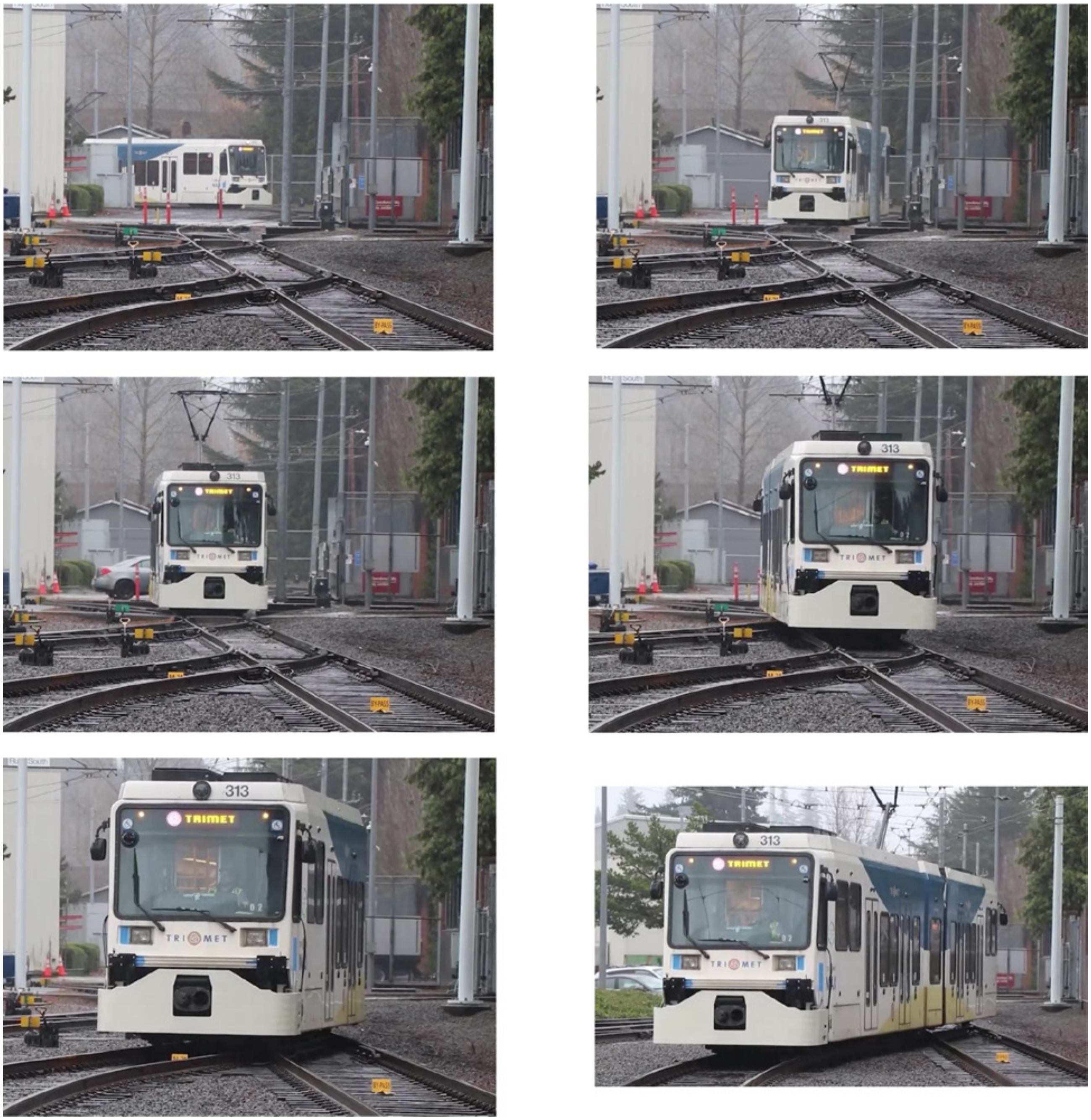


Figure 4-5 *Type 3 Ride Test with a Temporary Front Enclosure Retrofit*

Section 5 Crash Testing

Three (3) crash tests of the front-end structure were conducted at the Center for Advanced Product Evaluation (CAPE), operated by IMMI in Westfield, Indiana. Tests were conducted as follows:

- Test 1: Normal (90˚) impact at 12 mph with a 2003 Ford Explorer
- Test 2: Oblique (45˚) impact at 20 mph with a 2010 Toyota Yaris 4-door sedan
- Test 3: Sled Test - LRV impact at 10 mph with a barrier wall

For Tests 1 and 2, the configurations are shown in Figure 5-1. The test article was mounted to the rigid barrier wall at CAPE through a mounting frame. The automobile was accelerated on the test track to impact the test article at the required impact angle and speed. These tests were designed to evaluate the enclosure performance when impacting a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris). The normal (90˚) impact is representative of a street crossing and the oblique (45˚) impact represents a car turning in front of an LRV. Note that testing was conducted without a coupler. In a real-world side impact scenario, the coupler carries some portion of the impact loads. As such, we performed analyses to find an equivalent impact speed resulting in similar bumper-supported loads for the test condition without a coupler. Crash analyses of the Explorer showed that the loads on the front enclosure at 12 mph without a coupler are approximately equal to a 20-mph impact with the coupler.

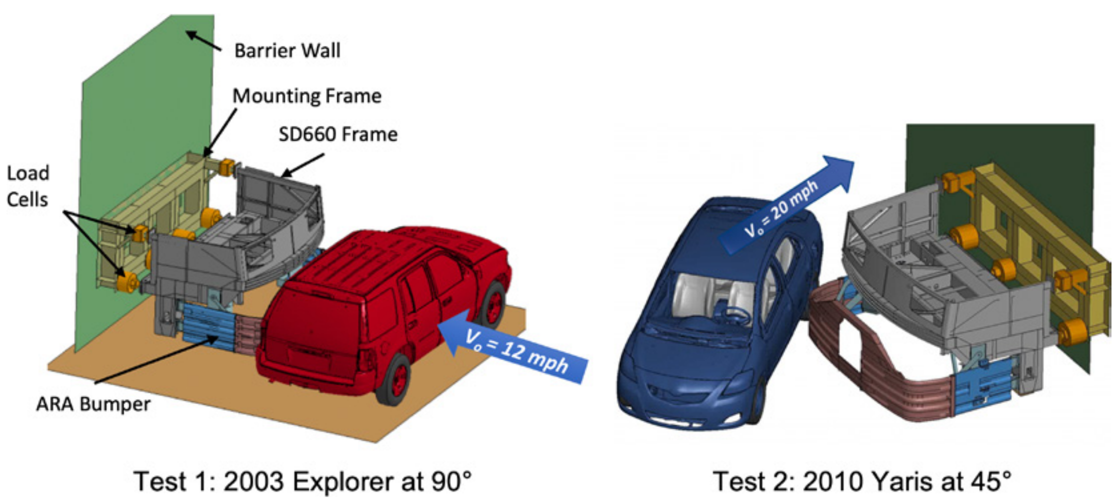


Figure 5-1 *Configurations for Automotive Impact*

For Test 3, the test article was mounted to a test sled and accelerated to the test speed at an angle of 90˚ to the rigid wall. This test is designed to evaluate the breakaway feature of the side panels for a crash between LRVs. The speed was selected to provide sufficient energy to break away the side panels, but a low enough speed to not damage the SD660 frame when hitting the wall-mounted anti-climber energy absorber.

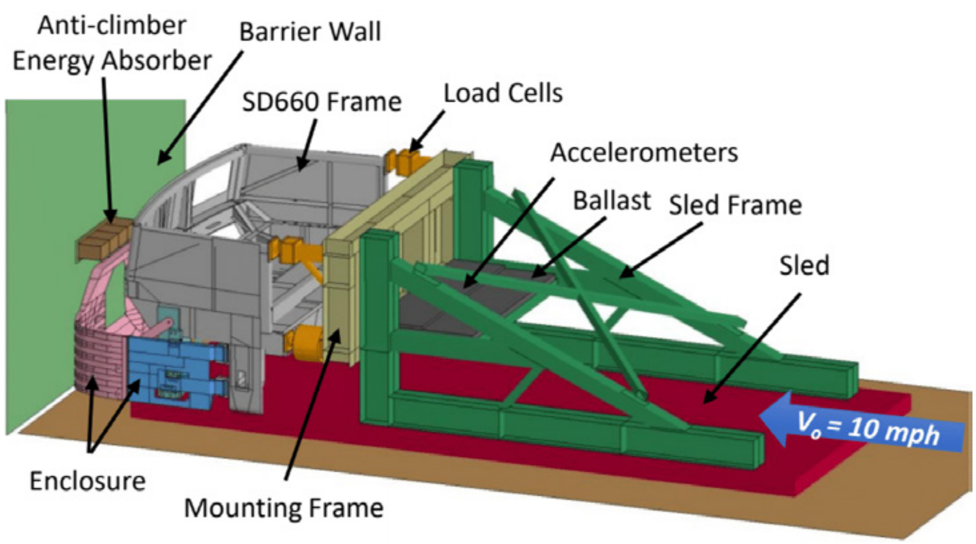


Figure 5-2 *Configuration for Wall Impact*

Testing Arrangements

The SD660 end frame was installed onto the mounting frame using bolted fasteners, as shown in Figure 5-3. The load cell configuration, which was sized for the anticipated load distribution, is shown in Figure 5-4. The mounting frame was either installed to the barrier wall or the sled frame, depending on the test.

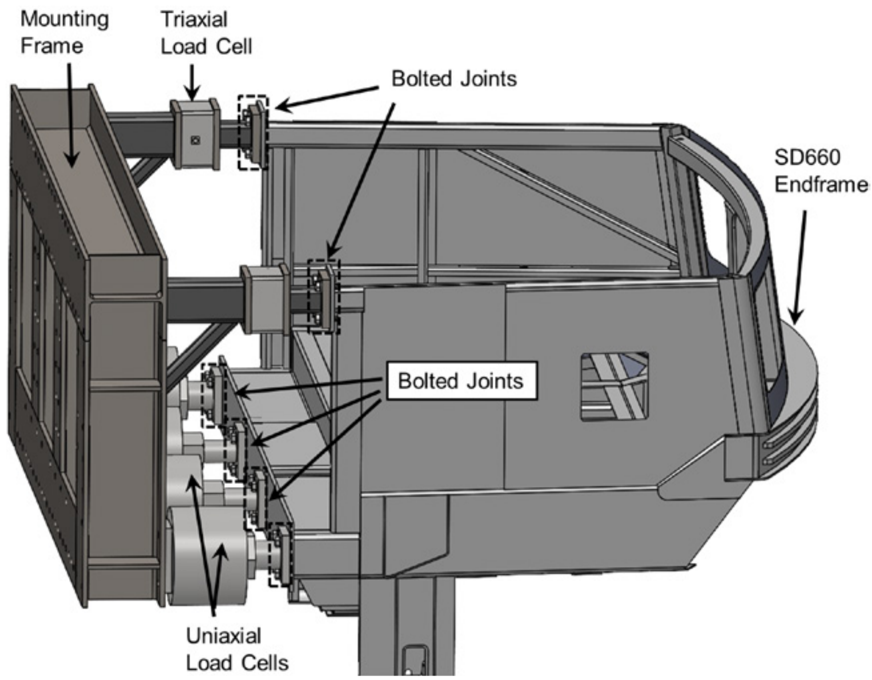
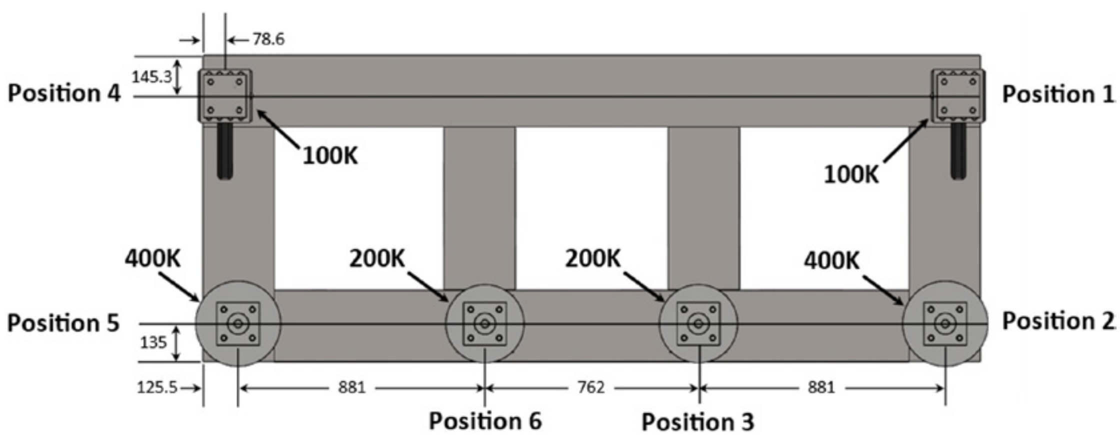


Figure 5-3 *SD660 End Frame Attachment to the Mounting Frame*



Note: Load cell capacity is labeled in kips

Figure 5-4 *Load Cell Configuration on Mounting Frame (view facing barrier wall) [mm]*

Test 1: Normal (90˚) impact with a 2003 Ford Explorer

The test article was positioned 100 mm off center of the track, as shown in Figure 5-5. Note that the side panels were painted green, parts of front enclosure are purple, and the linkage arm mounting blocks and shear blocks are pink in order to be more visible in high-speed video. Vertical positioning measured prior to testing is shown in Figure 5-6. The Explorer was positioned perpendicular to the centerline of the tow hook as shown in Figure 5-7.

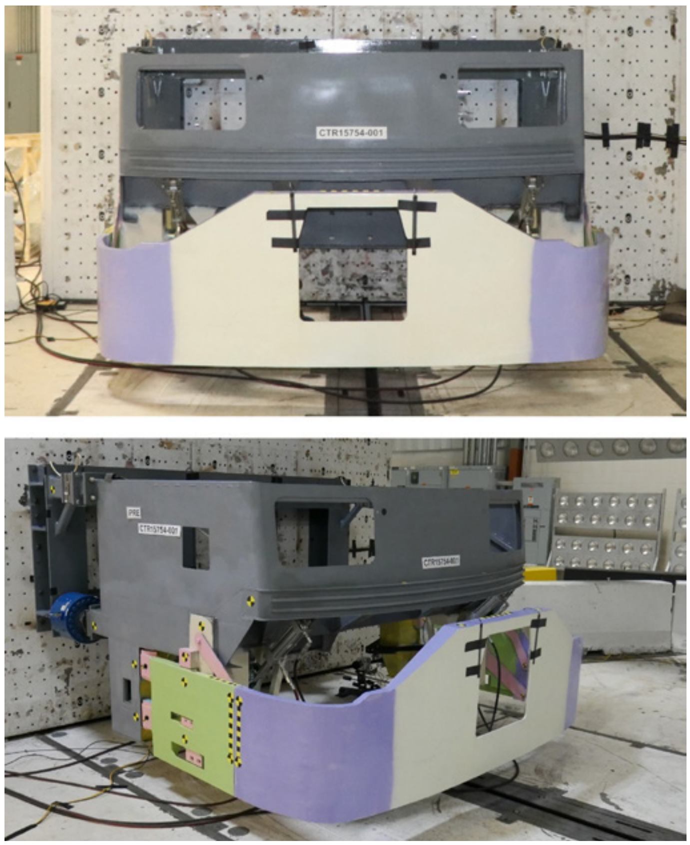


Figure 5-5 *Test Article Positioned on the Barrier Wall for Test 1*

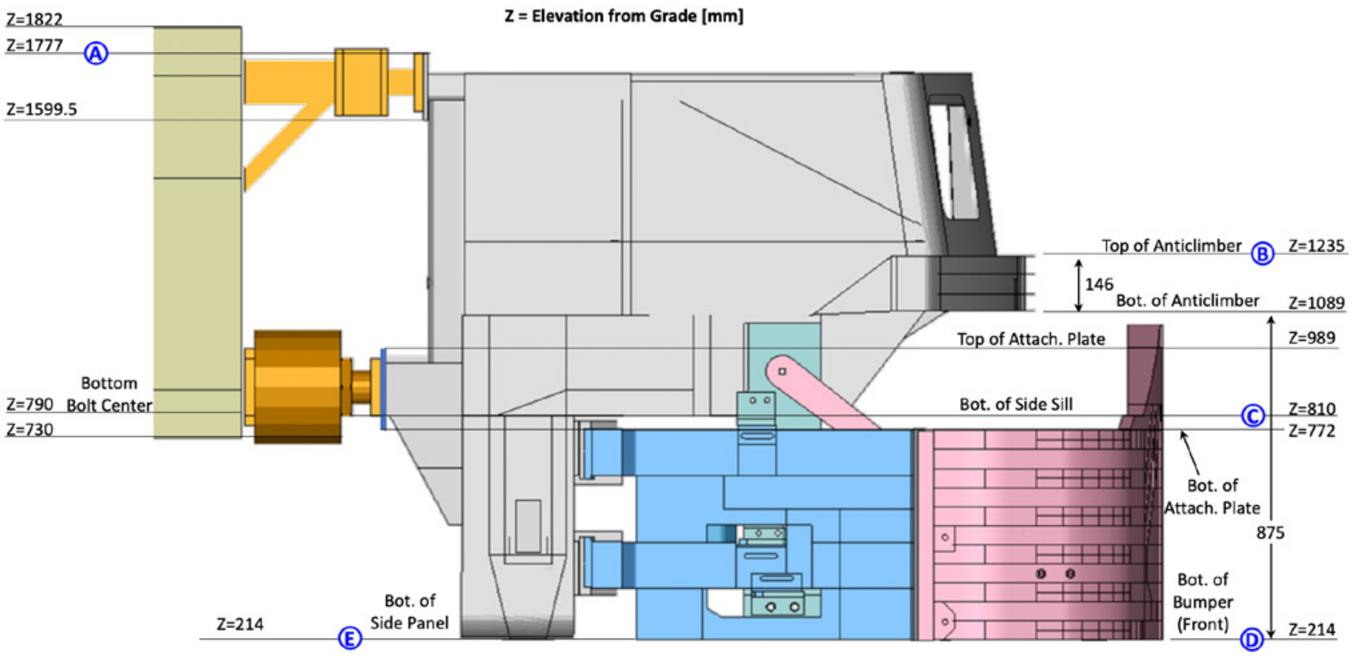


Figure 5-6 *Test Article and Mounting Frame Elevations from Grade [mm]*

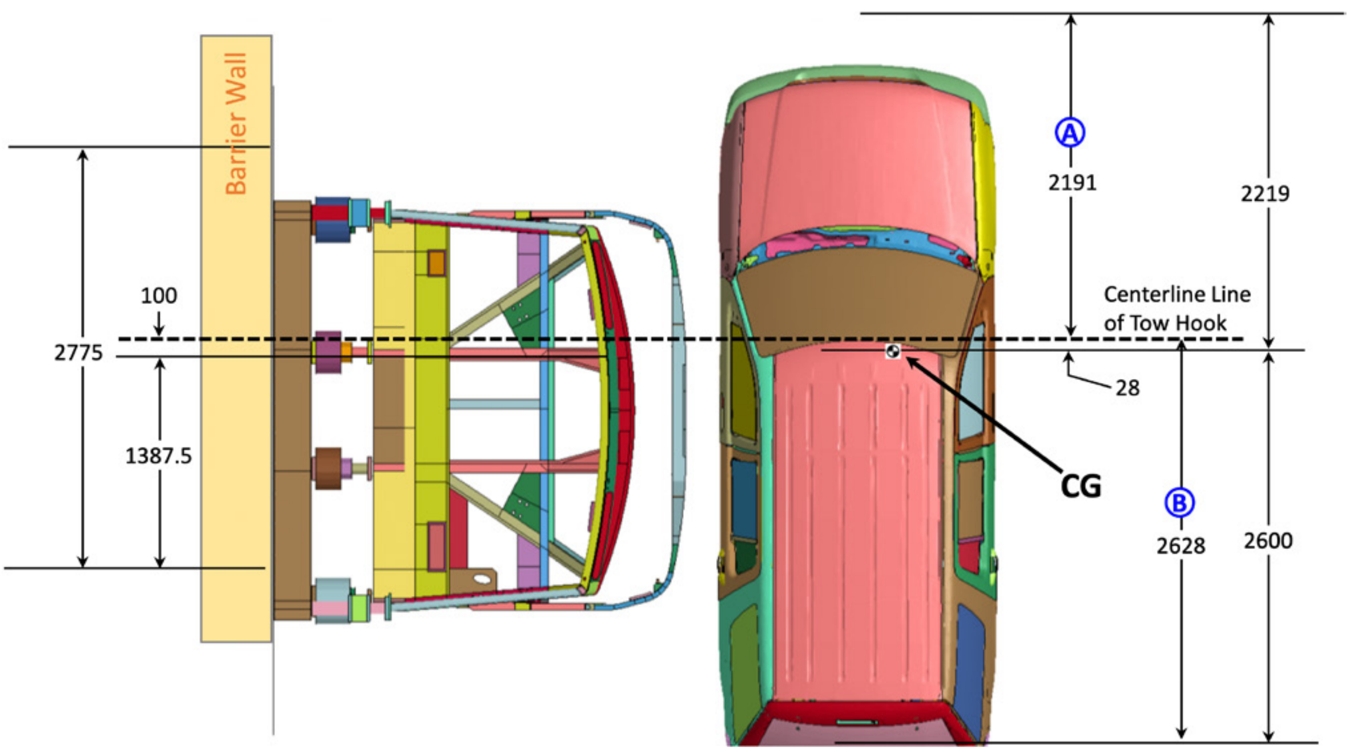


Figure 5-7 *Overhead View of Test 1 - 2003 Ford Explorer at 90° [mm]*

Instrumentation

Triaxial accelerometers were positioned at the longitudinal CG of the automobile to measure translational and rotational accelerations. These are shown mounted at the base of the center console in Figure 5-8. Load cells were mounted between the test article and the mounting frame to measure the reaction load at the barrier wall, as shown in Figure 5-9. Specific load cell instrumentation was provided, shown in Figure 5-4. Two (2) laser speed traps were used to measure the impact speed. These traps measure the time between interruption of the laser as they crossed forks mounted to the vehicle roof, as shown in Figure 5-10. Tape contact switches were attached to the front enclosure to trigger and synchronize the data acquisition equipment, as shown in Figure 5-11. High-speed photography was taken at overhead, left/right sides, and beneath the test article to view the side panels, as shown in Figure 5-12.

Figure 5-8 *Test 1 Accelerometers Mounted at the Base of the Center Console*

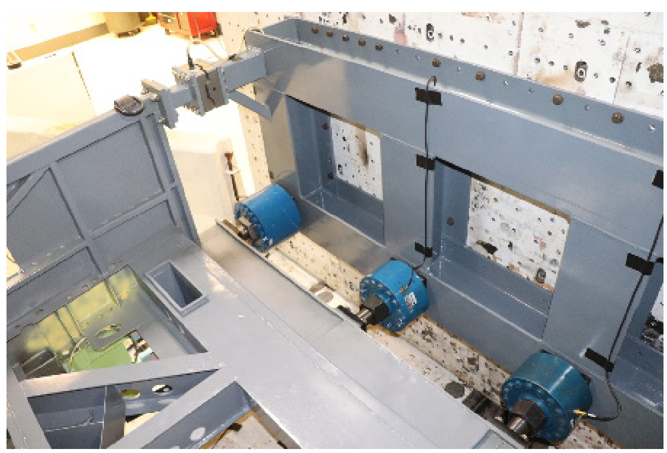


Figure 5-9 *Test 1 Load Cell Configuration*

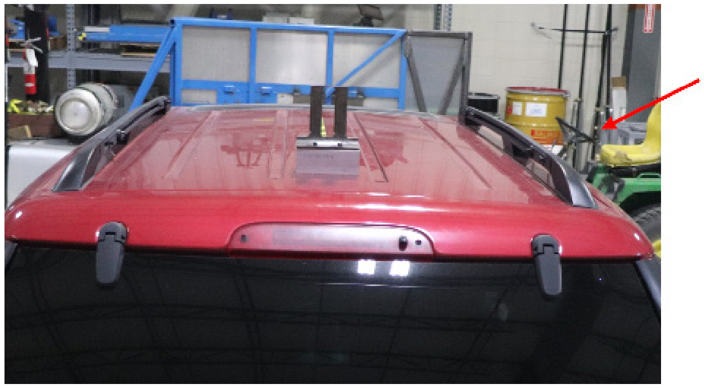


Figure 5-10 *Test 1 Forks for Laser Speed Trap Measurements*

Figure 5-11 *Tape Contact Switch Positions in Test*

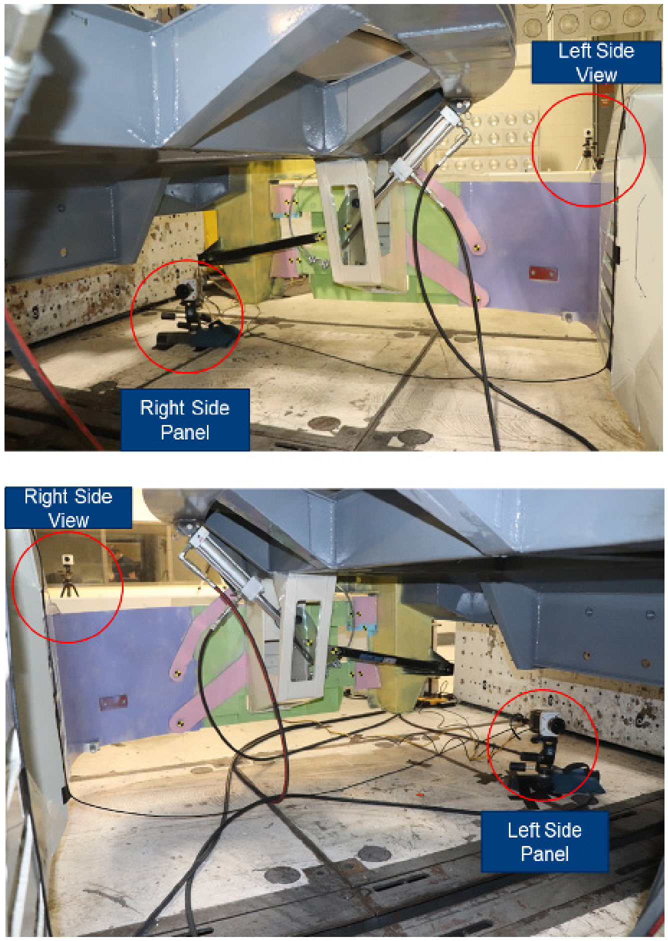


Figure 5-12 *High-Speed Camera Locations in Test 1*

Markers and Geometry Measurements

Markers (quad targets and inch tape) were positioned on the LRV test article and the automobile, as shown in Figure 5-13 to Figure 5-15. The markers on the test article (Figure 5-13) were placed on both sides, and positions from the wall and the ground were documented. The inch tape was positioned at three heights on the impact side of the Explorer (Figure 5-14) to measure the geometry before and after the test. Markers were also placed on each B-pillar at 4-inch spacing to measure pillar deformation into the occupant compartment.

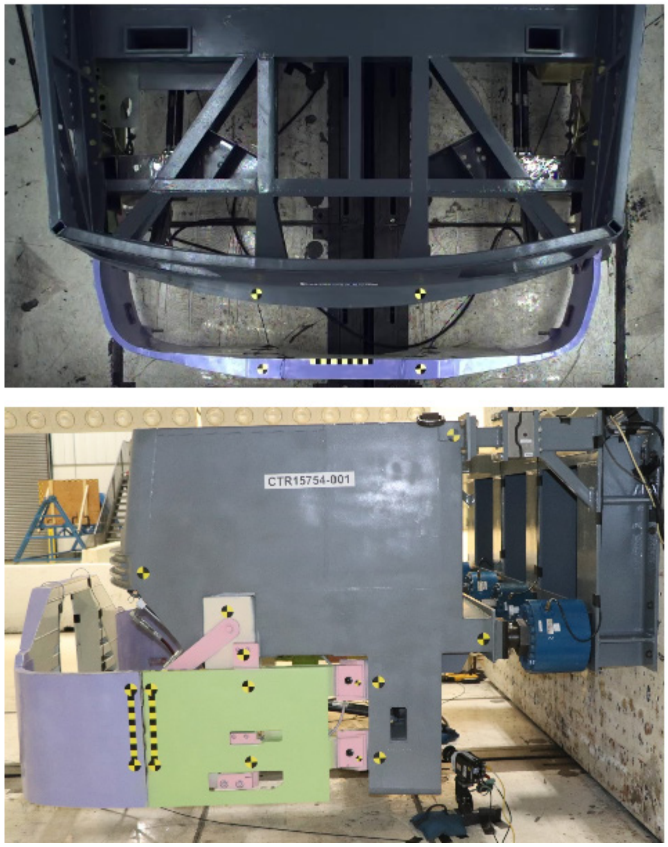


Figure 5-13 *Markers on the LRV Front-End Test Article*

Figure 5-14 *Markers on the Exterior of the 2003 Explorer in Test 1*

Figure 5-15 *B-Pillar Deformation Measurement Locations Pre-crash (left two images are driver side, right image is passenger side)*

Weight Measurements

The weight of the Explorer was measured with scales under each tire. Weights are shown in Table 5-1. The total weight is 105 lbs lower than nominal (fluids removed).

Table 5-1 *Test 1 Mass Measurements*

		Measured Mass (lb)				
Assembly	Nominal Mass (lb)	Scale #1 (DF)	Scale #2 (PF)	Scale #3 (PR)	Scale #4 (DR)	Total
Ford Explorer	4630	1200	1200	1100	1025	4525

DF – Driver Front, PF – Passenger Front, PR – Passenger Rear, DR – Driver Rear

Test 2: Oblique (45˚) impact at 20 mph with a 2010 Toyota Yaris

The test article was positioned off center of the track centerline, as shown in Figure 5-16 to accommodate the corner-focused oblique impact. Vertical positioning was the same as Test 1. The Yaris was positioned at an angle of 45 degrees to the track line and 105 mm off center of the tow hook, as shown in Figure 5-17.

Figure 5-16 *Test Article Positioned on the Barrier Wall for Test 2*

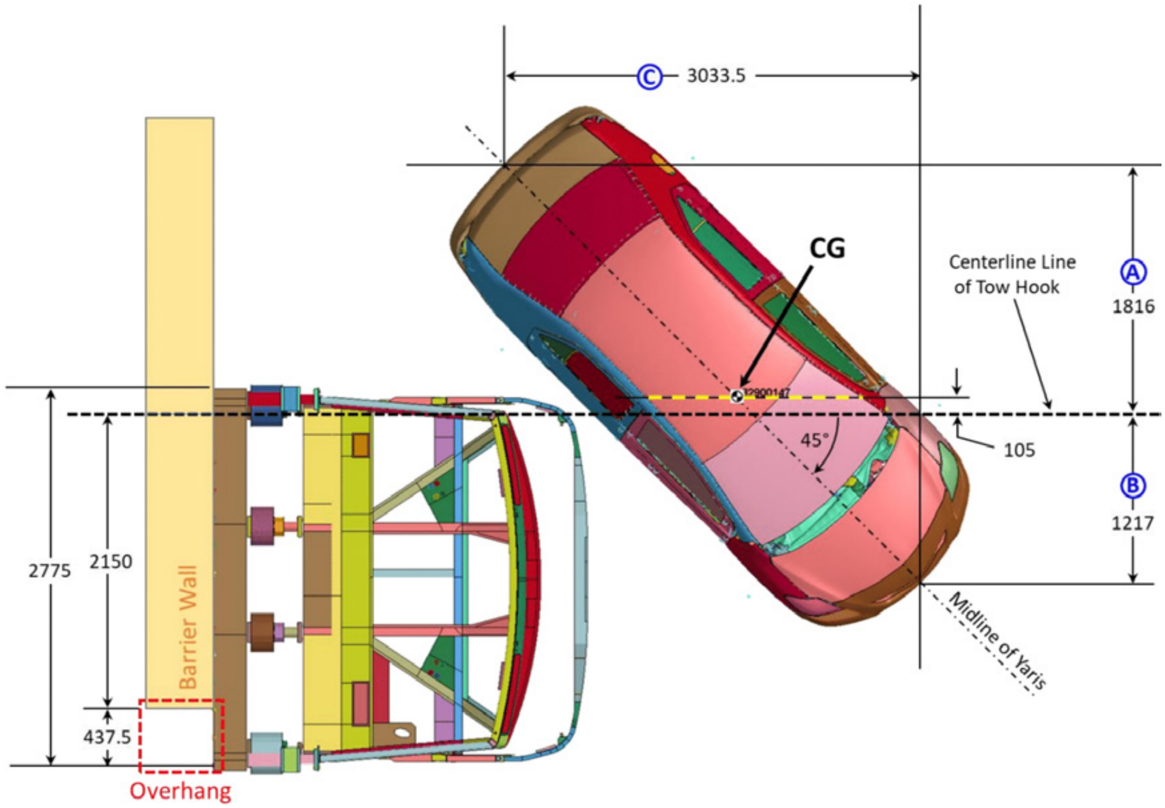


Figure 5-17 *Overhead View of Test 2 – 2010 Yaris at 45° [mm]*

Instrumentation

Triaxial accelerometers were positioned at the longitudinal CG of the automobile to measure translational and rotational accelerations. These are shown mounted at the base of the center console in Figure 5-18. Load cells were mounted between the test article and the mounting frame to measure the reaction load at the barrier wall, as shown Figure 5-19. Two (2) laser speed traps were used, as described for Test 1, as shown in Figure 5-20. Tape contact switches were attached to the front enclosure and to the Yaris door to trigger and synchronize the data acquisition equipment, as shown in Figure 5-21. High-speed photography was taken at overhead, left/right sides, and beneath the test article to view the side panels, as shown in Figure 5-12.

Figure 5-18 *Test 2 Accelerometers Mounted at the Base of the Center Console*

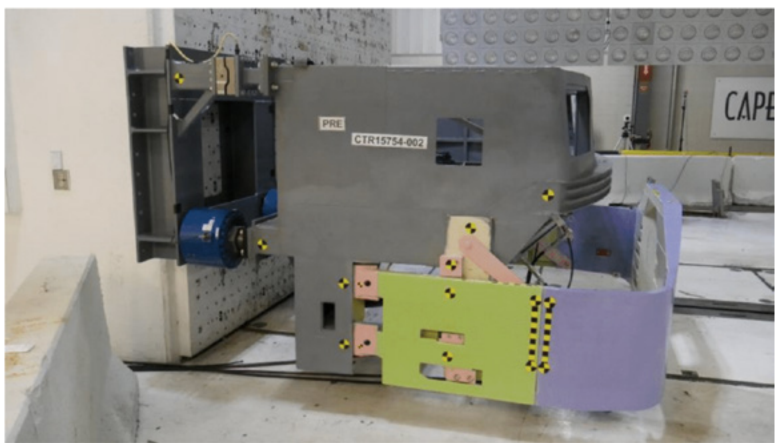


Figure 5-19 *Test 2 Load Cell Configuration*

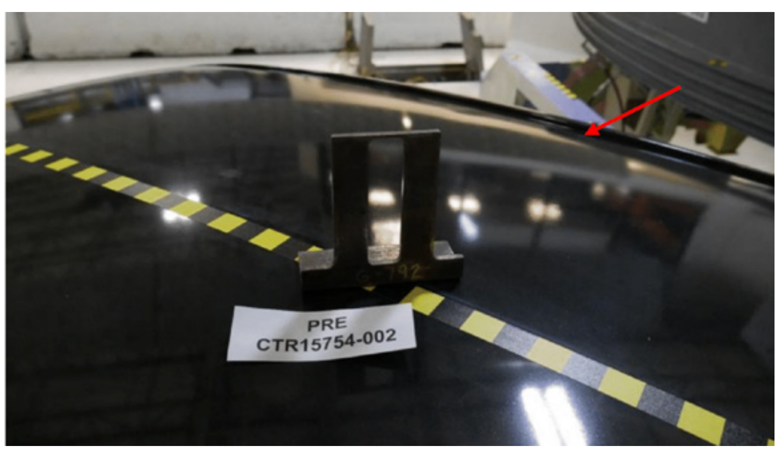


Figure 5-20 *Test 2 Forks for Laser Speed Trap Measurements*

Figure 5-21 *Tape Contact Switch Positions in Test 2*

Markers and Geometry Measurements

Markers (quad targets and inch tape) were positioned on the LRV test article and the automobile, as shown in Figures 5-22 to 5-24. The markers on the test article (Figure 5-22) were placed on both sides and positions from the wall and the ground were documented. The inch tape was positioned at three heights on the impact side of the Yaris (Figure 5-23) to measure the geometry before and after the test. Markers were also placed on each B-pillar at 4-inch spacing (Figure 5-24) to measure pillar deformation into the occupant compartment.

