U.S. Department of Transportation

Federal Railroad Administration

Improving Secondary Impact Protection for Freight Locomotive Engineers

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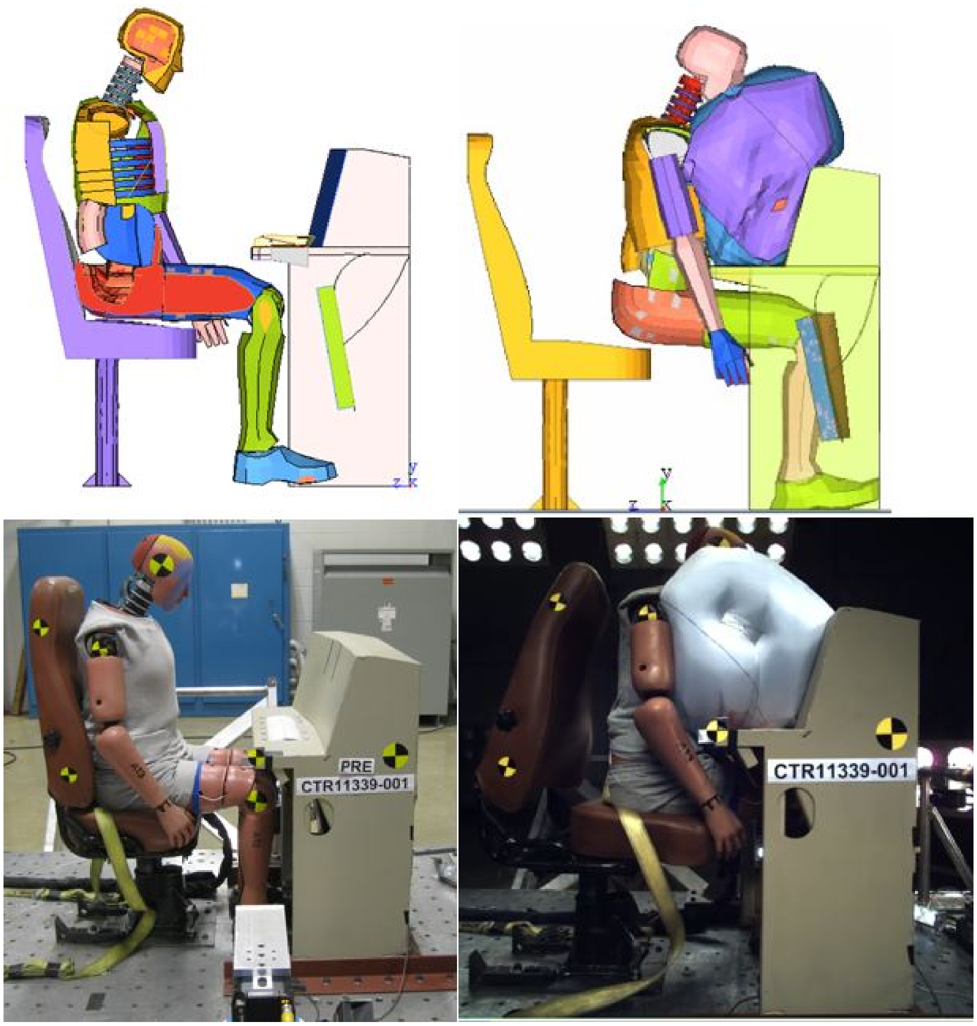
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)
A modern freight locomotive designed to the specifications of Title 49 Code of Federal Regulations (CFR) § 229.207 and the Association of American Railroads' (AAR) S-580 can preserve the space occupied by an engineer in the leading cab in a train collision up to moderate speeds. However, the space preservation does not provide protection against the injuries resulting from secondary impacts resulting from abrupt locomotive deceleration. The criteria for secondary impact protection are established in the Department of Transportation's Federal Motor Vehicle Safety Standard 208 (FMVSS 208).

A prototype Secondary Impact Protection System (SIPS) for locomotive engineers, consisting of an airbag and a deformable knee bolster, was developed and demonstrated under simulated collision conditions, using a dynamic sled test with a 95th percentile anthropomorphic test device (ATD). The airbag developed a tear at the time of maximum pressurization and was unable to slow the ATD sufficiently. However, the SIPS system met nine of the eleven injury criteria limits.

The simulation results for the latest airbag characteristics show that the design would meet the FMVSS 208 criteria including compartmentalization without impeding existing cab functional requirements. However, to optimize the modifications to the airbag design, characterization testing followed by sled testing is recommended.

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Airbag, anthropomorphic test device, ATD, crash test dummy, crashworthiness, energy absorption, finite element analysis, injury indices, knee bolster, secondary impact protection, sled testing

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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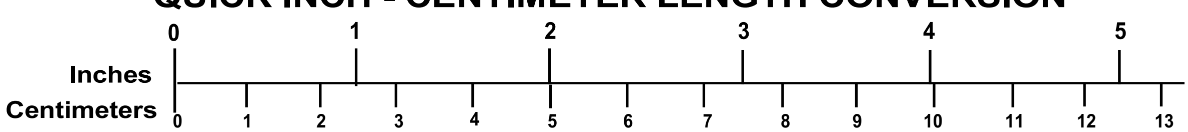
QUICK INCH - CENTIMETER LENGTH CONVERSION



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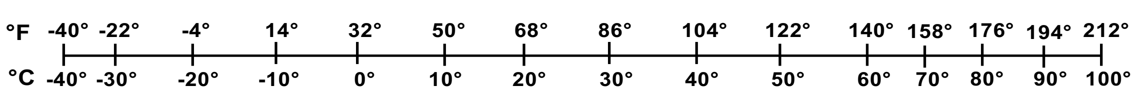

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

A modern freight locomotive designed to the specifications of Title 49 Code of Federal Regulations § 229.207 and the Association of American Railroads' S-580 can preserve the space occupied by an engineer during a train collision, particularly in the cab of a leading locomotive, up to moderate speed operations. However, the space preservation does not provide protection against the injuries resulting from secondary impacts that the engineer is likely to experience from the abrupt locomotive deceleration.

A previous effort supported by the Federal Railroad Administration (FRA) to develop, design and test a Cab Engineer Protection System (CEPS) for commuter cab car engineers, showed that a system consisting of an airbag and a deformable knee bolster can provide protection against injuries resulting from such secondary impacts. The CEPS system was successfully demonstrated to protect a cab car engineer in moderate-to-severe train collisions.

For the current effort, the CEPS concept was adapted by Sharma Associates, Inc. at their facility with necessary adjustments/modifications for the locomotive cab and desk space, i.e., the locomotive controls location and layout, and engineer desk geometry. This work was performed between August 2013 and April 2017.

Locomotive collision simulations were conducted using LS-DYNA, an advanced general-purpose multi-physics simulation software package, to ascertain that the acceleration pulse used in the CEPS system was appropriate to further develop the secondary impact protection system (SIPS).

It was established that the crash pulse used for the CEPS system was more conservative than the acceleration pulses seen in the LS-DYNA simulation of locomotive collisions. Therefore, the CEPS crash pulse was chosen for further simulations and developing the SIPS. RADIOSS® simulations revealed that to meet the injury criteria for the locomotive desk geometry and space environment, the airbag volume and shape needed to be modified. The modified airbag was designed and prototyped. Simple inflation and cold gas testing per SAE J1630 was carried out to study the final airbag deployed shape. Adjustments were made to the airbag geometry by altering tether lengths and orientations based on the LS-DYNA simulation of the airbag and anthropomorphic test device (ATD) interaction during deployment.

Once the integrated airbag and inflator system was confirmed to be functional, impactor testing was performed to estimate the airbag energy absorption. These tests indicated a need for controlled venting to manage the chest injury level as seen in the LS-DYNA simulations. A venting system was developed based on the airbag tethers' orientation and location such that as the airbag inflated and tethers developed tension, vent holes were exposed. The holes then would close after the ATD contacted the airbag and pushed it against the desk vertical surface to control venting of the airbag gas and provide resistance to ATD acceleration.

Once the venting system was integrated into the airbag, the LS-DYNA simulations showed the airbag and knee bolster system was effective in providing the locomotive design target protection against the injuries. A repeated impactor test confirmed the venting system functioned as expected. The SIPS sub-systems, i.e., airbag, inflator and knee bolster, were then assembled into the baseline locomotive cab/desk, and the full system was dynamically tested under the 23-g trapezoidal acceleration pulse used in the development and testing of the CEPS. During the test at the point of maximum pressure in the airbag at approximately 60 millisecond (ms) the lateral

right side of the airbag developed a tear and then deflated quickly leading to the ATD head impacting the desk top surface.

Post-test investigation of the airbag showed the weak spot in the airbag stitching where two perpendicular seams met and created a stress concentration point, ripping the airbag fabric and then tear propagated along one of the seams.

The sled test was repeated after modifications to the airbag stitching pattern and vent relocation. In the second test, the airbag deployed properly and held its shape and orientation until ~75 ms, but breached again in the same location as in the first test and deflated quickly.

In summary, the project successfully demonstrated the following:

- It is technically feasible to develop a secondary impact protection system for the freight locomotive engineer.
- The airbag and knee-bolster system prototype can be integrated into the locomotive cab layout and space environment.
- While the freight railway industry does not provide locomotive engineer injury criteria, the system simulations showed that it largely meets the United States Department of Transportation's FMVSS 208 safety performance requirements for automobiles which is also adhered to by the railway passenger equipment supply industry in the United States and overseas.

The system met 9 of the 11 FMVSS 208 injury indices. However, the system as designed and tested is quite promising and with modification to the airbag design and appropriate venting, the system can easily meet the requirements of providing protection against impact injuries.

As the final sled testing was not totally successful due to airbag failure, the system concept as designed and developed showed in a simulated environment the capability to meet the widely-accepted injury protection criteria. There were several challenges to the implementation of the designed concept. These are described in the report along with recommended solutions.

1. Introduction

A modern freight locomotive designed to the specifications of Title 49 Code of Federal Regulations (CFR) § 229.207 and the Association of American Railroads' S-580 can preserve the space occupied by an engineer during a train collision, particularly in the cab of a leading locomotive, up to moderate speed operations. However, the space preservation does not provide protection against the injuries resulting from secondary impacts he/she is likely to experience from the abrupt locomotive deceleration.

A previous effort supported by the Federal Railroad Administration (FRA) to develop, design and test a Cab Engineer Protection System (CEPS) for commuter cab car engineers, showed that a system consisting of an airbag and a deformable knee bolster can provide protection against injuries resulting from such secondary impacts [7] [8]. The CEPS system was successfully demonstrated to protect a cab car engineer in moderate-to-severe train collisions.

For the current effort, the CEPS concept was adapted with necessary adjustments/modifications for the locomotive cab and desk space, i.e., the locomotive controls location and layout, and engineer desk geometry.

1.1 Background

Positioned at the leading end of a train, locomotive engineers are exposed to significant injury potential in a frontal rail vehicle collision. The engineer's cab often suffers the most damage given that, generally, there is little energy-absorbing structure between the cab and the primary point of impact. While there is some ongoing research on improving the energy absorption at this interface using pushback couplers and deformable anti-climbers, these efforts are focused on passenger units and are presently far from full implementation on freight locomotives.

FRA has funded significant research into improving the crash protection of locomotives. In addition, working with the railroad industry and railroad labor through the Rail Safety Advisory Committee (RSAC) process, FRA has introduced newer crashworthiness standards for locomotives, such as stronger collision posts and corner post structures, which has provided a robust structural cage at the front of the locomotive and increased the survival space for locomotive engineers [5].

These newer standards, laid out in both Federal regulations (49 CFR § 229.207) and railroad industry standards, AAR S-580 have improved the survivability of locomotive engineers [2]. Full scale testing with these improved cabs has demonstrated the safety benefits associated with the newer standards, especially the preservation of the cab space.

Even when sufficient survival space in the locomotive cab is preserved, there is a high probability for serious injuries to the engineer from secondary impacts. Secondary impact occurs when the locomotive decelerates or accelerates suddenly due to collision forces and the cab occupant(s) strike some part of the interior. Given the hard surfaces and protruding knobs/controls in a locomotive cab, even a low speed collision can result in large, concentrated impact forces acting upon the engineer, with the consequence of serious bodily injuries and even fatality.

Recent research has suggested that without additional protection, under a moderate rail vehicle collision, a locomotive engineer could be subjected to injuries to the head, neck, and femur that are significantly over the limits prescribed by the Federal Motor Vehicle Safety Standards (FMVSS) 208 used in the automobile industry for qualifying the driver/passenger restraint and protection system, i.e., airbag [3].

The primary intent of this research effort was to develop and demonstrate a mechanism and methodology to protect a locomotive engineer from significant secondary impact injuries in moderate to severe rail vehicle collisions. Given the strong structural cage provided by modern locomotive cabs, providing secondary impact protection to the engineer is the next logical step in improving his/her survivability. Thus, there is a significant need to develop a system that can protect the locomotive engineers from secondary impact injuries in low-to-moderate speed (up to 30 mph) frontal collisions, considering the availability of modern, state-of-the-art occupant protection technologies.

1.2 Objectives

The objectives of this project include:

- Investigating and defining the technical requirements for a Secondary Impact Protection System (SIPS) for an engineer in modern locomotives.
- Developing a SIPS for such a locomotive that meets the defined performance requirements.
- Designing a prototype system against the performance goals through simulation, building, testing, and validation.

1.3 Overall Approach

Under a recent FRA sponsored effort, a commuter CEPS to protect engineers during frontal train collisions was developed [7]. The CEPS concept used a large automotive style passenger airbag in conjunction with a crushable knee bolster to provide the level of protection needed, without compromising egress for the engineer, or adding significant weight or cost.

Figure 1. Sled Test Evaluation of the CEPS under a 23-g Trapezoidal Crash Pulse

This CEPS system was prototyped and successfully tested under a dynamic sled test, shown in Figure 1, with a 23-g crash pulse (representing a moderate-severe collision) [6] [7] [8]. This system was shown to meet the human injury limit criteria (FMVSS 208) for the head, chest, neck, and femur [8].

SA's approach for the SIPS project was to adopt this proven CEPS concept and to develop and modify it for application for the freight locomotive cab environment. To ensure the suitability of this system for locomotive applications various other possible concepts were discussed in a brainstorming session and ranked against the CEPS. A similar process had been used to finalize the concept developed, prototyped and tested in the CEPS. The CEPS concept was determined to be the most viable from this discussion. The informal process used for the discussion is summarized in Appendix A.

1.4 Scope

The overall scope to accomplish the project objectives consisted of the following steps:

- Defining the design and performance goals requirements for SIPS
- Reviewing various locomotive cab layouts to select a representative layout for the SIPS development
- Developing a computer-aided design (CAD) model for the desk/console
- Conducting locomotive collision simulations to ascertain if the secondary impact velocity (SIV) profile from the 23-g crash pulse used in CEPS was viable for locomotive application
- Simulating the SIPS, which is comprised of the airbag and knee-bolster system from CEPS as initial design step
- Assessing and identifying the airbag and knee bolster modification/development effort to meet the performance requirement of the FMVSS 208 injury indices [3]
- Characterizing the new airbag for packaging, installation, unfolding and deployment through cold gas/compressed inflation, static deployment, and impactor testing
- Simulating the finalized airbag design to assess its performance against the FMVSS 208 requirements
- Conducting sled test followed by validation test

Execution of the process steps outlined above is described in the following sections.

1.5 Organization of the Report

This report consists of the following 10 sections, which contain:

Section 1: The background, objectives, overall approach, and scope of work for the project.

Section 2: A discussion of the design and performance requirements of the SIPS system as they relate to safety, system geometry and functionality, performance in service and overall system design.

Section 3: A discussion of the development of the design crash pulse for which system capacity requirements and characteristics are derived.

Section 4: The development of the surrogate cab control stand and its features.

Section 5: A description of the airbag design concept and the knee bolster component.

Section 6: A description of the component testing performed.

Section 7: A discussion of how the components are assembled into the sled test-ready system configuration.

Section 8: A description of the full-scale sled test and results in the context of the FMVSS 208 injury criteria.

Section 9: A discussion of the reasons for exceedance of certain FVMSS 208 injury criteria in the context of the sled test and the performance of the airbag.

Section 10: The overall conclusions drawn for the presented work as well as the recommendations for additional research.

The report also comprises five appendices:

Appendix A: Describes the initial brainstorming activities to develop the SIPS requirements.

Appendix B: Contains drawings and photographs of the engineer desk mock-up and its components.

Appendix C: Describes the airbag venting mechanism.

Appendix D: Contains photographs of the damage to the knee bolster sustained during the sled test.

Appendix E: Contains proposed injury criteria for the 95th percentile male anthropomorphic test device (ATD).

2. Design and Performance Requirements

To ensure a successful development and eventual implementation of the envisioned SIPS concept, the requirements may be classified as follows:

- Safety performance requirements
- Design geometry and functionality requirements
- Service performance requirements

2.1 Safety Performance Requirements

The design of the SIPS must address protection for the head, neck, torso, and femur of the engineer, effectively compartmentalize the engineer, and adequately position and control deceleration of the upper body, mid body, and lower body without the use of passive restraints (e.g., seatbelts).