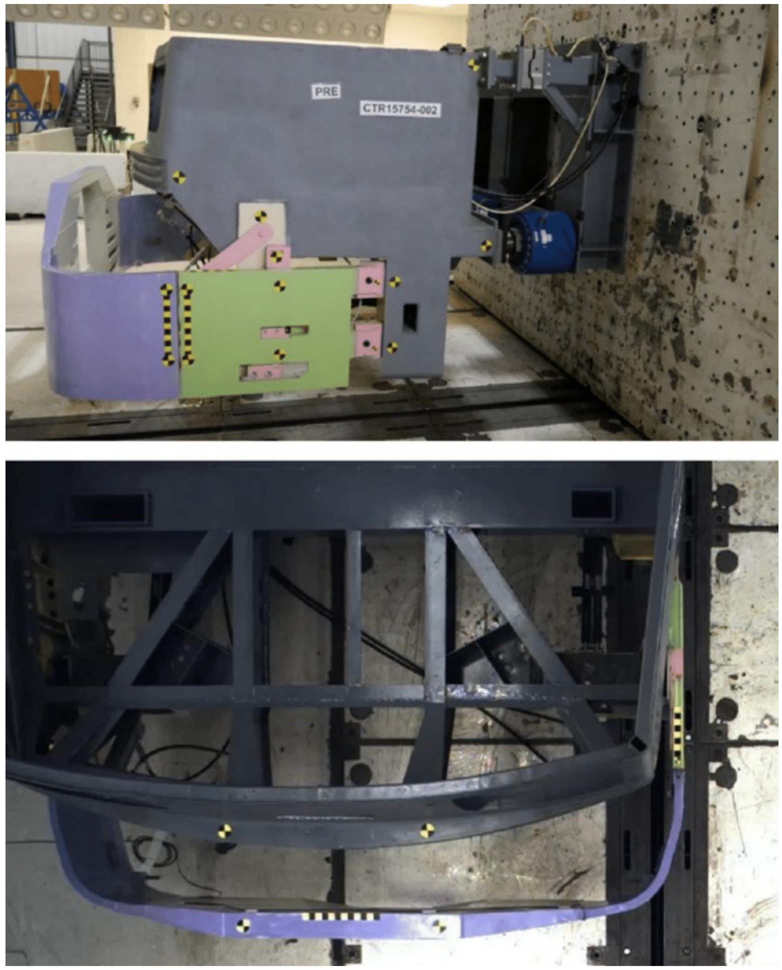


Figure 5-22 *Markers on the LRV Front-End Test Article (Test 2)*

Figure 5-23 *Markers on the Exterior of the 2010 Yaris in Test 2*

Figure 5-24 *B-Pillar Deformation Measurement Locations Pre-test in Test 2*

Weight Measurements

The weight of the Yaris was measured with scales under each tire. Weights are shown in Table 5-2. The total weight is 109 lbs lower than nominal (fluids removed).

Table 5-2 *Test 2 Mass Measurements*

		Measured Mass (lb)				
Assembly	Nominal Mass (lb)	Scale #1 (DF)	Scale #2 (PF)	Scale #3 (PR)	Scale #4 (DR)	Total
Toyota Yaris	2429	710	700	450	470	2320

DF – Driver Front, PF – Passenger Front, PR – Passenger Rear, DR – Driver Rear

Test 3: Sled Test - LRV impact at 10 mph with a barrier wall

The test configuration is shown in Figure 5-25. The SD660 front-end frame, end enclosure, and mounting frame were attached to the sled frame at the center of the sled. The sled was positioned on the test track centerline. In order to minimize damage to the test structure and the impact wall, an anti-climber energy absorber was attached to the center of the barrier wall, as shown in Figures 5-26 and 5-27.

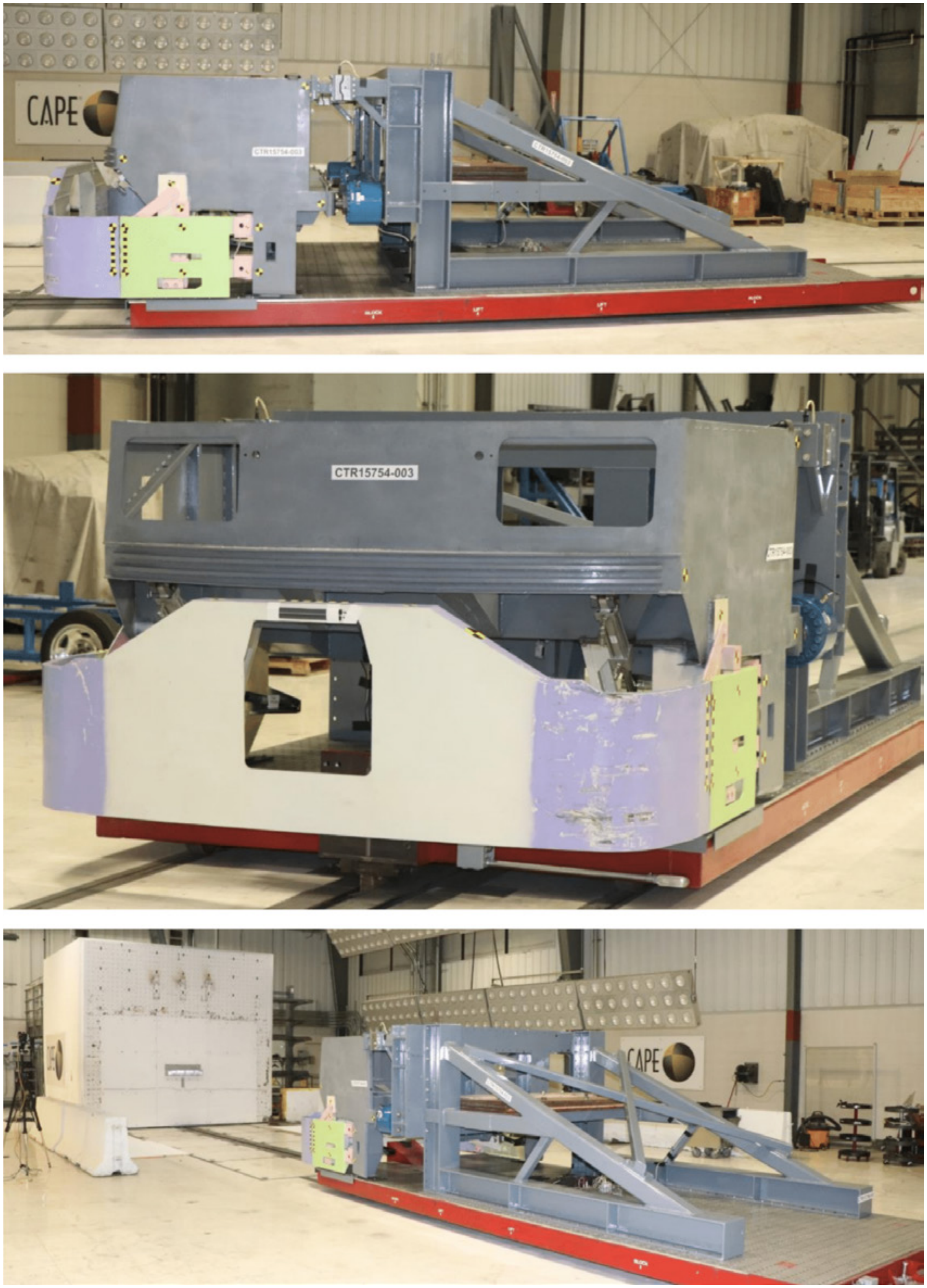


Figure 5-25 *Test Article Positioned on the Test Sled for Test 3*

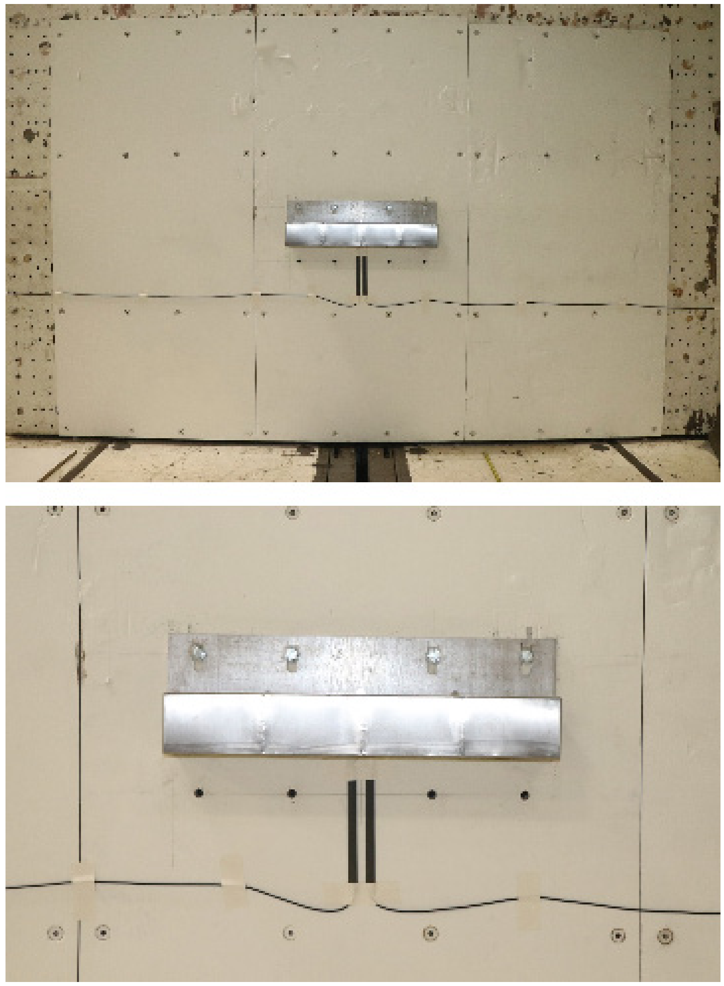


Figure 5-26 *Anti-climber Energy Absorber Bolt to the Barrier Wall for Test 3*

Figure 5-27 *Anti-climber Energy Absorber Position in Front of the Anti-climber for Test 3*

Instrumentation

Triaxial accelerometers were positioned at the longitudinal CG of the test sled at two heights to measure translational and rotational accelerations. These are shown mounted at the base of the center console in Figures 5-28 and 5-29. Load cells were mounted between the test article and the mounting frame to measure the reaction load on the sled, as shown Figure 5-30. Two (2) laser speed traps were used to measure the impact speed by measuring the time between interruption of the laser. Tape contact switches were attached to the barrier wall beneath the ACEA to trigger the data acquisition equipment, as shown in Figure 5-27 and on the front enclosure, as shown in Figure 5-31. High-speed photography was taken at overhead, left/right sides, and left/right oblique positions.

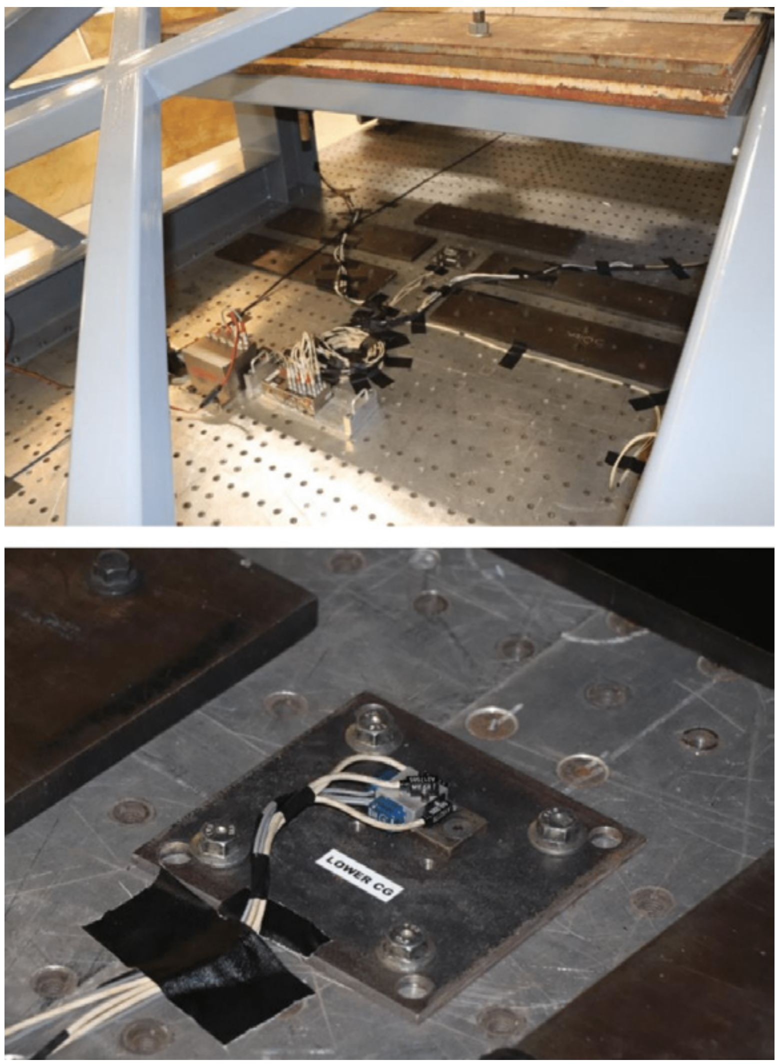


Figure 5-28 *Test 3 Accelerometers Mounted to the Test Sled*

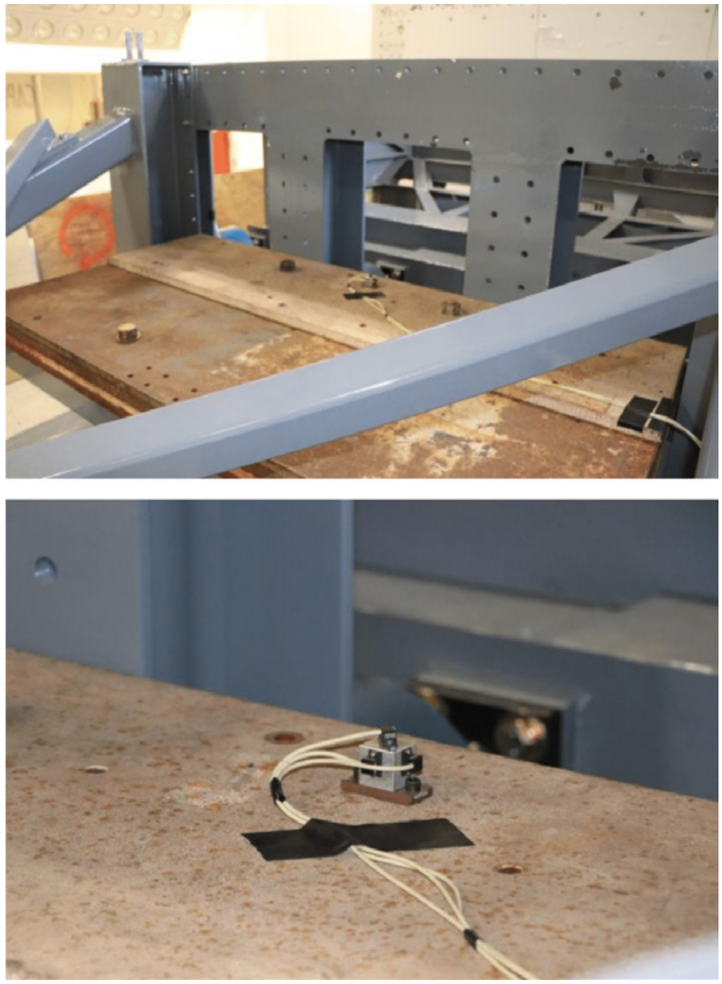


Figure 5-29 *Test 3 Accelerometers Mounted to the Ballast Weights*

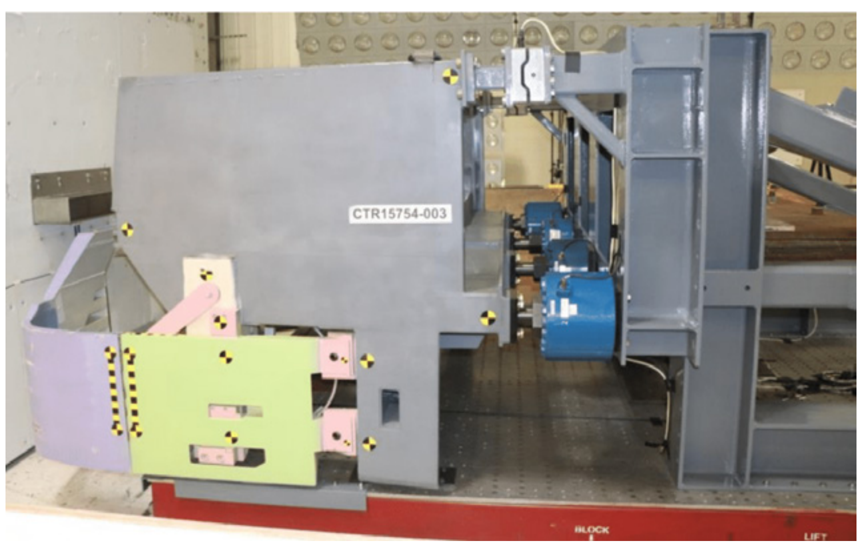


Figure 5-30 *Test 3 Load Cell Configuration*

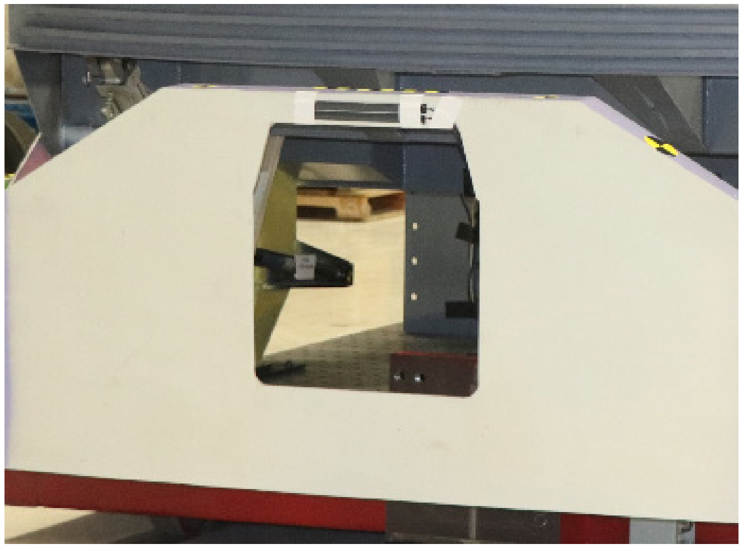


Figure 5-31 *Tape Contact Switch Position on the Front Enclosure in Test 3*

Weight Measurements

The weight of the test sled was measured with scales under each wheel (six total). Weights are shown in Table 5-3.

Table 5-3 *Test 3 Mass Measurements*

Assembly	Measured Mass (lb)
Sled Empty Weight	6920
Sled & Sled Frame	9390
Ballast Plates	2770
Sled, Sled Frame, Mounting Frame, and Load Cells	14920
Full Sled Test Weight	17690

Test Results

All three crash tests were successful in achieving the desired crash conditions. Test speeds are shown in Table 5-4. Both tests with the automobiles resulted in minimal damage to the enclosure, consisting only of scratches to the paint. There was a negligible change in measurements to each marker position before and after each test, indicating that deformation to the structure was not permanent. The front enclosure was retracted and deployed after each crash test with no loss in function.

In the sled test, the side panels sheared back as designed and the front enclosure pushed back beneath the anti-climber. In this way, the anti-climber is not obstructed for LRV-LRV collisions. The tethers attached to the side panels restrained the panels to land within 2 feet of the test sled. There were only two anomalies in the designed behavior. First, the tether eye bolt failed on the left side and should be sized to a larger diameter for production. Second, two of the sliding blocks, that attach the side panel to the linkage mount, separated on the right side. However, this happened late in the push-back process, such that both sides broke away nearly identically. The blocks also landed within 2 feet of the sled. In all tests, there was no damage to the carbody of the SD660 end frame due to the crash loads.

Table 5-4 *Test Speed Measurements*

	Speed (mph)		
	Explorer	Yaris	Sled
Nominal	12	20	10
Speed Trap	12.1	20.1	9.7
Difference	0.8%	0.5%	3%

Test 1 – 2003 Ford Explorer

The response of the front enclosure and Explorer in Test 1 is shown in Figure 5-32. The front enclosure after the crash test is shown in Figure 5-33. There was some small scratching on the paint, but no other visible damage. There was a negligible change in measurements to each marker position before and after each test, indicating no permanent deformation to the structure. The front enclosure was retracted and deployed with no loss in function. Forces and accelerations measured during the test are provided in Appendix C.

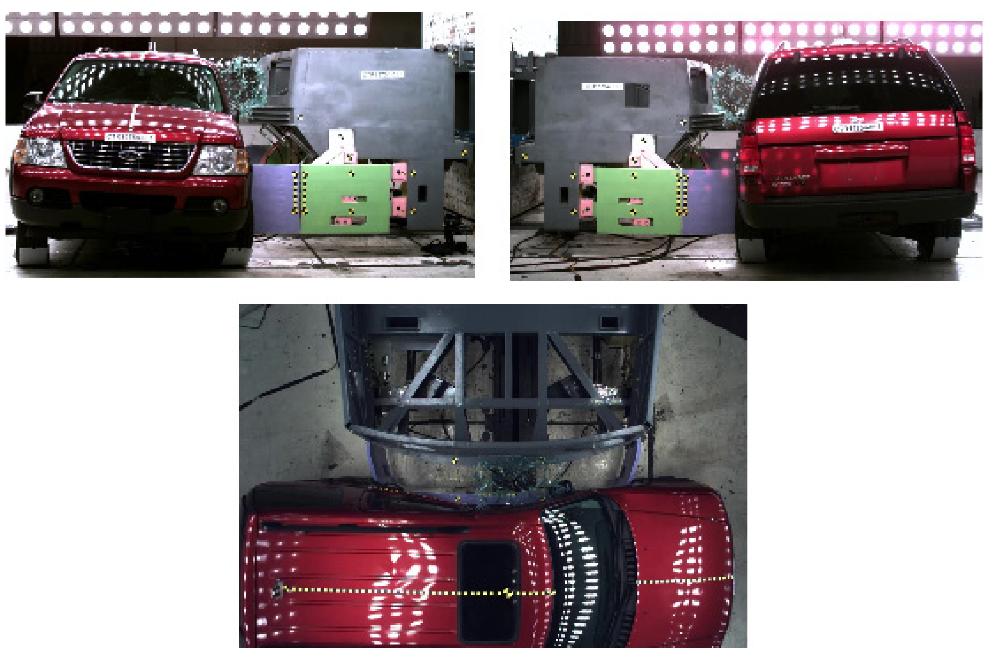


Figure 5-32 *Test 1 High-Speed Video*

Figure 5-33 *Front Enclosure Post-Test 1*

Surface profile data of the front and rear driver side doors were measured before and after the test. This was accomplished by placing inch tape across both doors at three different heights, as seen in Figure 5-34. Using a Leica Disto laser measurement tool, distance data were collected every 6-inches along the inch tape with reference to a planar surface. Figure 5-35 shows the location at which the laser was directed while maintaining perpendicularity to the plane, both vertically and horizontally. Deformation on the impact side of the Explorer post-test is shown in Figure 5-36.

Figure 5-34 *Location of Inch Tape on the 2003 Ford Explorer (pre-test)*

Figure 5-35 *Location of Inch Tape Measurements with the Laser (Test 1)*

Figure 5-36 *Impact Damage to the Explorer in Test 1 Where Inch Tape Measurements Were Made*

Laser measurements along each inch tape pre- and post-test are shown in Figures 5-37 to 5-39. The datum for the longitudinal position is the first tape measurement location at each height. Lateral positions are measured relative to the first and last measurement locations. Deformation of the tested Explorer compared with the computer simulated response in Figure 5-40 illustrates similar magnitude of intrusion and deformed shape. The largest discrepancy is seen in the bottom tape measurements (Figure 5-39). These are likely due to the molding on the test vehicle that is not included in the FEA model.

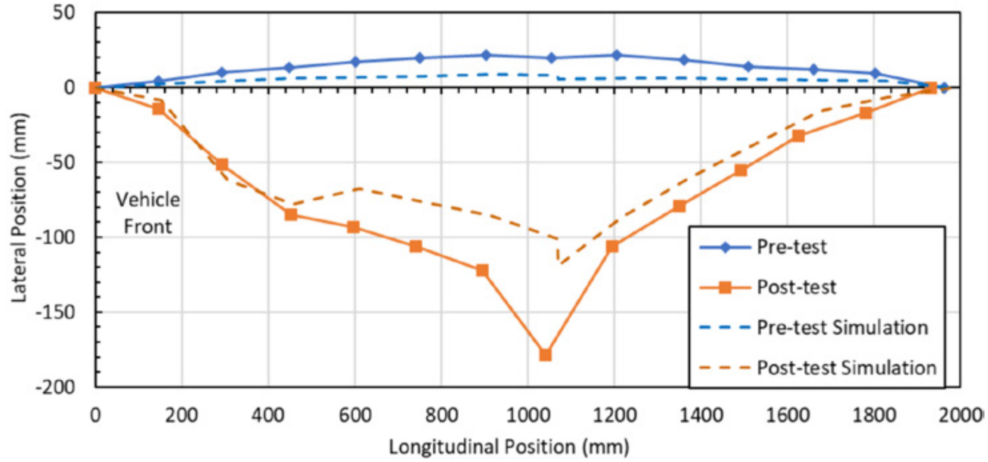


Figure 5-37 *Surface Profiles of the Top Tape Position on the Explorer*

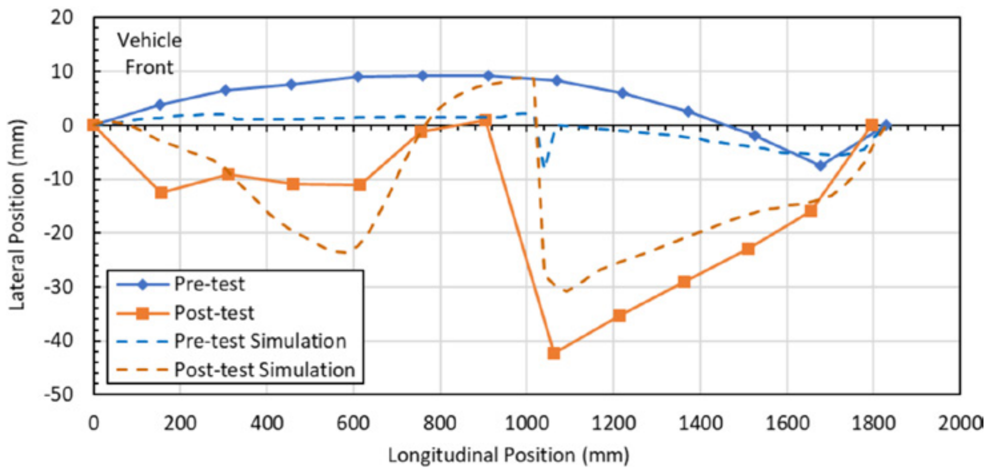


Figure 5-38 *Surface Profiles of the Middle Tape Position on the Explorer*

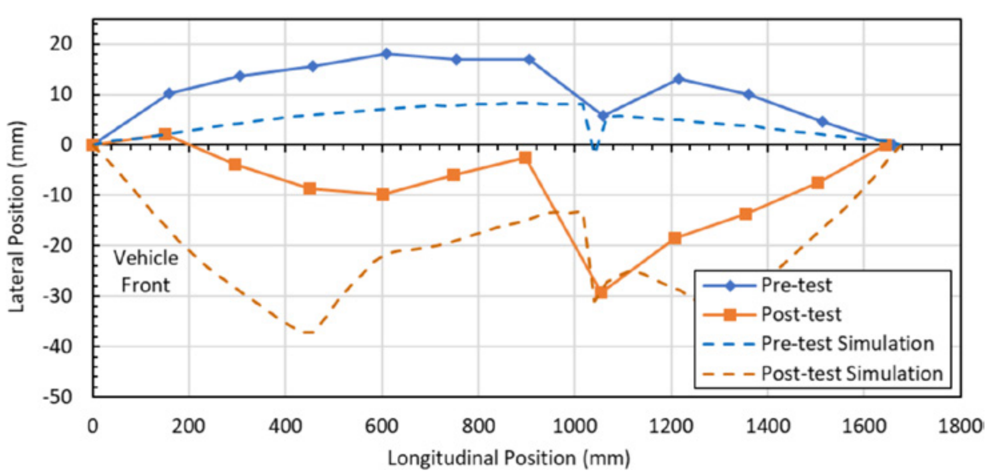


Figure 5-39 *Surface Profiles of the Bottom Tape Position on the Explorer*

Figure 5-40 *Explorer Deformations Compared with Simulated Response*

B-pillar deformation during the test was measured at set heights. The driver side pillar after the test is shown in Figure 5-41. The distance between markers on the passenger and driver side was measured with the Leica Disto laser to measure the pillar shape. The laser was directed at the center of the target on the driver side with the base of the laser located on the passenger side target center, with measurements taken before and after the test. The distance from the center of the automobile was then calculated, as are shown in Figure 5-42. Peak deformation was 182 mm. Agreement with the simulated response is also shown and in good agreement with the test results.

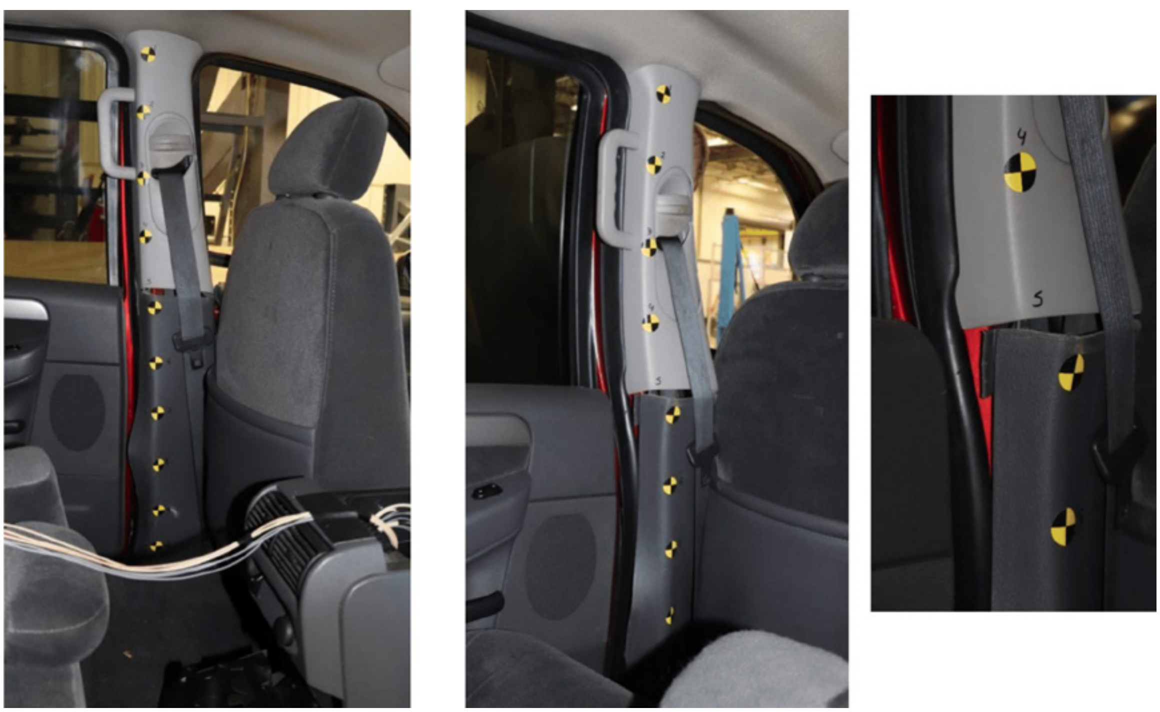


Figure 5-41 *B-Pillar Deformation in the Explorer*

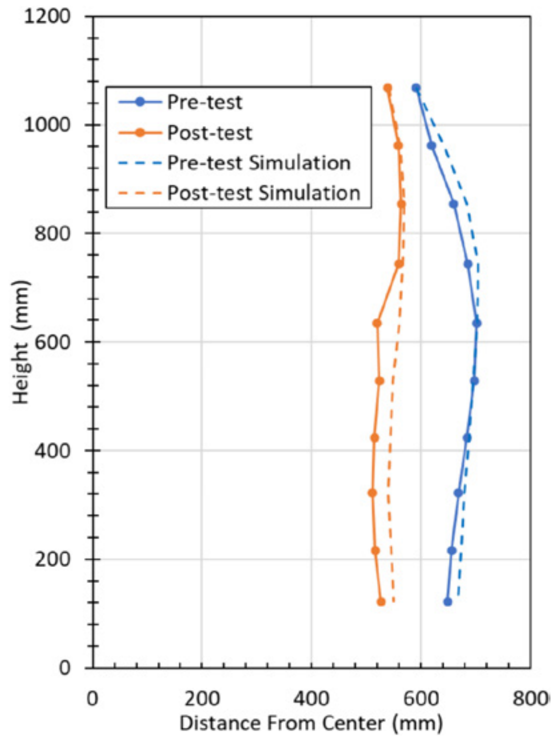


Figure 5-42 *Measured B-Pillar Shape in the Explorer Pre- and Post-test*

Test 2 – 2010 Toyota Yaris

The response of the front enclosure and Yaris in Test 2 is shown in Figure 5-43. The front enclosure after the crash test is shown in Figure 5-44. There was some small scratching on the paint, but no other visible damage. There was a negligible change in measurements to each marker position before and after each test, indicating no permanent deformation to the structure. The front enclosure was retracted and deployed with no loss in function. Forces and accelerations measured during the test are provided in in Appendix C.

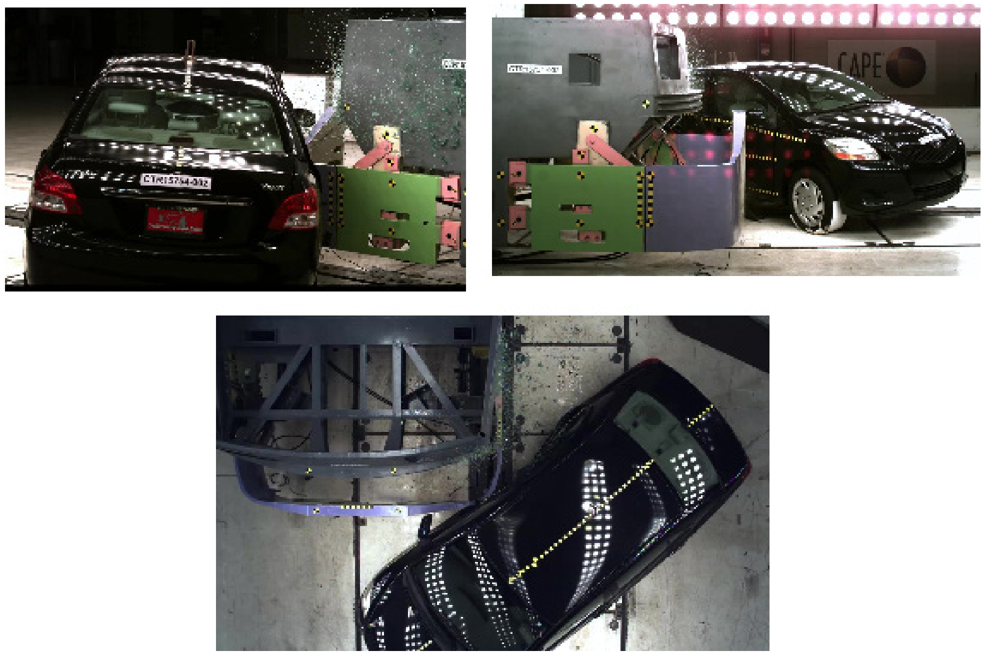


Figure 5-43 *Test 2 High-Speed Video*

Figure 5-44 *Front Enclosure Post-Test 2*

Surface profile data of the front and rear driver side doors were measured before and after the test. This was accomplished by placing inch tape across both doors at three different heights, as seen in Figure 5-45. Using a Leica Disto laser measurement tool, distance data were collected every 6 inches along the inch tape with reference to a planar surface. Deformation on the impact side of the Yaris post-test is shown in Figure 5-46.

Figure 5-45 *Location of Inch Tape on the 2010 Toyota Yaris (pre-test)*

Figure 5-46 *Impact Damage to the Yaris in Test 2 Where Inch Tape Measurements Were Made*

Laser measurements along each inch tape pre- and post-test are shown in Figures 5-47 to 5-49. The simulated response is also shown and in good agreement. The datum for the longitudinal position is the first tape measurement location at each height. Lateral positions are measured relative to the first and last measurement locations. Deformation of the tested Yaris compared with the computer simulated response in Figure 5-50 illustrates similar magnitude of intrusion and deformed shape.

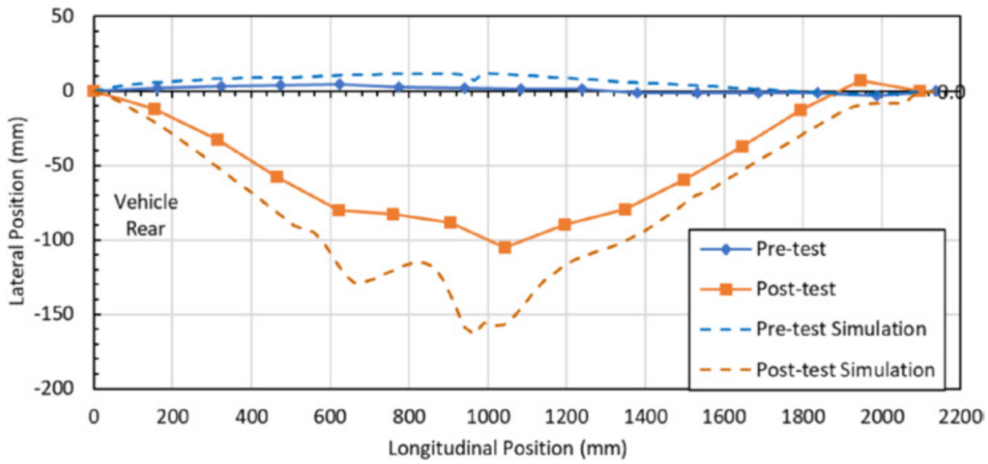


Figure 5-47 *Surface Profiles of the Top Tape Position on the Yaris*

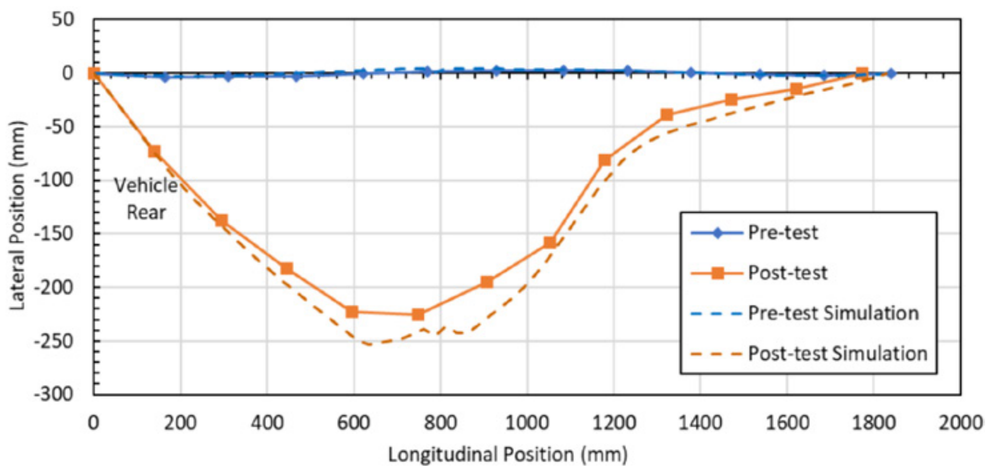


Figure 5-48 *Surface Profiles of the Middle Tape Position on the Yaris*

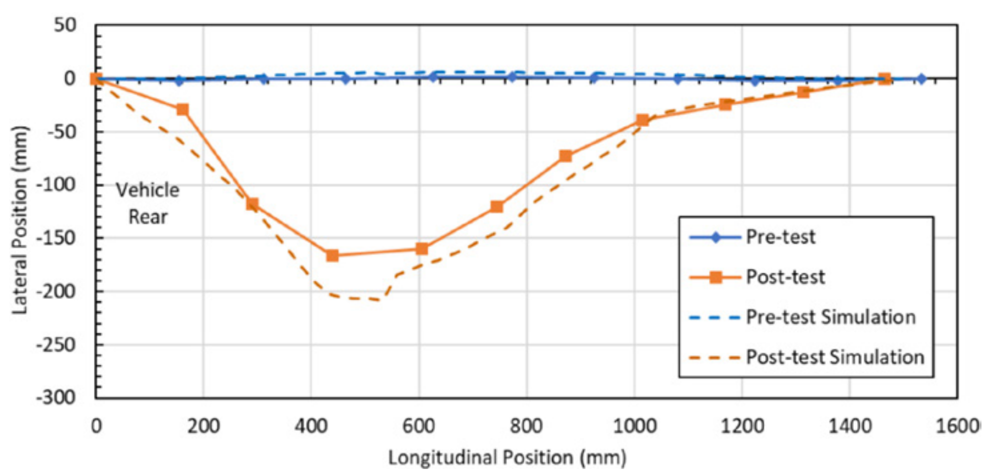


Figure 5-49 *Surface Profiles of the Bottom Tape Position on the Yaris*

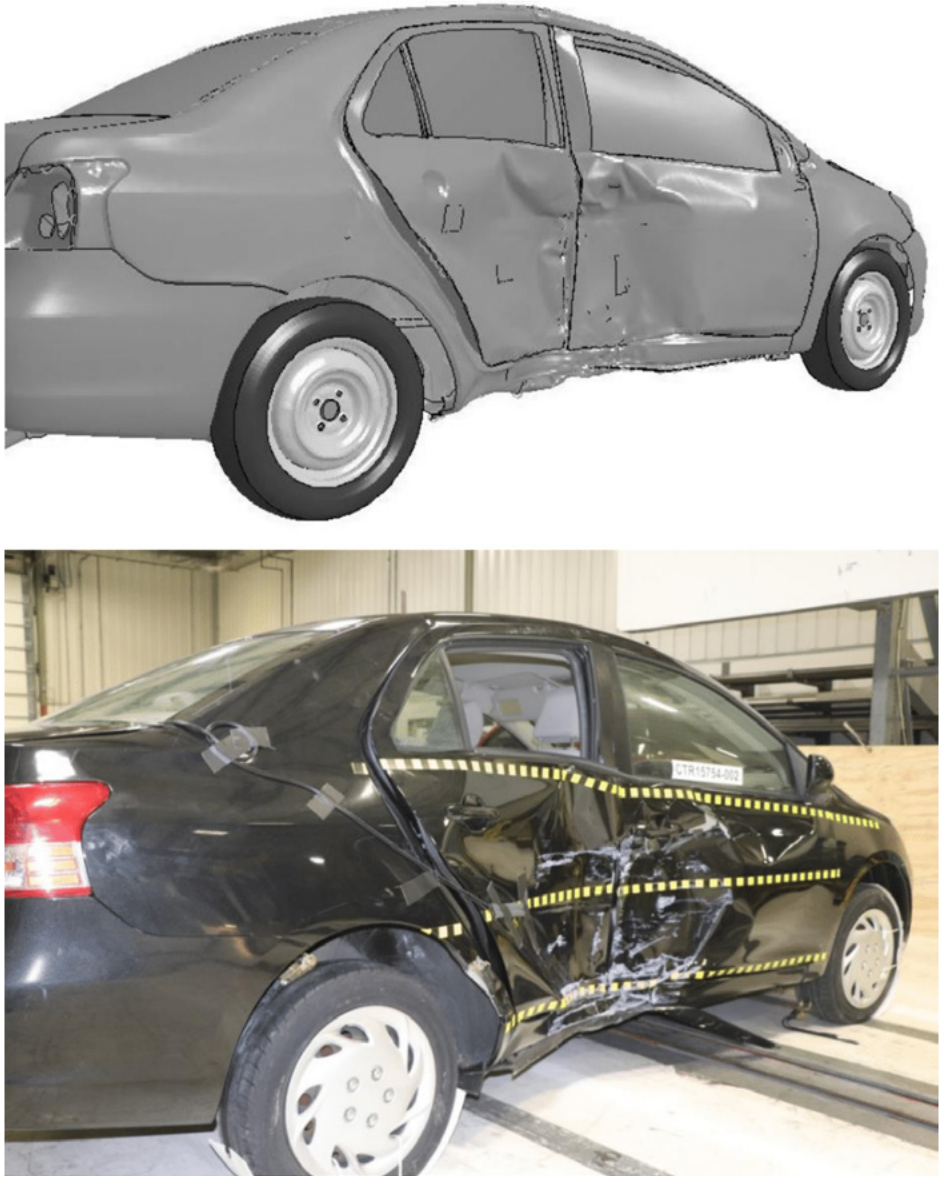
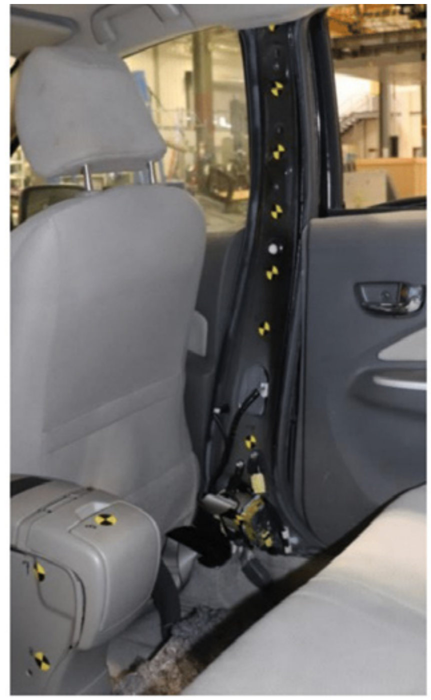


Figure 5-50 *Yaris Deformations Compared with Simulated Response*

B-pillar deformation during the test was measured at set heights, as shown by the markers in Figure 5-51. The distance between markers on the passenger and driver side was measured with a Leica Disto laser to measure the pillar shape. Note that the bottom two locations were measured to the center console. The passenger side pillar after the test is also shown in Figure 5-51. The laser was directed at the center of the target on the driver side with the base of the laser located on the passenger side target center with measurements taken before and after the test. The distance from the center of the automobile was then calculated, as are shown in Figure 5-52. Peak deformation was 193 mm at the bottom measurement location.

Pre-test



Post-test

Figure 5-51 *B-Pillar Deformation in the Yaris*

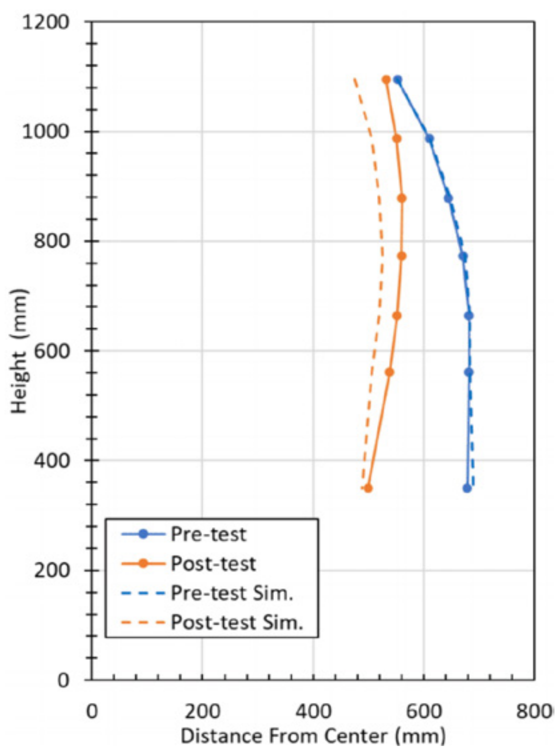


Figure 5-52 *Measured B-Pillar Shape in the Yaris Pre- and Post-test*

Test 3 – Sled Test

The response of the front enclosure when impacting the barrier wall is shown in Figures 5-53 to 5-56. The side panels sheared back as designed and the front enclosure pushed back beneath the anti-climber. The panels released nearly simultaneously at approximately 25 ms (left) and 27 ms (right) from the time of wall impact. This release time is most easily seen in the side views of Figures 5-53 and 5-54. The panels were directed rearward and outward by the shear blocks, such that they cleared the carbody without contact, as seen in Figure 5-56. This allowed the front enclosure to push backward beneath the anti-climber without obstruction.

The test sled in its final resting position is shown in Figure 5-57. The front enclosure remained attached to the upper linkage arms, which bent backward but did not separate. There was no damage to the carbody of the SD660 end frame or the linkage mounts due to the crash loads and they are completely reusable. The gas springs and hydraulic cylinders remained attached to their anchored locations and the swivel arm. Return to service would require replacing the linkage arms, new or refurbished side panels, and a new or refurbished front-end enclosure.

The tethers attached to the side panels restrained the panels to land within 2 feet of the test sled. Their final resting positions are shown in Figures 5-58 and 5-59. There were only two anomalies in the designed behavior. First, the tether eye bolt failed on the left side and should be sized to a larger diameter for production. Second, two of the sliding blocks, that attach the side panel to the linkage mount, separated on the right side. However, this happened late in the push-back process such that both sides broke away nearly identically. These should be changed to a larger diameter for production to minimize the risk of uncontained impact debris.

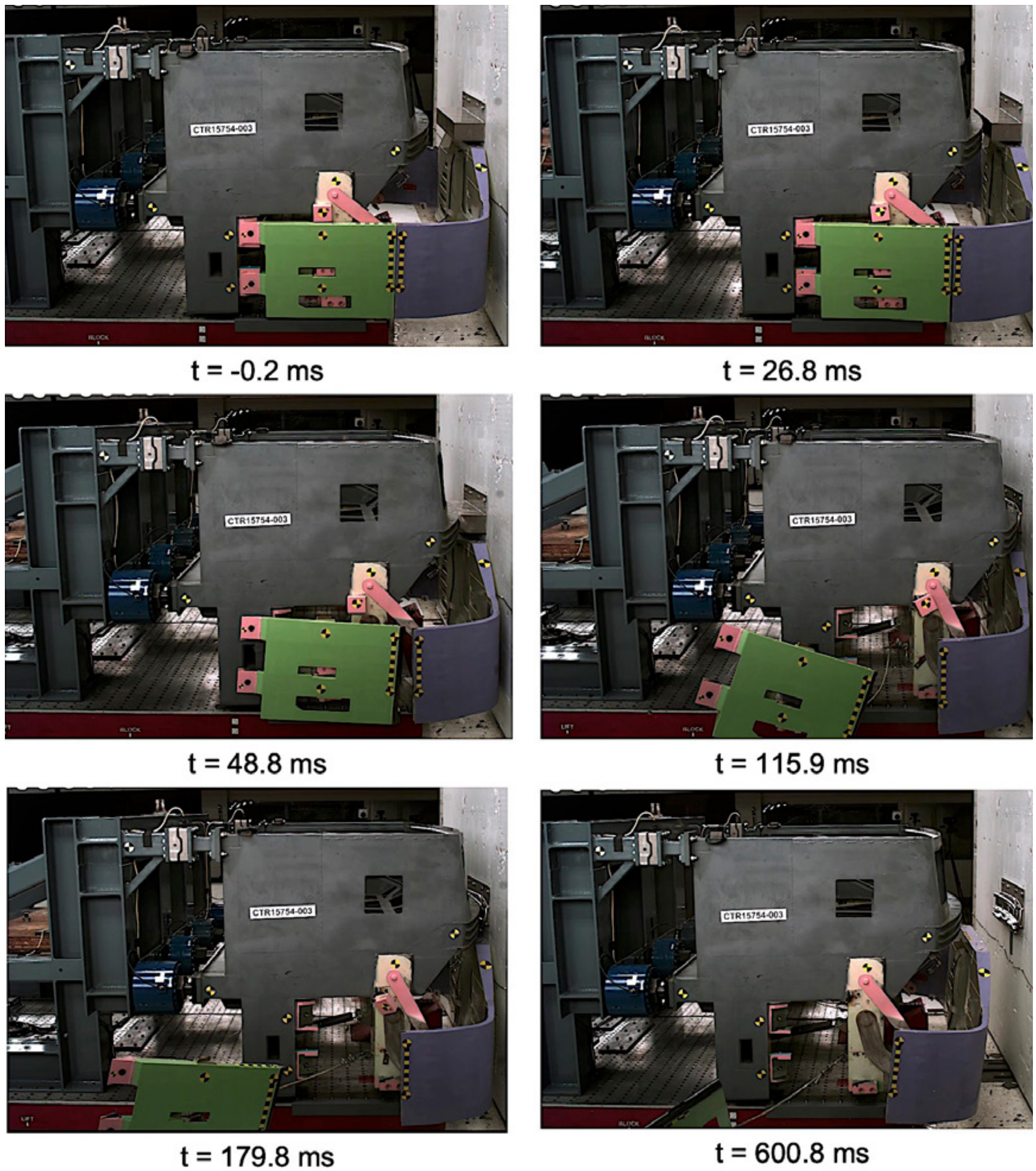


Figure 5-53 *High-Speed Video (right) of Test 3*

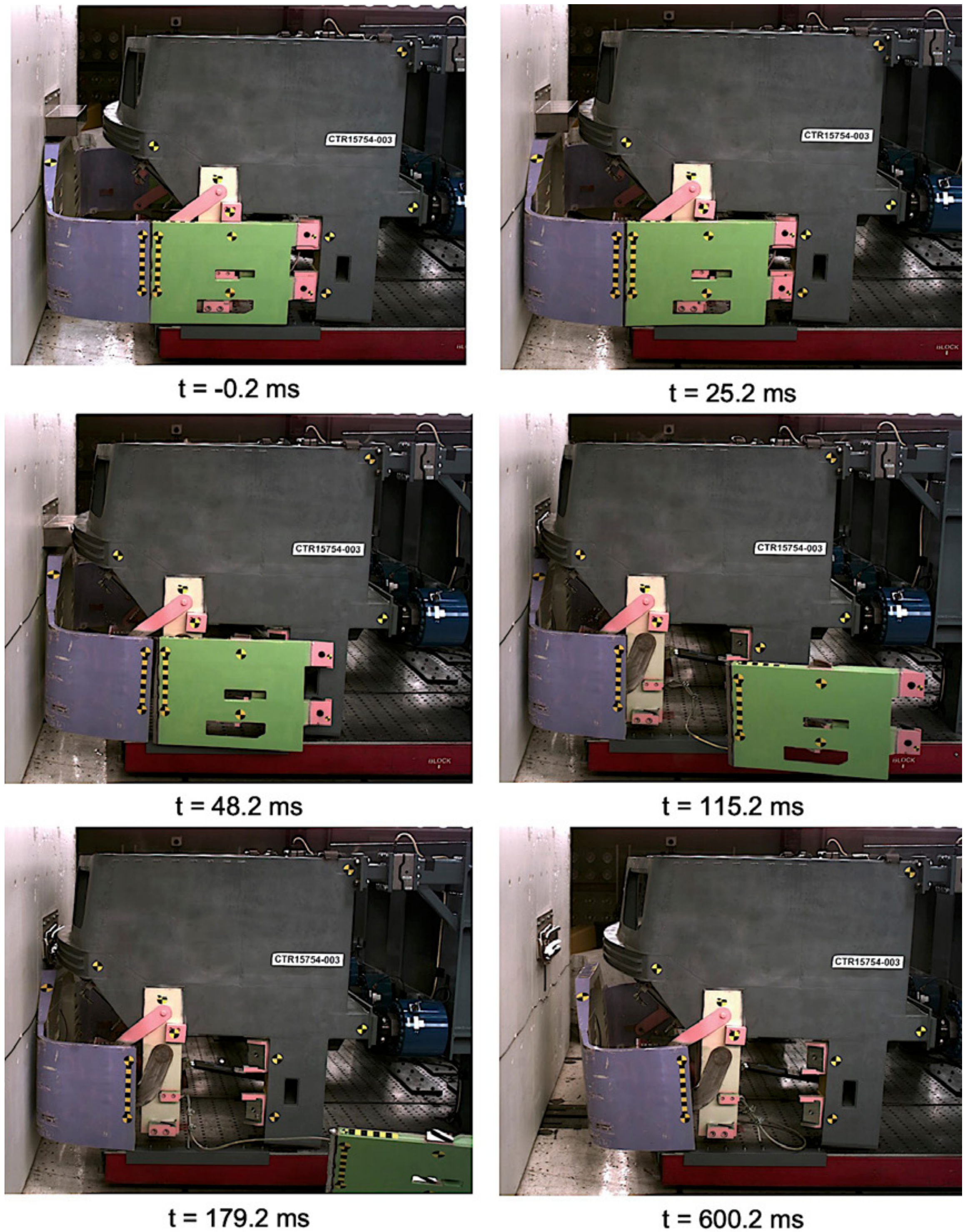


Figure 5-54 *High-Speed Video (left) of Test 3*

Figure 5-55 *High-Speed Video (right-oblique) of Test 3*

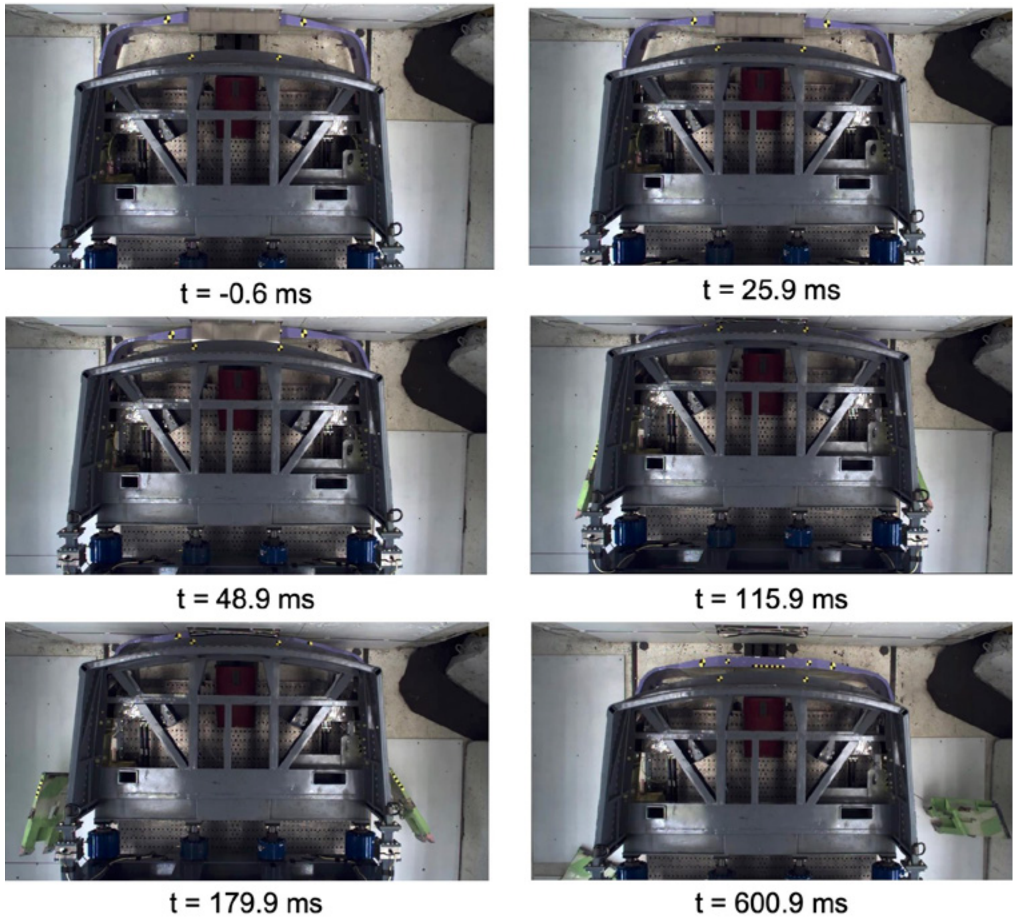


Figure 5-56 *High-Speed Video (top) of Test 3*

Figure 5-57 *Final Resting Position of Test Sled in Test 3*

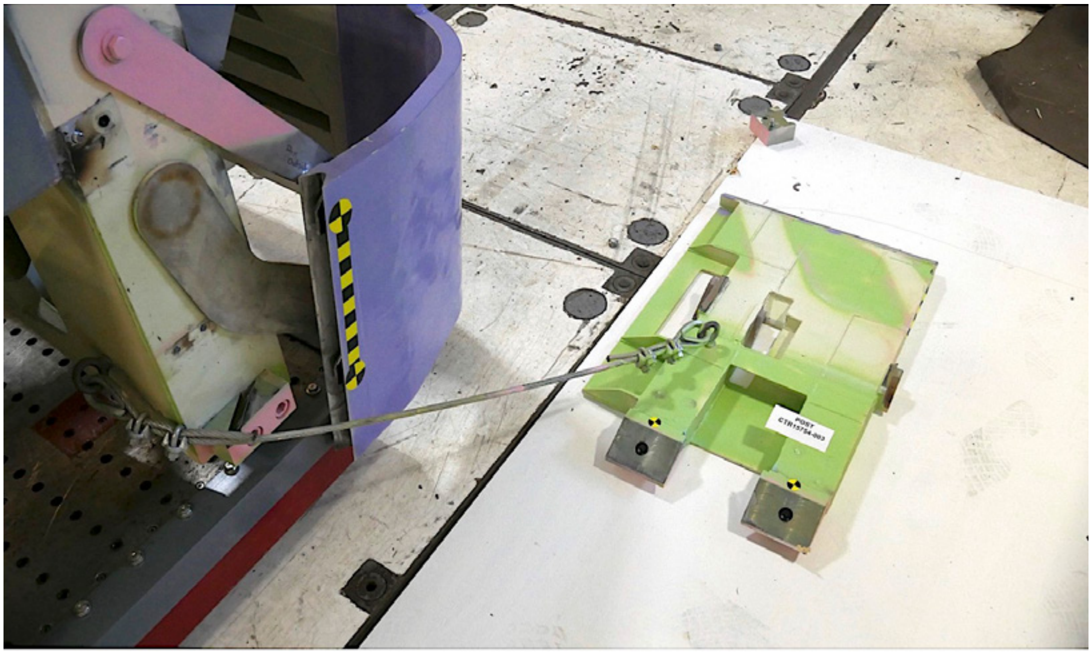


Figure 5-58 *Final Position of Side Panel (right)*

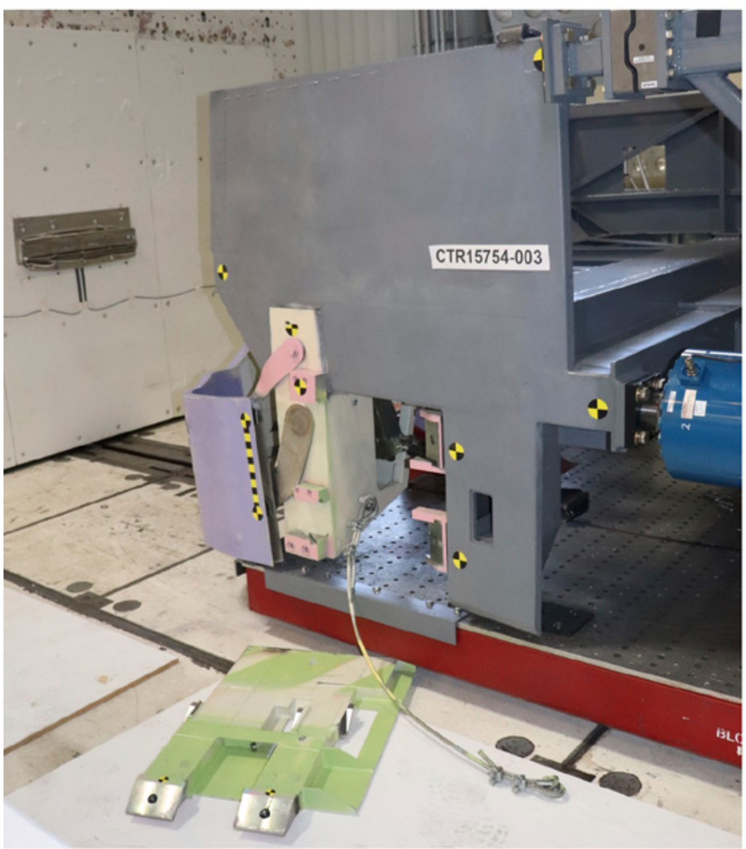


Figure 5-59 *Final Position of Side Panel (left)*

Section 6 Return on Investment

This section is focused on quantifying the benefit of bringing existing LRVs up to current crash safety standards with regard to automobile and pedestrian safety. To make this determination, effort was made to collect information from various transit agencies that operate LRVs with open front ends. In general, the following information was requested:

1. Annual rate of automobile crashes and pedestrian impacts
2. Resulting injuries and fatalities for each event
3. Legal and insurance costs associated with these events
4. Repair costs to LRVs
5. Down time of each LRV after each crash

Unfortunately, none were able to provide sufficient data to make a complete determination of these costs. However, two case studies were considered where partial cost data could be obtained. In the first, Valley Metro in Phoenix, AZ conducted a light rail collision analysis from 2009 to 2016, where information on the number of collisions, injuries, and repair costs to LRVs was collected when operating the KI low-floor LRV with a front enclosure. The results from this analysis were summarized by Swanson 2017 [8]. Although this is not an ideal dataset since this LRV already had a front enclosure, it does provide what is believed to be a lower bound on the cost of automobile and pedestrian collisions with this type of LRV to the City of Phoenix. The second case study is of specific crash incidents between TriMet Type 4/5 LRVs and automobiles.

Case Study: Valley Metro LRV Collisions from 2009 to 2016

The KI Low Floor LRV with a front enclosure operated by Valley Metro is shown in Figure 6-1. This design displayed significant damage during automobile collisions during this period where thirty-five bumpers were replaced due to automobile collisions. An example of damage after a crash is shown in Figure 6-2. The following items were considered in the cost analysis: (1) repair costs to LRVs, (2) loss of LRV use, and (3) value of statistical life (VSL). Legal and insurance costs were not considered since they were not available.

Crash incident data collected by Valley Metro are shown in Table 6-1. The collisions are separated into automobiles and pedestrians with the number of injuries for each. The total cost to repair LRVs over this 8-year period was $2.9M, with an average repair time of 4 to 5 days. From these data, repair costs and loss-of-use costs are calculated on an annual basis, as shown in Table 6-2. Both 2012 costs and 2022 costs are shown. The year 2012 is the median year for the dataset. A cost for 2022 is calculated by scaling the 2012 costs by the Consumer

Price Index (CPI) for Phoenix [18]. The cost for the loss of use of the LRV was estimated using a basis of $320/hr (provided by TriMet). With an average repair time of 4.5 days and an LRV typically operated at 18 hrs/day, the cost for loss of use is higher than the repair costs.

Figure 6-1 *Kinkisharyo Low Floor LRV with a Front Enclosure [8]*

Figure 6-2 *Example of Damage to the Front Enclosure of the KI LRV After Impact with an Automobile [8]*

Table 6-1 *Valley Metro Collisions and Injuries from 2009 to 2016*

Crash Incident Data	No.
Total Collisions	259
Automobiles	
LRV and Auto Collisions	227
Injuries (riders and road users)	148
People Transported for Injuries	43
Minor Injuries	18
Fatalities	2
Pedestrians	
LRV and Pedestrians Collisions	28
People Transported for Injuries	11
Minor Injuries	3
Fatalities	1

Table 6-2 *Crash Incident Costs*

	2012 Cost	2022 Cost
Costs per Year	$897,767	$1,233,571
LRV Repairs	$362,500	$498,091
Loss of LRV Use	$535,267	$735,480

The DOT-recommended methodology for calculating the value of a statistical life (VSL) and applying it in analyses that assess the economic benefits of preventing fatalities was used for this case study [19]. The VSL is calculated in a given year by:

$$VSL_T = VSL_O \left({}^{P_T}/_{P_O} \right) \left({}^{I_T}/_{I_O} \right)^{\varepsilon}$$

where

O = original base year

T = current base year

P_T = price index in year T

I_T = real incomes in year T

ε = income elasticity of VSL (1.0 recommended)

According to the US DOT Departmental Guidance on Valuation of a Statistical Life in Economic Analysis [19], the VSL for 2012 is $9.1M. Once again, the year 2012 was chosen because it is the median year over which injuries and fatalities occurred. The VSL for 2022 is then calculated based on the ratio of Phoenix's CPI for these two years [20] and the real incomes ratio. The index recommended for real income growth as it affects VSL is the Median Usual Weekly Earnings (MUWE) [19]. Values were taken from the U.S. Department of Labor, Bureau of Labor Statistics [21]. These data and the VSL calculated for 2022 are shown in Table 6-3.

Table 6-3 *VSL Calculation Data*

VSL_O	$9,100,000
VSL_T	$13,626,885
Year 0	2012
Year T	2022
P_o	124.2
P_t	170.7
I_o	334
I_t	364
e	1

Using these VSL values, with two fatalities from automobile crashes and one from a pedestrian collision, the annual cost over the eight-year period of the dataset for loss of life is over $3.5M, as shown in Table 6-4. Value of preventing injuries is also calculated from the VSL in the same way, except scaled by the Maximum Abbreviated Injury Scale (MAIS), as shown in Table 6-5.

This is the same injury scale used to evaluate injuries in simulations presented in Section 3. In eight years, there were 43 people transported (assumed at least MAIS 3) and 18 minor injuries (MAIS 1) for crashes with automobiles. Using these and the pedestrian injuries listed in Table 6-1, the total value of preventing injuries per year was over $6.5M in 2012.

Table 6-4 *Economic Benefit of Preventing Fatalities and Injuries (per year)*

	2012 Cost	2022 Cost
Loss of Life - Auto	$2,582,125	$3,866,629
Loss of Life - Pedestrian	$955,500	$1,430,823
Value of Preventing Injuries - Auto	$5,213,310	$7,713,924
Value of Preventing Injuries - Pedestrian	$1,304,258	$1,953,073

Table 6-5 *Relative Disutility Factors by Injury Severity Level (MAIS) [19]*

MAIS Level	Severity	Fraction of VSL
MAIS 1	Minor	0.003
MAIS 2	Moderate	0.047
MAIS 3	Serious	0.105
MAIS 4	Severe	0.266
MAIS 5	Critical	0.593
MAIS 6	Unsurvivable	1.000

Total annual costs (direct costs, loss of life, and value of preventing injuries) on an annual basis are summarized in Table 6-6 for the years 2012 and 2022. The total cost to the City of Phoenix for these LRV crashes is approximately $16M in 2022 ($11M for 2012). Legal costs were not available or considered, so this is considered a lower bound estimate.

Table 6-6 *Total Annual Costs*

	2012 Cost	2022 Cost
Direct Cost to Transit Agency	$897,767	$1,233,571
Loss of Life - Auto	$2,582,125	$3,866,629
Loss of Life - Pedestrian	$955,500	$1,430,823
Injuries - Auto	$5,213,310	$7,713,924
Injuries - Pedestrian	$1,304,258	$1,953,073
Total Cost	**$10,952,960**	**$16,198,019**

There are several limitations in applying the costs in this case study to LRVs with open front ends. The KI LRV has a lower anti-climber and an alternate bumper design (more susceptible to damage). A vehicle with a higher front end and no bumper produces more override collisions, produces a higher injury and fatality occurrence, and likely much higher vehicle repair costs and out-of-service repair durations (direct costs). As this research has shown, retrofitting the SD660 operated by TriMet will lead to a significant reduction in injuries and fatalities (both auto and pedestrian). The design will not experience any damage under realistic crash conditions, potentially eliminating most, if not all, of the repair costs. Using these costs as a lower bound, even a modest reduction in damage costs, loss of life, and injuries warrants the cost of retrofit.

Case Study: TriMet LRV Collisions

TriMet collects collision data for its entire MAX LRV fleet on a monthly basis [22]. These data, shown in Figure 6-3, are not differentiated by line or car type. Types 2 and 3 are the SD660 LRV evaluated in this project. Types 4 and 5 are newer and have an existing front enclosure. The average collision rate from February 2009 to December 2022 is 1.40 per 100,000 miles. These include all types of collisions (automobiles, pedestrians, fixed objects, animals, etc.). With an average of 11,600 miles traveled per day, this is 4.83 collisions per month.

Type 2 (Type 3 similar) | Type 4 | Type 5

Figure 6-3 *TriMet MAX LRVs*

TriMet was able to provide cost and crash incident data on three crashes with automobiles by Type 4 and 5 LRVs where speeds were sufficient to cause damage to the LRV. Repairs to LRVs included a variety of items depending on the crash: replacement of coupler cover, cab side panels, coupler hinges, coupler brackets, and body work and painting. No injury data were available. All three cases were illegal left turns in front of the LRV.

Crash incident information is provided in Table 6-7. The relative speed of the sedans at time of impact was calculated from forward-facing video on the LRV and LRV speed information. No video was available for the minivan, so the relative speed is estimated. Note that the speeds are all close to the 20-mph target range that the front enclosure for the SD660 was designed to withstand without damage. Impact angles were estimated to be 45° as the automobile made an illegal left turn.

Table 6-7 *TriMet Automobile Crash Incident Data with Type 4/5 LRVs*

Automobile	Relative Speed (mph)	Impact Angle (estimated)	LRV Repair Time (days)
Sedan 1	25.4	45°	3
Sedan 2	19.8	45°	Unknown
Minivan	18*	45°	14

**Estimated by typical turning speed of sedans*

Total cost of each crash (assuming no injuries) is shown in Table 6-8. The same methodology for calculating the cost of loss of use was used here. Once again, no legal costs were available, so this should be considered a lower bound on the cost of these crashes. Given the crash speeds, automobile types, and impact conditions, it is reasonable to assume that the retrofit bumper design would have negligible damage in similar incidents. The LRV repair costs would likely be paint with very little loss of use.