The safety performance requirements consist of a defined input crash pulse, the ATD requirements, and the limiting injury criteria to FMVSS 208, as well as, other needed constraints due to operating practices.

2.1.1 Input Crash Pulse

The CEPS were developed for a 23 g, 130 ms, trapezoidal crash pulse (Figure 2), which was derived from the full-scale, multi-level, passenger rail car test that was conducted at the Transportation Technology Center (TTC) [9]. This pulse represents a moderate-to-severe collision. The SIV for this pulse is also shown in Figure 2.

The approach for SIPS is to calculate the SIV curves from the acceleration pulse in locomotive collision simulations and evaluate those against the pulse and the SIV used in the CEPS. If these crash pulses are found to be less severe than the 23-g pulse, it is proposed that the 23-g trapezoidal pulse of Figure 2 be used for the SIPS development effort instead to ensure designing for the worst known case.

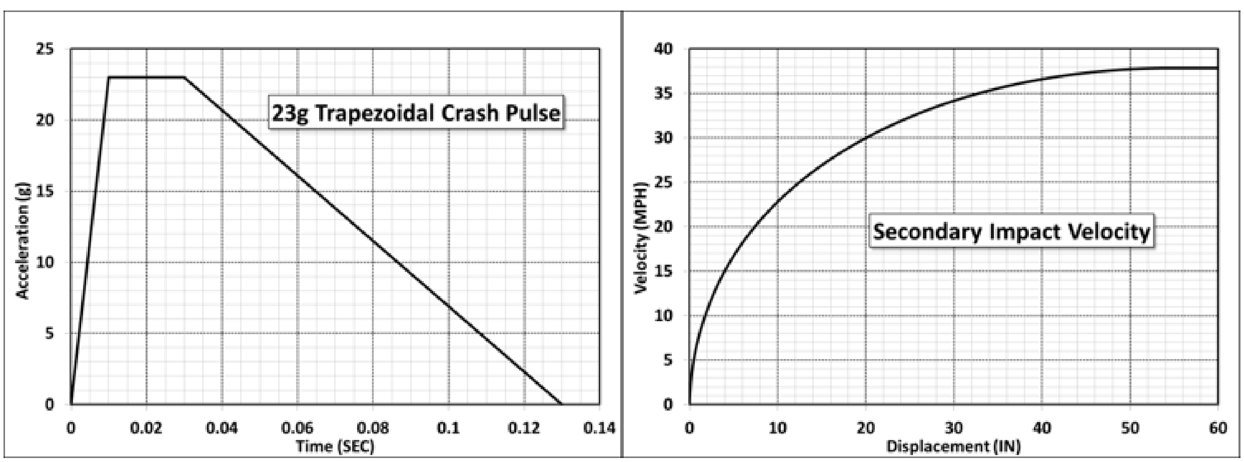
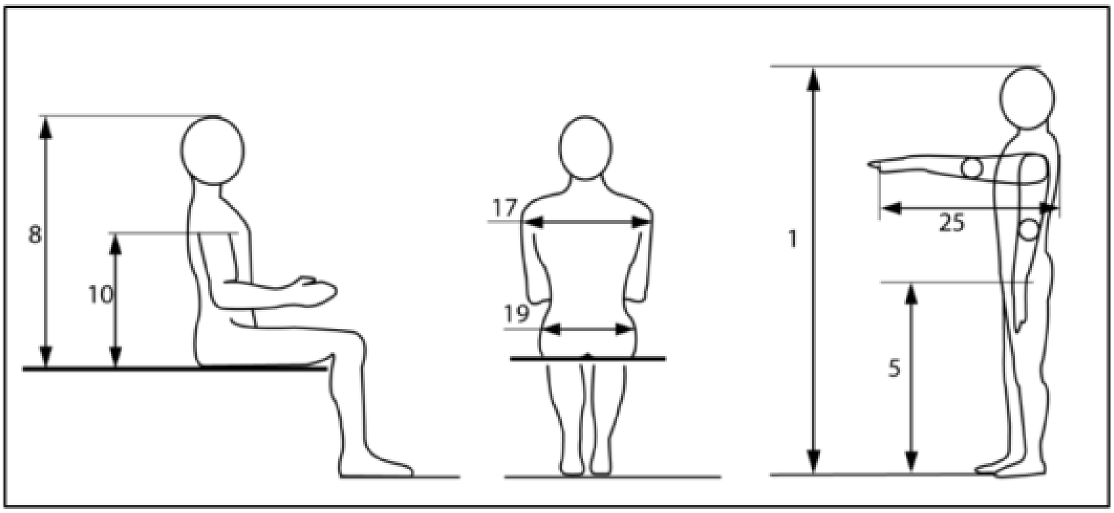


Figure 2. Trapezoidal Crash Acceleration Pulse and Secondary Impact Velocity—CEPS

2.1.2 ATD Requirements

The automobile industry uses a 50th percentile Hybrid III male ATD for the crash testing required for FMVSS 208 certification. However, due to the general dimensions (height and weight) of locomotive engineers, it was decided that SIPS be designed for a 95th percentile Hybrid III male ATD. The physical attributes of a 95th percentile Hybrid III male ATD are shown in Figure 3 below.



#	Dimension	Measurement	
		Metric	Imperial
	Weight	102 kg	225 lb.
1	Standing Height	186.5 cm	73.4 in
5	Hip Height	100.0 cm	39.4 in
8	Erect Sitting Height	97.0 cm	38.2 in
10	Sitting Shoulder Height	64.5 cm	25.4 in
17	Sitting Shoulder Width	50.5 cm	19.9 in
19	Hip Width	40.5 cm	15.9 in
25	Shoulder Grip Length	71.5 cm	28.1 in
30	Foot Length - bare	28.5 cm	11.2 in
31	Foot Width - bare	11.0 cm	4.3 in

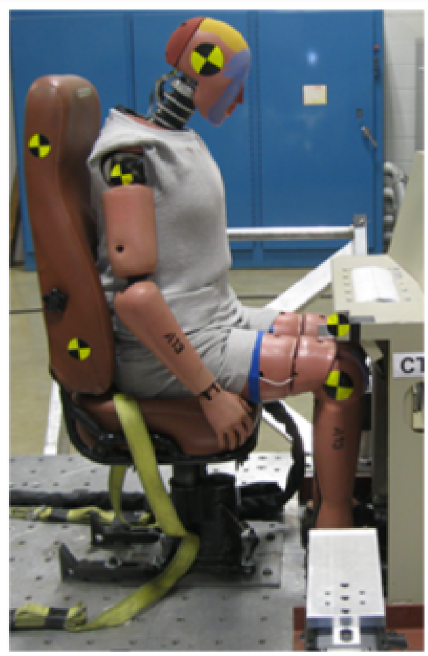


Figure 3. Characteristics—95th Percentile Hybrid III Male ATD

2.1.3 Injury Criteria

FRA does not have any injury criteria standards for freight rail operations crew. The CEPS effort used FMVSS 208, which is the controlling Federal standard for crash design of automobiles. This standard has also been adopted by the American Public Transit Agency (APTA) as part of its seats and interiors standard, and there is existing precedent of its use in the railroad industry.

2.1.4 Engineer Position

To minimize injuries, the ATD needs to physically remain away from the surfaces in the vicinity of the desk during a crash situation. However, the absence of a seatbelt in the locomotive cab is a challenge for any system to minimize injuries, because the engineer might not be seated facing forward and centered relative to his seat and the airbag location. Thus, the airbag location and shape must be optimized to promote engineer compartmentalization with this additional constraint in mind.

2.1.5 Other Constraints

Past interviews with representatives of the Brotherhood of Locomotive Engineers and Trainmen (BLET), the union representing locomotive engineers, have indicated that locomotive engineers wish to retain the ability to quickly flee the locomotive in case of impending impact, and that the use of seatbelts has the potential to inhibit free egress. Therefore, the SA design will attempt to satisfy the injury criteria without the use of seatbelts. A related additional criterion is that the system will not require input from the engineer to deploy. To implement this criterion, the system will be designed to deploy automatically based on detecting an impact of the appropriate magnitude using acceleration sensors that are to be mounted to the structure of the locomotive.

2.2 Design Geometry and Functionality Requirements

To ensure functionality, and effectively gain field acceptance, it is imperative that the designed SIPS integrate well into the nominal console structure used in a modern locomotive. The following guidelines were used by the SA team to develop the design of the SIPS.

- The geometry of the design must meet the requirements of the "clean cab" concept, as outlined in AAR's 2006 "Manual of Standards and Recommended Practices, Section M, Locomotives and Locomotive Interchange Equipment."
- To the extent possible, the location and the size of the controls will not be changed substantially from conventional design layouts.
- The SIPS must not impede or protrude into the regular workspace of the locomotive engineer. The system must be designed so that deployable and impact absorption surfaces cannot be used to append, support or store "non-installed" items (for example, coffee mugs or writing pads). Active deployable systems must be designed to prevent foreign objects from being placed in the deployment path of the system to prevent the foreign objects from becoming projectiles and from impeding the airbag deployment.
- Surfaces of the "clean cab" that are designated as impact or impact absorption surfaces must be designed with friendly edges devoid of sharp corners or thin edges that could cut and cause acute injury to the engineer. Additionally, surfaces designated as reaction or

support surfaces for active airbag safety systems must be designed to prevent any lacerations of the airbag during deployment.

- While cost and weight are only secondary factors in system performance, they are nonetheless, the key to success in the final implementation phase. Therefore, appropriate cost and weight limits/requirements for the system will be developed as part of this effort.

2.3 Service Performance Requirements

From the perspective of long term performance and viability, the following service requirements were considered by SA in the development of the SIPS.

- Active protection systems will not trigger under normal operational loads. The controller for an active protection system, such as an airbag must determine the severity of an actual impact event from normal operational loads/accelerations to prevent unintended triggering of the active protection system.
- Active safety systems that employ ignition deployment devices must have a process to deactivate the system for service and maintenance.

2.4 System Design Goals

The SIPS design was governed by the following key characteristics:

- Protect engineers from the secondary impact that occurs following a frontal train collision, when the engineer strikes the control console.
- Require no action from the engineer to trigger the system.
- Allow for an unencumbered post-deployment exit of the engineer.
- Seatbelts or other systems that must be disengaged before the engineer can flee the locomotive cab must not be incorporated into the design.
- Provide compartmentalization of a 95th percentile ATD, and keep the measured injury criteria for the ATD’s head, chest, neck, and femur below the limits (see Table 1) currently specified in FMVSS 208 [3].

Table 1. FMVSS 208—Limiting Injury Values (49 CFR § 571.208—Section 6)

Injury Criterion	**Limiting Value**
HIC_{15}	<700
Chest Deceleration	<60 g over a 3 ms clip
Chest Deflection	<2.5 in. (63 mm)
Axial Femur Loads (Left and Right)	<2,250 lbf (10,000 N)
Neck Tension	<937 lbf (4,170 N)
Neck Compression	<899 lbf (4,000 N)
N_{ij} (N_{te}, N_{tf}, N_{ce}, N_{cf})	<1.0

3. Crash Pulse Simulations

In this section, the derivation of the input crash pulse (acceleration time history) is presented. Three collision scenarios are conceived and analyzed. The secondary impact velocities (SIVs) are computed for each scenario and compared to those obtained from the 23-g trapezoidal crash pulse described in Section 2.1.1 which was used in the development of the CEPS.

3.1 Input Crash Pulse

One of the primary requirements of this task was to develop and analyze a series of crash models to determine a typical acceleration pulse history at the cab seat locations. All finite element (FE) models were developed using HyperMesh, a high-performance FE preprocessor [11]. Simulations were performed using LS-DYNA3D, a commercial nonlinear explicit finite element analysis (FEA) solver [12] [13]. This simulation tool is capable of accurately predicting the behavior of nonlinear large-deformation crash problems.

The locomotive model was based on 49 CFR § 229.207 and the AAR S-580 compliant modern 6-axle 4000 HP locomotive and included all the basic structural and mechanical components with their corresponding masses and inertias, as shown in Figure 4.

The draft gear is a simplified model that accounts for appropriate nonlinearities. The collision simulations were conducted for three scenarios:

- A single locomotive crashing into the rigid wall, Figure 5.
- A single locomotive crashing into the rigid wall with a weight equivalent to three loaded 263,000 lb. cars behind the locomotive to simulate the first order effect of a train consist.
- A single locomotive crashing into another stationary locomotive with an equivalent weight of 10 loaded 263,000 lb. cars added behind the locomotive to simulate the first order effect of a train consist, Figure 6.