Table 6-8 *Direct Costs of Automobile Crash Incidents with Type 4/5 LRVs*

Automobile	Repair Cost	Loss of Use	Total
Sedan 1	$14,313		$31,593
Sedan 2	Unknown	Unknown	
Minivan	$43,416	$80,640	$124,056

Section 7 Conclusion

A prototype end enclosure, or bumper, was designed to retrofit the Siemens SD660 LRV. Crash simulations for the SD660 LRV without a bumper demonstrate many aggressive features of this geometry when impacting automobiles, including a high anti-climber that can directly impact drivers of small automobiles, a fixed coupler that locally impacts doors during side collisions, and a front-end profile with significant potential to override automobiles. When the bumper is incorporated in the collision analyses, the LRV becomes a much less aggressive collision partner for an automobile and the potential for serious injuries and fatalities is significantly reduced.

Side and oblique impact simulations were performed when impacting a high and heavy SUV (2003 Ford Explorer) and low and light sedan (2010 Toyota Yaris), with two crash conditions: a normal (90˚) impact representative of a street crossing, and an oblique (45˚) impact representing a car turning in front of a LRV traveling at 20 mph. Adding the enclosure to the collision interface significantly reduced the potential for serious injuries in all the collision scenarios evaluated. For example, the 2003 Explorer injuries were reduced from an AIS3+ (serious) chest injury probability of 48.5 percent without bumper to 21.8 percent with the bumper when considering normal (90°) side impact. For the 2010 Yaris, injuries were reduced from 100 percent AIS6+ (fatal) injury probability, due to head impact against the LRV anti-climber, to 12.4 percent.

The bumper was also designed to be functional and remain in service for LRV-to-LRV hard coupling speeds of 5 mph. To protect against LRV collisions at higher speeds, the bumper side panels break away at 11 mph, and the existing LRV crash energy management performance is unaffected.

Once a prototype was manufactured, operational testing was conducted with an enclosure mounted to a TriMet Type 3 (Siemens SD660) LRV. Testing of both powered and unpowered function was performed to raise and lower the front enclosure and coupling to another LRV. Operations went smoothly with no interference with car geometry. The operator in the retrofitted car noted that coupling was an easy process, and their view was not hindered by the raised enclosure. Moving operation was also performed in the Ruby Junction Rail Yard to demonstrate compatibility with trackside structures. No issues were noted by the operator and good clearance with track-side equipment was confirmed by recorded video.

Three crash tests of the front-end structure of the SD660 retrofit with an end enclosure were conducted at the Center for Advanced Product Evaluation (CAPE). All three crash tests were successful in achieving the desired crash conditions. Both tests with the automobiles resulted in minimal damage to the enclosure, consisting only of scratches to the paint. There was no permanent deformation to the structure. The front enclosure was retracted and deployed after each crash test with no loss in function. In the breakaway test, the side panels sheared back as designed and the front enclosure pushed back beneath the anti-climber. In this way, the anti-climber is not obstructed for LRV-LRV collisions.

Crash test results were consistent with pre-test crash simulations. In particular, the automobile deformation compares well with measurements. This agreement provides a partial validation of the analysis methods used to determine the reduction in injuries predicted from the matrix of crash simulations.

Two case studies were considered to quantify the benefit of bringing existing LRVs up to current crash safety standards with regard to automobile and pedestrian safety. There was not a complete dataset in either case, but the light rail collision analysis performed by Valley Metro in Phoenix, AZ provides what is believed to be a lower bound on the cost of automobile and pedestrian collisions. The following items were considered in the cost analysis: (1) repair costs to LRVs, (2) loss of LRV use, and (3) value of statistical life (VSL). Using these costs as a lower bound, even a modest reduction in damage costs, loss of life, and injuries warrants the cost of retrofit.

This project demonstrates the feasibility of retrofitting existing LRVs with front enclosures, with the following potential benefits:

- Improves crash energy management (CEM) when impacting automobiles
- Reduces injury to automobile occupants
- Lowers risk of override and LRV derailment
- Reduces repair costs to LRV operators from automobile crashes
- Reduces system and equipment down times after a crash

Although the prototype bumper was designed specifically for the Siemens SD660 LRV in this study, the approach and structures were designed with the objective of being readily adapted for other LRV designs. There would likely be specific changes needed to attach the linkage mounts, for example, and/or front geometry changes to accommodate different front geometries. However, these changes would be more easily accomplished now that this prototype bumper has been designed and validated.

Appendix A Third-Party Review Report

31 March 2023

Dr. Robert Bocchieri
Applied Research Associates, Inc.
95 1st Street, Suite 100
Los Altos, CA 94022

Re: LRV Bumper Safety Technology Development – Independent Assessment

Dear Dr. Bocchieri:

I am pleased to provide this report summarizing my independent review of your Federal Transit Administration (FTA) sponsored project to develop a light rail vehicle (LRV) retrofit bumper system. My evaluation relies on my experience with passenger vehicle safety standards; with rail vehicles crashworthiness design and implementation, including crashworthy bumper design for shared right-of-way interactions; with this specific project and preceding related research; and with my review of the final project report you have prepared for FTA.

1. SCOPE OF REVIEW

Per the overall project scope, I have considered the following evaluation criteria in my project assessment:

- System performance against stated design goals and performance criteria
- System effectiveness against key metrics
    - Safety improvement tied to monetary value
    - Operational/Capital improvement
    - Return on Investment (ROI)

I have included my assessment, organized by these categories, in the sections below.

2. PROJECT ASSESSMENT

2.1 Assessment Against Project Goals and Performance Criteria

Your project report abstract concisely states the project goals:

> *The objective of this project is to design, build, and test a prototype LRV end enclosure, or bumper, as a retrofit to an existing LRV operated in the US in order to reduce potential for injury to automobile occupants, damage to the LRV, and lower costs to operators from crashes.*

In this statement there is first an objective to design and implement the bumper prototype. Then there are motivational goals for developing this product. My assessment of the status regarding implementation and its status against the design motivation is included here.

Regarding the objective to design, build, and test a prototype bumper retrofit for an operating US-based LRV, the project is a complete success. All objectives have been fulfilled, resulting in a working prototype that has been shown effective in functional, operational, and crash testing.

The end design was developed for the TriMet Type 3 Siemens SD660 LRV. The retrofit bumper was designed to interface and integrate with the vehicle with minimal alterations to the as-built basic structure. This approach enhances its ease of retrofit. Minimization of alterations to the existing car minimizes installation time and cost, which will be an attractive consideration for owners implementing this system.

The design was developed and vetted analytically to ensure safety improvements against struck automobile occupants. Detailed nonlinear dynamic finite element analysis (FEA) was performed to demonstrate reduced passenger injuries in struck road vehicles. Analysis and crash testing was performed on a representative sample of passenger road vehicle traffic. Crash testing confirmed the analysis results: struck vehicle damage matched the analysis and the bumper was relatively undamaged and still functioning after striking multiple road cars.

Operational testing showed that the bumper is compatible with the TriMet vehicle. During this testing, an LRV with the mounted prototype was able to travel in the yard, navigating the trackwork without interference or other issues. The bumper profile was designed such that the overall vehicle envelope can navigate the worst-case conditions in TriMet's right of way. Coupling tests performed during operational testing showed that the bumper structure can survive normal LRV-to-LRV coupling loads. Crash testing confirmed that the bumper performs as designed at higher LRV-to-LRV crash speed, whereby components break away from the vehicle, bypassing the bumper-to-LRV load path that is engaged at lower speed. This functionality allows couplers to actuate and absorb energy and for colliding LRV anticlimbers to engage in higher speed collisions.

The prototype bumper design is robust and damage resistant. This minimizes service interruption and repair costs when road vehicle collisions occur because the LRV will likely be fully functional. Further, the bumper profile prevents vehicle override, which also eases downtime after a collision and greatly reduces the possibility of LRV underframe and coupler damage. Most importantly, override prevention greatly reduces fatality probability for struck road vehicle occupants.

2.2 Assessment Against Key Metrics

2.2.1 Safety Improvement

Train and street traffic interactions dominate the occurrence of collisions in shared rights of way. LRV-to-LRV collisions are rare. Analysis from this project and preceding research, as well as real-world applications (e.g., Phoenix car with retractable bumper), shows that front end LRV enclosures are very effective at reducing injuries to struck vehicles and pedestrians.

The main factors contributing to safety improvement for the bumper system are 1) override prevention, 2) engaging automobiles low and along key structural elements (e.g., pillars and sills), and 3) preventing intrusion at chest and head height (e.g., from couplers or anticlimbers). These are key ingredients that this prototype design incorporates and that other bumper designs should strive for as well.

Tables 3-3 and 3-4 from your report, which show injury metrics with and without the bumper system, consistently show reduced injury probabilities with the bumper system. Table 3-3 focuses on AIS3+ (serious) injury probability and shows almost universally significant reductions in head, chest, abdominal, and neck injury probability. The main exception was for the Yaris (low, light vehicle) normal impact that is prone to higher head injury due to the inherent engagement geometry. Table 3-4 further explores head injury for higher injury severity curves: AIS4+ (severe), AIS5+ (critical), and AIS6+ (fatal). The table shows significantly reduced probabilities from 100% without a bumper to 81%, 49% and 12%, respectively for these AIS probability curves. This is a significant improvement from assured fatality to a high probability of survival.

As described in your report, the bumper profile is a good improvement for pedestrians over an open LRV front end. At a minimum, the bumper will help deflect pedestrians while preventing override and entanglement in the LRV underframe. There is another unmentioned but tangible benefit for pedestrian injury prevention: by taking up much of the gap between coupled cars, the bumpers provide a secondary benefit by deterring pedestrians from stepping through the gap when the train is stopped. Sacramento RT identified pedestrians stepping through coupled cars as an issue leading to injuries and fatalities.

Overall, the prototype bumper system provides significant safety improvements for road vehicle occupants and pedestrians.

2.2.2 Operational/Capital Improvement

There are clear benefits to operational costs and function with a front-end enclosure. Your Return on Investment (ROI) section highlights some of the costs associated with downtime and vehicle repair. Your more robust bumper system, compared to the Phoenix Kinkisharyo system, will result in less LRV accident damage, lower repair costs, and less downtime. Per your estimates, downtime and repair savings could be $1M per year.

The greatest saving will likely be in injury and fatality prevention. It is difficult to estimate specific savings, given the data available, but it seems the value is in the millions or tens of millions of dollars per year, compared to LRVs with open front ends.

The capital improvement value is also tangible and significant. Enclosed front ends are a requirement of the current LRV safety standard ASME RT-1. This approach to retrofitting existing LRVs helps extend their useful life while bringing them closer to modern safety standards. In this way, transit agencies may be able to reduce their capital investments through modest retrofit costs in lieu of total vehicle replacement, while reaping annual operational cost benefits afforded by safer equipment.

2.2.3 Return on Investment

There are at least two aspects of ROI to consider. One is relative to FTA and industry investment on this specific project. The other is from the owner/operator standpoint when investing in this system.

The budget for this grant was roughly $1.6M with 80/20% FTA/industry investment. The prototype bumper is operationally effective and little additional investment is required to render it production ready. If TriMet were to outfit its 27 Type 3 cars, assuming a rough estimate of $100K per car, their cost would be $2.7M. The total investment to outfit a fleet of LRVs would be $4.3M. As shown in your ROI evaluation, the cost can be recouped in as little as a year, through injury and death prevention alone. Over several years, this would be a very good investment from the standpoint of vehicle life extension (capital investment) and annual costs (operational investment).

The conceptual design is highly adaptable and can be tailored to many other North American LRVs, chiefly to high-floor LRVs or those with significant traffic-facing open volume below the anti-climber, where couplers are mounted. In this study, suitable bumper designs have been conceptualized and partially developed for two other LRVs: Sacramento RT’s CAF S/200 and LA Metro’s Kinkisharyo P3010 cars. With modest costs to adapt the design to other vehicles, the ROI of the initial FTA and industry cost can be significantly increased. There are hundreds of LRVs operating in North America that can benefit from this retrofit.

3. SUMMARY AND CONCLUSIONS

Based on my review and involvement with this project, I conclude that the project has been very successful. Specifically, all project goals and performance metrics were met:

- A prototype LRV bumper was designed, built, and tested for the TriMet Type 3 SD660 vehicle.
- The bumper was shown through analysis and testing to reduce the injury potential for automobile occupants.
- The bumper minimizes damage to the LRV and lowers costs to the operator in crashes.

Further, compared to key evaluation metrics, the retrofit bumper system demonstrates significant safety improvements, operational and capital cost improvements, and provides a very good return on investment for FTA and vehicle owners interested in implementing an LRV bumper retrofit.

Congratulations on your efforts. It is a great achievement that has the potential to extend the useful life of many transit vehicles while preventing injury and death in crash events that happen every day in shared right of way environments.

Sincerely yours,

Robert A. MacNeill
Associate Principal
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Appendix B

Preliminary Design for P3010

The front end of Metro's Kinkisharyo P3010 is shown in Figure B-1. The open-ended design with the coupler protruding well ahead of the high anti-climber makes the P3010 well-suited for retrofit. With cooperation from Metro, a preliminary design for the enclosure was developed. The design of the end enclosure is shown in the deployed and retracted positions in Figure B-2. Note that a final facia design would blend with the carbody to improve aesthetics. The structure with the facia removed is shown in Figure B-3.

Figure B-1 *Metro P3010 Front End*

There are three main components to the retrofit: (1) the retractable front enclosure, (2) a breakaway side panel, and (3) mechanical linkage to connect them. The geometry conforms tightly to the cab profile when in the retracted state and minimizes the profile ahead of the coupler with a broad engagement area to improve crash energy management. Note that in the retracted position the operator window is not obstructed, and the anti-climbers are clear to engage. The retrofit is performed by removing the existing side panels shown in Figure B-4 and replacing them with the breakaway structural side panel. The breakaway connections have not yet been designed for this vehicle.

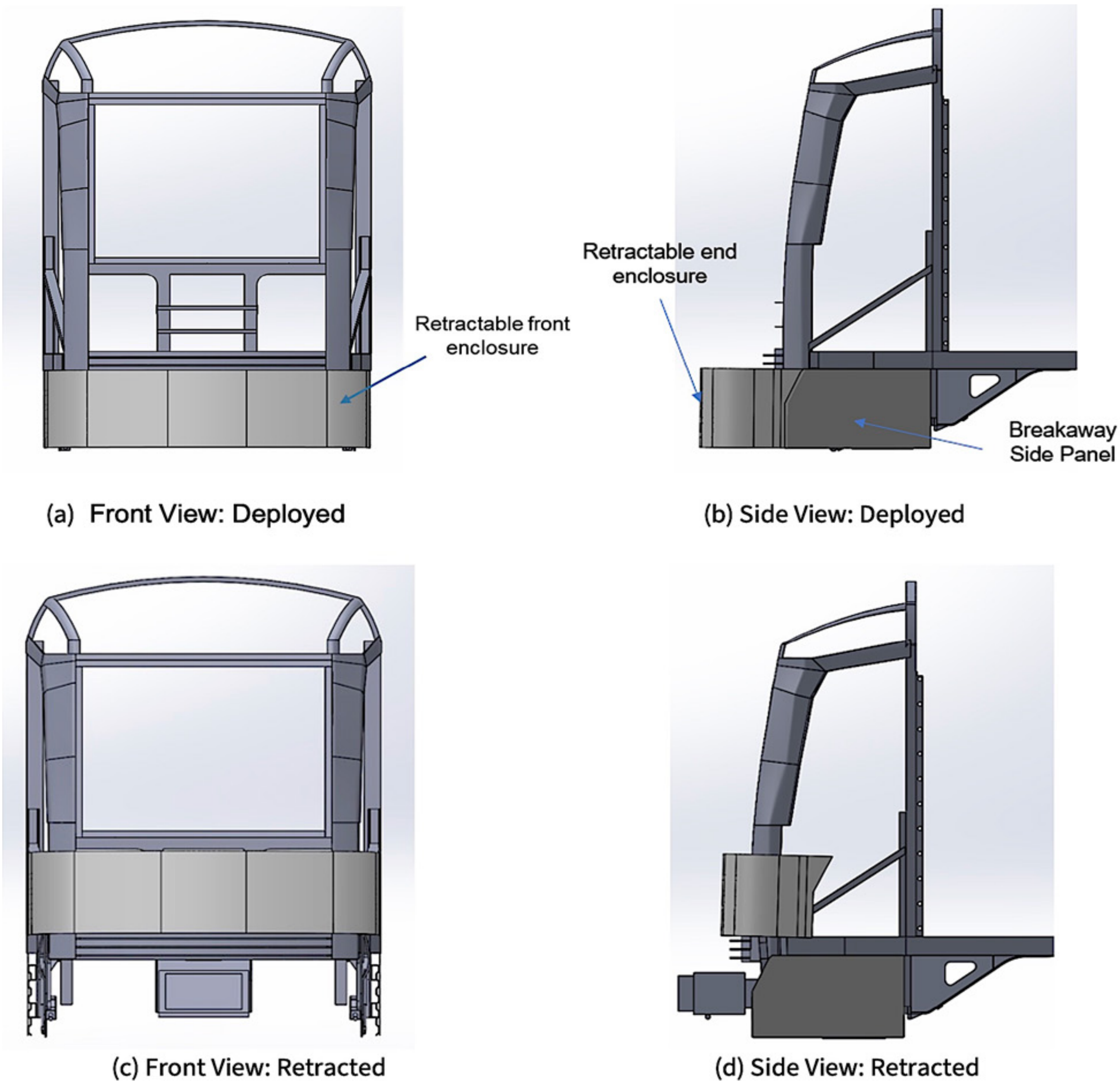

Figure B-2 *End Enclosure in Deployed Position with Facia*

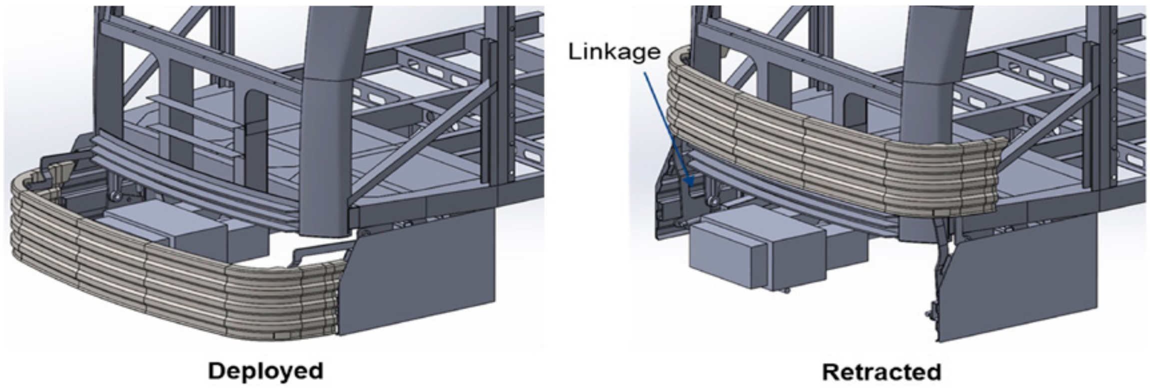

Figure B-3 *End Enclosure Mechanical Design*

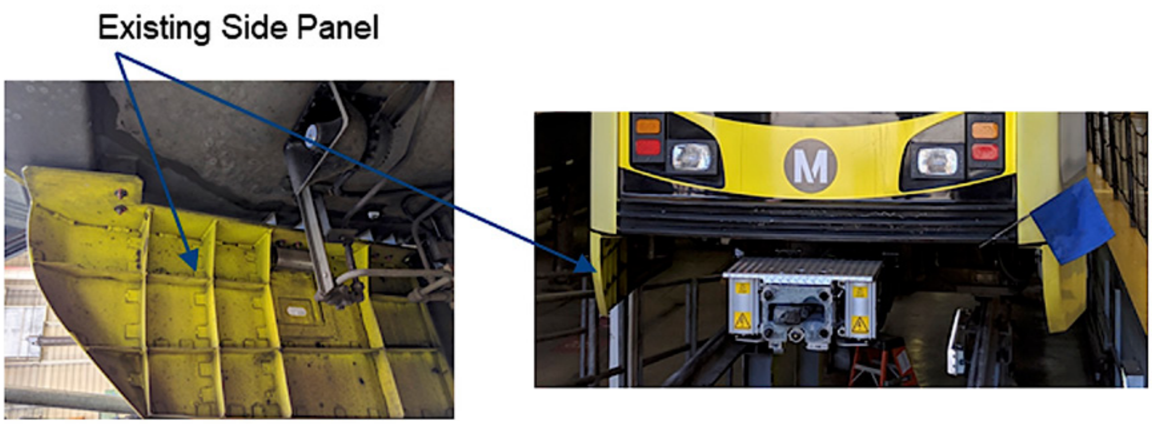

Figure B-4 *Existing Side Panel on the P3010*

The mechanical linkage to raise and lower the retractable enclosure is shown in Figure B-5. The linkage is attached to the side panel and assisted by a gas-hydraulic spring and electrical actuator to raise and lower the enclosure. In this way, it can be deployed and retracted either automatically or by manual lifting.

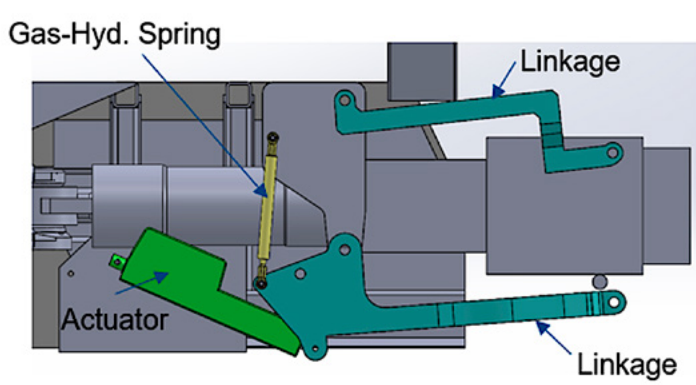

Figure B-5 *Prototype Linkage Profile with the Enclosure Removed from View (side view)*

The enclosure and linkage geometry is designed to provide clearance with the coupler and vehicle front-end structures. A top view in the retracted position is shown in Figure B-6. There is a small gap in the preliminary design between the linkage and the corner post.

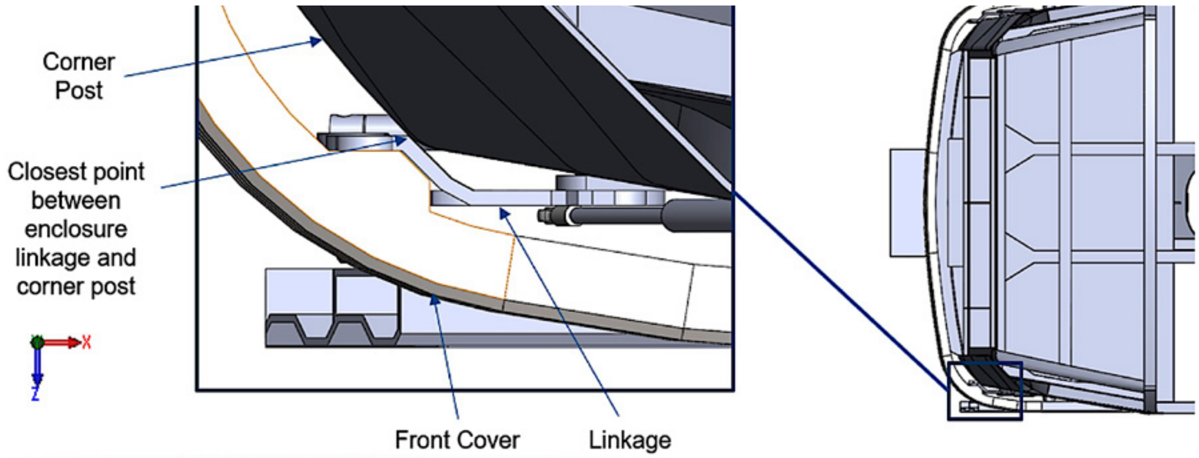

Figure B-6 *Clearance between the Linkage and Corner Post in the Enclosure Retracted Position (cab end top view)*

The end enclosure is designed to allow for clearance for the coupler spring. In Figure B-7, the coupler geometry is roughly represented by volume blocks, and the maximum coupler swing of 34° is shown with the enclosure in the deployed position. There is enough clearance for the maximum coupler swing. In the retracted position, the coupled clearance between the forwardmost point of the enclosure is 16.7 inches, as shown in Figure B-8. Based on the coupler used, a recoverable stroke of 9 inches is estimated, based on an 8-mph collision, leaving 4.5 inches of clearance.

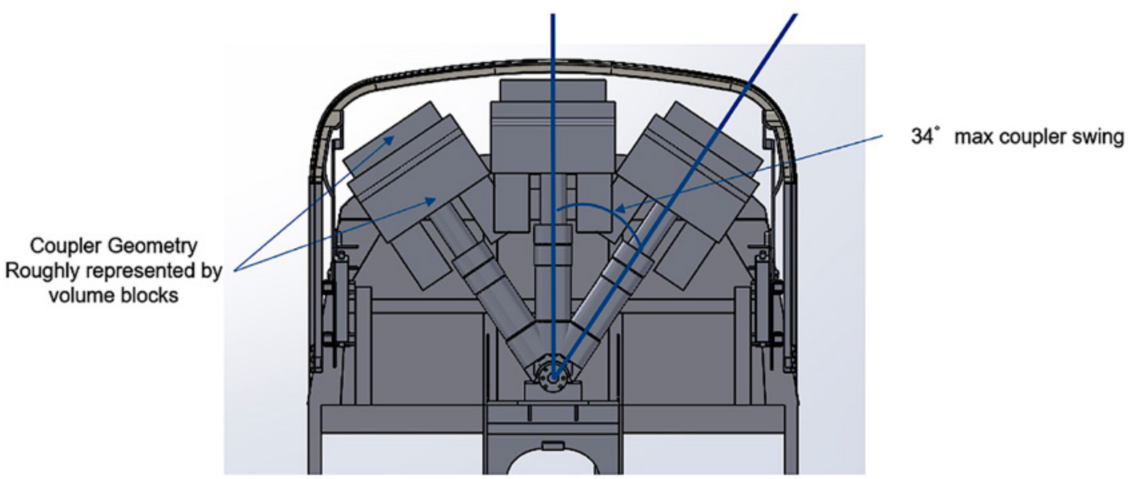

Figure B-7 *Bottom View of Coupler Swing (enclosure deployed)*

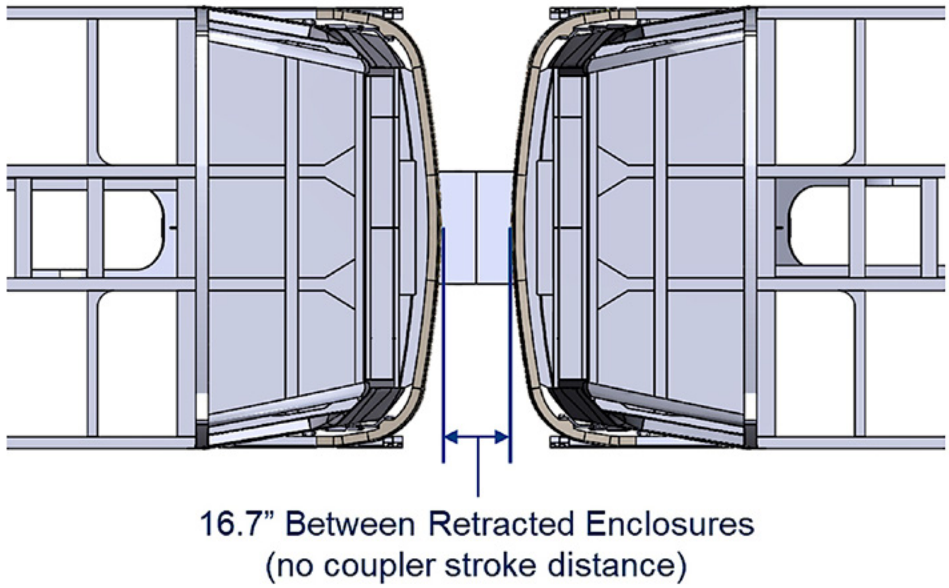

Figure B-8 *Coupled Clearance When Retracted*

To ensure that the end enclosure geometry is compatible with the Metro service environment, preliminary envelope analyses were conducted. A curvature analysis of the P3010 was performed for the worst-case curve on the Metro blue line. The enclosure envelope while coupled was evaluated for a 26.5m curve in Figure B-9. There is approximately 5.5 inches of clearance between enclosure corners, leaving clearance for small coupler motions. The lateral clearance required in the same curve with the enclosure deployed on the lead car is shown in Figure B-10. This is approximately a 6.5-inch increase in the clearance required without the retrofit.

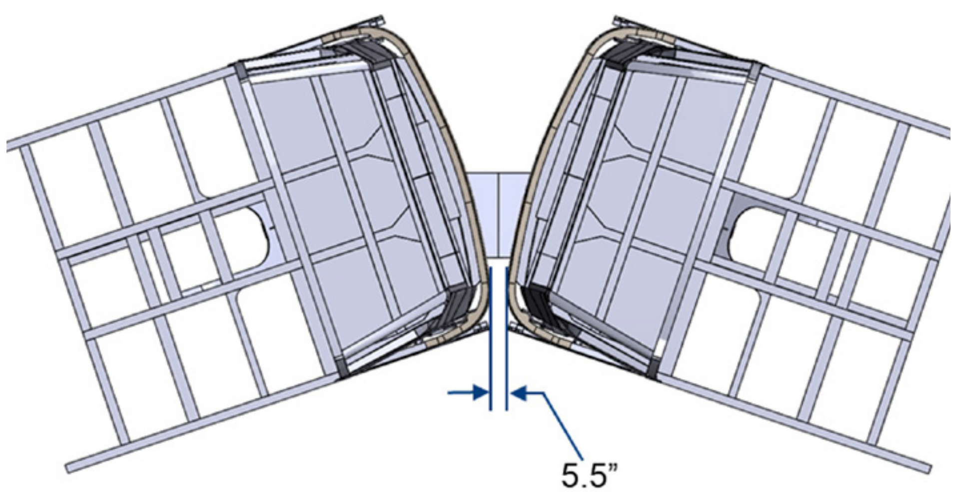

Figure B-9 *Curvature Analysis of P3010 with End Enclosure Retracted*

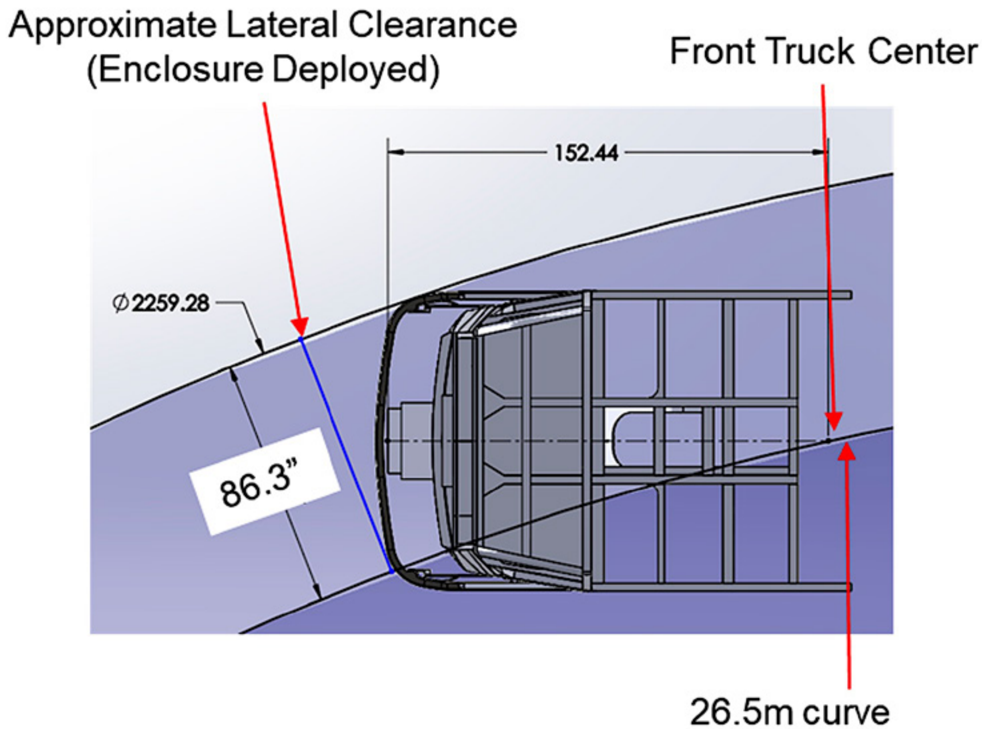

Figure B-10 *Required Lateral Clearance of the P3010 with End Enclosure Deployed*

Structural Design and Analysis

The preliminary structural design for the P3010 retrofit end enclosure is shown in Figure B-11. There are two main structural components: a corrugated cover and internal frame. The frame for the side panel is attached to the underframe, as shown in Figure B-11. This frame would include breakaway components such that no damage is done to the vehicle underframe under high loads from an LRV-LRV impact. This part of the structure has not yet been designed. The corrugated structure and frame transfer the crash impact loads from the front enclosure into the side panels.

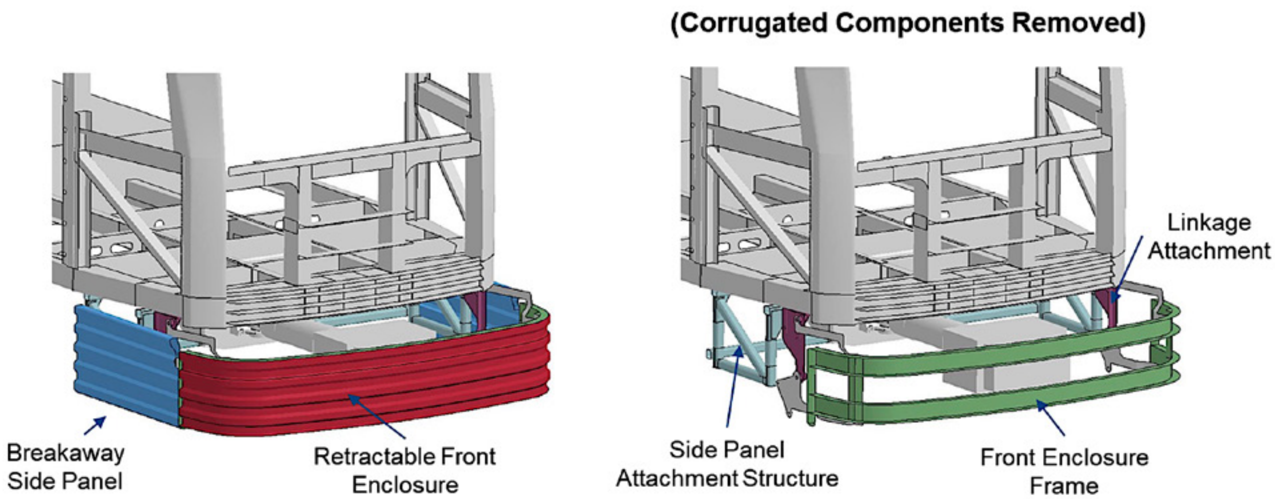

Figure B-11 *Main Structural Components for the End Enclosure Retrofit to the P3010*

Envelope Testing

A frangible end enclosure was developed and built for envelope testing of the Kinkisharyo P3010 on the Blue Line. The frangible prototype is made of foam board, PVC pipe, clamps, plywood, and carbon fiber (CF) tubing shown in Figure B-12 and has the same external geometry as the preliminary enclosure design. The foam is covered in grease paint, and the total weight is estimated to be 130 lbs. To transition from the foam board to the PVC, a plywood bumper receptacle is used for the bonded connection, shown in Figure B-13. The constructed frangible prototype test article is shown in Figure B-14.