Figure 4. FE model of a Typical 6-Axle North American Freight Locomotive

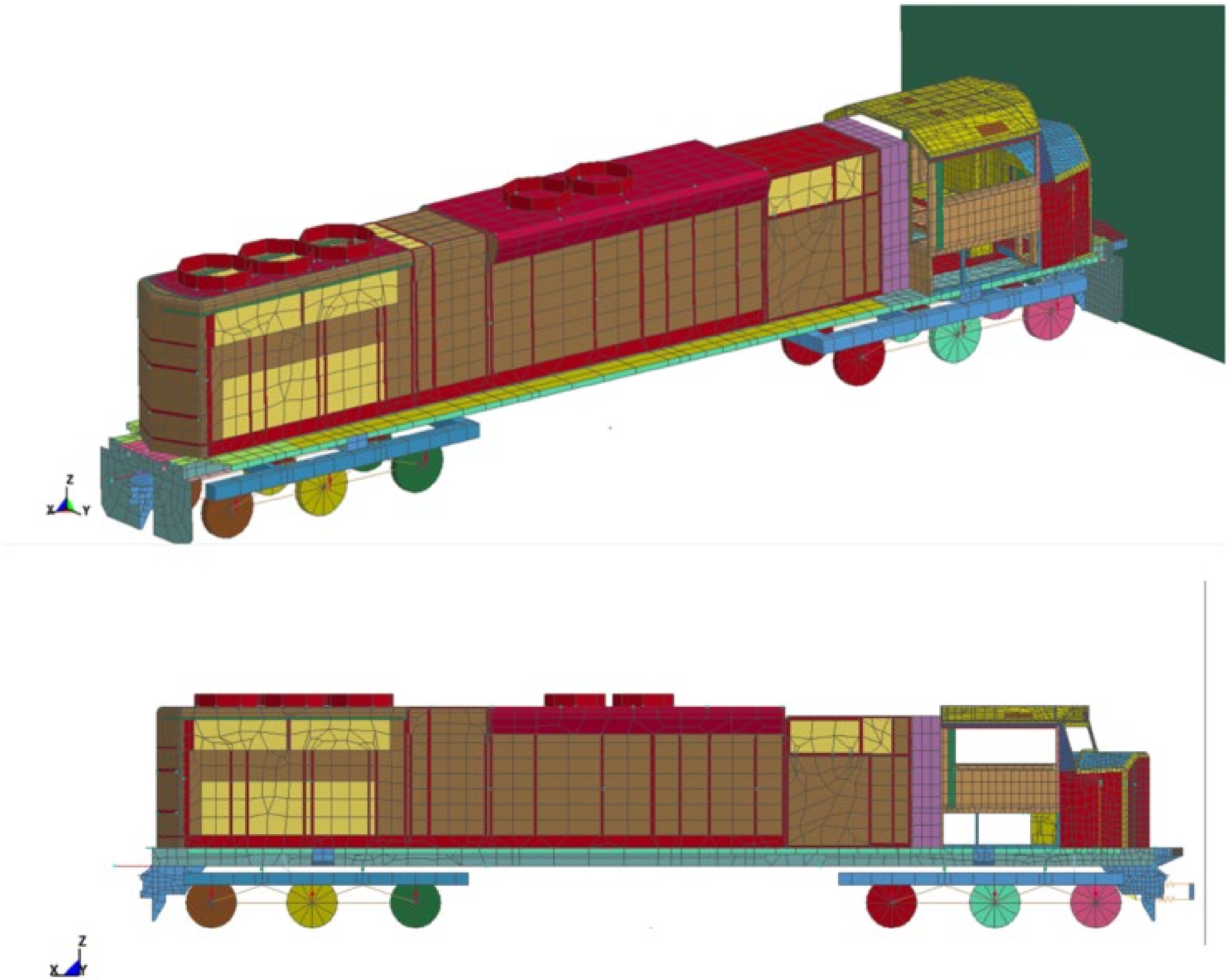


Figure 5. Locomotive to Rigid Wall Collision

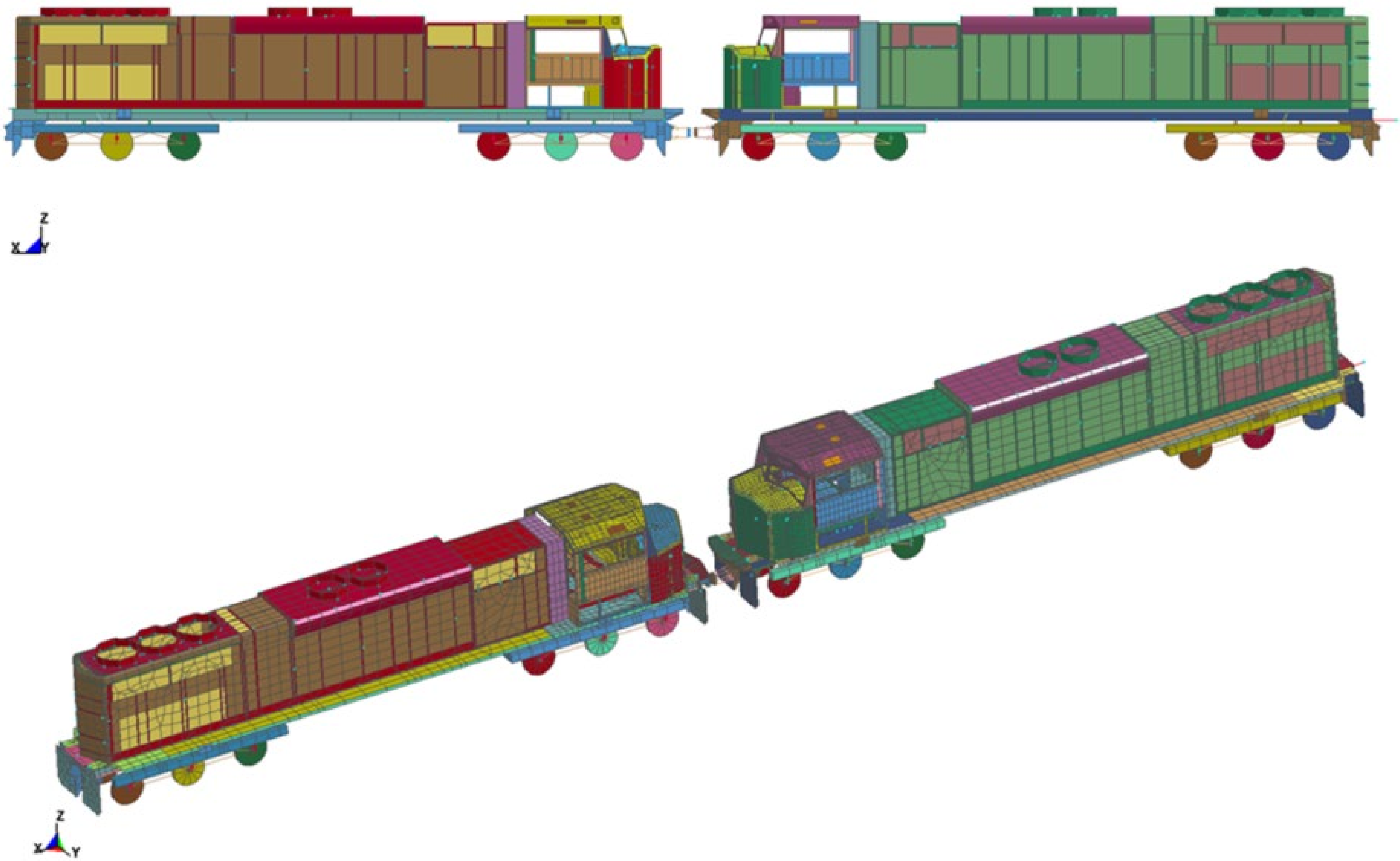


Figure 6. Locomotive-to-Locomotive Collision

The SIVs for the three simulated cases at various speeds are shown in Figure 7, Figure 8, and Figure 9.

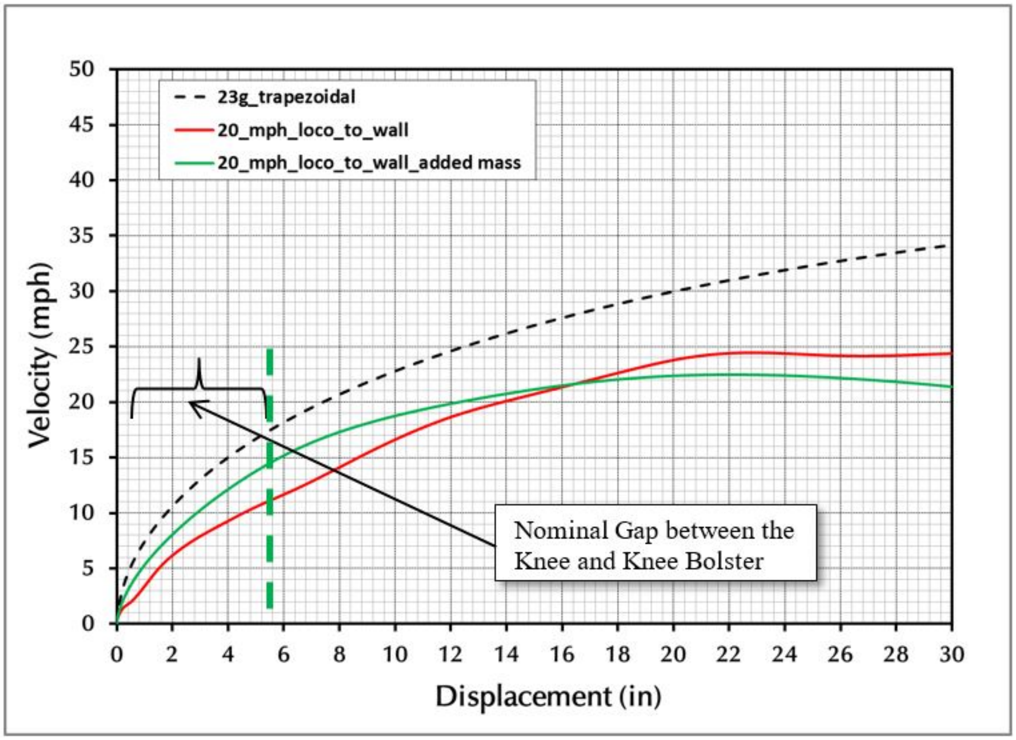


Figure 7. SIV for Locomotive-to-Rigid Wall Collision (Single Locomotive)

In Figure 7, the SIVs are shown for the case of a single locomotive impacting a rigid wall at 20 mph along with the SIV for the 23-g trapezoidal pulse. It is seen that the SIV produced in the simulations for both cases. The locomotive by itself and the locomotive with added mass are lower than the SIV for the 23-g pulse. The SIV for the case of the locomotive with added mass is higher than the case of the locomotive by itself up to 16 inches of distance. This distance is much larger than the nominal clearance between the knees of seated engineer and the potential knee bolster location. After the knees contact the knee bolster, the engineer's upper body begins to rotate forward and the injury protection will be provided by the air bag as it deploys and arrests the forward motion of the engineer before the lower torso contacts the desk edge.

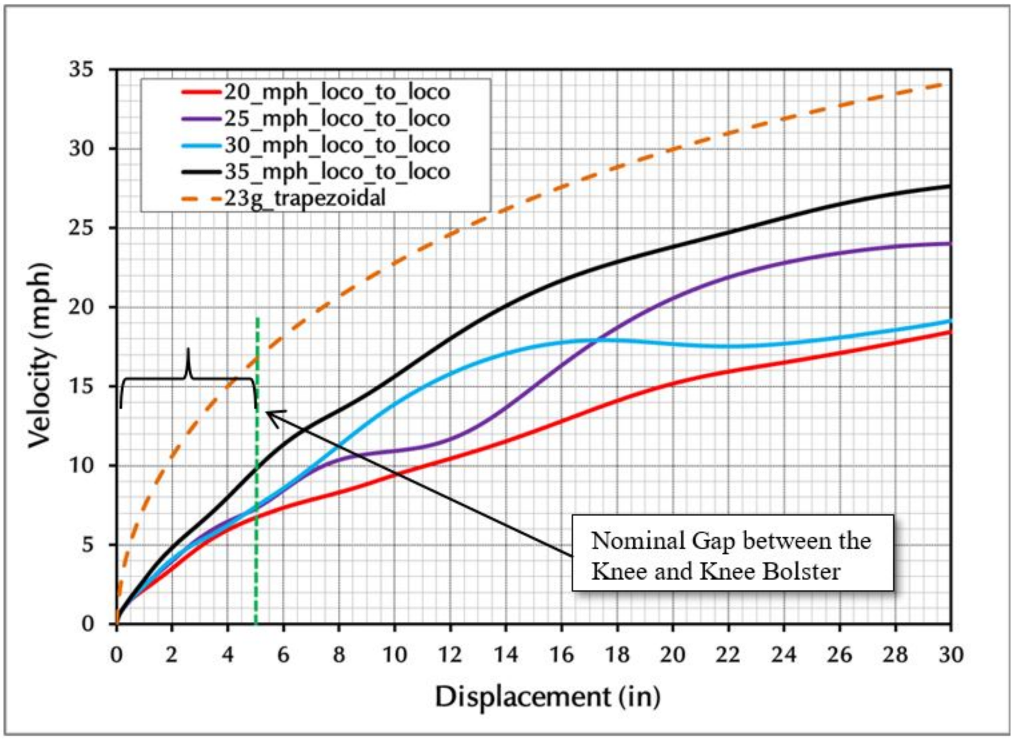


Figure 8. SIV for Locomotive-to-Locomotive Collision (Single Locomotive into a Locomotive with 10 Cars Equivalent Mass Behind It)

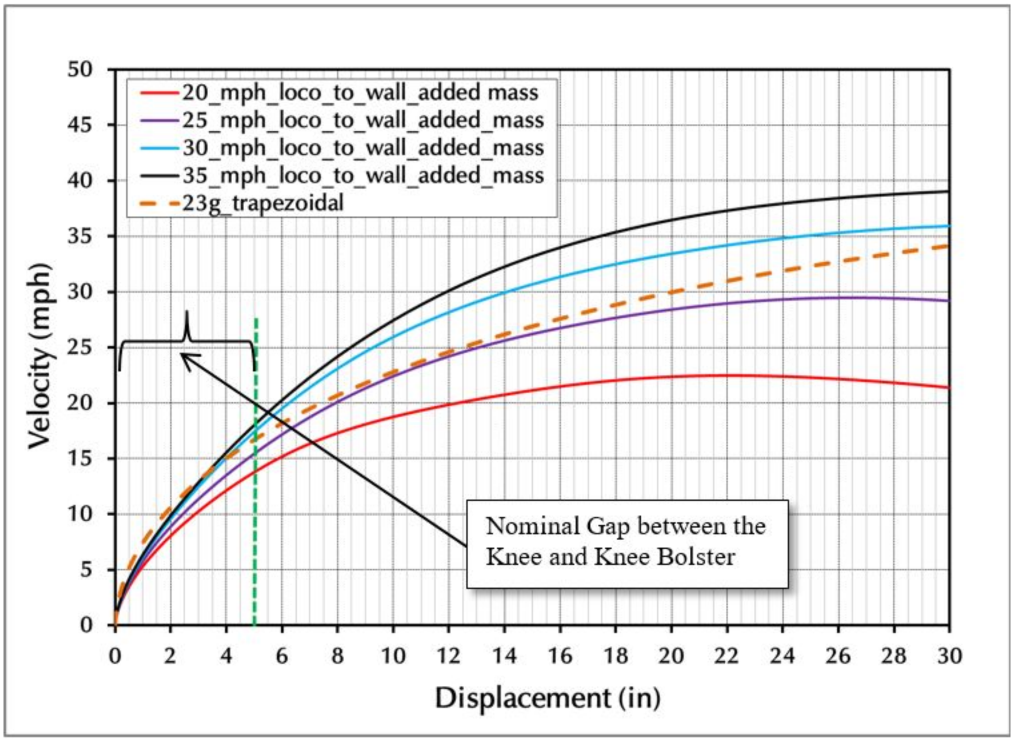


Figure 9. SIV for Locomotive-to-Rigid Wall Collision (Single Locomotive with Three Cars Equivalent Mass Behind It)

For both collision cases, four speeds of 20 mph, 25 mph, 30 mph and 35 mph were simulated to extract the acceleration pulse at the engineer cab floor to develop SIV curve. The SIVs from these simulations for both collision cases are shown in Figure 8 and Figure 9.

Figure 8 includes the case of the locomotive colliding with another locomotive with a string of 10 cars behind it. For this case, the SIV for the 23-g trapezoidal pulse shown in Figure 2 has higher SIV than the simulated cases for all four speeds up to a distance of 30 inches.

Figure 9 includes the case of the locomotive colliding into a wall with a string of three cars behind it. Although the SIVs at all four speeds in this case are higher than the ones for the locomotive-to-locomotive collision case, the SIV for the 23-g trapezoidal pulse is either still higher or nearly the same in the initial area of interest, i.e., the knee to knee bolster gap.

Both Figure 8 and Figure 9 show a nominal gap between the knee of the locomotive engineer and the knee bolster. This is based on the CEPS work and is approximately 4–5 inches. Once this gap is taken up by the ATD in a collision, the locomotive engineer will begin to slow down and the kinematics would cause the engineer's upper body to lean forward and contact the airbag.

These simulations showed that the SIV in the first 5–6 inches of deflection were less severe than the 23-g trapezoidal crash pulse used in the CEPS effort. Therefore, all further simulations and tests were planned and conducted with the same 23 g trapezoidal crash pulse as in the CEPS project. This pulse was derived from the crash test of a single multi-level passenger car into a rigid wall at a speed of 36.6 mph [9].

4. Cab Layout Review

During the design and development of the CEPS system for commuter cab cars, a careful review of the various cab control layouts was conducted to select the most representative system. The same approach was used in the selection of representative locomotive cab layout to develop the SIPS.

4.1 Locomotive Cab and Desk Model

To select the locomotive engineer desk configurations for the SIPS project, several locomotive cabs were visited to understand the location of the desk surface, throttle and brake controls, and any computer console relative to the engineer seat. Four such layouts are shown in Figure 10. There are some minor variations in how the various cab configurations are laid out. However, in most cases, the locomotive controls and handles are located left of the engineer, away from the console in front of the engineer. This provides for a suitable option for locating the airbag in front of the engineer.

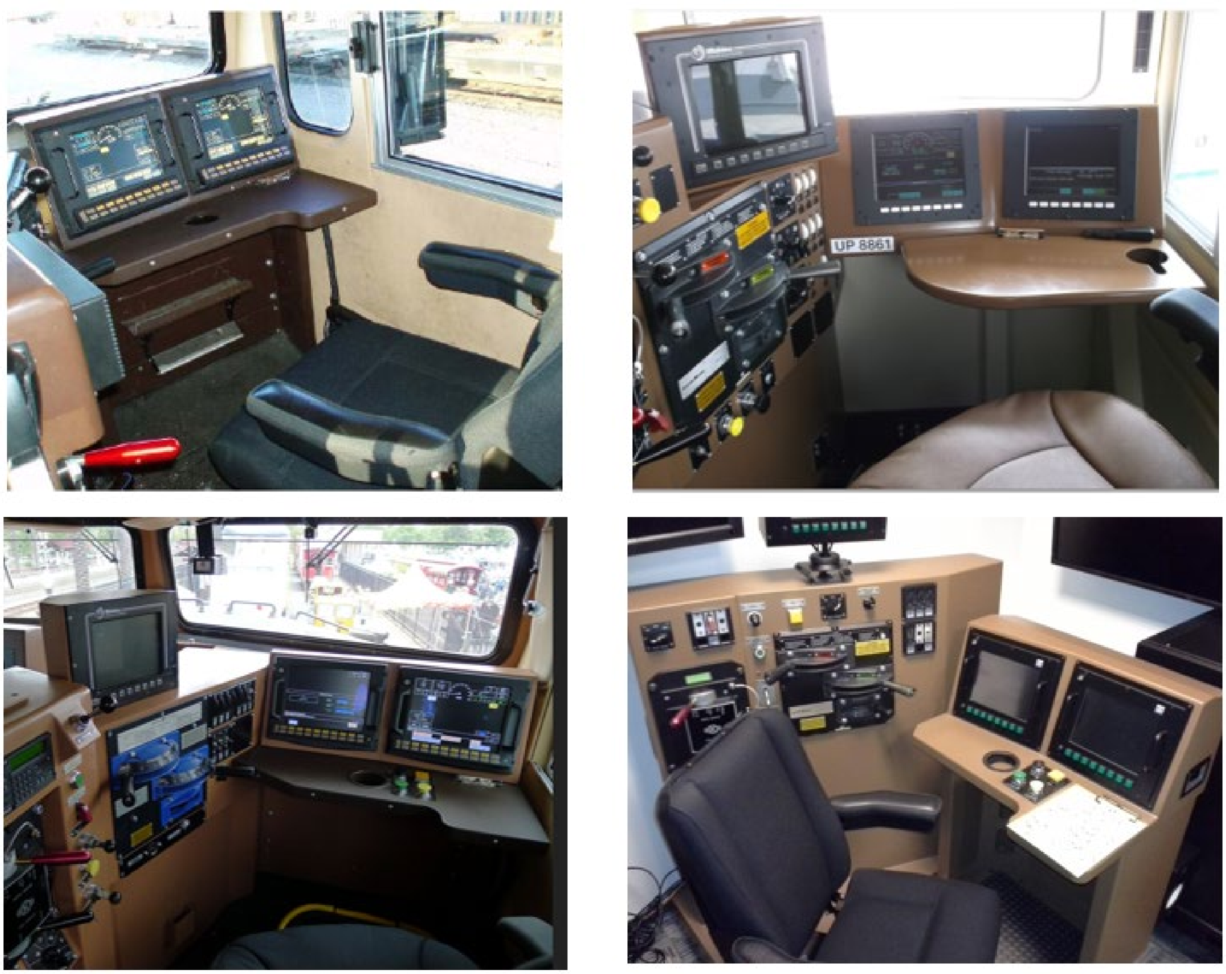


Figure 10. Various Modern Locomotive Engineer Cab and Desk/Console Arrangements

Once the desk layout was selected, geometric measurements were made of the layout to develop the space envelope in front of the engineer seat. This provided a measure of the clearances between the vertical wall surface under the console and locomotive engineer knees (considering a 95th percentile Hybrid III male ATD). Sufficient longitudinal clearance is required in this space to permit accommodation of a knee-bolster system which is essential in controlling and managing the compartmentalization and energy absorption for decelerating the locomotive engineer in a frontal collision. The initial CAD of the desk is shown in Figure 11.

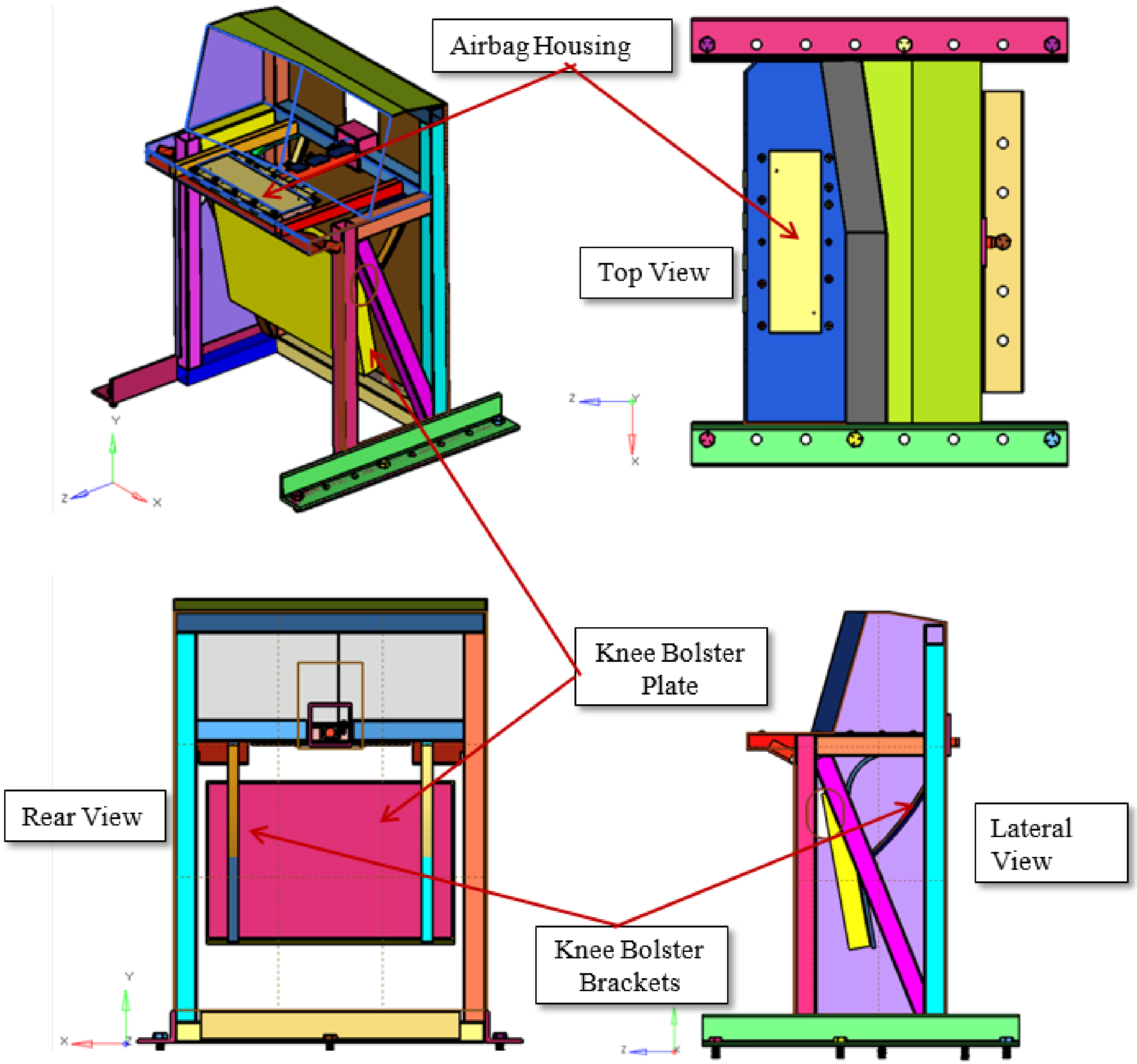


Figure 11. CAD Layout of the Engineer Seat, Control Stand the Console Desk with Knee Bolster

A review of the knee bolster system used in CEPS relative to the selected cab showed that the knee bolster would fit under the console with a 4-inch longitudinal clearance between the engineer's knees and the bolster, and was considered to be an appropriate and viable design for SIPS application.

A computer aided model of the systems was generated. The extended desk edge on the right side was eliminated after the base simulation run without any SIPS components as it was shown to intrude the ATD abdomen. This extended edge is to provide a place for a notepad, which can be accommodated easily at other locations on the desk surface.

The CEPS design consists of a baseline desk arrangement, an airbag system, and a knee bolster system. The knee bolster system is comprised of deformable brackets and a honeycomb material arranged in series along with a knee impact plate facing the engineer's knees. The same schematic arrangement was adopted for the SIPS design.

The sled testing of the CEPS design had shown that the honeycomb element in the knee bolster did not absorb much energy compared to the energy dissipated in the inelastic deformation of the knee bolster brackets, therefore, for the SIPS design, the honeycomb material was replaced with simple foam of equivalent thickness to minimize spurious spikes in the knee loads due to the direct contact between the knee cap and knee bolster plate.

The FEM of the desk and the 95th percentile Hybrid III male ATD is shown in Figure 12.

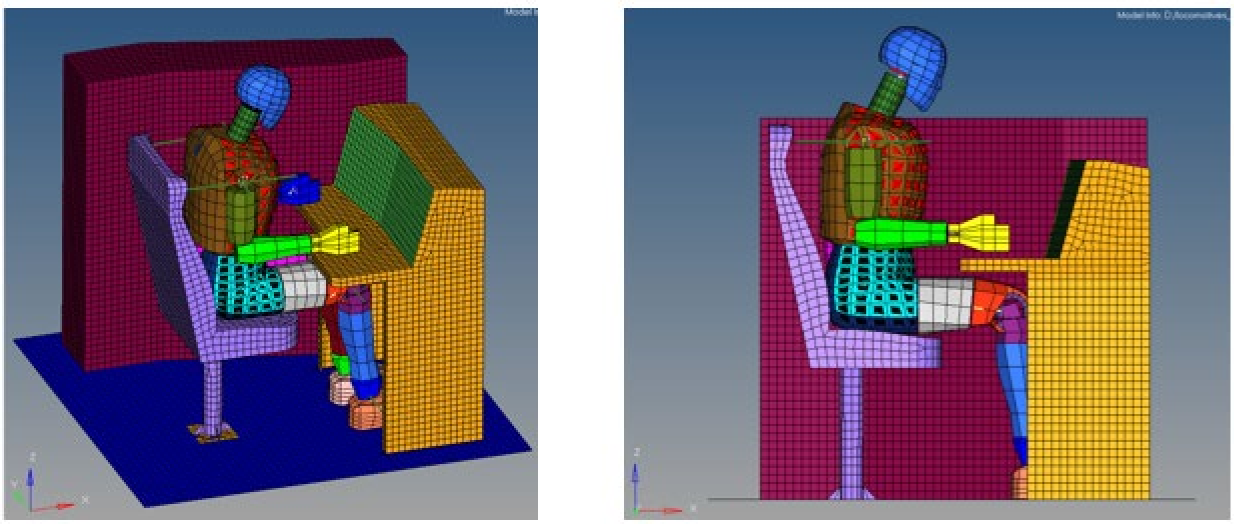


Figure 12. FE Representation of the Engineer Seat, Desk and 95th percentile ATD

5. Airbag Design

The purpose of a frontal airbag is to improve the outcome for vehicle occupants in a significant frontal crash. For most of its service life, an airbag rests in the stored position, with the airbag folded and stowed behind a deployment cover or door. A crash sensing system continually monitors the readiness of the inflator system while stored. When the vehicle experiences a significant frontal deceleration event, sufficient for the crash sensing system to rapidly determine that it is severe enough to warrant airbag deployment, an electrical signal starts a chain of events to rapidly release gas into the airbag. The airbag opens the cover or door, and rapidly inflates between the occupant and the vehicle surroundings which forms reaction surfaces. To be effective, the frontal airbag must deploy in a short time, typically 50 ms.

The major components of any airbag system include an inflator, airbag, cover, and mounting attachments. While the details differ in each module, every frontal airbag system has components which perform these functions. The inflator is the most complex part of any airbag system and stores the gas until needed. Several inflator technologies exist. Some store gas as a solid propellant, and rapidly combust it to produce inflation gases. Other inflators function as a high-pressure gas storage cylinder, released through a burst valve. Hybrid inflators use a combination of solid propellant and stored gas. All inflators in automotive applications use a standard electrical initiator to begin the deployment process.

The airbag is an expanding fabric whose purpose is to fill the space between a vehicle occupant and the vehicle interior surfaces in front of the occupant. The airbag must rapidly inflate to the protection position, and then must redirect the crash energy into the vehicle's interior surfaces.

Ideally, the airbag engages the occupant early in the event, and then slowly decelerates the occupant using the available space, without allowing contact with hard interior surfaces. Since each vehicle design has a unique occupant position, unique interior reaction surfaces, and a unique three-dimensional gap between them, each vehicle design has a unique airbag.

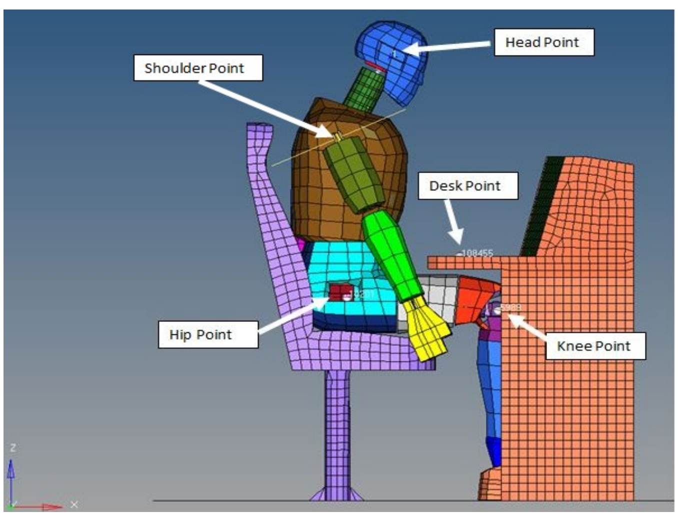


Figure 13. Locomotive Engineer Position Relative to the Desk

As shown in Figure 13 the locomotive engineer sits in a more upright position compared to automobile drivers and passengers. The control stand is situated like a desk, and is geometrically different than the interior of light on-road vehicles. A suitable off-the-shelf automotive airbag solution could not be found for this project. Therefore, the SIPS locomotive system required a custom airbag.

Airbag covers are designed to assure long-term storage of the folded airbag, and then to rapidly open without separating or producing fragments during deployment. Airbag covers must be durable and reliable in deployment. Oftentimes, a vehicle's airbag cover's external surface is visible, and must present a finished color, texture and feel to the occupant. For the SIPS project, the cover was intended to be functional, maintaining the folded shape of the airbag and opening reliably during deployment. No attempt was made to develop a finished, attractive and durable "class A" interior surface.

Lastly, airbag modules include mounting attachments to the vehicle. The typical design is an all-in-one module that can be attached to the vehicle structure using some combination of fasteners. In most vehicles, frontal airbags must compete for package space in the instrument panel or steering wheel with other vehicle systems. Therefore, frontal airbag modules are uniquely shaped for each application.

5.1 Initial SIPS Airbag Design

Design of the SIPS airbag module began with two essential inputs. First, successive simulation iterations established a deployed airbag geometry that was likely to produce promising test results. The deployed airbag geometry from RADIOSS® simulation ITER77 (the iteration numbering was carried over from the CEPS series) was selected as the starting point for the design, Figure 14.

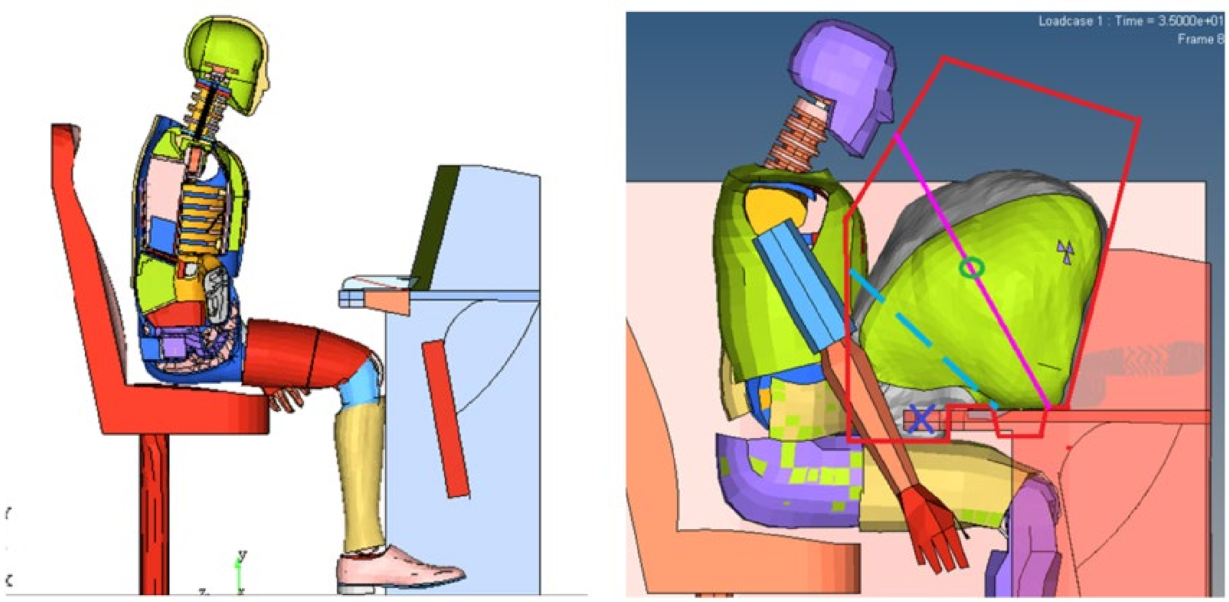


Figure 14. RADIOSS® Model of 95th Percentile ATD with CEPS Airbag and Knee Bolster System Simulation for SIPS Desk (ITER77)

Second, a design requirements document (DRD) established the required and desired features of the airbag module. The DRD included the following general categories:

- Injury criteria targets for the 95th percentile Hybrid III, unbelted ATD
- Frontal deceleration event description: CEPS crash pulse

- Available packaging space and mounting in the operator's control stand/desk
- Reaction surface available in the operator's control stand/desk
- Maximize use of commercially available components

Table 2. Initial Simulation of 95th Percentile ATD in SIPS Desk with CEPS Crash Pulse and Airbag and Knee Bolster (No Honeycomb Element)

Injury Response	Upper Limit	RADIOSS® Model - Run77
HIC_{15}	700	144
Chest 3 ms (g)	60	44
Femur Left (N)	10,000	7,652
Femur Right (N)	10,000	7,735
Neck Tension (N)	4,170	2,550
Neck Compression (N)	4,000	1,063
N_{te}	1.00	0.75
N_{tf}	1.00	0.50
N_{ce}	1.00	0.16
N_{cf}	1.00	0.27

The injury criteria targets for the 95th percentile Hybrid III male ATD are shown in Table 2. The 95th percentile ATD is not currently included in 49 CFR Part 572, and is not used for regulatory compliance in any standard. Therefore, injury criteria targets for the 95th percentile Hybrid III male ATD are not included in FMVSS 208. For this project, FMVSS 208 targets for the 50th percentile Hybrid III ATD were applied to the 95th percentile ATD. This approach is conservative, since proposed injury criteria published by NHTSA for some of the indices indicate a higher injury tolerance for the 95th percentile ATD [4].