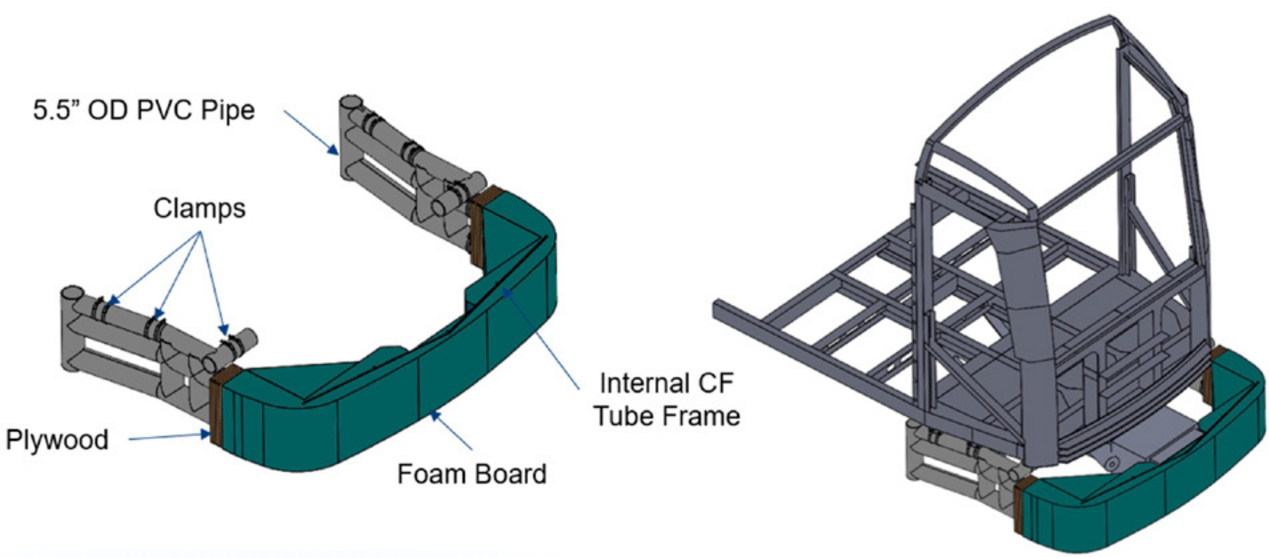

Figure B-12 *Frangible Prototype Materials*

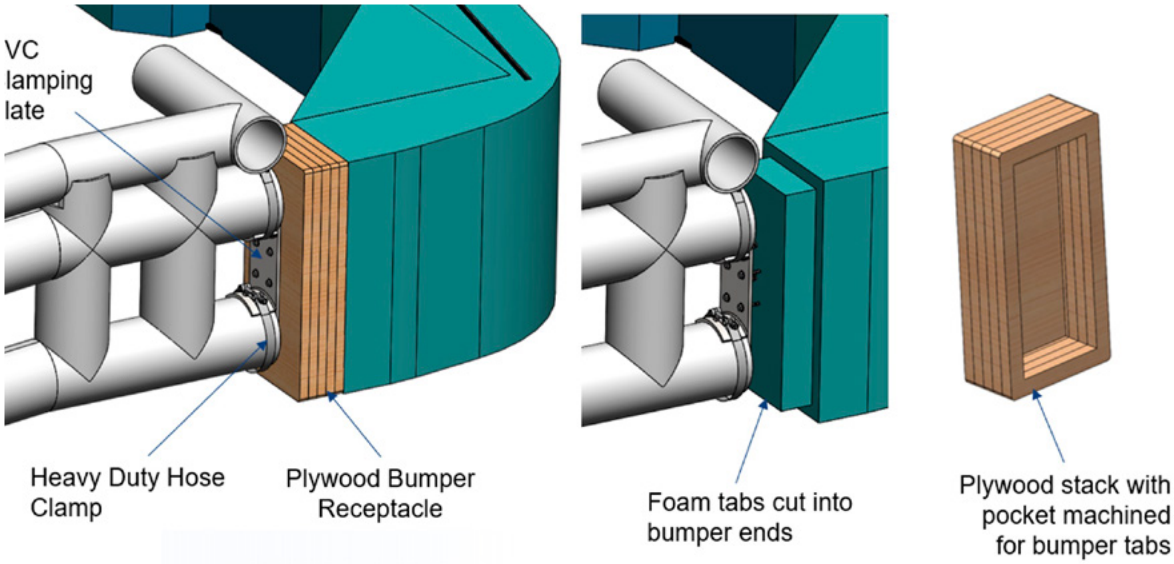

Figure B-13 *Plywood Bumper Receptable Used to Transition from Foam Board to PVC*

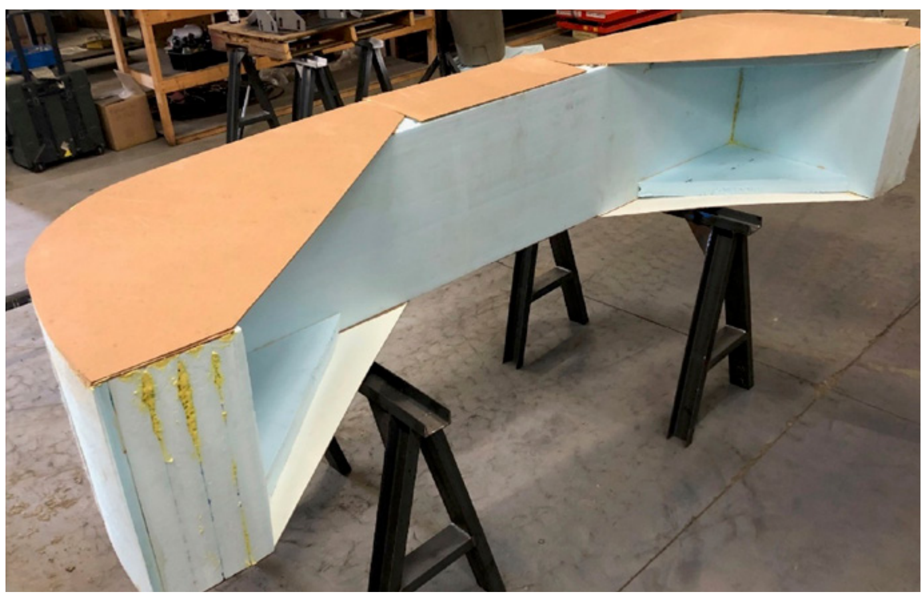

Figure B-14 *Frangible Prototype Test Article*

Envelope testing was planned using the frangible enclosure structures attached to Kinkisharyo P3010 vehicles in Long Beach, CA to evaluate potential interaction of the end enclosure with railroad equipment during operations. The envelope testing consists of attaching the frangible prototype to the P3010 lead car, attaching foam spacers between coupled cars (as shown in Figure B-15), and operating a coupled car in the yard and on the Blue Line. These are temporary attachments requiring no permanent modification to the P3010 structure.

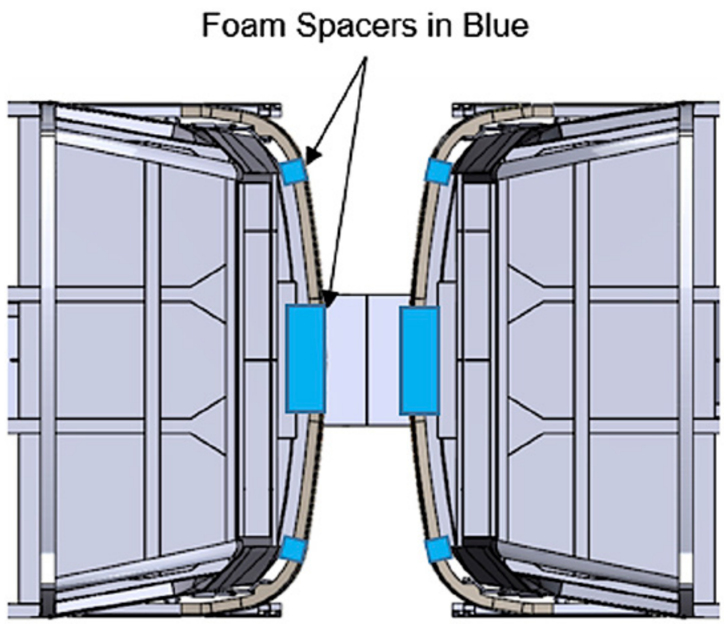

Figure B-15 *Top View of Coupled P3010 LRV with End Enclosure Retracted (foam spacers are shown in blue)*

Both yard testing and operation on the Blue Line were planned. The objective of the yard test was to verify that the newly installed end enclosure would not come into contact with any equipment during normal yard operations, that the frangible components were installed correctly, and that video equipment was functioning correctly. The objective of the Blue Line test was to verify that the end enclosure would not come in contact with any wayside equipment during operation of the Blue Line. These tests were not conducted as part of the project, but a test plan is in place and reviewed by Metro in case the agency decides to pursue a retrofit.