Dimensional and performance analysis of over 60 automotive airbag systems were reviewed to identify which combination of components would potentially fit in the available packaging space. The airbag geometry from ITER77 had an approximate volume of 4.6 ft^3 (129 liters) which is closest to the volume of an automotive passenger airbag. However, no available passenger airbag modules or even passenger inflators fit within the available package space. The principal limitation was the 55-mm available in the vertical direction, between the horizontal desk top surface and the required clearance for the operator's thighs.

Several potential design options were considered and evaluated using a Pugh Decision Matrix. Based on this analysis, a knee airbag module from a 2012 Range Rover was selected as the best starting point for the SIPS module. This knee module included an integral inflator, and a deployed airbag volume of approximately 20 liters. Airbag pack analysis indicated that the ITER77 airbag could be folded to fit within the Range Rover knee module pan, if modern light weight fabric was used, and the inflator was located outside of the pan.

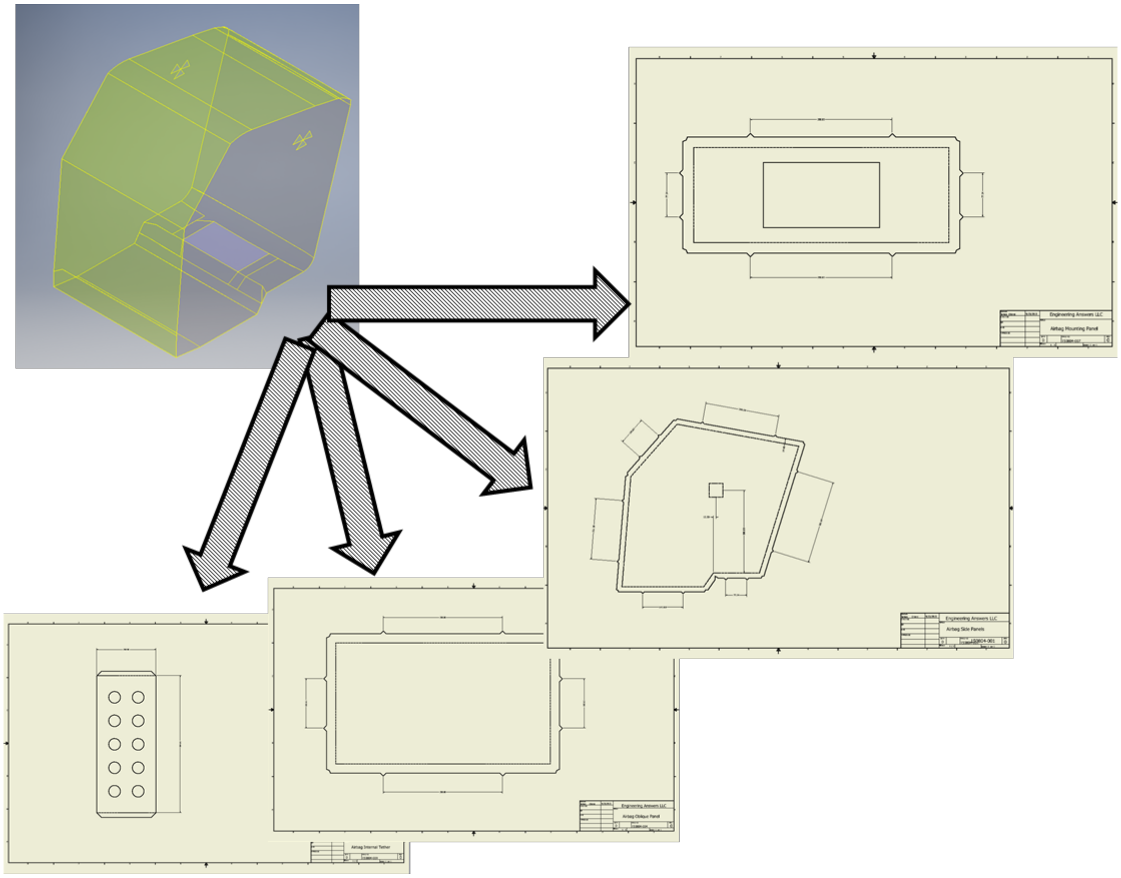


Figure 15. Initial Airbag Design to Develop Shape and Size Based on the RADIOSS® Simulation

Figure 16. Compressed Air Inflation of the Airbag to Ascertain Geometry and Shape

The design requirements for the SIPS airbag module included injury criteria for an unbelted 95th percentile Hybrid III ATD during a crash pulse with the 37-mph velocity change of the CEPS crash pulse. For comparison, FMVSS 208 S5.1.2[1] requires passenger cars to meet these same injury criteria using an unbelted 50th percentile Hybrid III ATD during a crash test with a 25-mph impact velocity. Compared to the unbelted automotive test requirement, the SIPS airbag and knee bolster were required to dissipate 186 percent more kinetic energy than the equivalent automotive systems. Given this higher energy dissipation requirement, the SIPS airbag was originally designed using uncoated, permeable fabric to allow the gas to vent through the fabric. The uncoated fabric chosen was a 200 x 200 construction of 470 dtex[2] polyester yarn produced by Global Safety Textiles. In common automotive use today, this modern fabric is comparatively lightweight, allowing for a compact airbag pack, with a high strength bag construction.

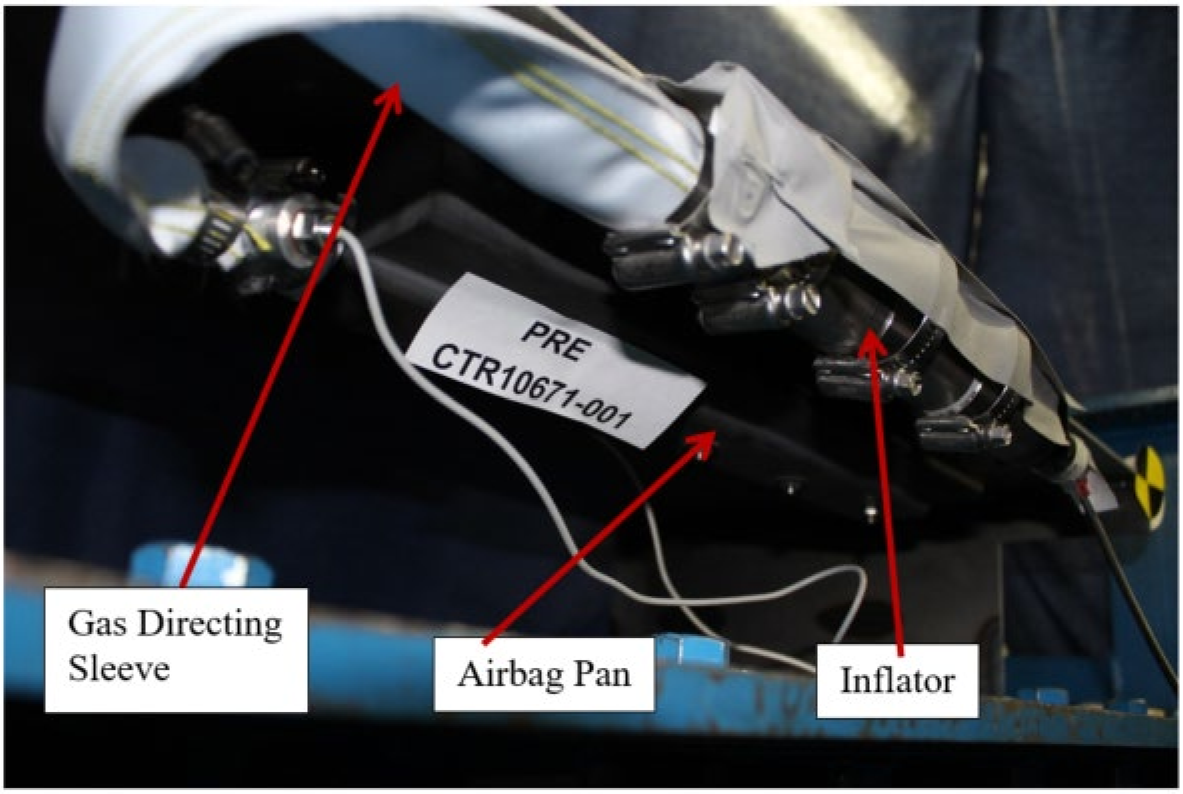


Figure 17. Initial Design of SIPS Airbag Module and Inflator Connection

The initial design layout for the module positioned the inflator laterally alongside the pan. A fabric tube guided gas into the end of the pan and folded airbag. Figure 17 shows a view of this initial layout installed underneath a deployment fixture representing the operator's control stand/desk. This design fits completely within the available package space in the DRD and was used to assemble module serial numbers 1 and 2.

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[1] National Highway Traffic Safety Administration, DOT, Section 571.208, S5.1.2.

[2] 200 x 200 Construction: 200 threads/cm in both directions. 470 dtex: 470 grams/10,000-meter yarn length

5.2 SIPS Airbag Design Iterations

Throughout the project, a total of 12 SIPS airbag modules were built to various design iterations for testing. Each test revealed the need for design improvements, and the major design variables are depicted in Table 3, along with their implementation. The final configuration of each major design variable is shown in green.

Table 3. SIPS Airbag Design Iterations

	Serial/Module Number												
Design Characteristics	**1**	**2**	**3**	**4**	**3r**	**4r**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Inflator Mount	End Fill				Center Fill								
Venting	All Uncoated		Uncoated/Sides				Uncoated Back		None		Active, Back		
Bag Volume	~121 Liters								~97 Liters				
Transducer Location	None		1xFront				2xRear		1xRear				
Port Attachment	None		Gasket				Gasket/Sillicone			Washer/Gasket/Sillicone			
Baffle	Single		None				Single	Double					
Folding Pattern	Dbl Fwd	Dbl Rev	Dbl Fwd	Dbl Rev	Dbl Fwd	Dbl Rev	Single Reverse Roll						
Attachment (to Pan)	3xBolts				5xBolts		Bolt Plate - 5xBolts						

Dbl Fwd: Double Forward Dbl Rev: Double Reverse

The earliest deployments showed the lateral inflator orientation and end-fill into the airbag was unsatisfactory. The inflator generated gas more rapidly than the airbag could expand, causing the fill tube to burst. End fill also caused asymmetric unfolding of the airbag due to gas jetting. The design was modified such that the inflator was oriented in the longitudinal direction, with its nozzle centrally located in the airbag pan as shown in Figure 18.

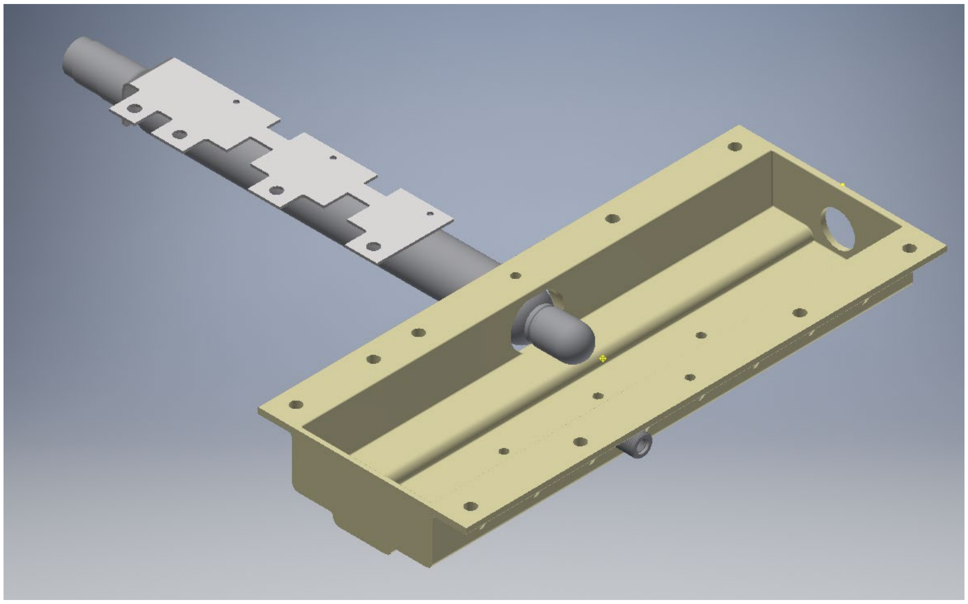

Figure 18. Final Schematic for the Inflator and Airbag Pan Assembly

This mounting scenario compromised the allowable package space in the X-direction (longitudinal direction of the cab/desk), and the end of the inflator extended through the front plane of the operator's control stand/desk. This was considered acceptable for testing purposes. This mounting and gas delivery system proved satisfactory and was used for all modules starting with reworked serial number 3.

The second major design iteration shown in Figure 17 involved airbag venting. The SHI2 (single-stage hybrid) inflator produced enough gas to inflate the final airbag, but not much extra. The first prototypes were constructed of all uncoated, permeable fabric. Given the large surface area of the airbag, the effective venting rate was too high to permit full inflation. Modules 3, 4, 5 and 6 included increasing proportions of coated, sealed fabric to reduce the venting rate. This fabric of similar construction included a silicone coating applied at 25 g/m^2.

Even with these reduced surface areas of permeable fabric, the effective venting rate was too high to achieve full inflation. Modules 7 and 8 were constructed using only coated, sealed fabric to minimize venting. These modules achieved fuller inflation, but much of their energy absorption was returned as elastic rebound and not dissipated. Beginning with module 9, the SIPS modules were constructed using all coated fabric, but included two active vents. The design of these active vents is shown on the right-hand side of Figure 19. These vents were initially closed to minimize leakage. At a design point of 60 ms, tension in internal tethers opened these vents to improve non-elastic energy dissipation. Tests demonstrated that these active vents opened as intended, but their location on the back panel of the airbag was obstructed by the control stand's reaction surface, inhibiting venting.

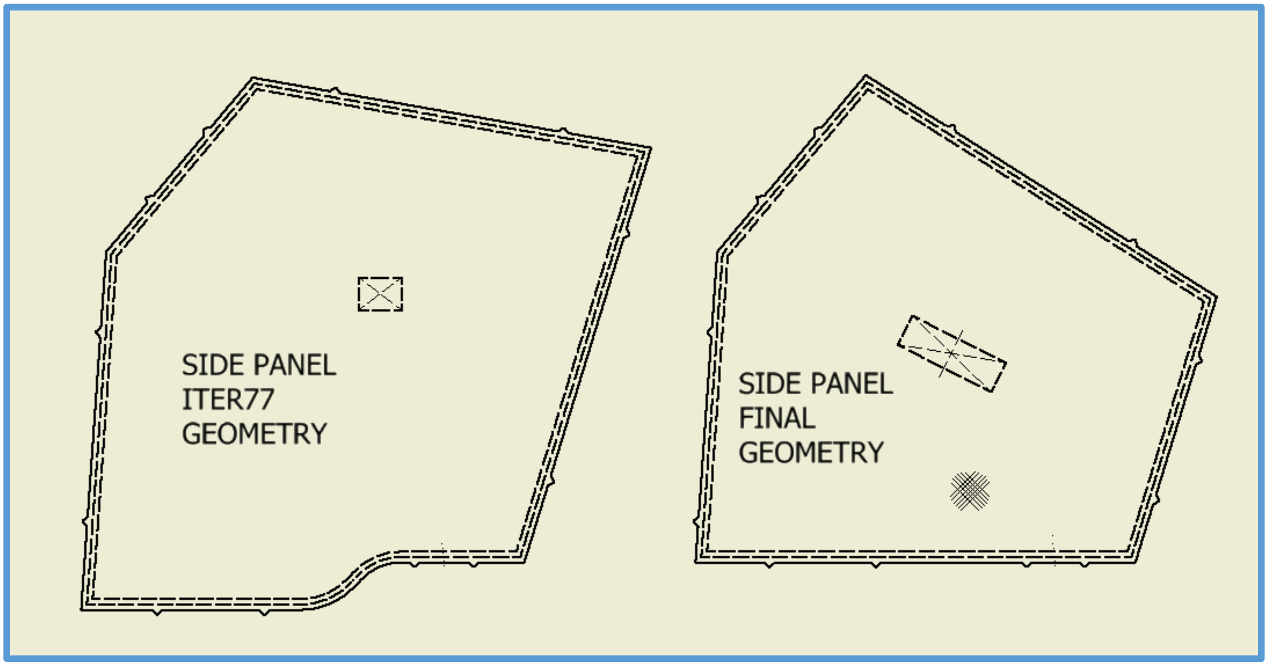

Figure 19. Side Panel Geometry Comparison

The third significant design iteration involved the shape and volume of the deployed airbag. Using the simulation geometry from ITER77, the initial airbag volume was calculated at 121 liters. As mentioned above, the SHI2 inflator did not produce enough gas to fully inflate this airbag.