Appendix C Crash Test Data

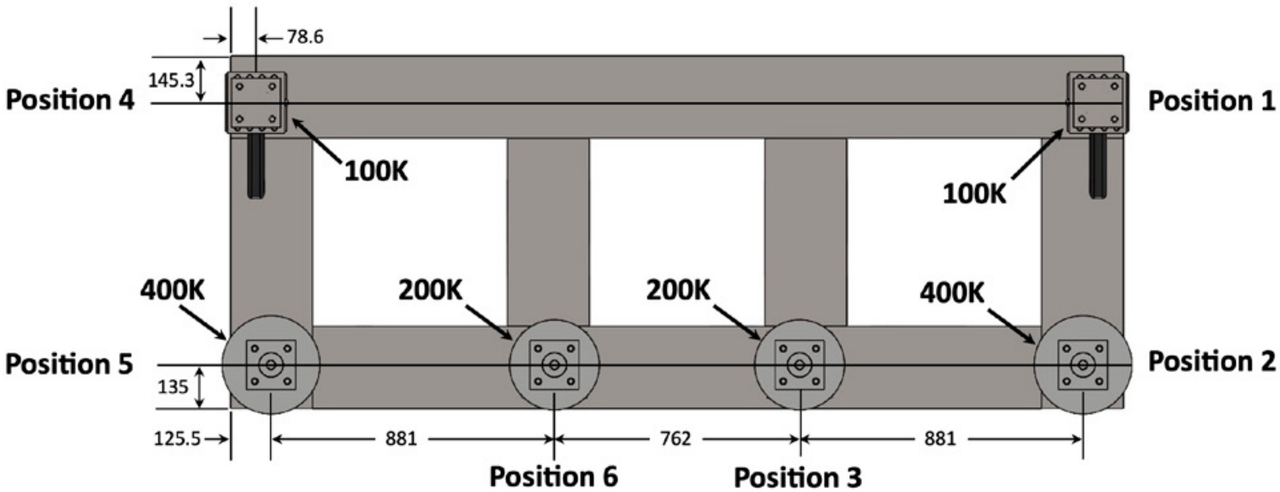

Figure C-1 *Load Cell Positions While Facing Crash Test Wall*

Test 1 – 2003 Ford Explorer

Load Cell Data

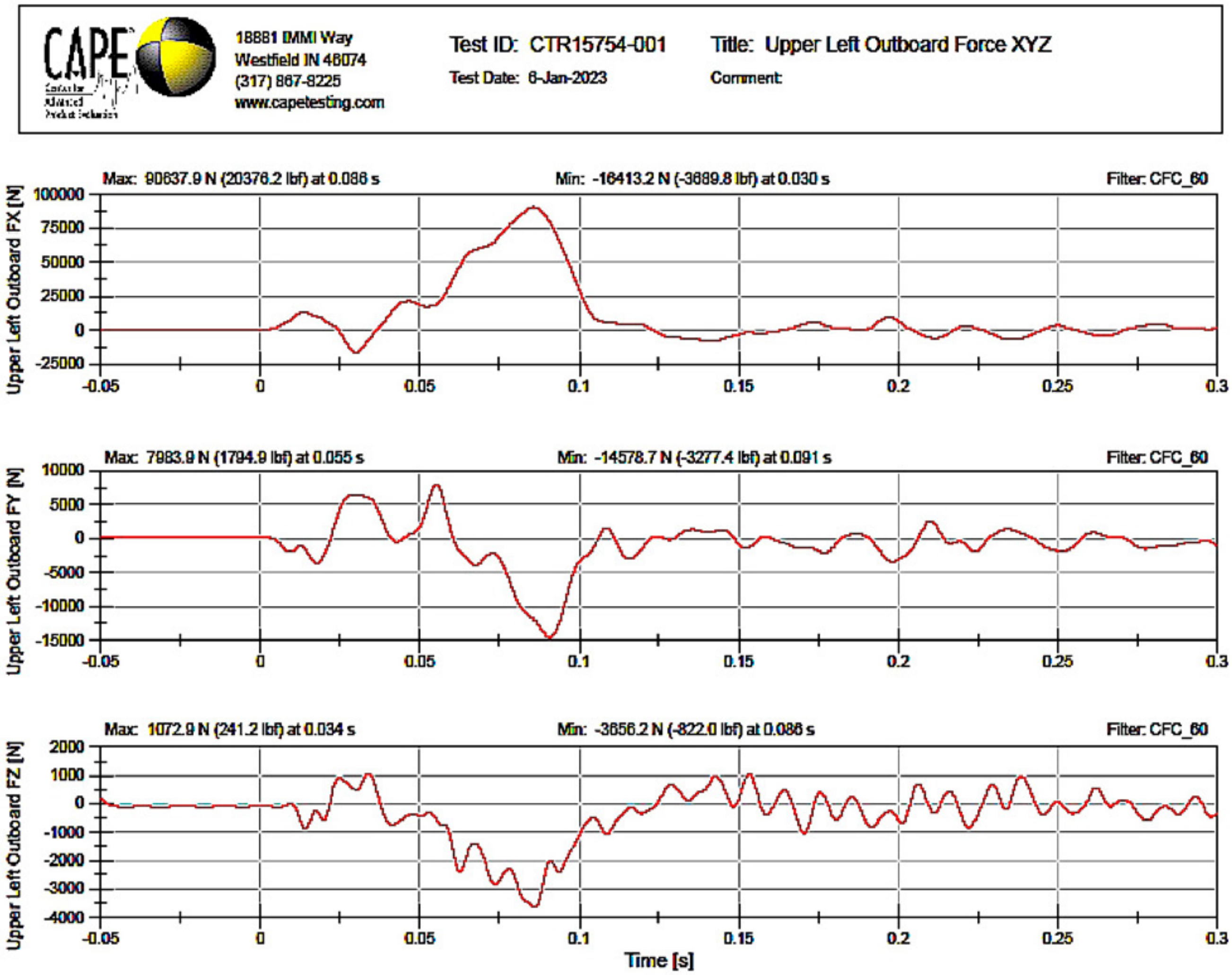

Figure C-2 *Test 1, Position 1, 100K Load Cell*

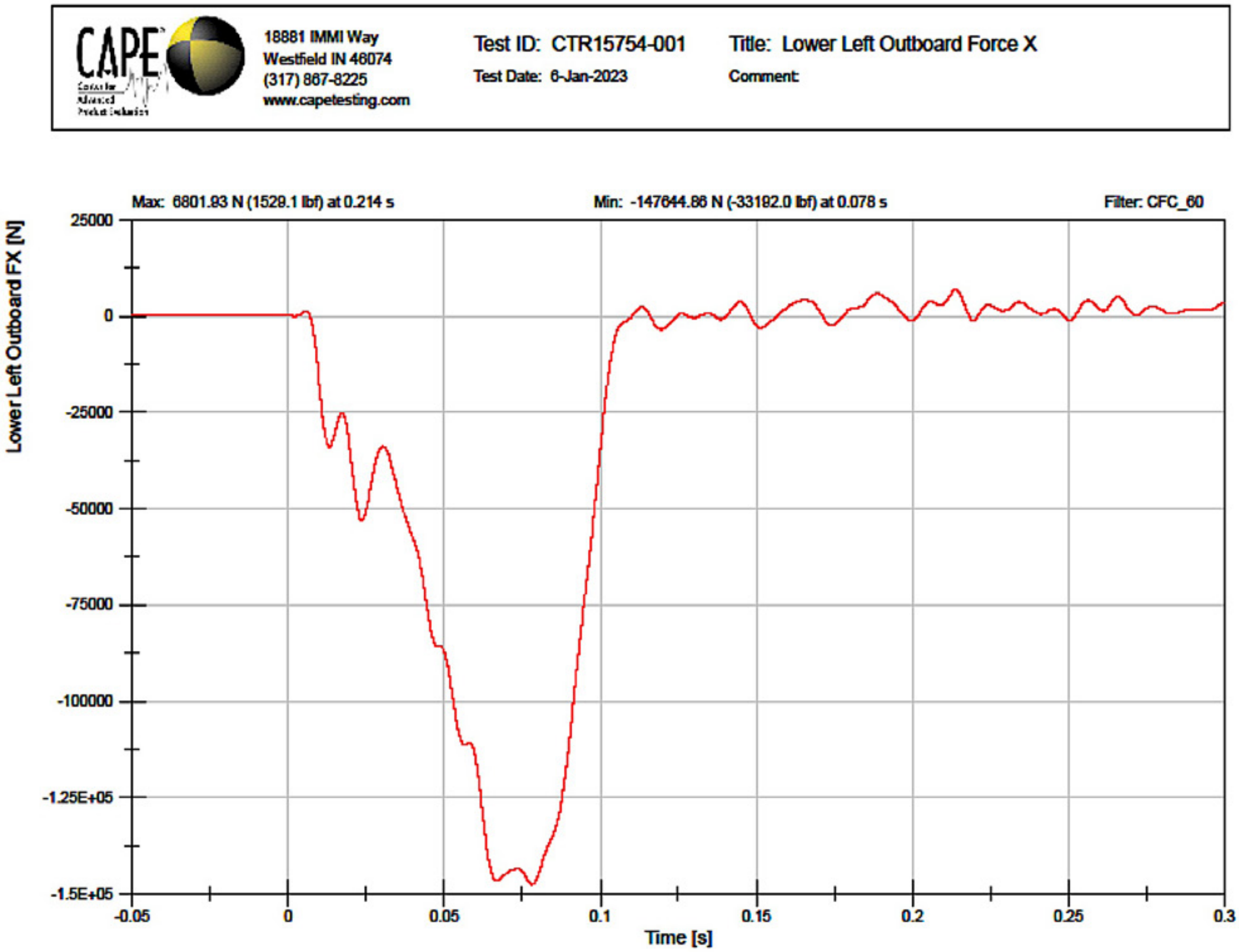

Figure C-3 *Test 1, Position 2, 400K Load Cell*

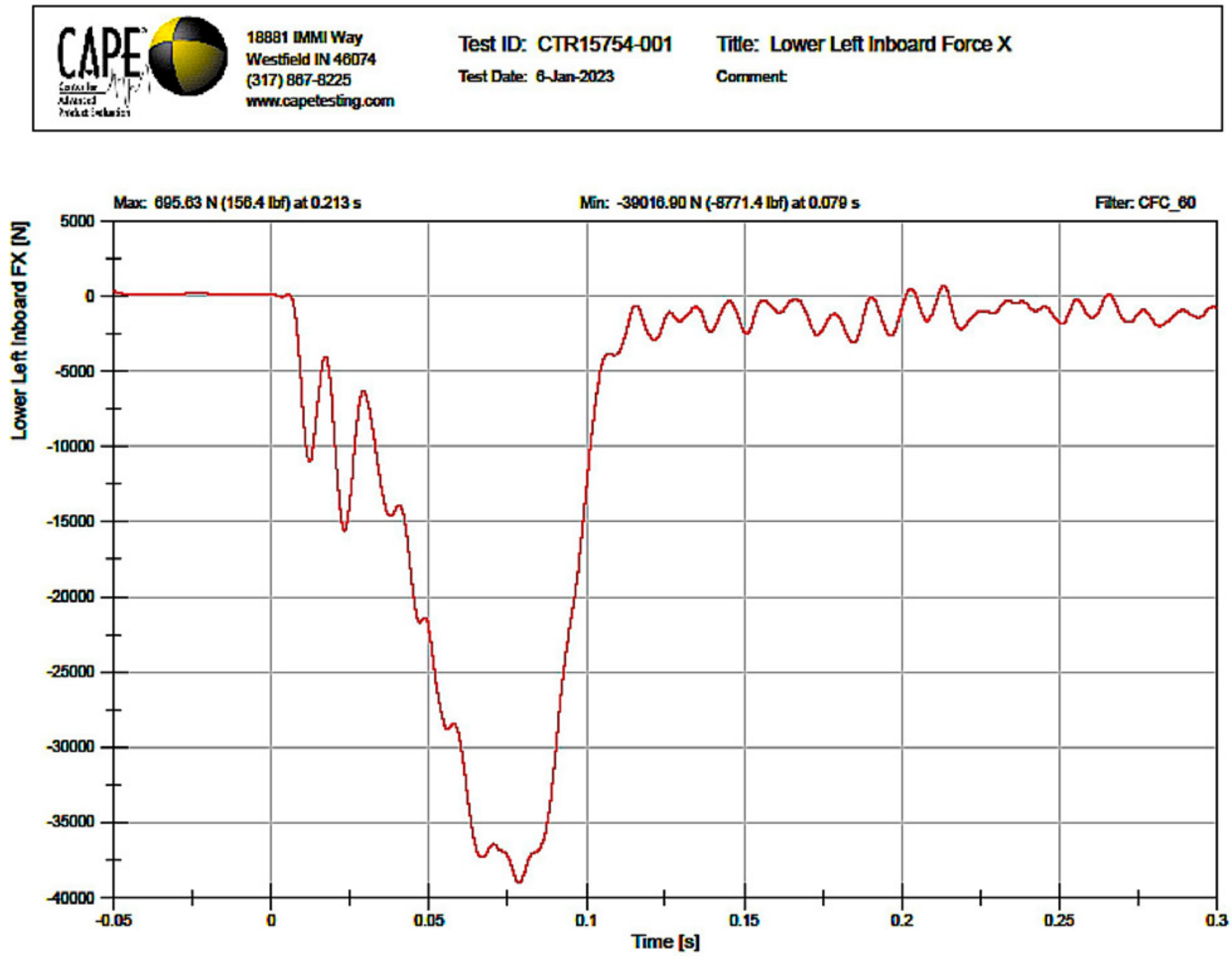

Figure C-4 *Test 1, Position 3, 200K Load Cell*

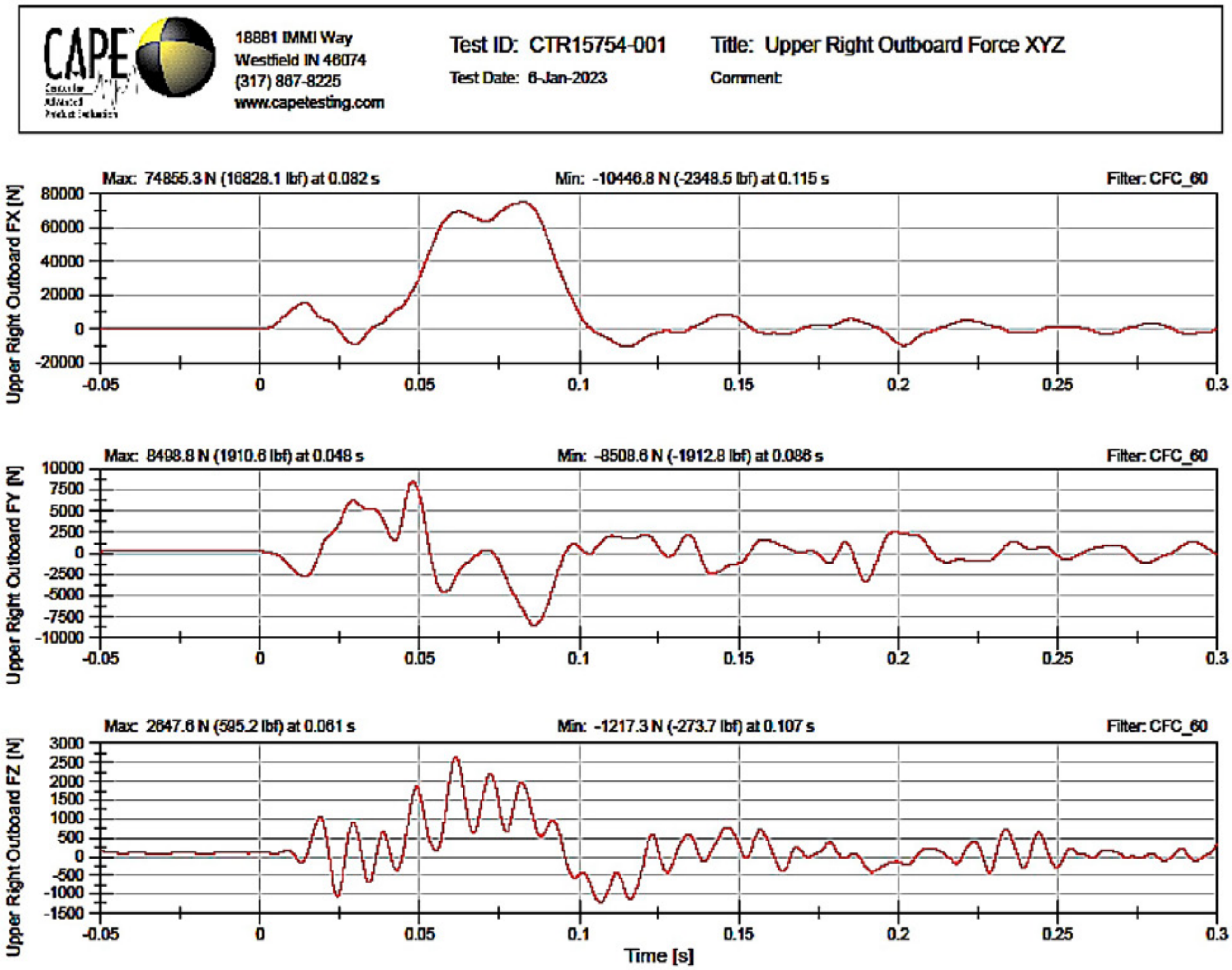

Figure C-5 *Test 1, Position 4, 100K Load Cell*

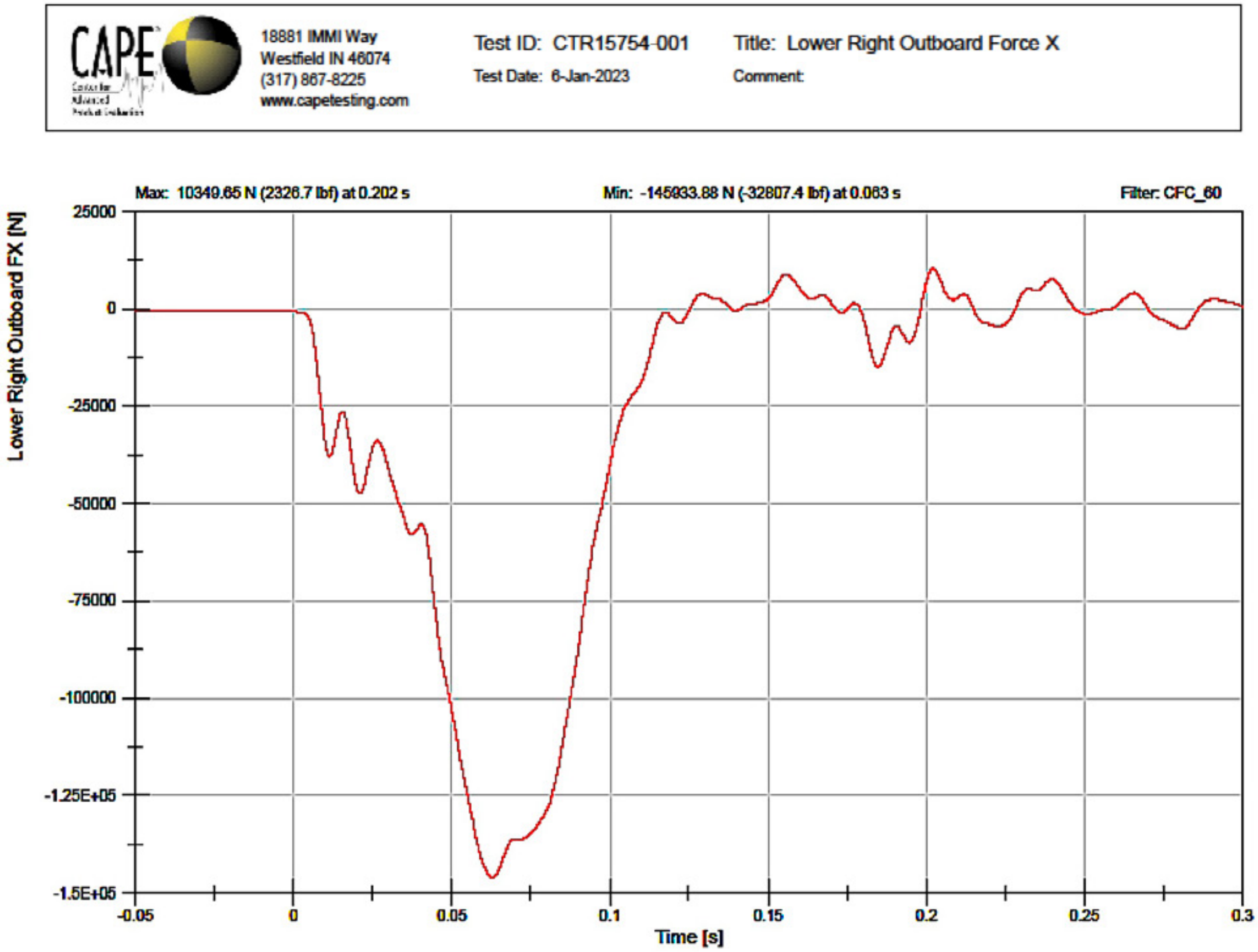

Figure C-6 *Test 1, Position 5, 400K Load Cell*

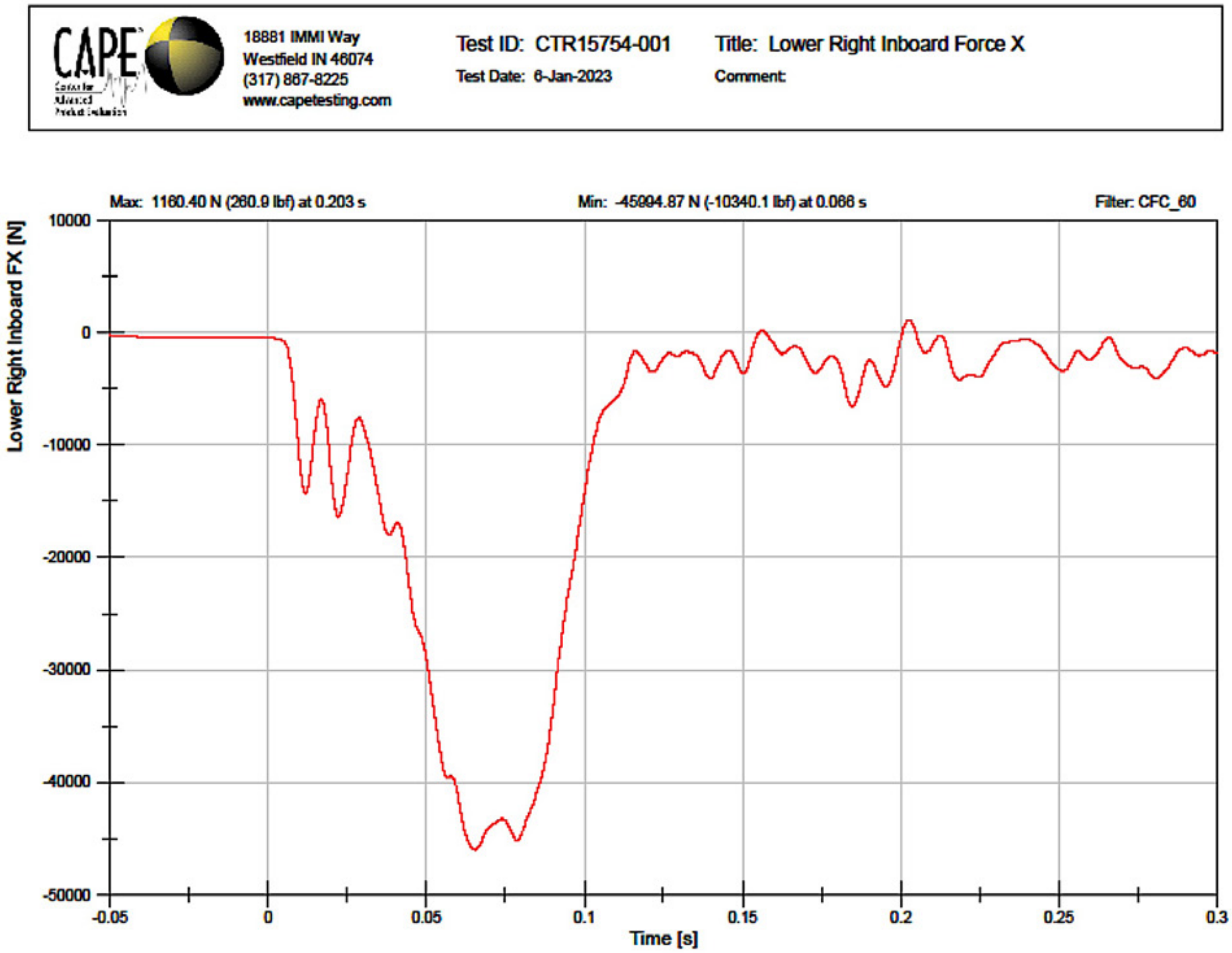

Figure C-7 *Test 1, Position 6, 200K Load Cell*

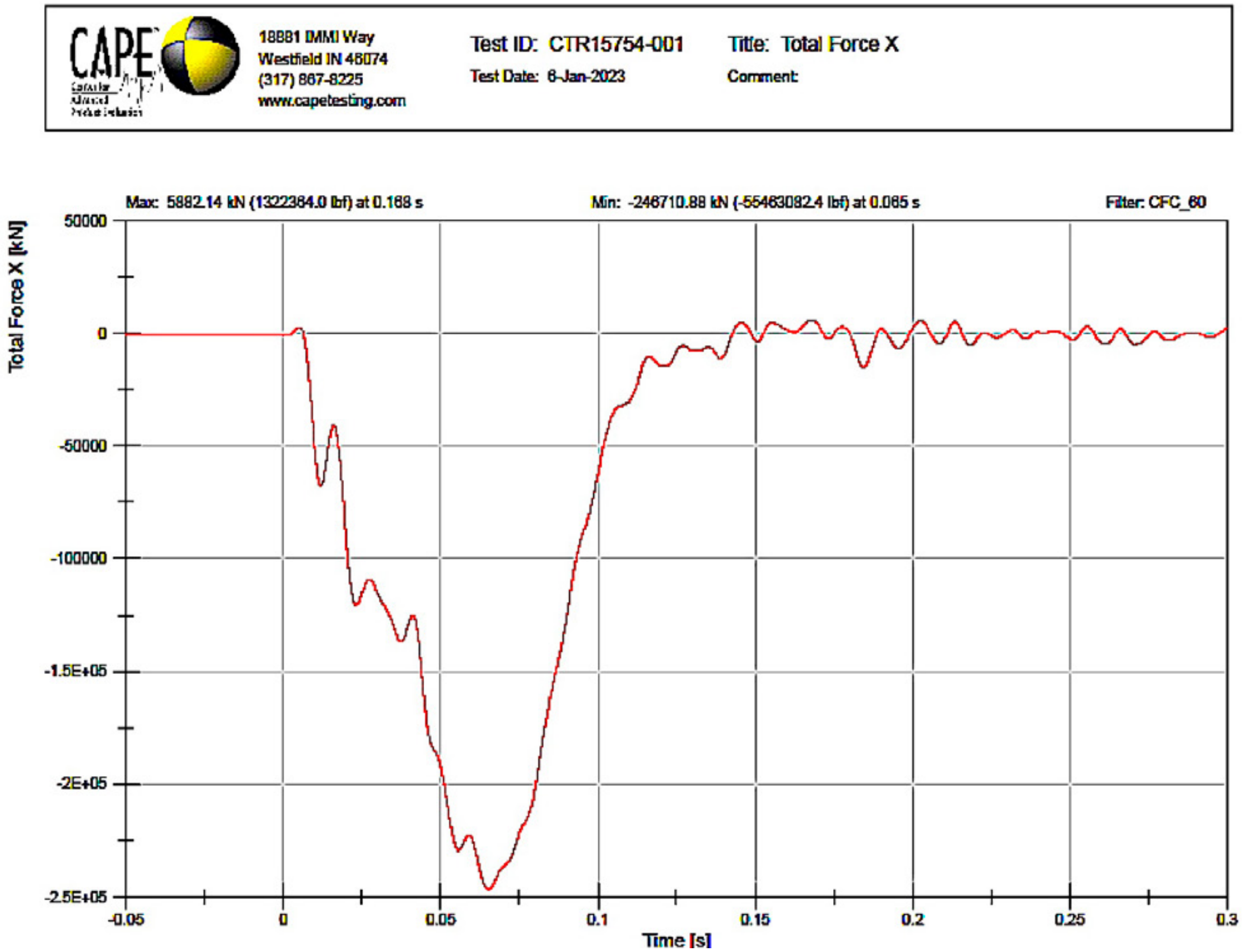

Figure C-8 *Test 1, Total Force Impact (X) Direction for all Load Cells*

Accelerometer Data

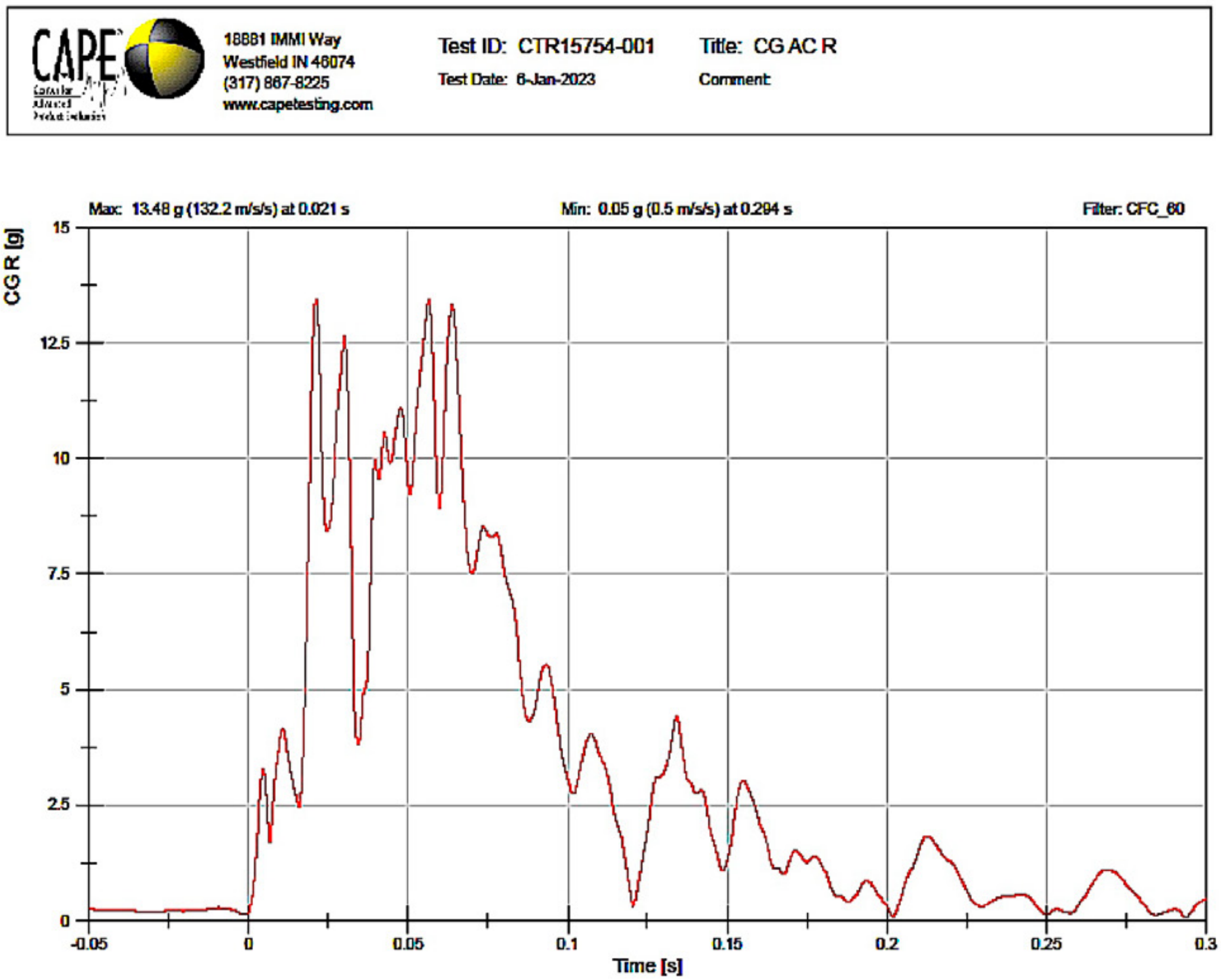

Figure C-9 *Test 1, Resultant Translational Acceleration at the Vehicle CG*

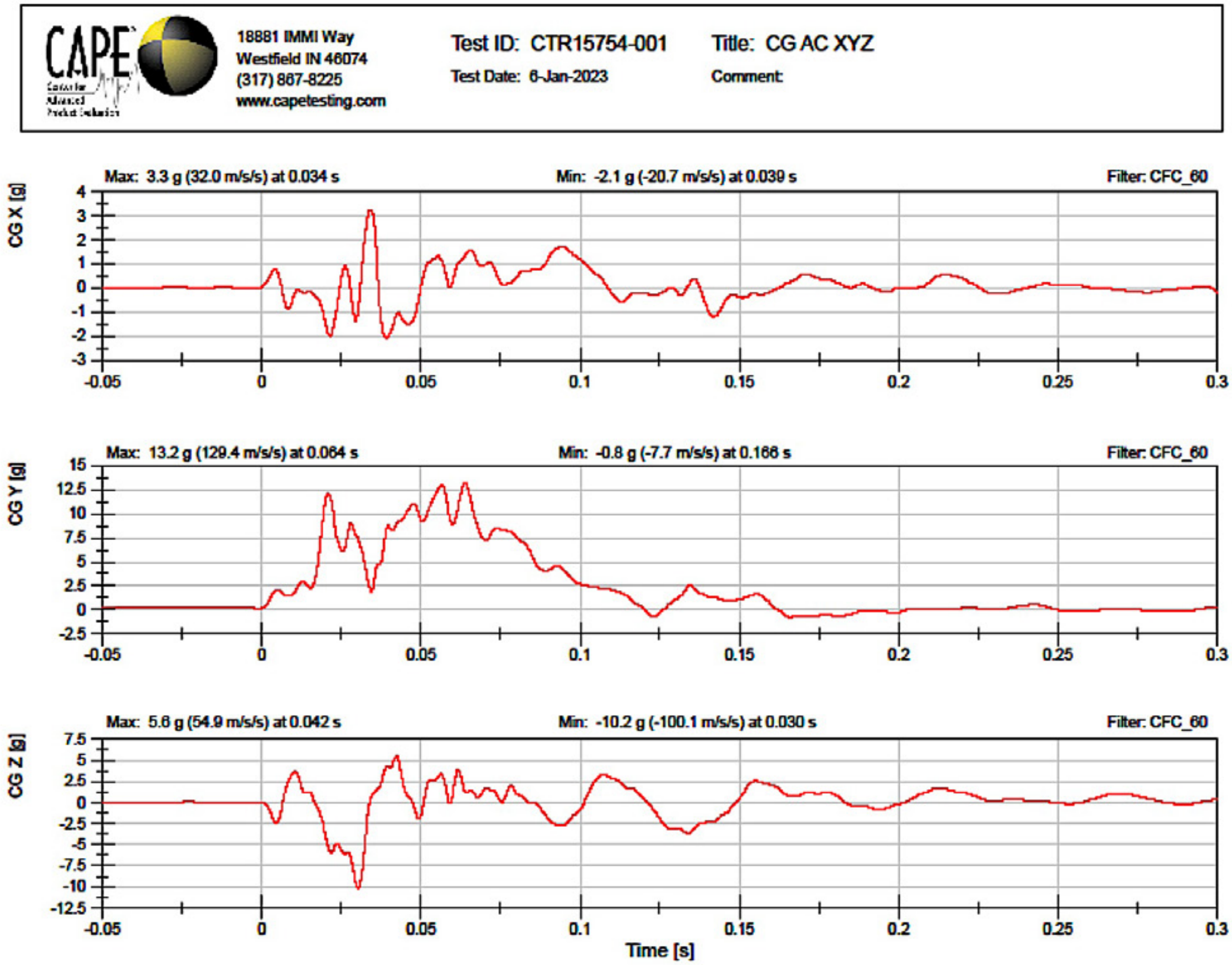

Figure C-10 *Test 1, Acceleration Translational Components at the Vehicle CG*

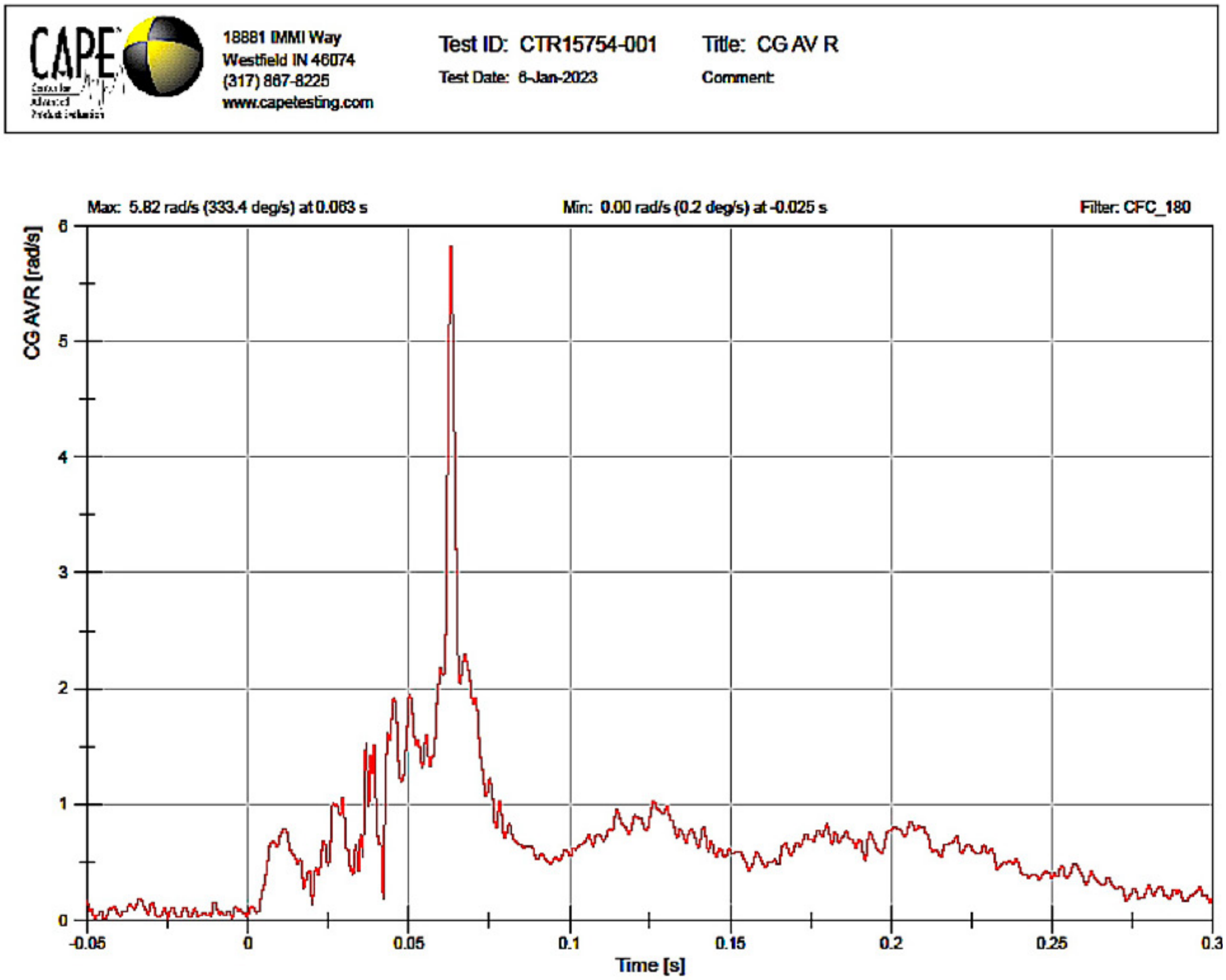

Figure C-11 *Test 1, Resultant Rotational Acceleration at the Vehicle CG*

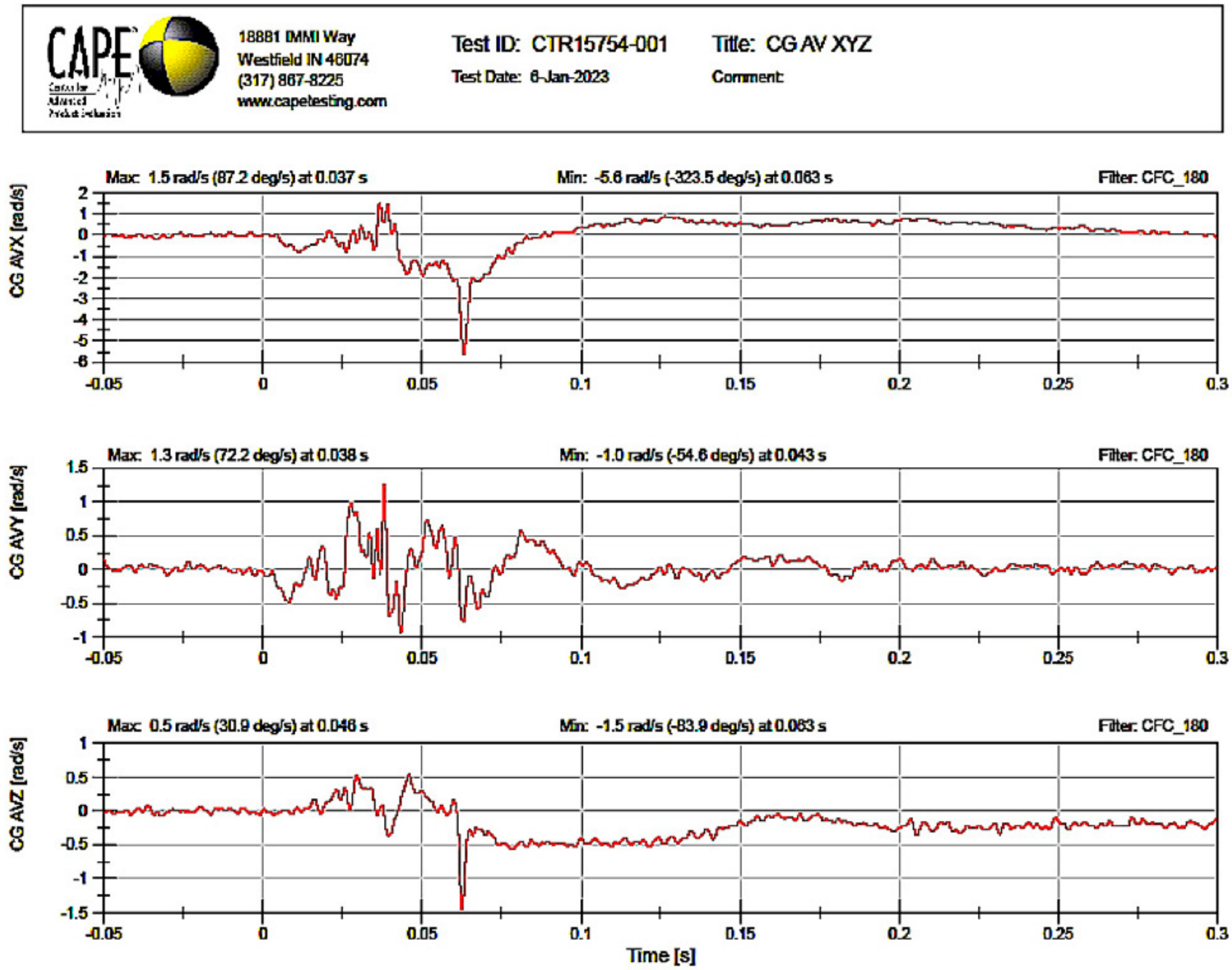

Figure C-12 *Test 1, Acceleration Rotational Components at the Vehicle CG*

Test 2 – 2010 Toyota Yaris

Load Cell Data

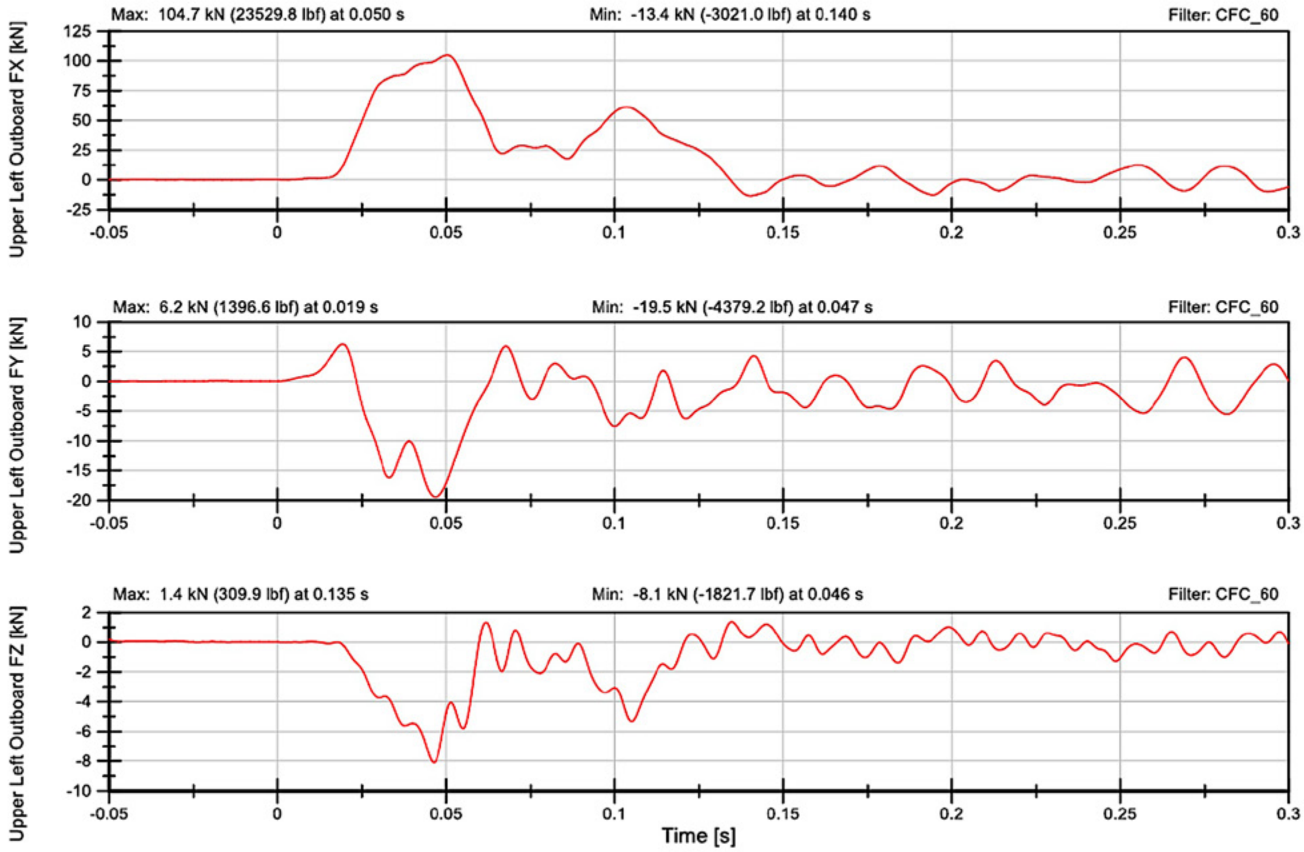

Figure C-13 *Test 2, Position 1, 100K Load Cell*

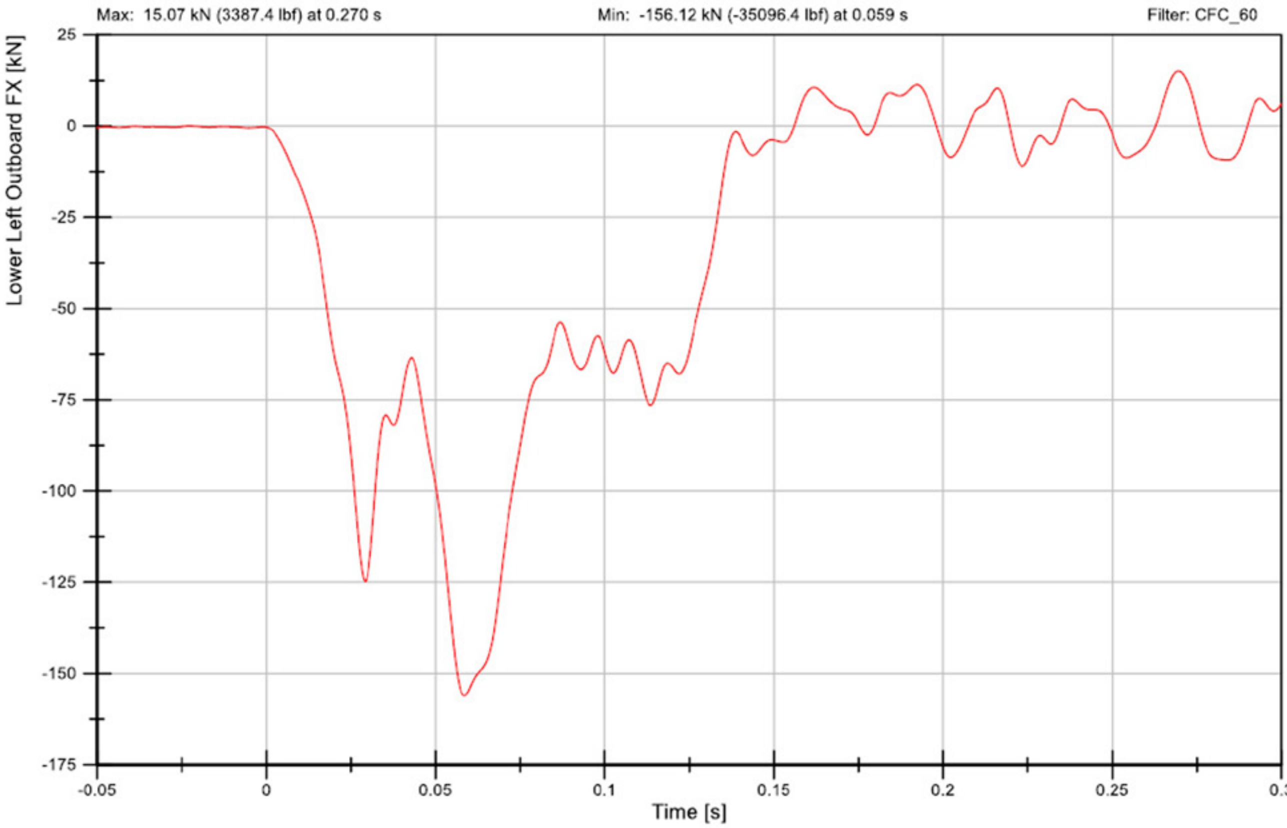

Figure C-14 *Test 2, Position 2, 400K Load Cell*

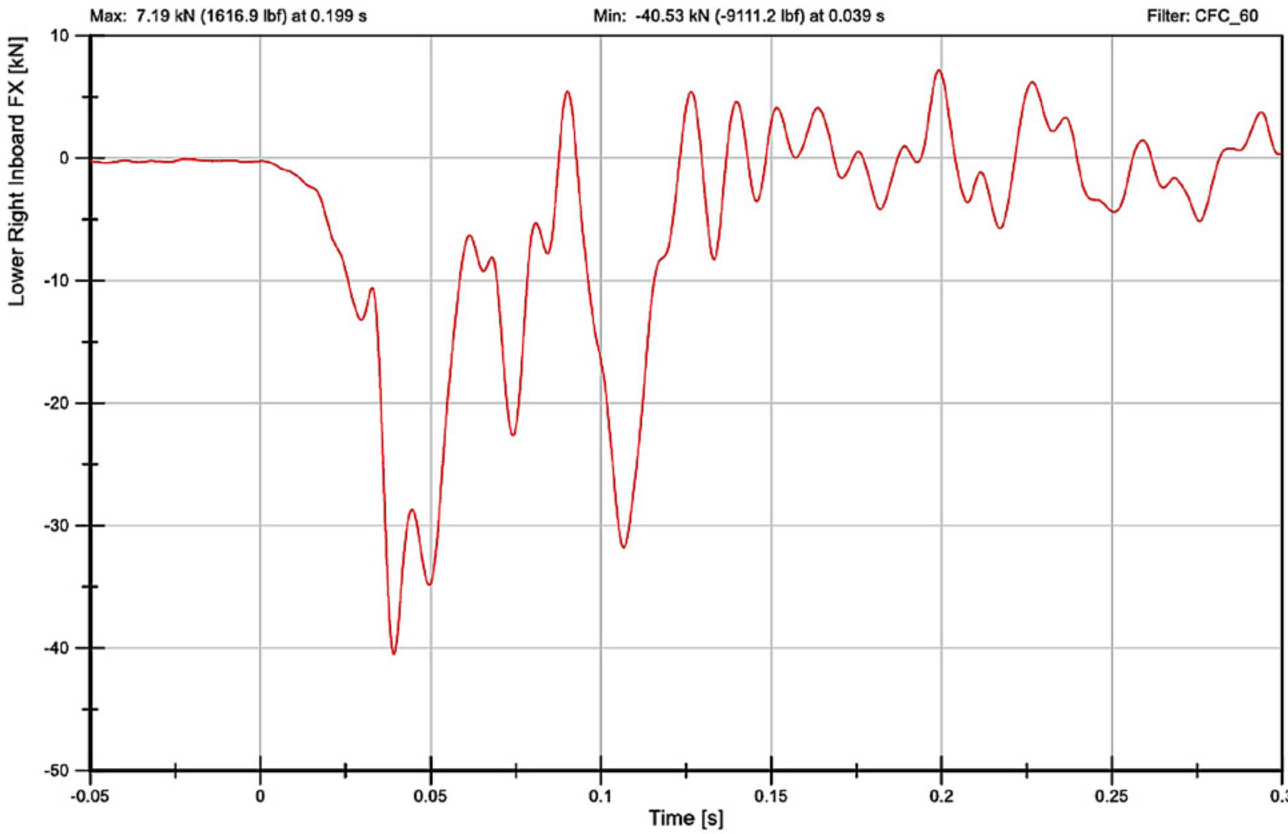

Figure C-15 *Test 2, Position 3, 200K Load Cell*

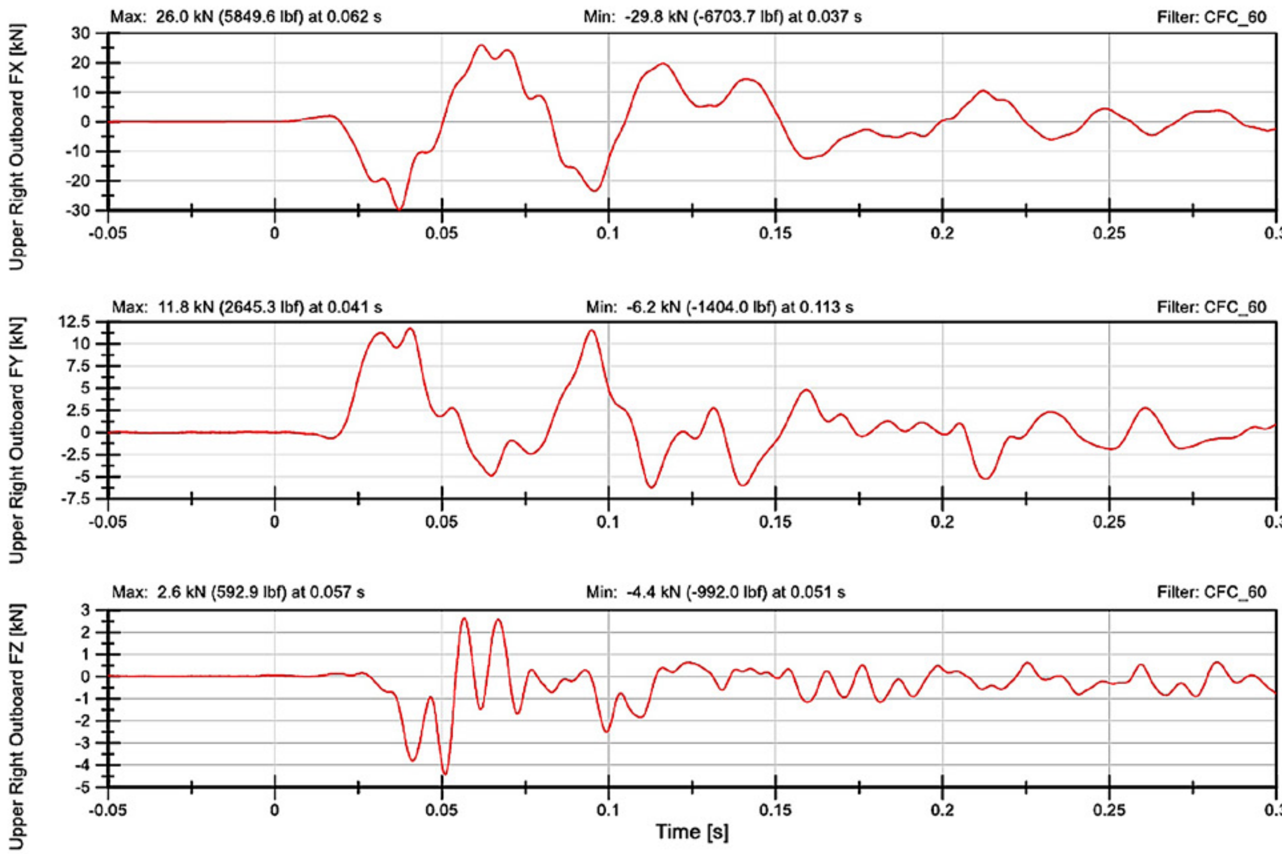