Beginning with module 8, the geometry of the airbag was reduced 20 percent to a calculated value of 97 liters. Figure 19 illustrates a comparison between the side panels of the two airbag designs. To reduce the volume, the airbag's back panel was reduced to the height of the desk's reaction surface. The upper panel's width was narrowed, since it engaged the ATD's head only. The lower portion of the bottom panel was reduced as well. The lateral tethers were reconfigured and repositioned for better shape control. An exploded view of the final airbag geometry is shown in Figure 20. The SHI2 inflator produced enough gas to inflate this smaller airbag, but with little extra capacity. Ultimately, this airbag geometry proved satisfactory in engaging head, neck, chest and abdomen of the ATD and the reaction surfaces, as shown in Figure 22. The size and shape of the final airbag design was sufficient to achieve the proper position, engage the front of the ATD, and to direct forces to the control stand/desk.

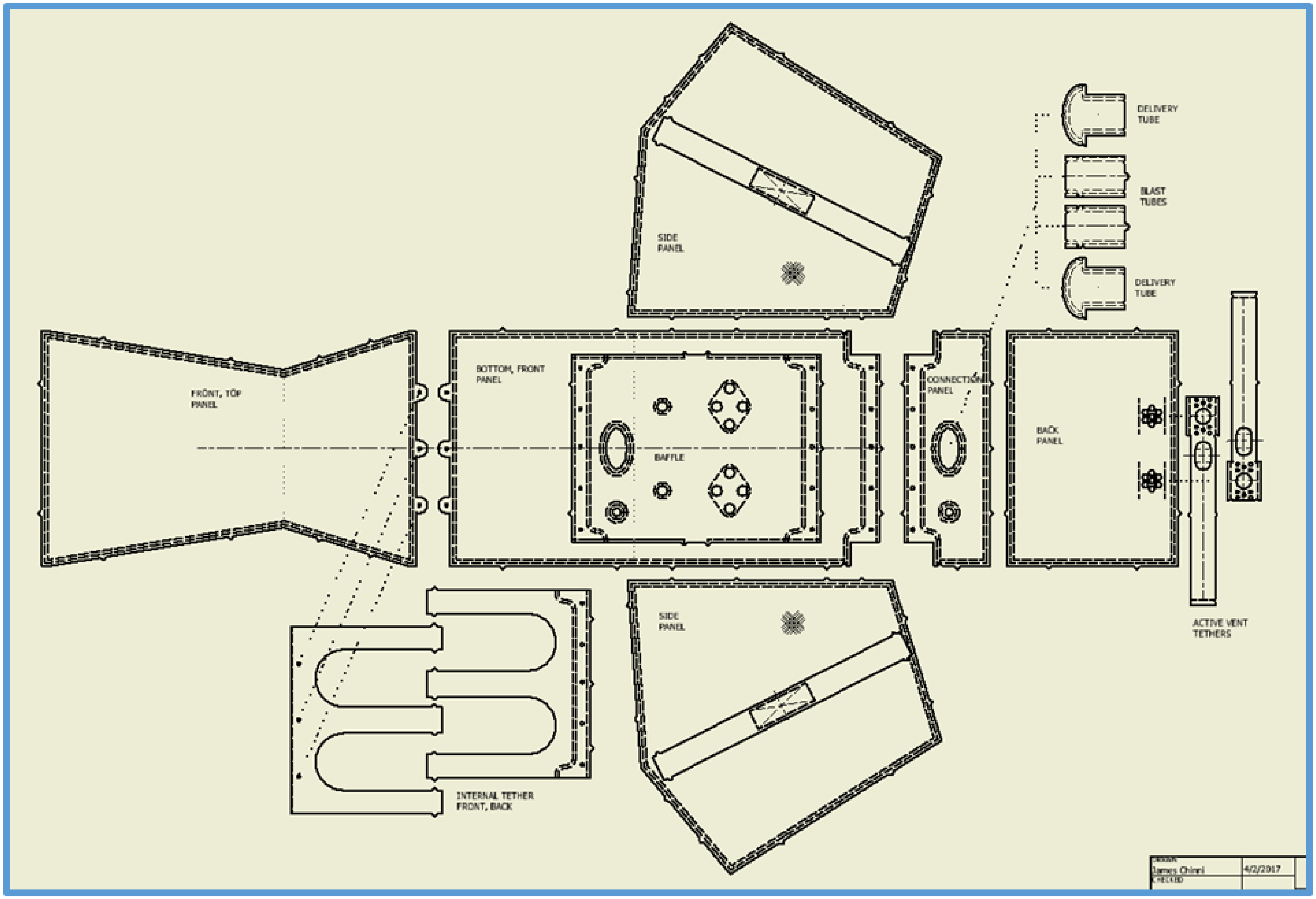

Figure 20. Exploded View of SIPS Airbag

As a research project, the SIPS airbag module included provisions to mount pressure transducer(s) to the pan which would port into the expanding space inside the airbag. These would not be present in any type of production airbag, but provide test data useful for analysis and simulation. These tests used the Meggitt model 8511A-5k piezo-resistive pressure transducer. This sensor is specifically designed for ballistic applications and is commonly used in airbag development. The transducer location and port attachment changed throughout the project in response to the test results.

The initial design included one transducer mounted to the front side of the pan (opposite the inflator) and one transducer mounted to the fill tube. The centrally located inflator attachment eliminated the need for the fill tube mounted transducer, Figure 17. Subsequent tests demonstrated that the front pan mount placed excessive mechanical stress on the fabric attachment, tearing it during deployment. Starting with module 5, the transducers were repositioned to the back side of the pan, on either side of the inflator as shown in Figure 21. Deployment tests continued to demonstrate weakness at this joint, until an oblong washer and gasket were combined with epoxy adhesive to maintain fabric integrity at the joint. Starting with module 7, one transducer was used to reduce potential tear locations. Even so, the transducer attachment location added mechanical stresses to the airbag fabric, and airbag ruptures during sled testing occurred on the same side as the transducer attachment.

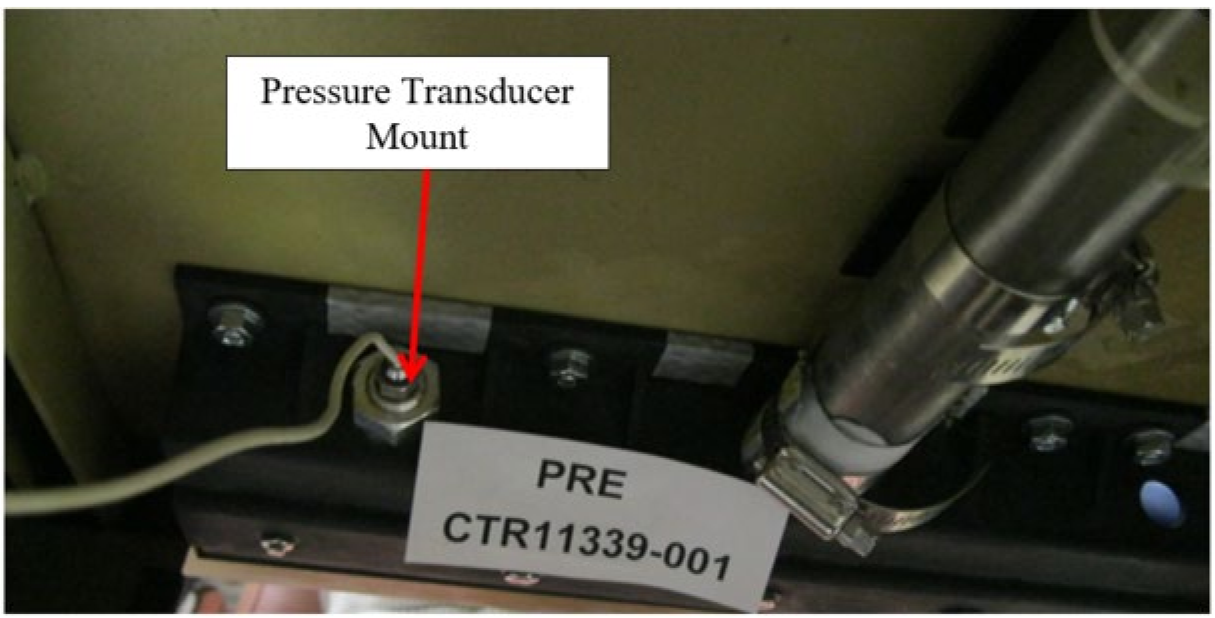

Figure 21. Airbag Module Mounted with Center Fill (Installed Under the Desk)

To properly position the airbag for engagement with the ATD, the airbag needed to deploy with a significant horizontal (longitudinal) vector, towards the ATD. Given that the SIPS module installation is under a flat horizontal desk surface, the SIPS module design had to alter the gas flow and deploy the airbag momentum as close to 90 degrees as possible. The design addressed this challenge using two primary methods: an internal baffle inside the airbag and the folding pattern.

Starting with module 5, the SIPS airbag design includes an internal baffle to direct gas flow. Conceptually, the baffle is an airbag inside the main airbag, and it is shown in Figure 21. The exhaust gas from the inflator ported directly into the baffle through the elongated opening. The baffle was sized to provide the initial vertical deployment vector to push the airbag out of the pan. Then, vent orifices in the baffle redirected inflation gases 2/3 towards the front, 1/6 towards the rear and 1/12 towards each side. When folded, the baffle lies nearest the exhaust blast of the inflator. Once the thickness of the baffle was doubled and rip-stop sews (specialized sewing for rip-stop nylon fabric) were added in module 6, the baffle worked well, and the inflation trajectory satisfactorily positioned the airbag for ATD contact, as shown in Figure 22.

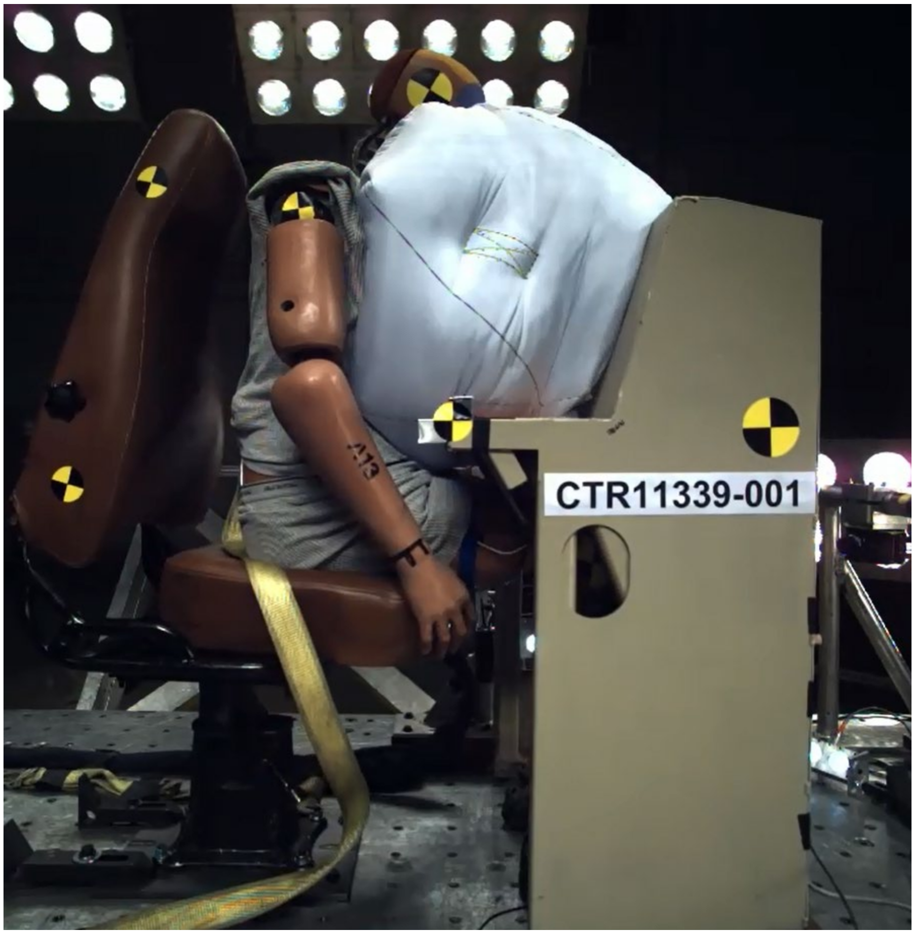

Figure 22. Airbag Geometry During Sled Test

The folding pattern also contributed towards proper inflation trajectory. Initial compressed air deployments identified a double roll folding pattern as the most promising. The double roll also efficiently packed the airbag into the module pan. Early experiments compared forward and reverse double rolls. Once the inflator was repositioned longitudinally for center fill, the double roll concept no longer produced acceptable results. Beginning with module 5, the single reverse roll folding pattern from the CEPS airbag project was adopted. When coupled with the baffle, the reverse roll folding pattern produced the desired inflation trajectory.

The last significant design iteration involved the airbag's attachment to the pan. The Range Rover knee airbag uses three fasteners along the bottom of the pan to attach the airbag, so this approach was initially used. Static deployments tore the airbag away from the bolts, so two bolted connections were added on the bottom surface of the pan. Static deployments partially separated the airbags from the pan. A narrow bolt plate was added to increase the bearing area on the airbag and all further deployments remained fully attached at the pan. The bolt plate is shown in Figure 23 below.

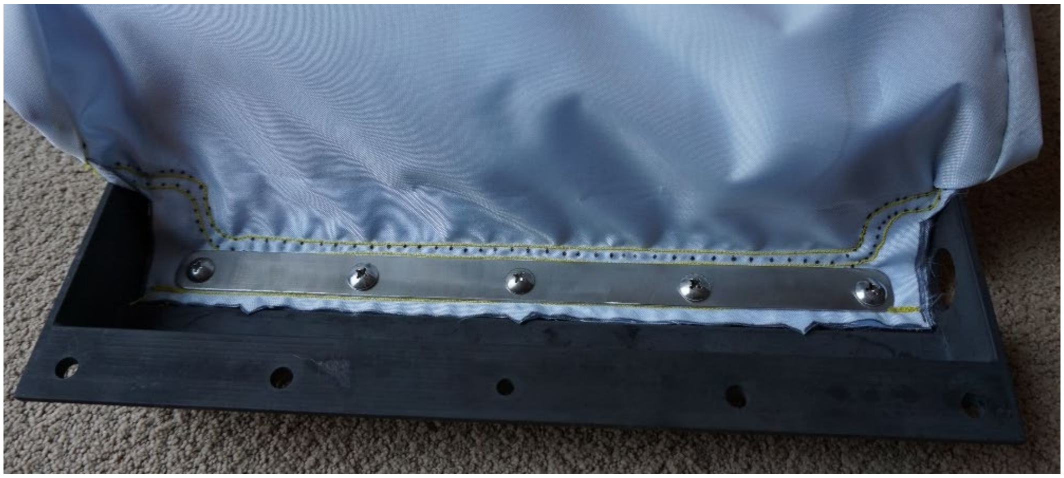

Figure 23. SIPS Airbag Attachment with Bolt Plate

One net effect of design changes that added materials, including inflator repositioning, oblong transducer washer and gasket, baffle and bolt plate, is that the module pack became continually tighter and tighter. Due to the added material, later modules tended to bulge underneath the cover. The cover was designed as a thin polyethylene sheet that was applied to the pan using adhesive. The flexible cover design accommodated the bulging airbag pack. The cover design and tear seam opened properly each time and required no significant revision. Figure 24 shows the cover mounted to the simulated operator's stand/desk used for testing.

Figure 24. SIPS Module Cover and Tear Seam

5.3 Knee Bolster Design

Modeling of system performance, using a RADIOSS® model with validated sub-models, showed that the system without the use of the honeycomb layer in the knee bolster would be effective in meeting the performance goals shown in the initial simulations results in Table 2 [1]. The simulated knee bolster consisted of the same brackets and the plate as used in the CEPS project.

5.4 Inflator Selection

The available package space limited the selection of commercially available inflators that could be used in this application as well. The inflator and its attachments also had to fit within the 55-mm vertical dimension limit. With an outer diameter of 35 mm, the TRW SHI2-210/35 offered the highest available output that would fit under the horizontal desk surface. This inflator is currently used in automotive side curtain applications, where it is packaged inside vehicle pillars.

The SHI2 is a single stage, hybrid inflator, meaning it inflates the airbag using a combination of stored, high pressure gas and pyrotechnically generated gas. In operation, the SHI2 inflator receives an electric deployment signal from an external source such as a crash sensor. The electric signal ignites a small amount of solid propellant which vents into the stored gas chamber of the inflator. The pyrotechnically generated gas adds mass and heat to the stored gas, causing a disk to burst due to overpressure, allowing the mixed gases to vent into the airbag in a controlled fashion. The SHI2 inflator produces 3.8 moles of gas, which is 97 percent inert, non-toxic Argon. Compared to a fully pyrotechnic inflator, the SHI2 gas output is low temperature, reducing deployment risk due to thermal effects. The SHI2-210/35 inflator is shown in Figure 25.

Figure 25. TRW SHI2-210/35 Inflator

The pressure and mass flow characteristics of the inflator are shown in Figure 26. These characteristics were used in the RADIOSS® and LS-DYNA simulations during evaluation of the airbag design iterations.

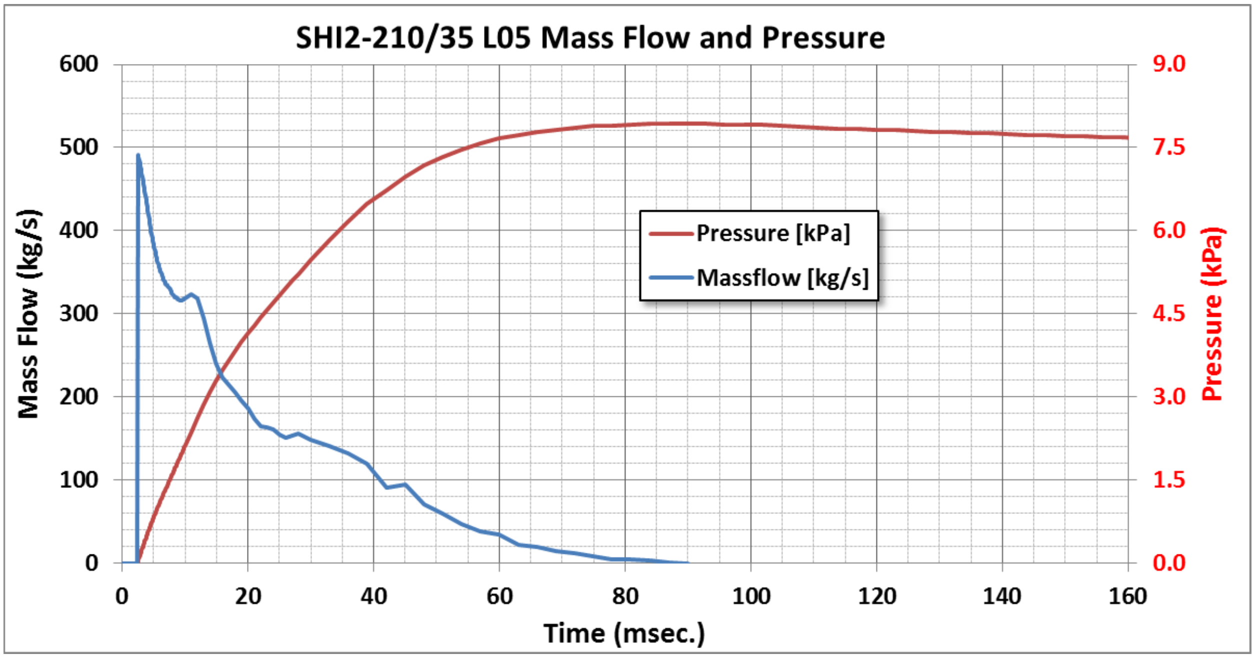

Figure 26. Mass Flow and Pressure Characteristics of TRW SHI2-210/35 Inflator

6. System Component Design Evaluation Tests

The purpose of the physical tests in this project was two-fold. First, the tests measured the performance of prototype SIPS and compared key performance characteristics against the design requirements. Second, the tests provided valuable input for simulation refinement, enabling evaluation of the design for conditions not physically tested. Meeting the injury criteria shown in the DRD was the principal measure of success.

To achieve these design requirements, the test program was structured to allow design adjustment and fine-tuning throughout the project. The test program featured simple component-level tests first, followed by progressively more complex tests, until the final system-level dynamic sled test was conducted. In this way, opportunities for design improvement became apparent during lower cost, simpler tests. Successful results at each test stage helped improve the probability of success and reduce risk for successive tests. The FEA dynamic system modeling is the principal engineering tool used for this project, and the measurements made during each test facilitated adjustment, tuning and correlation of the analytical model as well as the physical prototypes. As shown in Table 4, each of these SIPS airbag modules was deployed in a series of increasingly complex tests, described in the following sections.

Table 4. Test Matrix for Component Design Evaluation

Test #	Test Description	No of Tests
1	Compressed air inflation	CTR10612-004
2	Static Deployment	CTR10612-005
3	Static Deployment	CTR10671-001
4	Static Deployment	CTR10671-001
3r	Static Deployment	CTR10671-001
4r	Static Deployment	CTR10671-001
5	Static Deployment	CTR10671-001
6	Static Deployment	CTR10671-001
7	Linear Impact Test	CTR10877-001
8	Linear Impact Test	CTR11031-001
9	Linear Impact Test	CTR11338-001
10	Not Tested	None
11	Dynamic Sled Test	CTR11339-001

These elements and relevant fabrication details are described in the following sections.

6.1 Compressed Air Inflation Tests

Prior to starting the airbag characterization testing, the airbag was made from simple fabric and attached to a compressed air source to verify that the inflated shape was as designed.

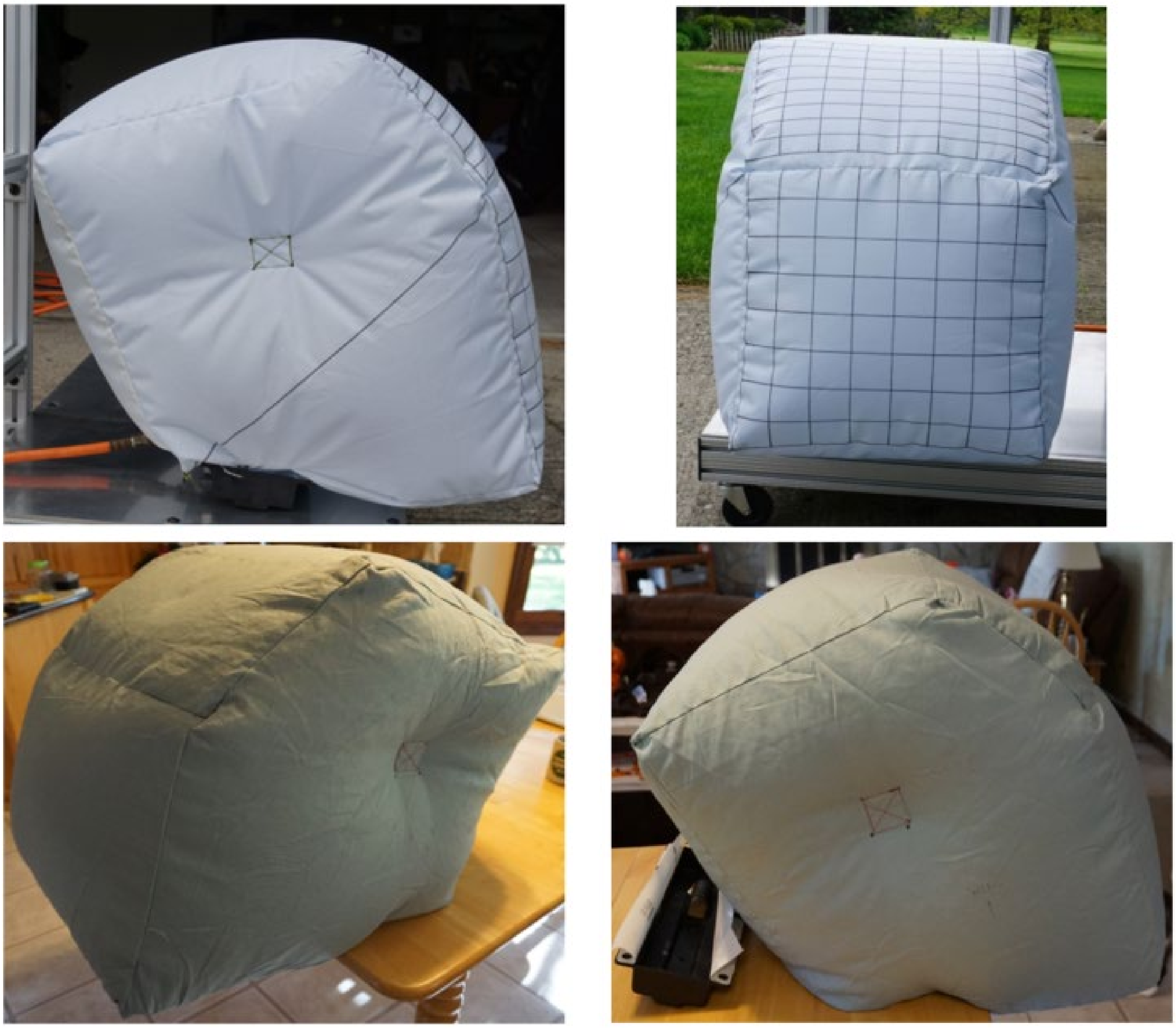

Figure 27. Airbag Inflation Using Compressed Air

6.2 Static Deployment Tests

The purpose of the static deployment tests was to evaluate component-level performance and operating characteristics of the SIPS airbag module. Data collection was intended to quantify these characteristics and provide information for analytical model tuning and correlation. In addition, static deployments enabled assessment of the structural and thermal integrity of the SIPS module due to deployment alone.

Figure 28. Initial Design of SIPS Airbag Module

For this test series, a complete SIPS module was mounted to a rigid fixture that simulated the geometry of the operator's control stand/desk. The test procedures used generally reflected the SAE International (SAE) Recommended Practices, J1630–Airbag Module Deployment Test Procedure [10].

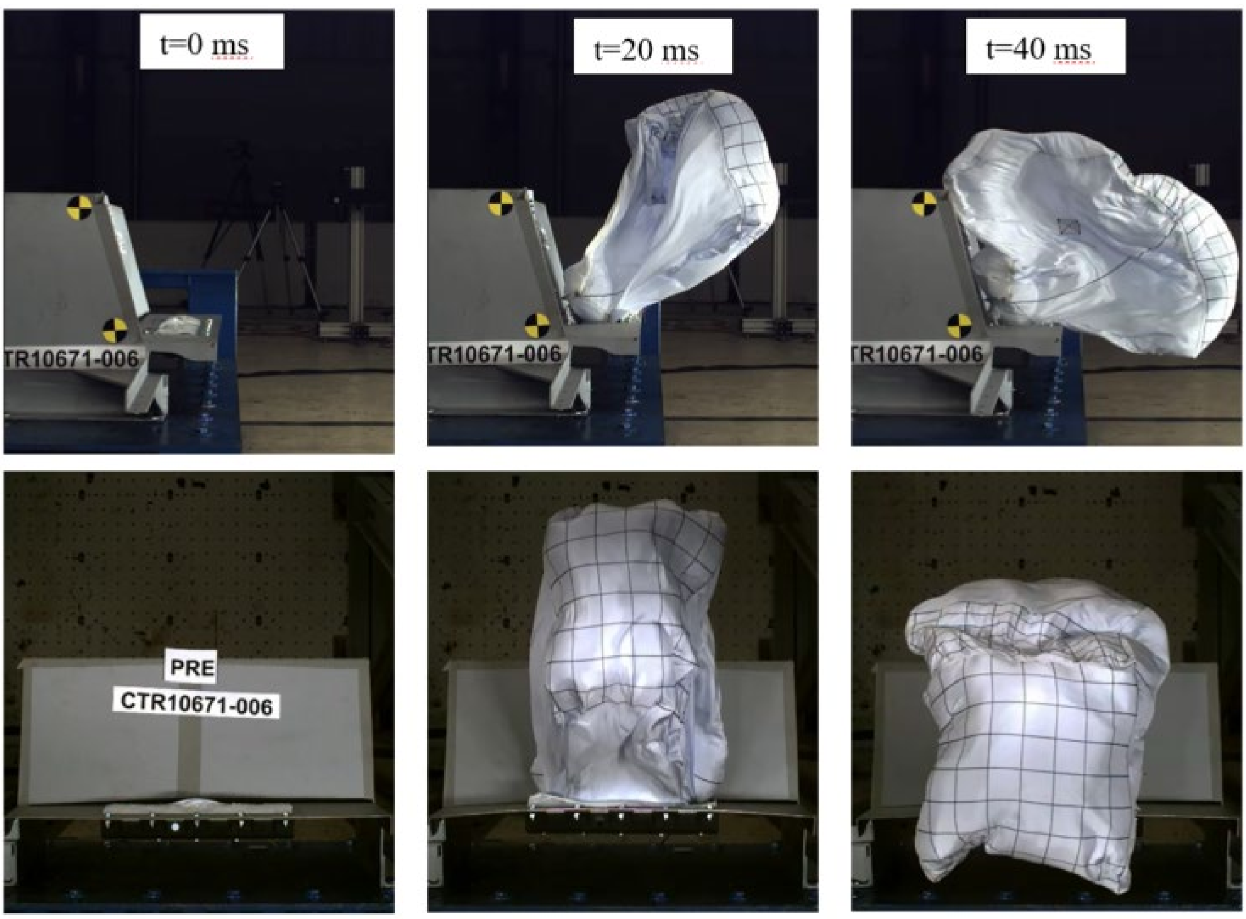

Figure 29. Static Deployment #2 to Study Airbag Unfolding and Deployment—Lateral (Top Row) and (Bottom Row) Front View at 0, 20 and 40 ms After Inflator Trigger

The static deployments were recorded using two high speed digital imagers, positioned 90 degrees apart in the horizontal plane, as a front view and a side view. Video was captured at 3,000 frames/second, in accordance with SAE J211-2. Reference targets were included in the anticipated motion planes, enabling the video to be used for motion analysis.
The SIPS modules were deployed using a manually operated electronic switch that also triggers the data acquisition system and high speed digital imagers, synchronizing them in time. The tests were conducted at ambient temperature, and the SIPS modules were stored at ambient temperature (approximately 72 °F) for no less than 4 hours prior to the test. Static deployment test setup is shown in Figure 28.

Internal airbag pressure was measured during the deployment, at two locations. Data were recorded at 20,000 Hz and filtered per SAE J211-1. Recorded data included at least 20 ms of data prior to deployment. Six static deployments were conducted, each providing design guidance, and none producing entirely acceptable results. The last static deployment test on module 6 demonstrated promising deployment trajectory, but failed to fully inflate. Module 6 included uncoated, permeable fabric on the back panel which vented gas too rapidly. Moreover, the airbag separated from the transducer port during the test, providing a large, unintended vent. Module 6 also featured the larger 121-liter airbag volume. The static deployment did not produce results sufficient for use in tuning the simulation model. The side and front camera views from one of these tests are shown in Figure 29.

6.3 Linear Impact Energy Absorption Deployment Tests

The purpose of the impact energy absorption deployment testing is to evaluate component-level performance and operating characteristics of the SIPS airbag module, with interaction. These characteristics include both the elastic and inelastic energy absorbed by the SIPS airbag module. Data collection quantified these characteristics and provided information for analytical model tuning and correlation. In addition, these deployments enabled assessment of the structural and thermal integrity of the SIPS module, due to both deployment and airbag interaction with the desk (mockup).

For this test series, a completed SIPS module was mounted to a rigid fixture that mimicked the geometry of a representative locomotive operator’s control stand. The rigid fixture included all geometric features of the control stand that are likely to react with the deploying airbag. A small shelf was added to the fixture, 55 mm below the desk surface, to simulate the top surface of the ATD’s thighs. In addition, the vertical surfaces of the fixture were extended upward to provide a more easily modeled reaction surface. Figure 30 shows the desk, impactor, inflator and the airbag installed for testing.

The deploying SIPS module was impacted by a single degree-of-freedom moving platen of defined geometry, at a known initial kinetic energy. The platen was propelled using air pressure, and the test was conducted in accordance with recommended practice SAE J2961–Linear Impact Testing for Passenger Airbag Modules – Component Evaluation.