Figure C-16 *Test 2, Position 4, 100K Load Cell*

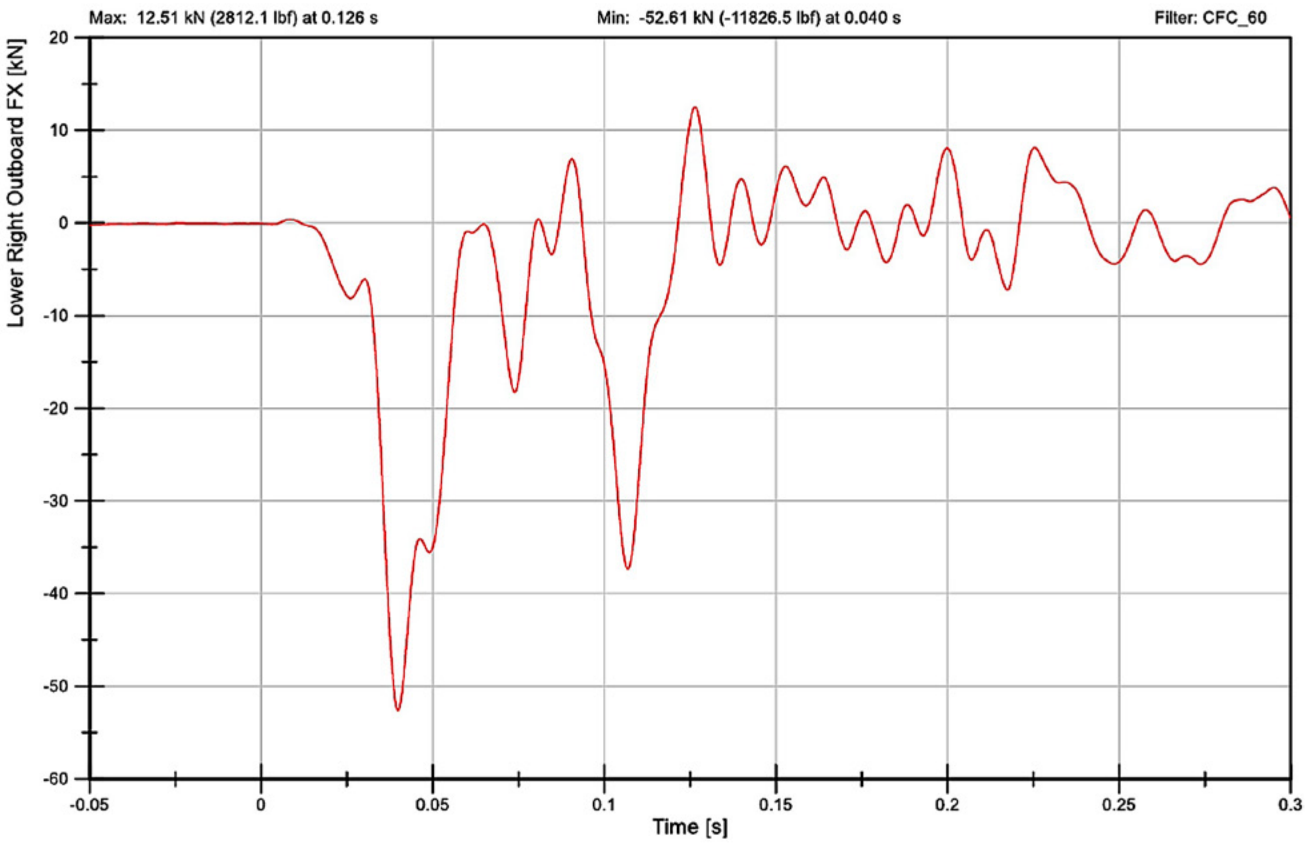

Figure C-17 *Test 2, Position 5, 400K Load Cell*

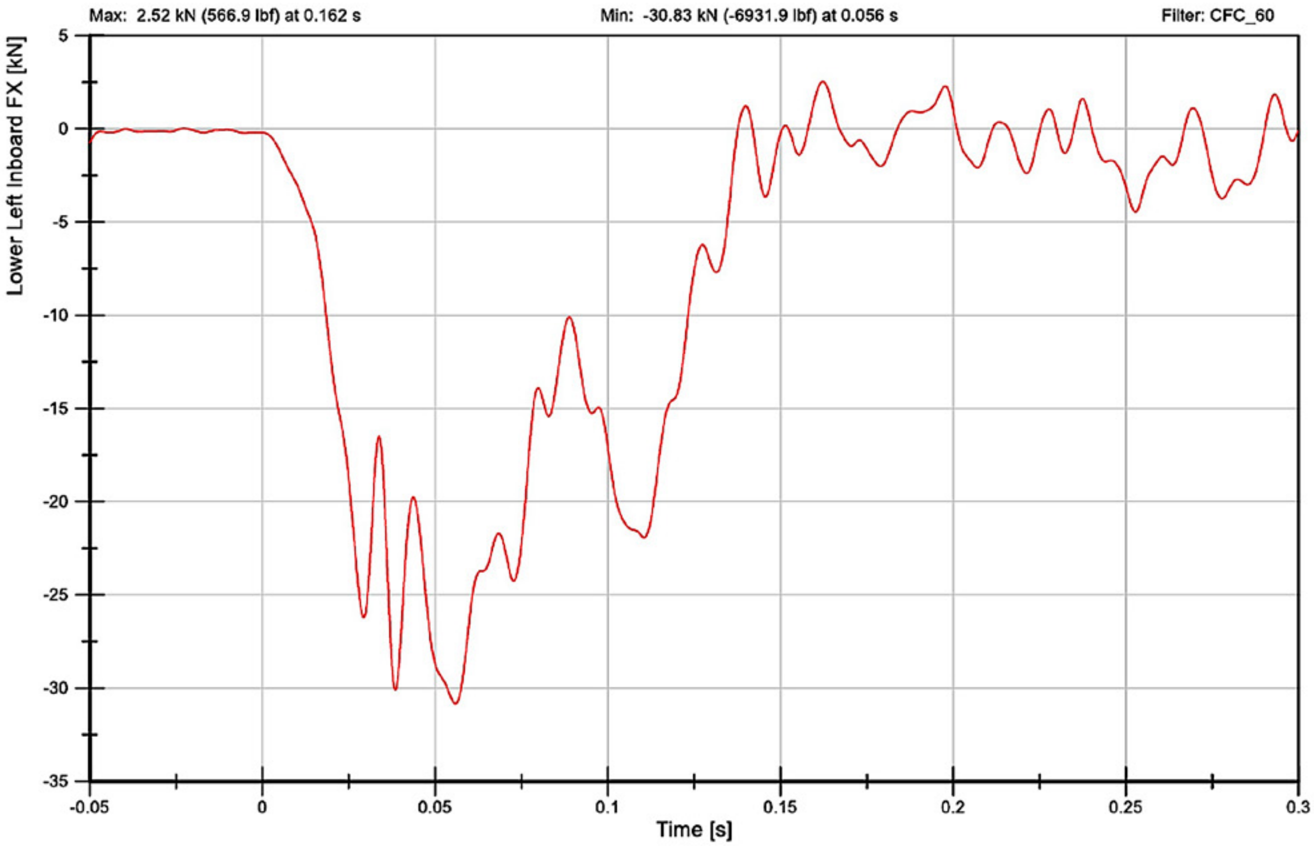

Figure C-18 *Test 2, Position 6, 200K Load Cell*

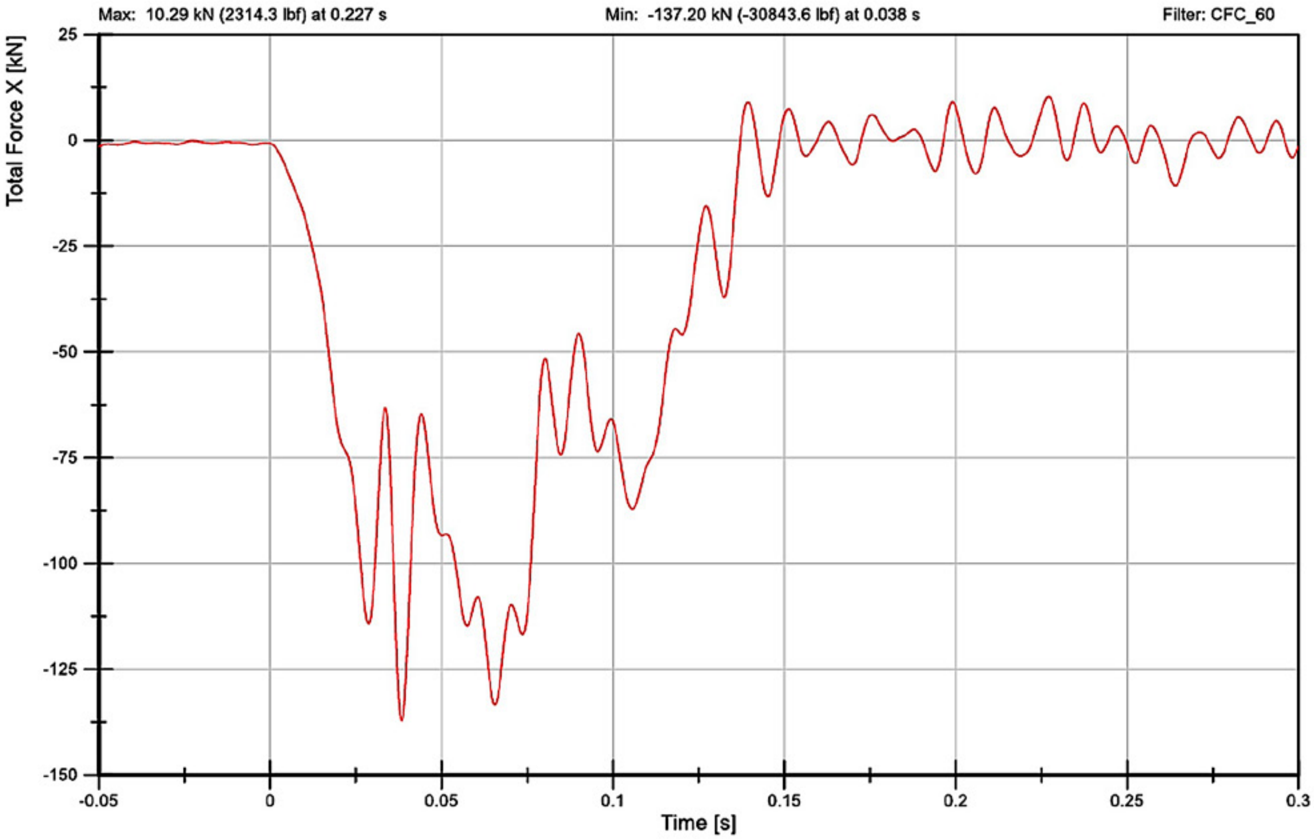

Figure C-19 *Test 2, Total Force Impact (X) Direction for all Load Cells*

Accelerometer Data

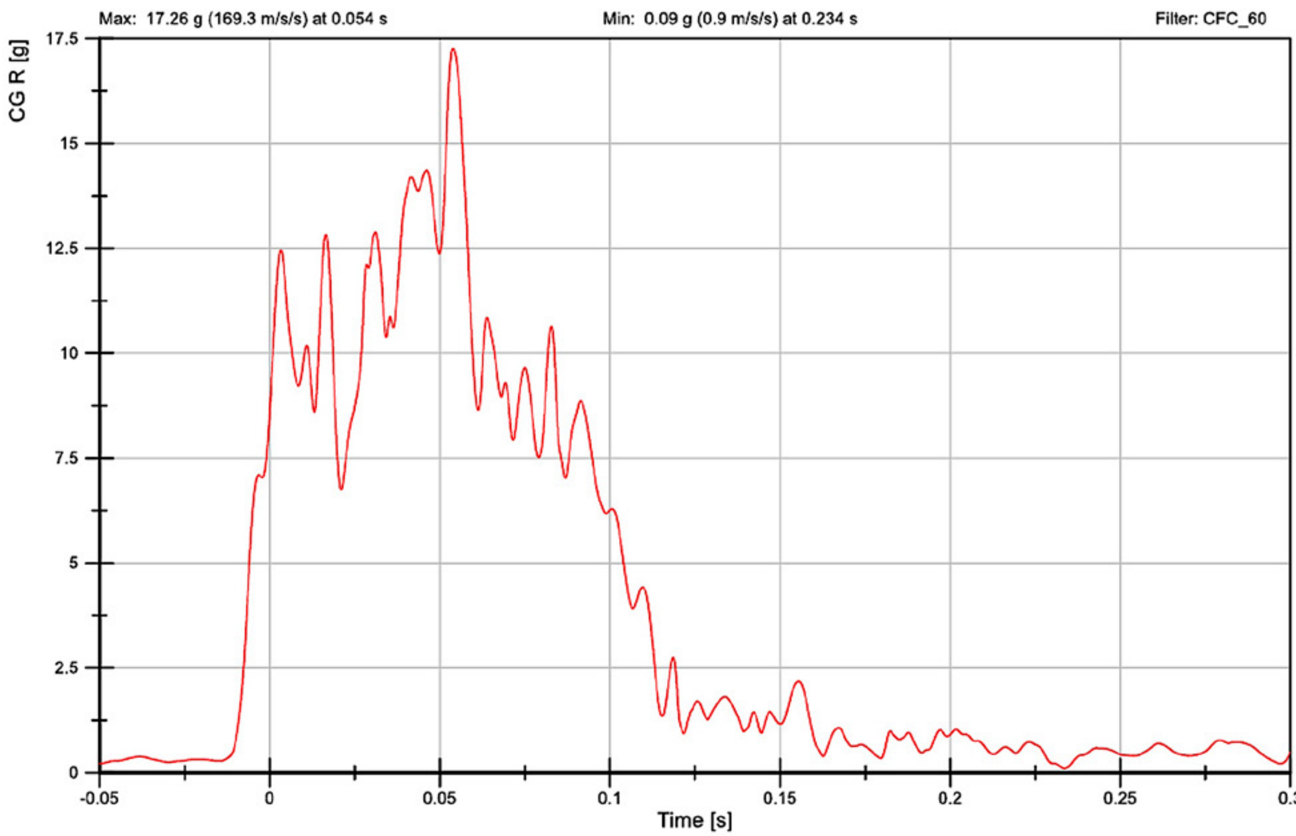

Figure C-20 *Test 2, Resultant Translational Acceleration at the Vehicle CG*

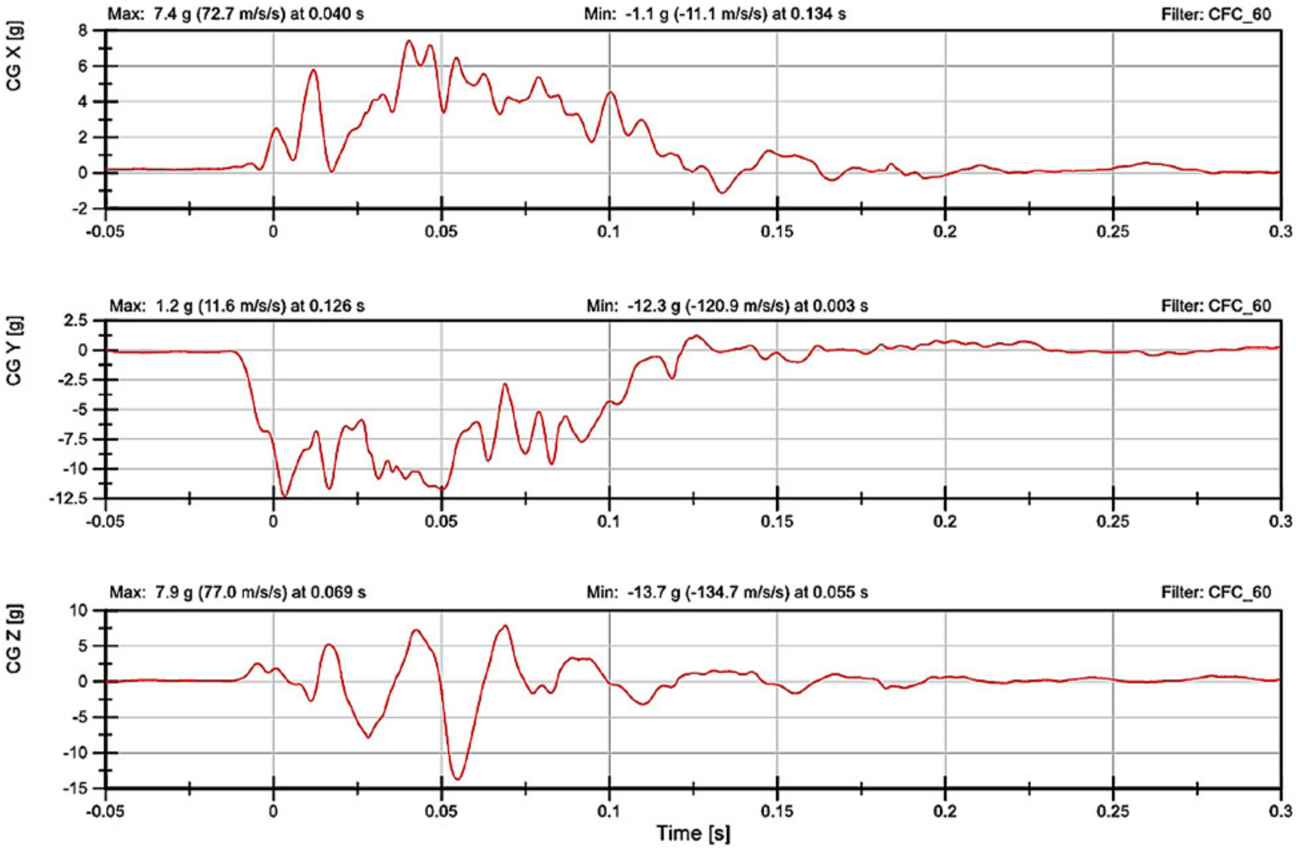

Figure C-21 *Test 2, Acceleration Translational Components at the Vehicle CG*

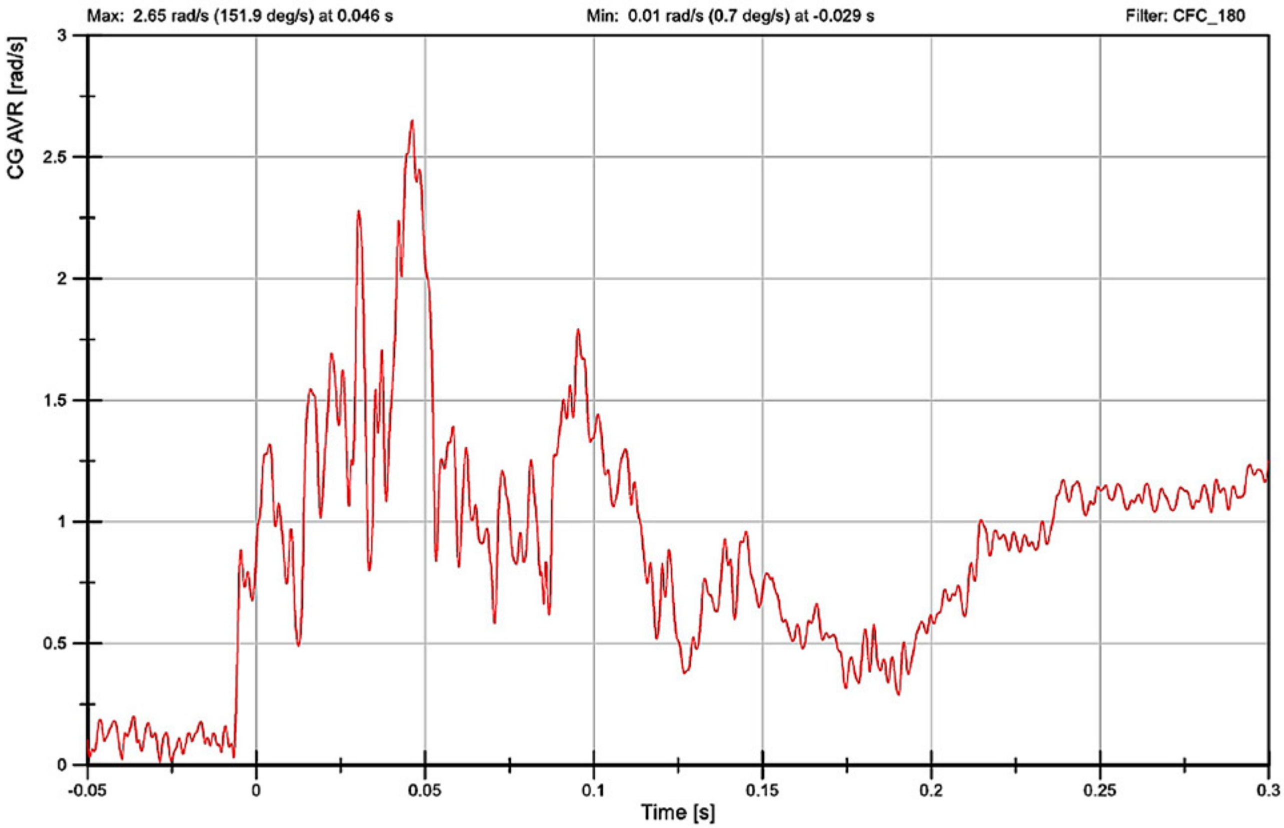

Figure C-22 *Test 2, Resultant Rotational Acceleration at the Vehicle CG*

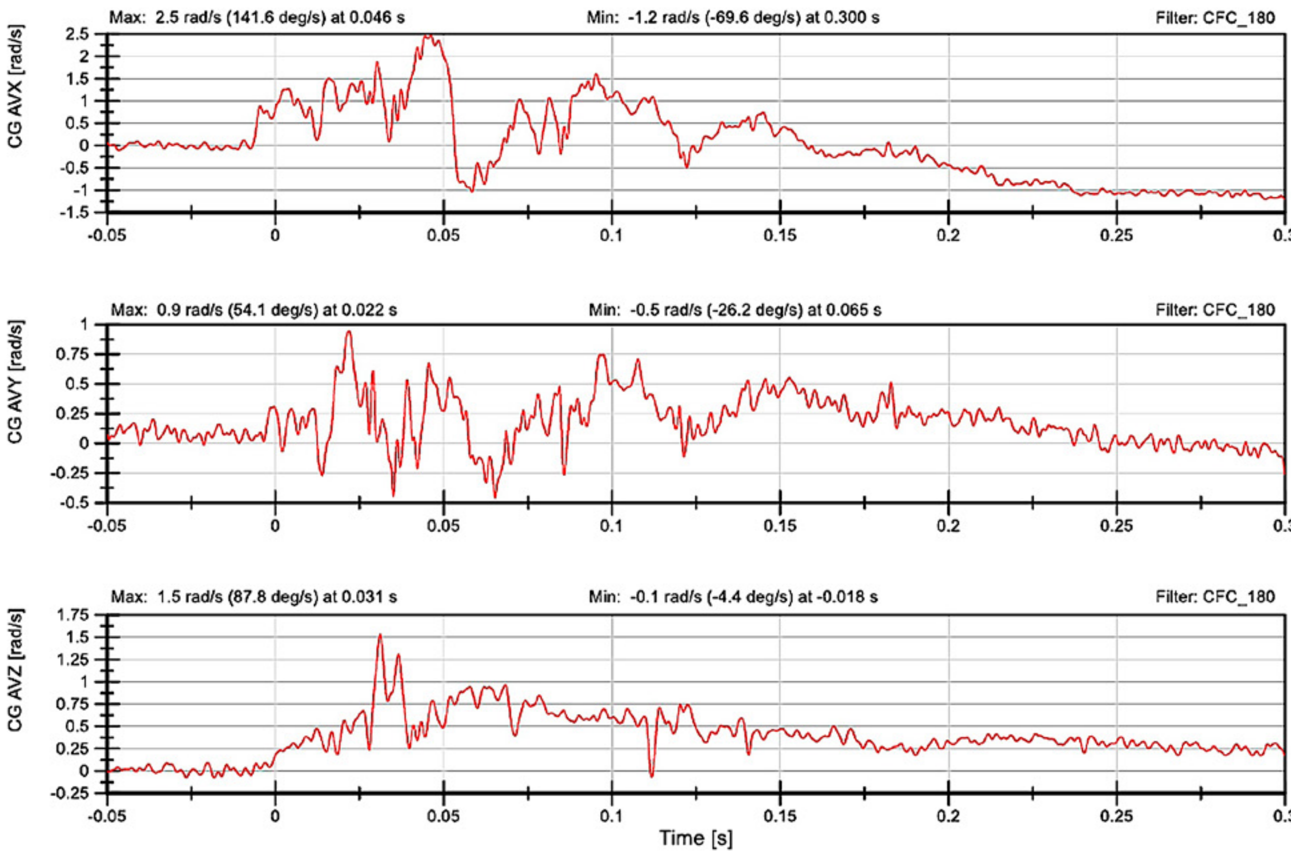

Figure C-23 *Test 2, Acceleration Rotational Components at the Vehicle CG*

Test 3 – Sled Test

Load Cell Data

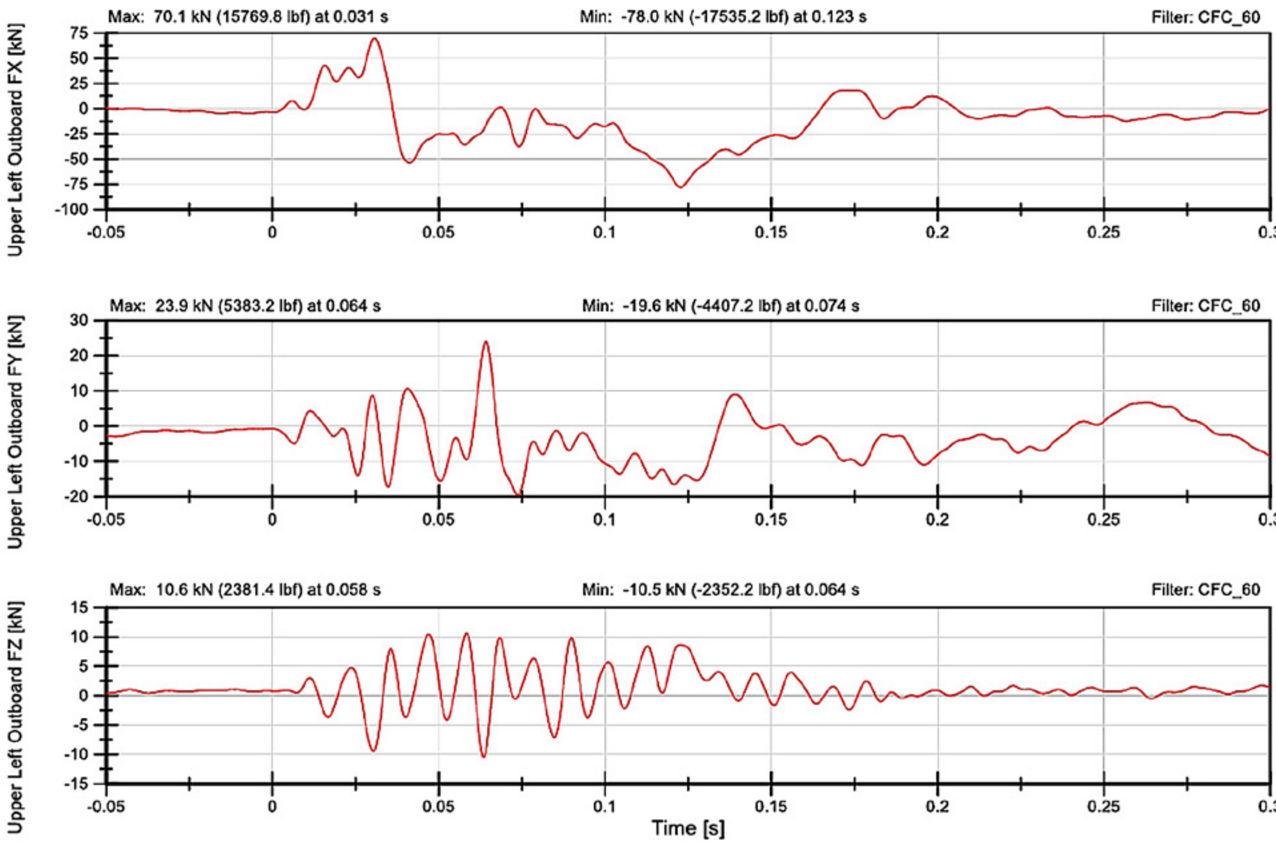

Figure C-24 *Test 3, Position 1, 100K Load Cell*

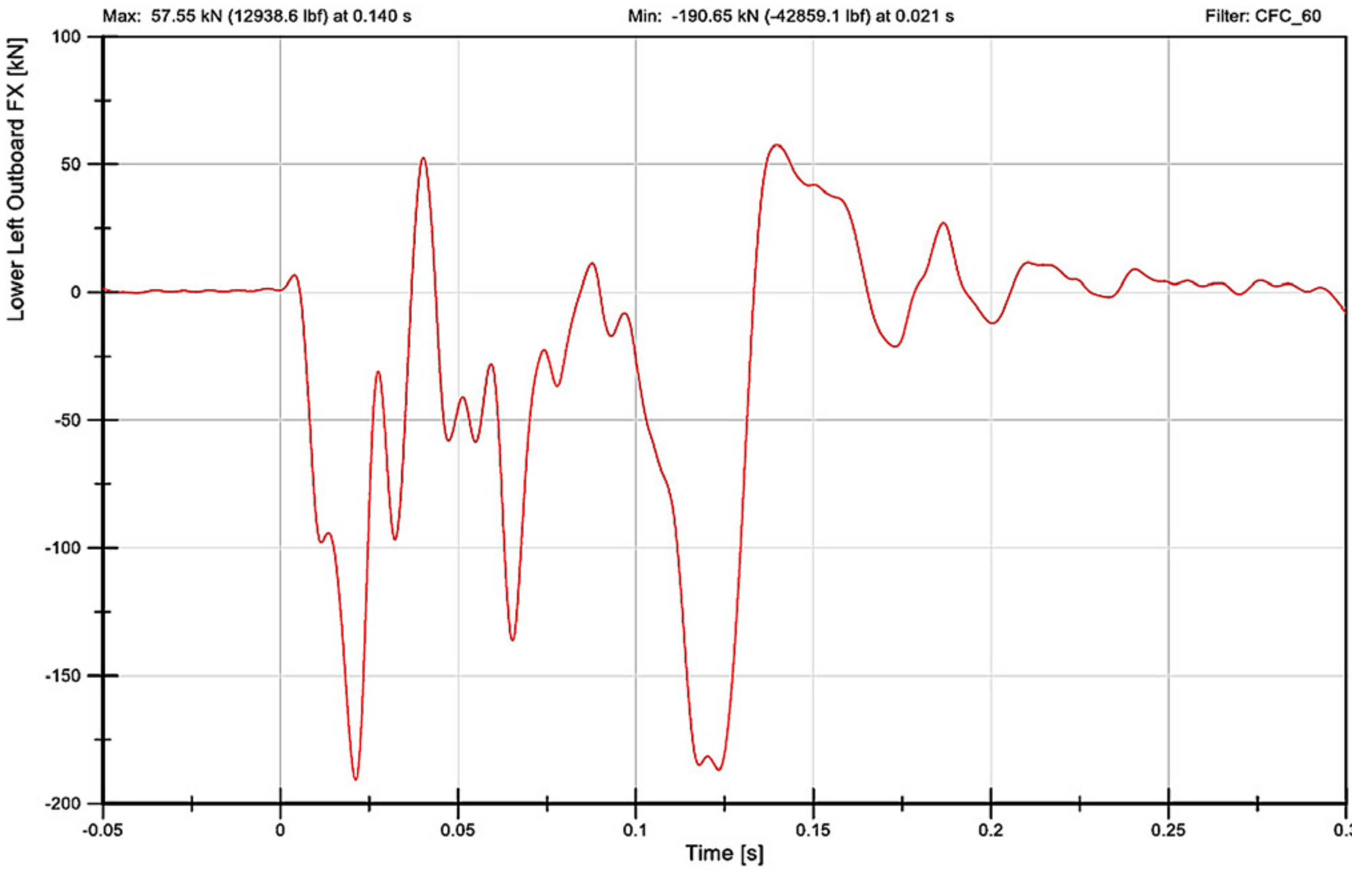

Figure C-25 *Test 3, Position 2, 400K Load Cell*

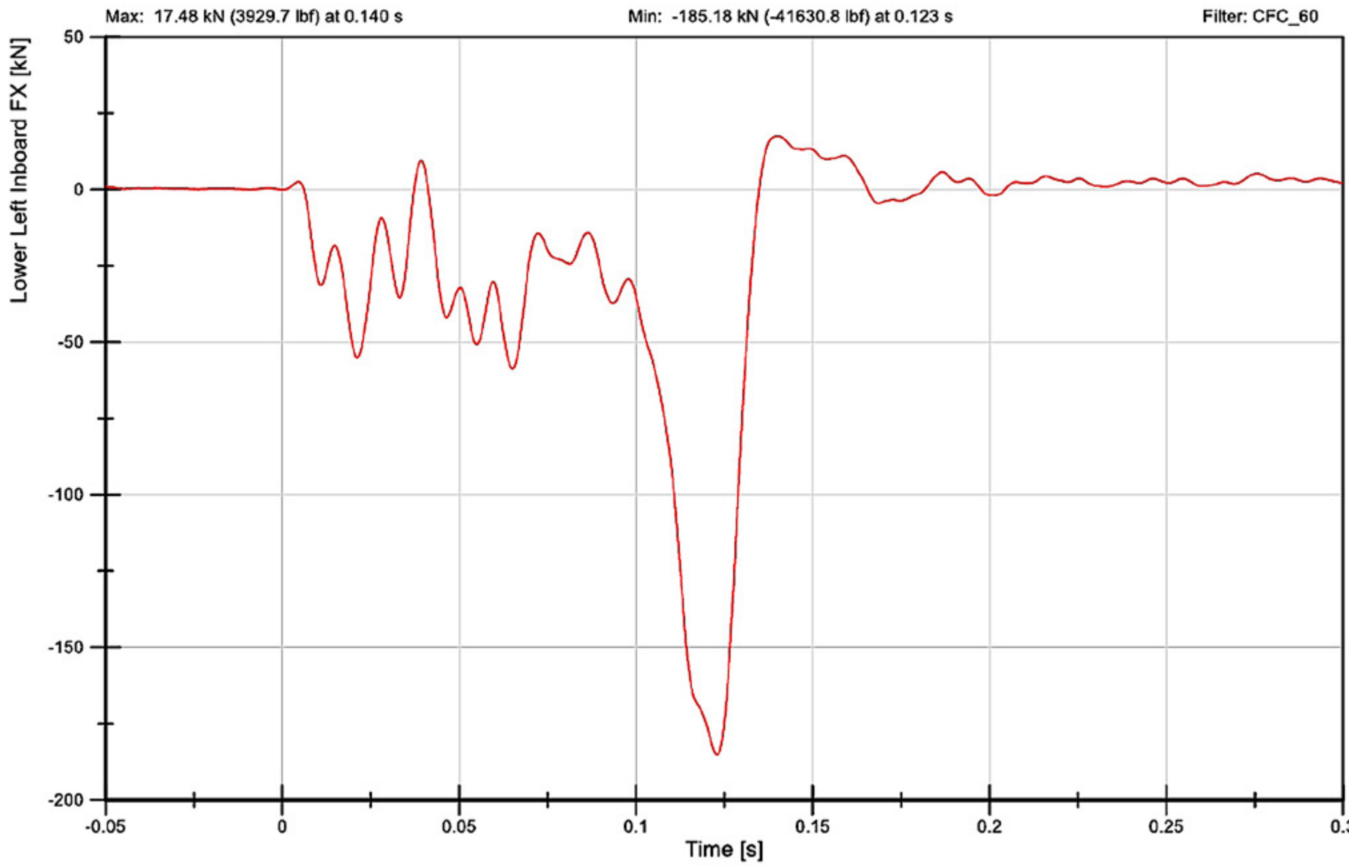

Figure C-26 *Test 3, Position 3, 200K Load Cell*

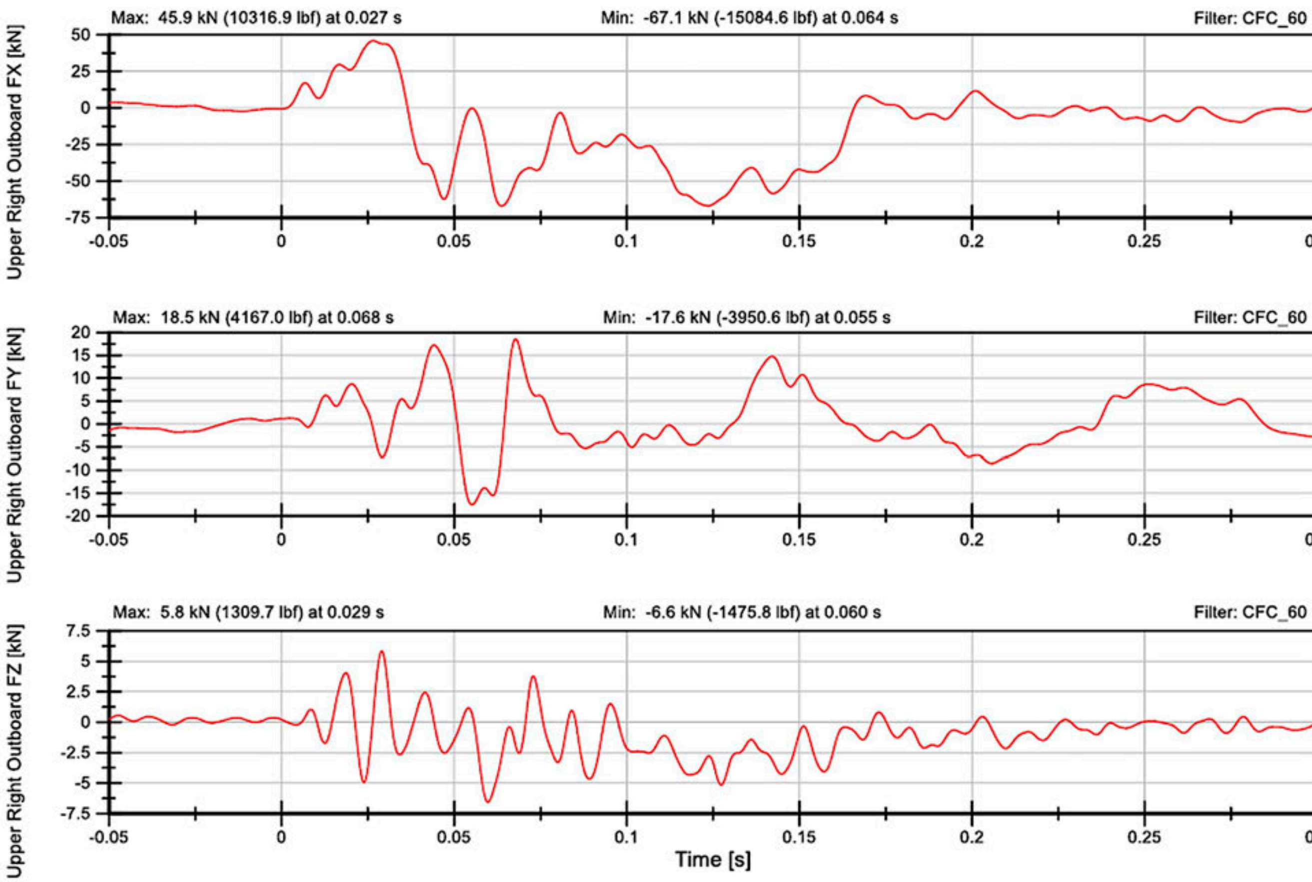

Figure C-27 *Test 3, Position 4, 100K Load Cell*

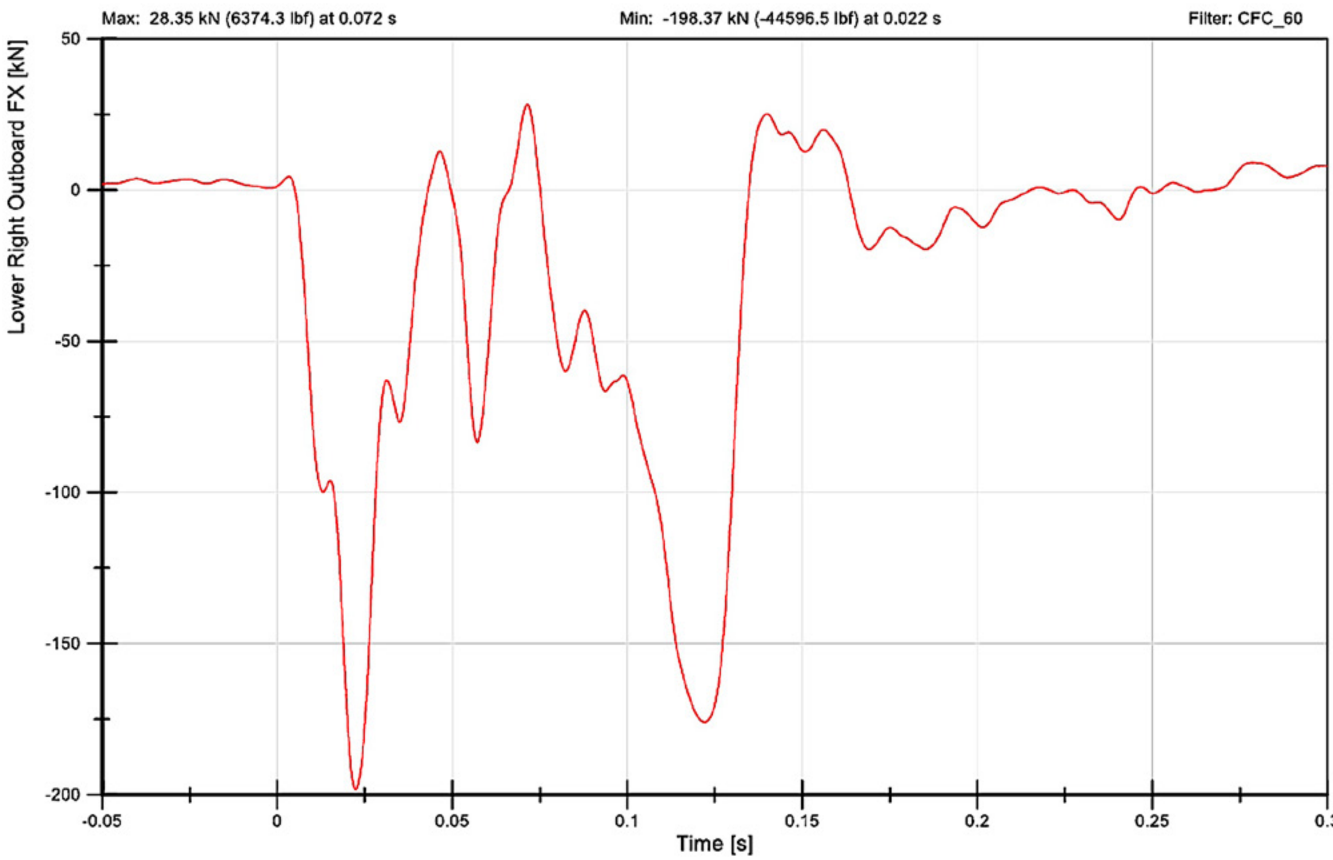

Figure C-28 *Test 3, Position 5, 400K Load Cell*

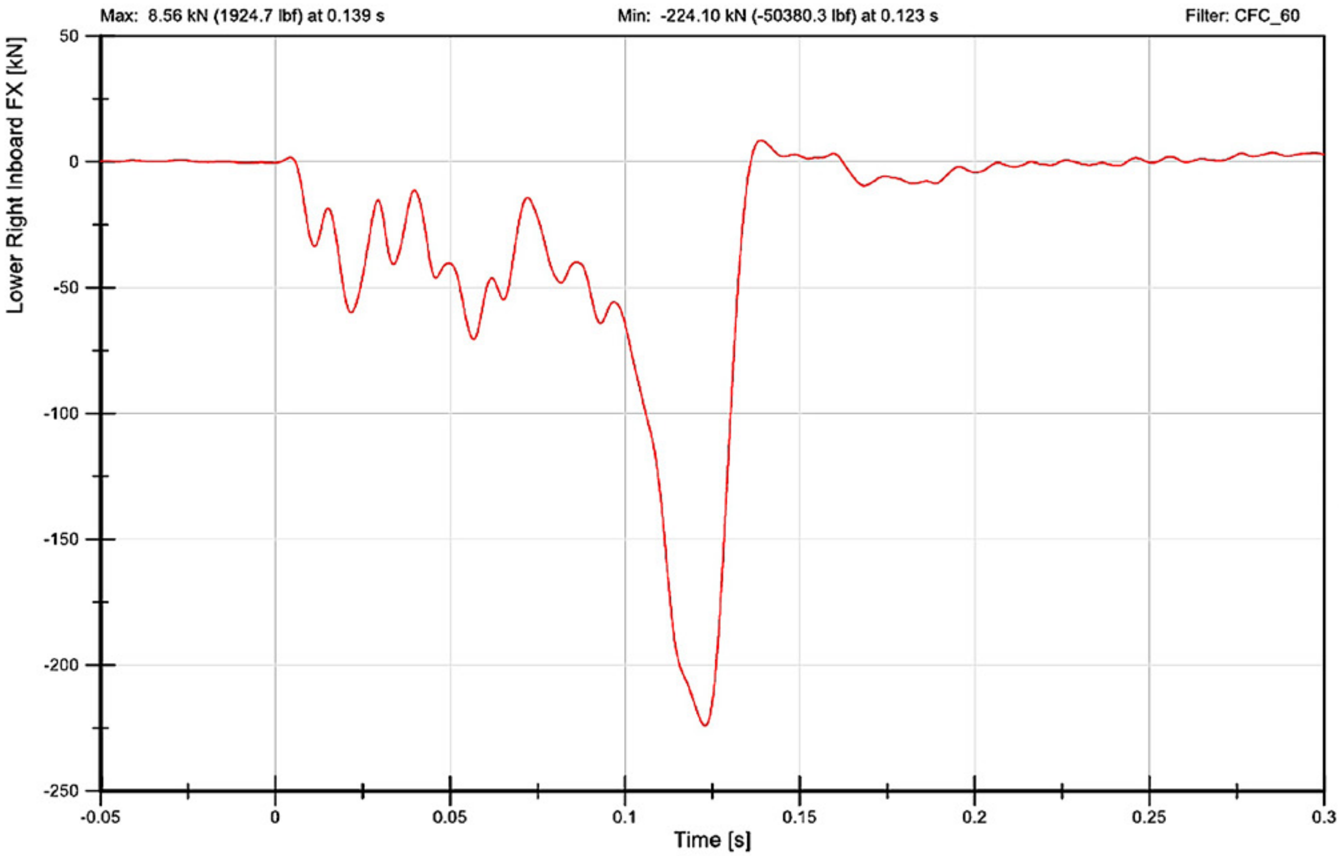

Figure C-29 *Test 3, Position 6, 200K Load Cell*

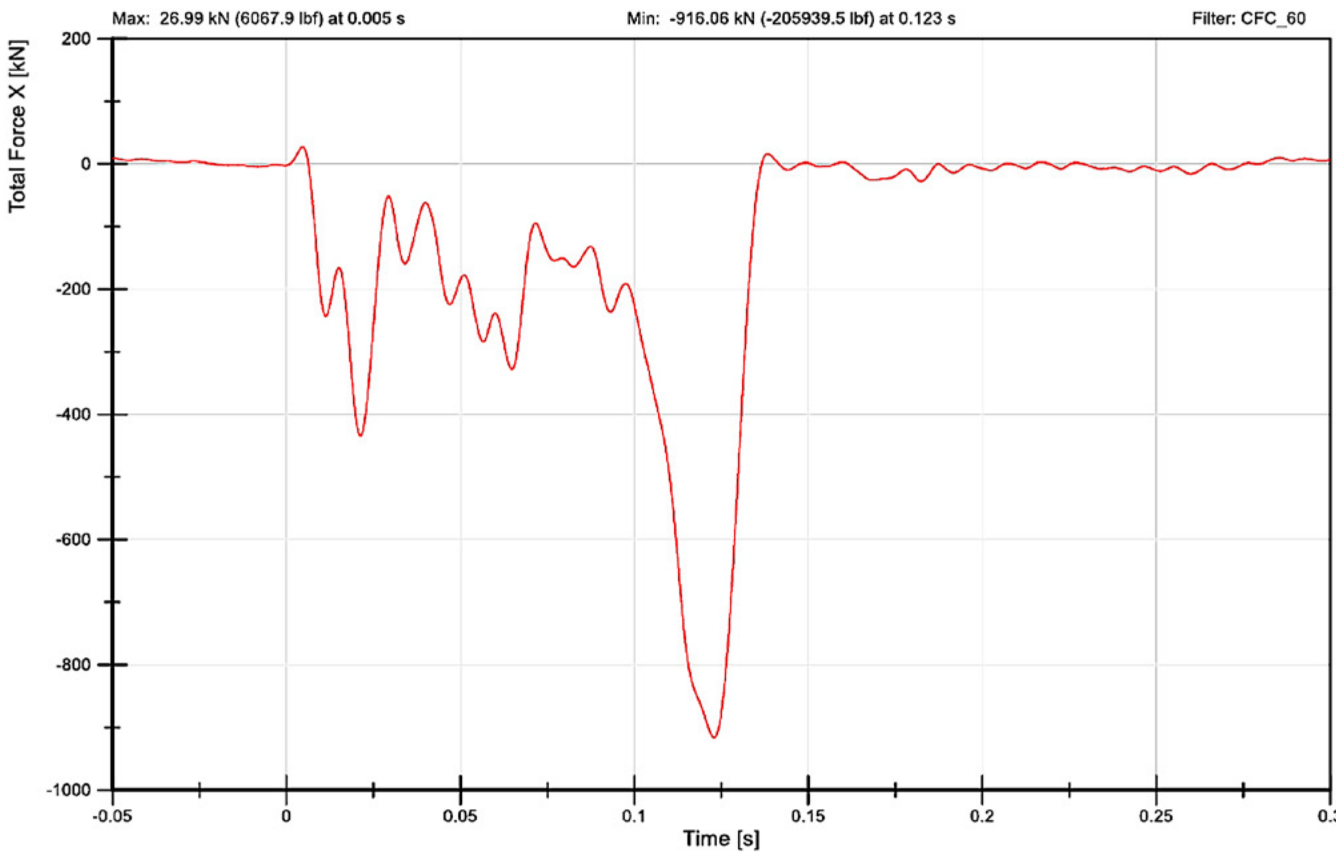

Figure C-30 *Test 3, Total Force Impact (X) Direction for all Load Cells*

Accelerometer Data

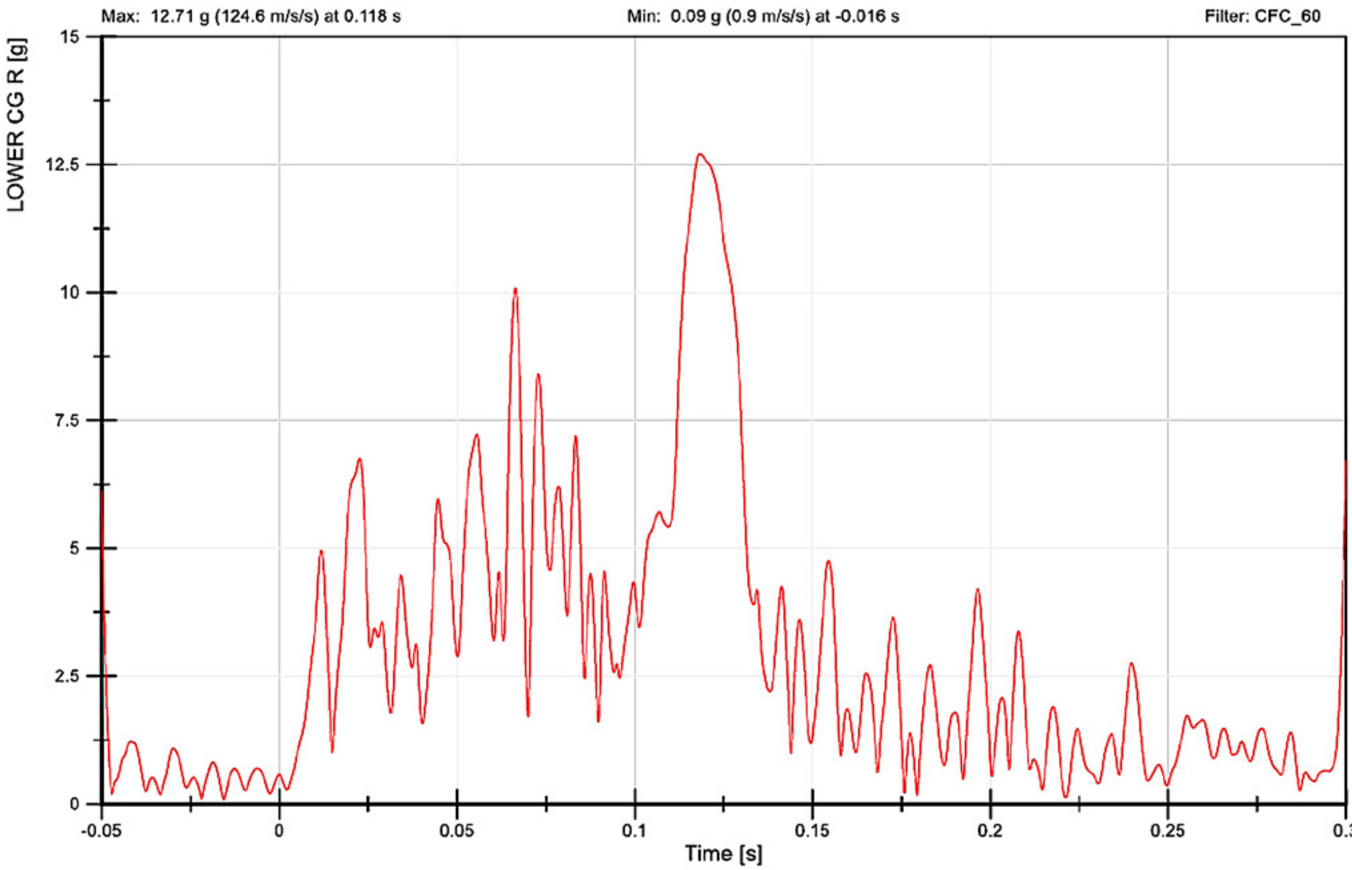

Figure C-31 *Test 3, Resultant Translational Acceleration at the Sled CG (lower)*

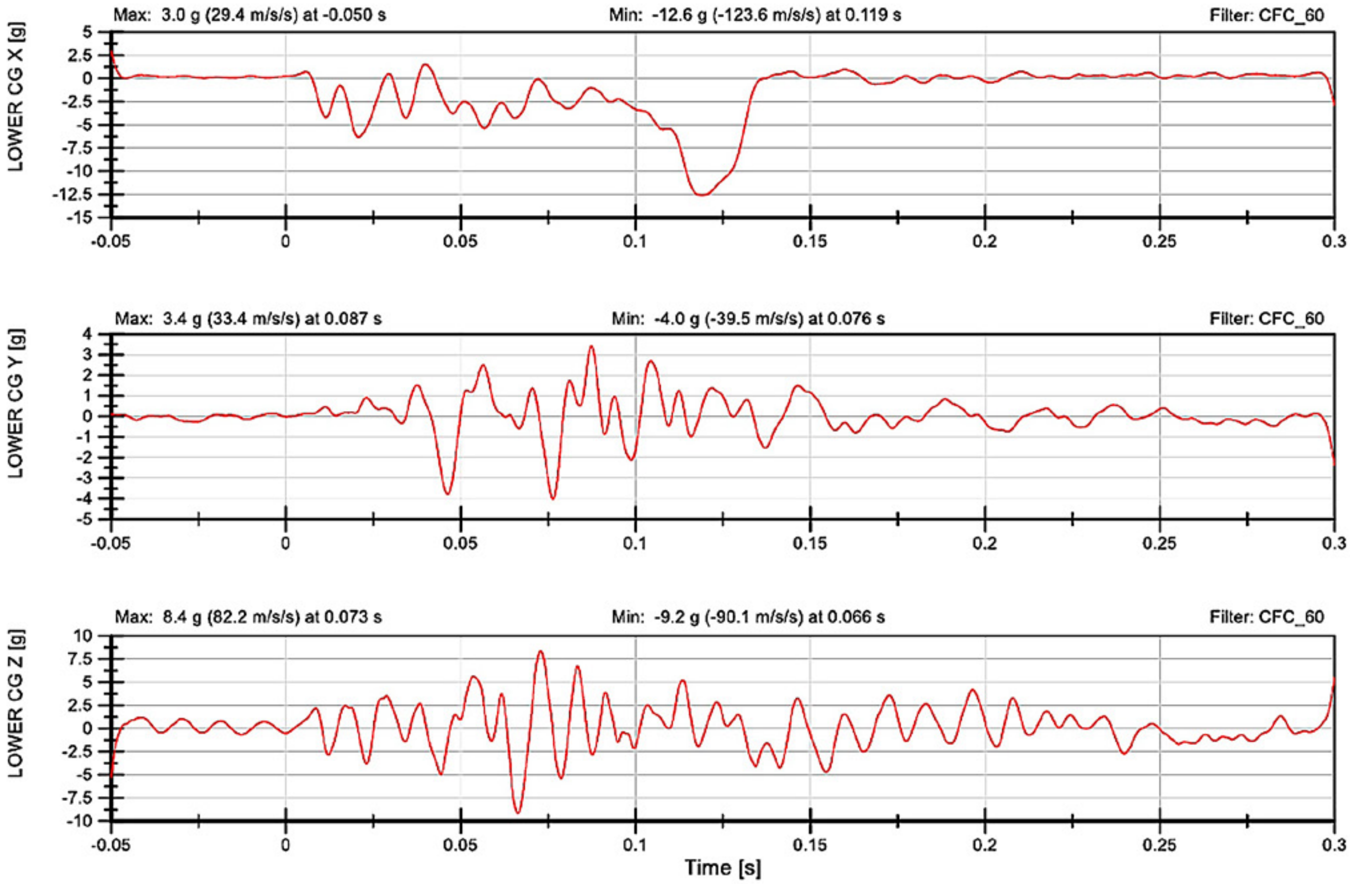

Figure C-32 *Test 3, Acceleration Translational Components at the Sled CG (lower)*

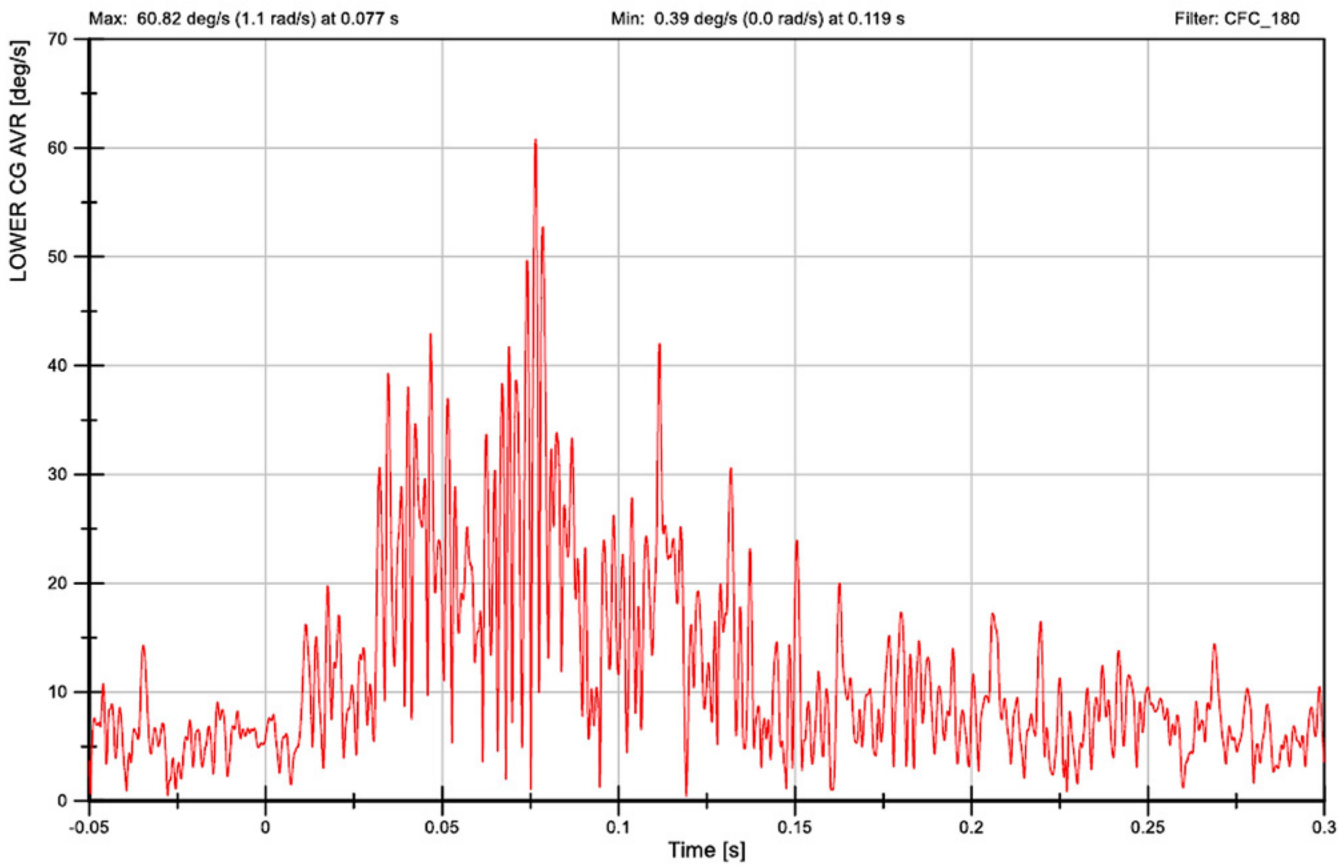

Figure C-33 *Test 3, Resultant Rotational Acceleration at the Sled CG (lower)*

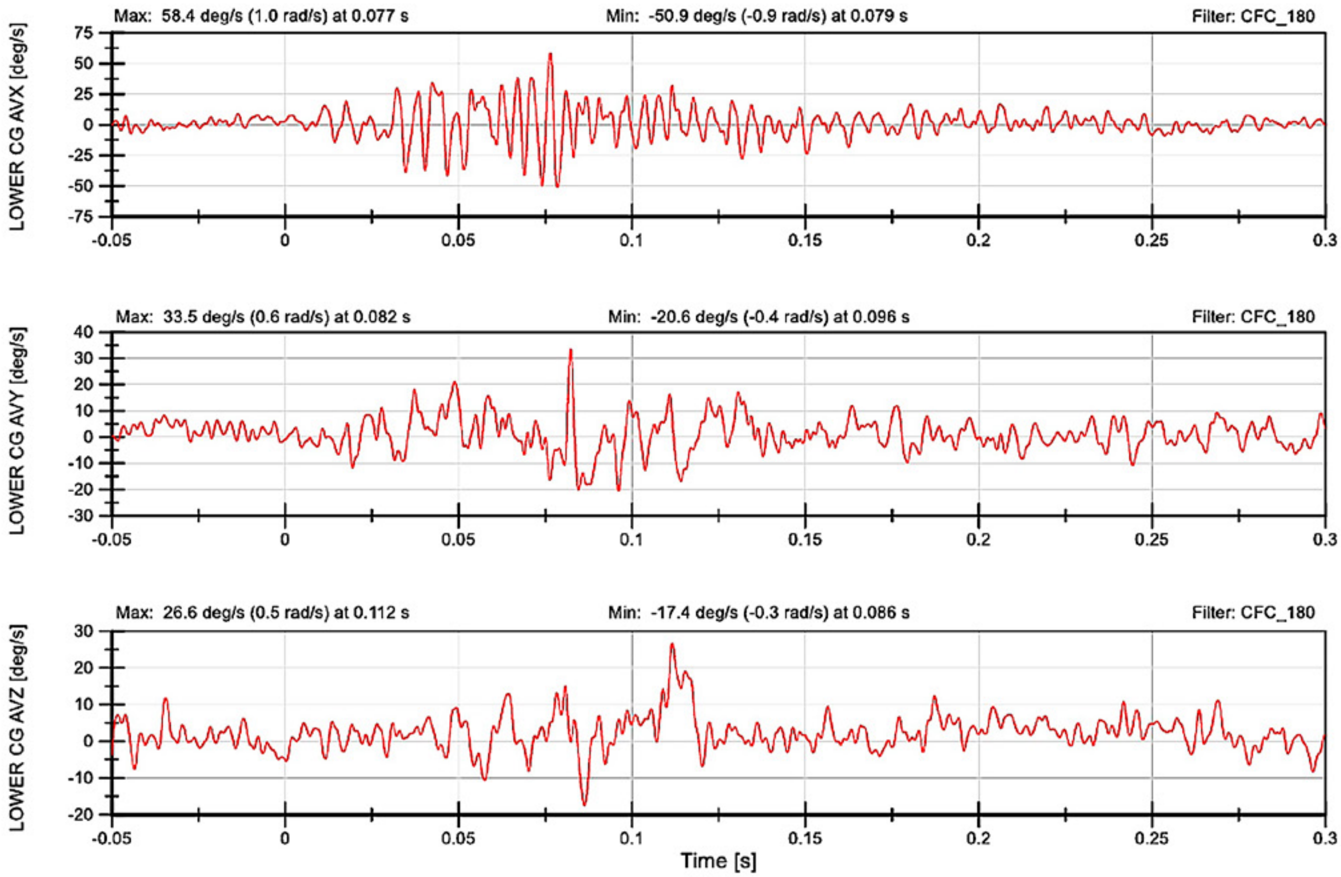

Figure C-34 *Test 3, Acceleration Rotational Components at the Sled CG (lower)*

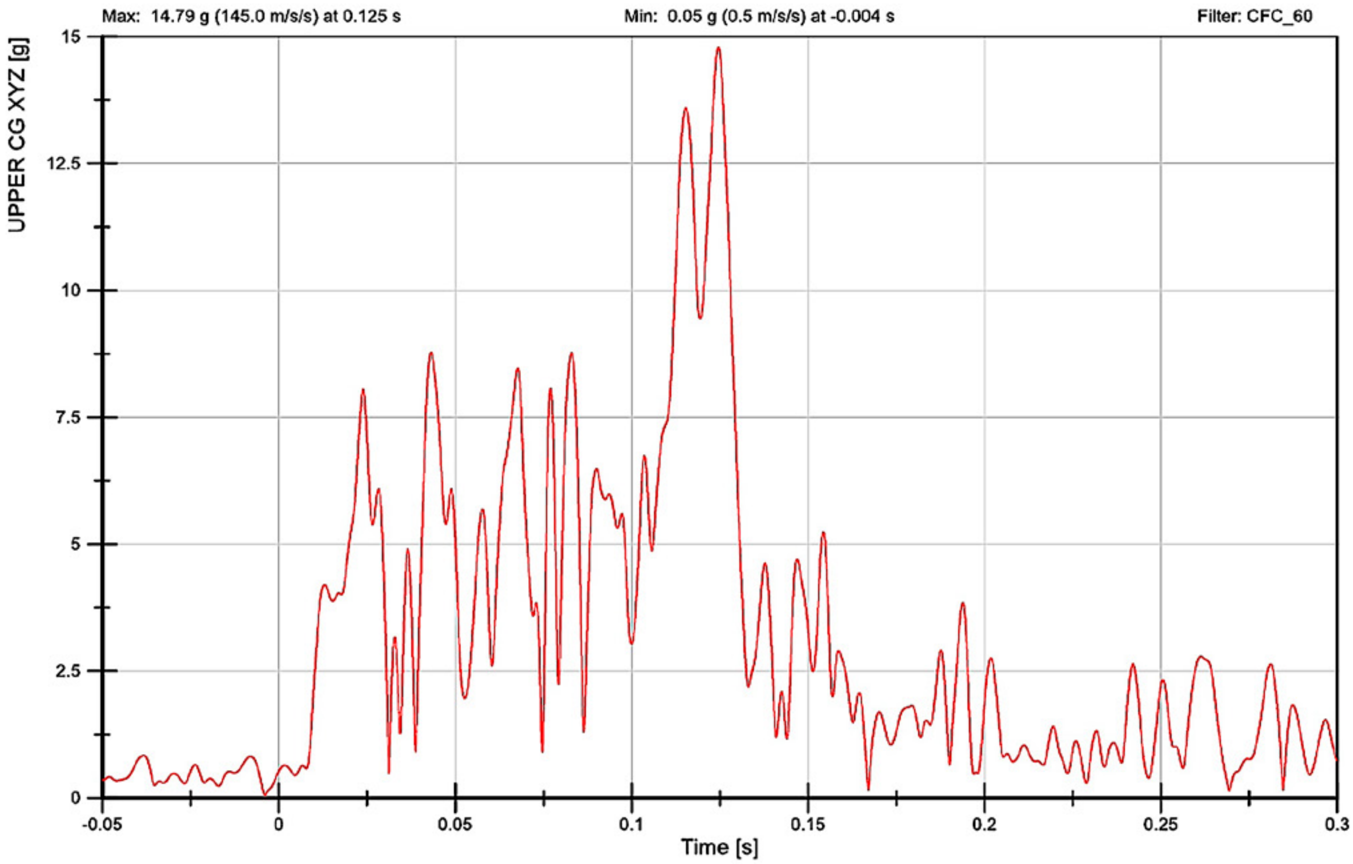

Figure C-35 *Test 3, Resultant Translational Acceleration at the Sled CG (upper)*

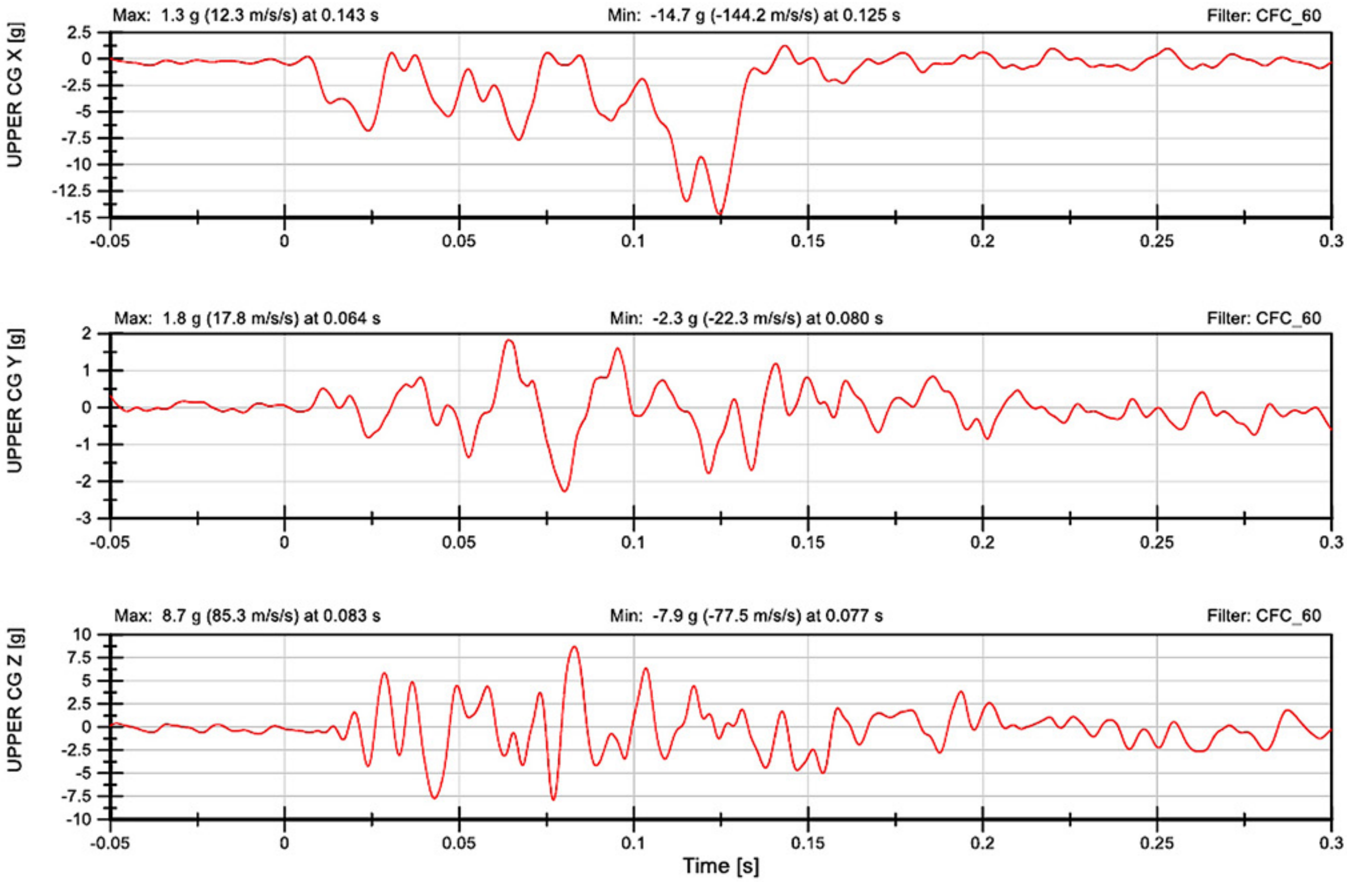

Figure C-36 *Test 3, Acceleration Translational Components at the Sled CG (upper)*

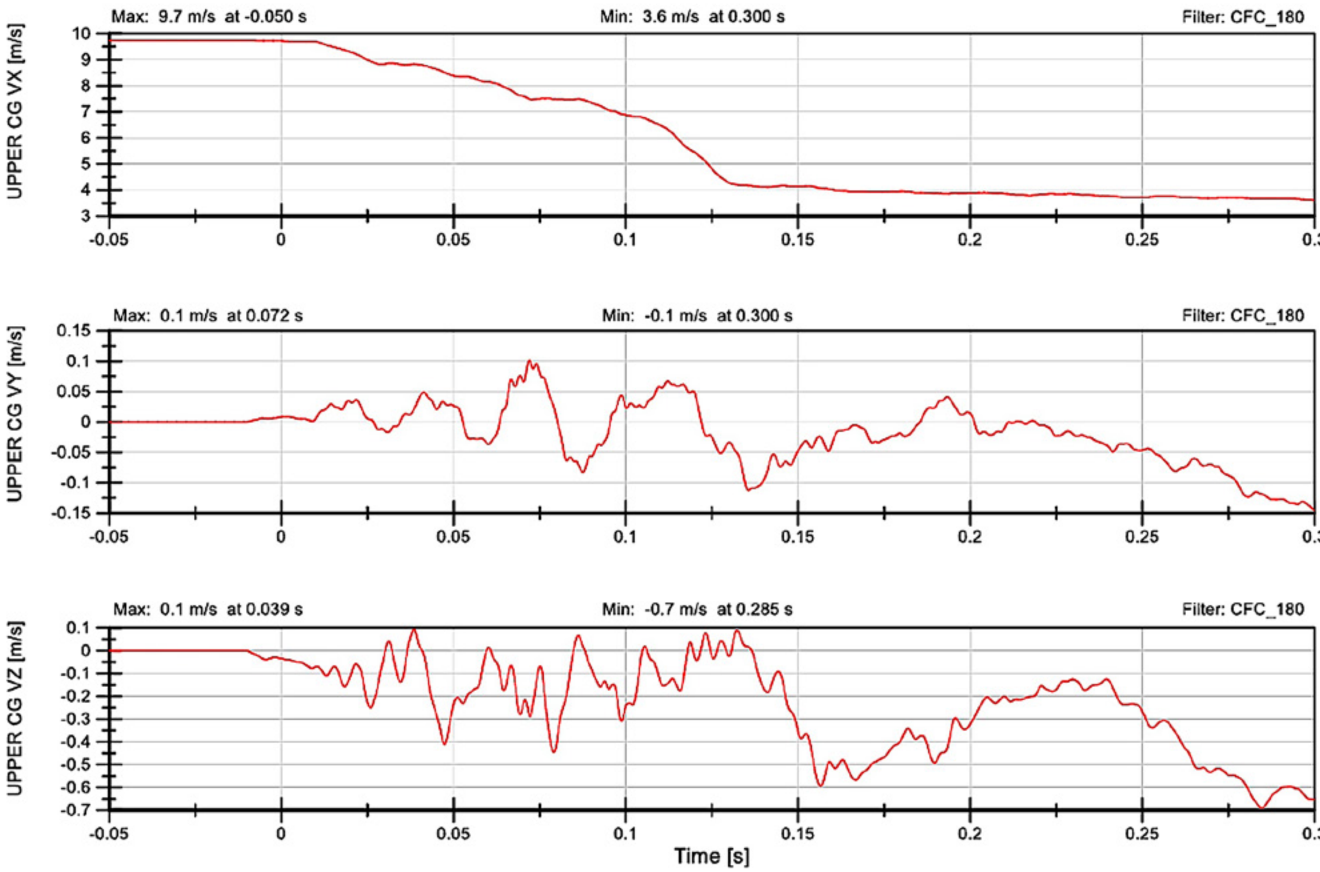

Figure C-37 *Test 3, Change in Translational Velocity Components at the Sled CG (upper)*

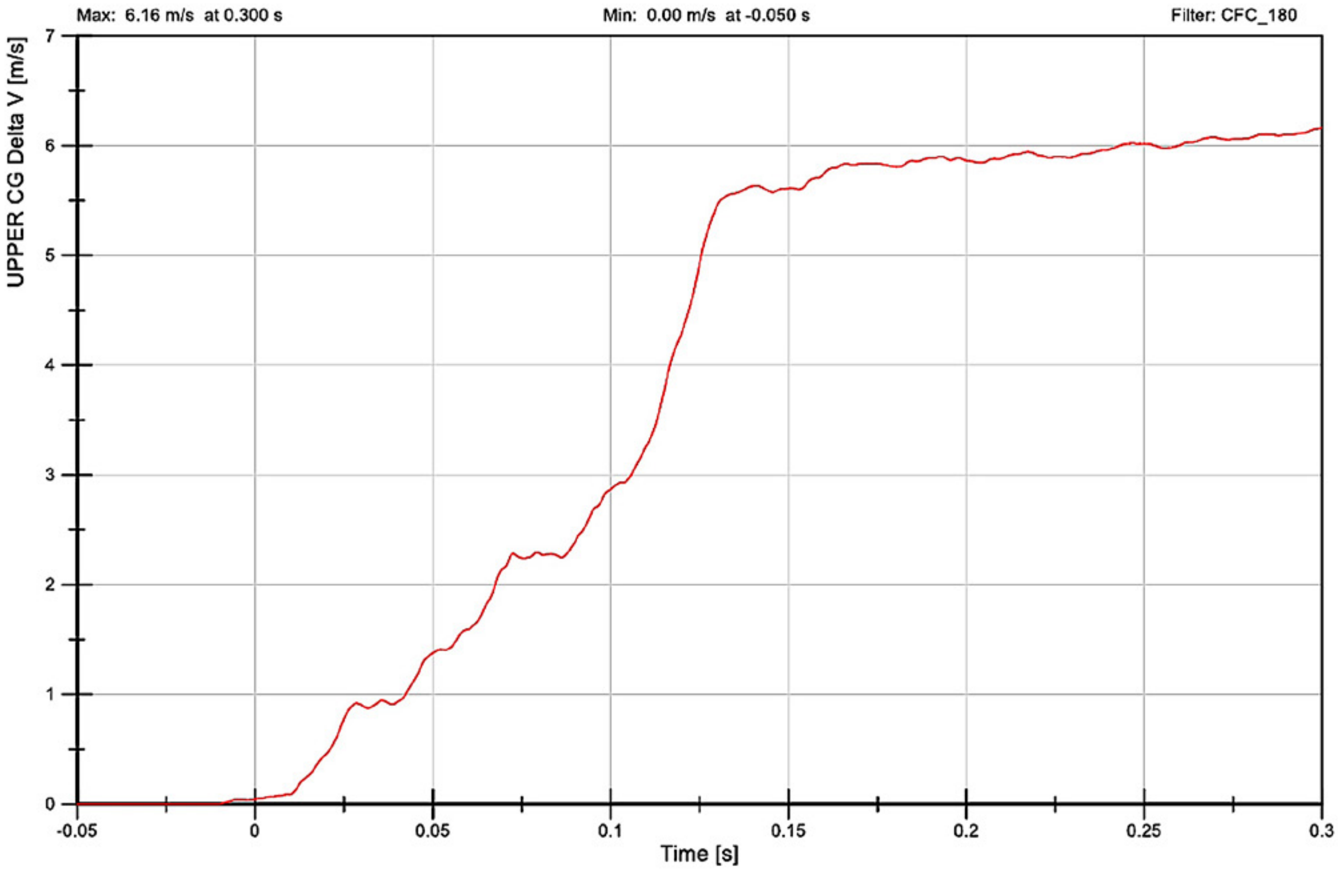

Figure C-38 *Test 3, Total Change in Translational Velocity at the Sled CG (upper)*

Acronyms and Abbreviations

AIS	Abbreviated Injury Scale
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATD	Anthropomorphic Test Device
CAPE	Center for Advanced Product Evaluation
CEM	Crash Energy Management
CF	Carbon Fiber
CG	Center of Gravity
CPI	Consumer Price Index
FE	Finite Element
HPU	Hydraulic Power Unit
KI	Kinkisharyo
LACMTA	Los Angeles County Metropolitan Transportation Authority (Metro)
LRV	Light Rail Vehicle
LST	Livermore Software Technology
MAIS	Maximum Abbreviated Injury Scale
MUWE	Median Usual Weekly Earnings
NHTSA	National Highway Traffic Safety Administration
SID	Side Impact Dummy
SUV	Sport Utility Vehicle
mph	Miles per Hour
ROI	Return on Investment
STRMTG	Le Service Technique des Remontées Mécaniques et des Transports Guidés
THUMS	Total HUman Model for Safety
VSL	Value of Statistical Life

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