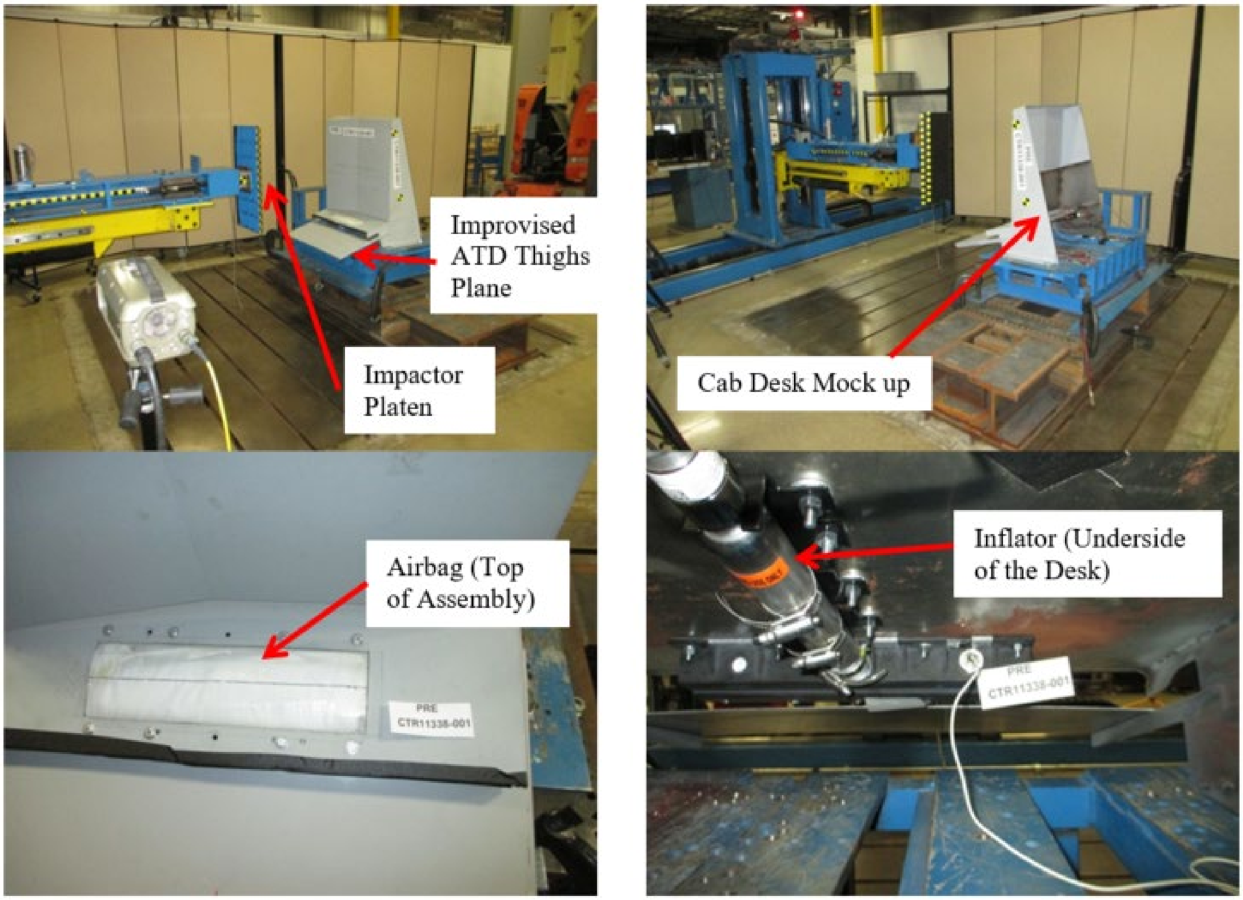

Figure 30. Linear Impactor Test Set Up—Engineer Desk Mock Up, Air Airbag and Inflator Mounting Shown

For purposes of the recommended practice, the SIPS airbag module was considered equivalent to a class IV (large sedan or a sport utility vehicle [SUV]) passenger airbag module. The fixture was tilted forward at a 15-degree angle, enabling the linear impactor's body block to travel horizontally. The overall setup for the linear impact tests is shown in Figure 31.

6.3.1 Instrumentation

The data acquisition system and high-speed imagers were triggered by a switch that synchronized them in time. The linear impactor started motion shortly after these systems were enabled, triggered by the first non-zero measurement of the impactor's accelerometer.

The SIPS airbag module was deployed by the data acquisition system at a predetermined time. The time was chosen such that it would be 45 ms before the platen reached a position 490 mm away from the vertical plane of the fixture, traveling at a target speed of 4.5 m/s. These values were chosen by simulation, to be reasonably representative of ATD contact with the deploying airbag. Extensive pretest setup was completed to determine the conditions necessary to assure the platen was traveling at the correct speed, at the specified position, at the specified time.

Figure 31. Pre-Test Setup of Linear Impact Test

Tests were conducted at ambient temperature, and the SIPS module was stored at ambient temperature for no less than 4 hours prior to the test.

The guided mass of the impact platen weighed 35 kg and the flat portion of the interface surface measures 250 mm wide by 700 mm tall. For additional details related to the impact platen, refer to SAE J2961. The centerline of the platen was aligned with the centerline of the SIPS airbag module for all tests. The bottom edge of the platen was vertically aligned with the junction between the "horizontal" and "vertical" planes of the angled desk fixture. In retrospect, positioning the platen lower to engage the full face of the deploying airbag would have been more representative of the sled test geometry.

6.3.2 Data Acquisition

Each impact energy deployment event was recorded using two high speed digital imagers, positioned in the horizontal plane, as overhead and side views. High speed video was recorded at 3,000 fps, in accordance with SAE J211-2. Reference targets in the side view motion plane enabled the video to be used for motion analysis. A separate high-speed imager was used to track linear motion of the piston attached to the platen.

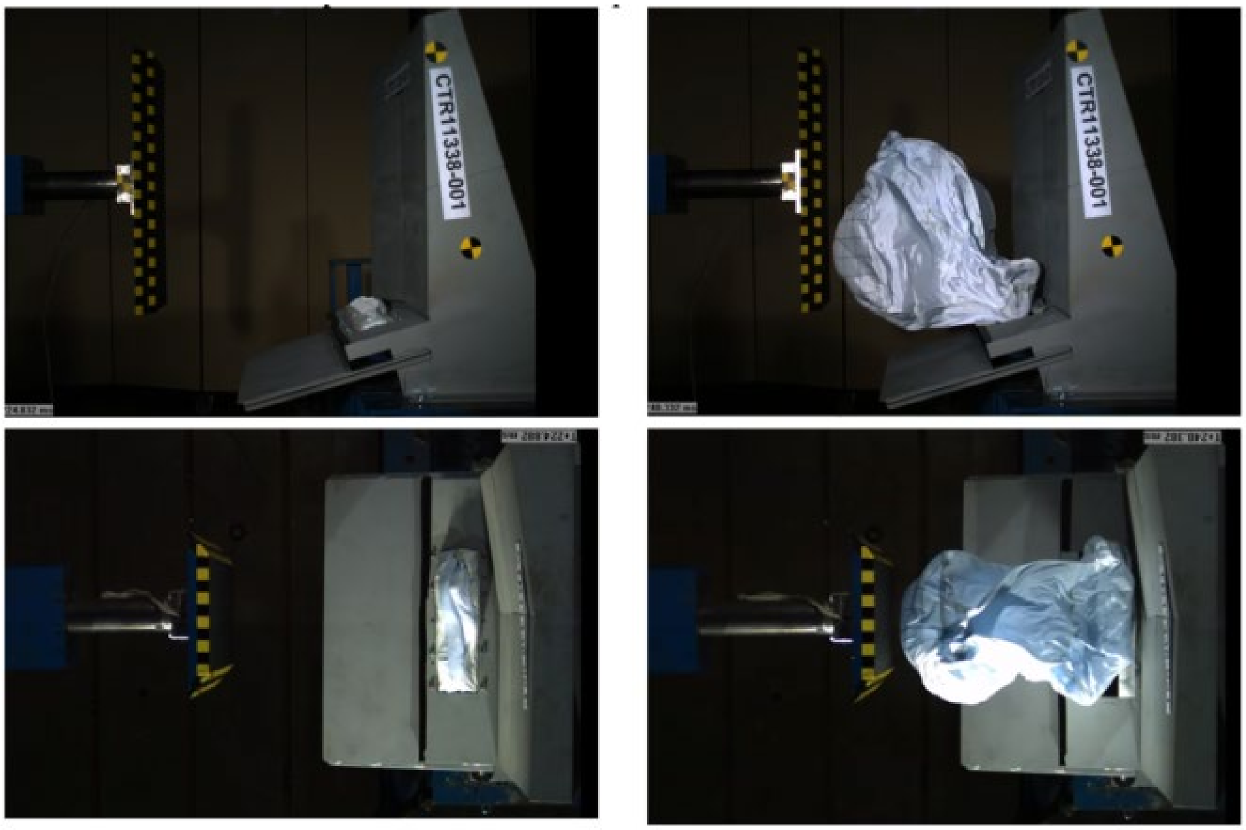

Figure 32. Right Side and Overhead Video Camera Views—Impactor Test (24 and 240 ms)

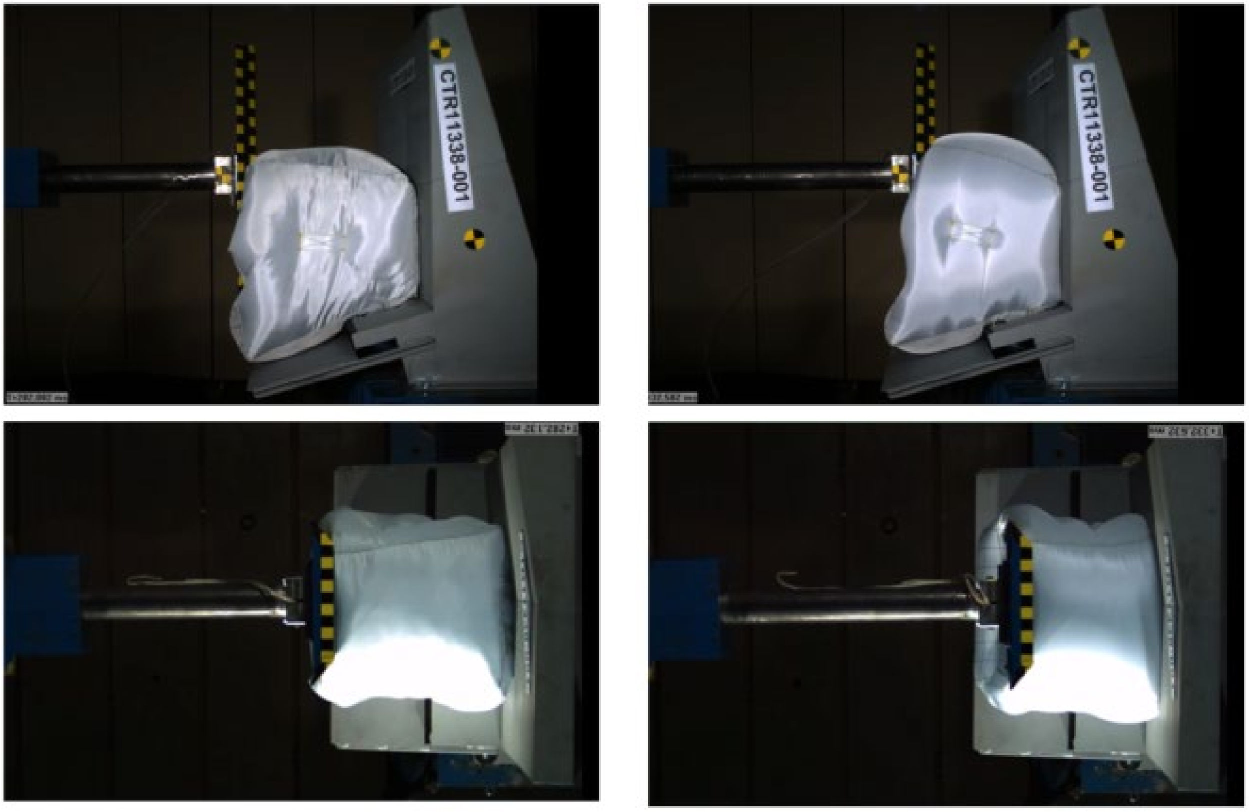

Figure 33. Right Side and Overhead Video Camera Views—Impactor Test (282 and 332 ms)

Internal airbag pressure was measured during the deployment at one location on the back of the pan. In addition, tri-axial acceleration of the platen was measured throughout the event. Data were recorded at 20,000 Hz and filtered per SAE J211-1 at 20,000 Hz. Recorded data included at least 20 ms of data prior to deployment.

The test of module 8, CTR11031-001, met the target conditions: The airbag deployed symmetrically, with forward trajectory, decelerating the body block 33 ms after deployment. Forty-five ms after airbag deployment the body block was positioned 488 mm away from the vertical face of the fixture, traveling at 4.57 m/s. The airbag was in position at 45 ms, and fully deployed at 60 ms, when the inflator was fully exhausted. The airbag halted the body block's motion without bottoming out. The body block stopped 315 mm away from the fixture. The lateral and top video camera shots of the linear impactor test are shown in Figure 32 and Figure 33.

The SIPS airbag module absorbed 99 percent of the body block's 378J of kinetic energy during forward motion of the body block, but returned 60 percent of the energy as rebound. This observation led to the development of the active venting concept for module 9.

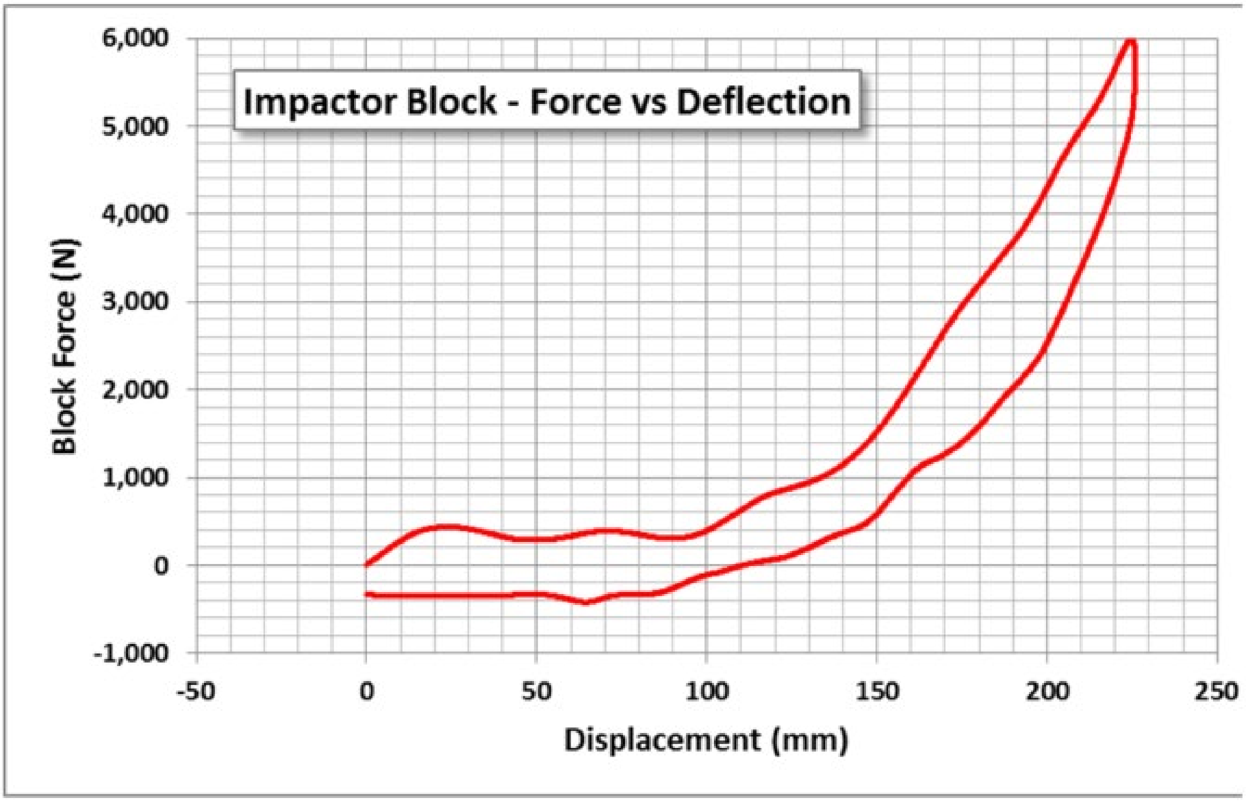

Figure 34. Impactor Body Block Force vs. Displacement-Module 9

The linear impact test of module 9, CTR11338-001, improved upon the results of the previous test. The test conditions were reasonably close to the target: The airbag deployed symmetrically, with forward trajectory, decelerating the body block 38 ms after deployment. Forty-five milliseconds after the airbag deployment, the body block was positioned 513 mm away from the vertical face of the fixture, traveling at 4.47 m/s. The airbag was in position at 50 ms, and fully deployed at 60 ms, when the inflator was fully exhausted. High speed video suggests that the active vents opened between 48 and 60 ms after deployment. The vent openings were pressed against the fixture at 69 ms after deployment, partially blocking the openings and limiting vent effectiveness thereafter. The airbag halted the body block's motion without bottoming out. The body block stopped 317 mm away from the fixture.

Figure 34 shows the force that the SIPS airbag exerted on the body block as a function of the body block's displacement, starting from the moment that the body block began to decelerate. The upper curve represents loading into the airbag, and the lower curve represents unloading or rebound. The SIPS airbag module exerted a maximum force of 1347.8 lb. (5,995 N) after the body block penetrated 225 mm into the airbag. The area under each curve represents energy, therefore, the area between the curves represents the energy dissipated by the SIPS airbag, not returned as rebound.

The SIPS airbag module 9 absorbed 93 percent of the body block's 383J of kinetic energy, and returned 50 percent of the energy as rebound. The active venting improved the percentage of inelastic energy dissipation, and demonstrated some effectiveness before the vents were at least partially blocked by the test fixture. The results from test 9 provided sufficient confidence to proceed with dynamic sled testing.

7. SIPS System Assembly

Based on the desk layout described in Section 4, the baseline desk was derived as a composite of several relevant engineer cabs. This layout was then extended into a detailed design, incorporating the appropriate dimensions, structural sheets and members, and connection/weld details.

7.1 Engineer Desk

The design and drawing effort was completed using Pro/Engineer software. The CAD drawings for the desk are shown in Appendix B as Figures B-1 and B-2.

The baseline desk was fabricated based on the drawings created, using the appropriate materials, including steel sheets, steel tubes, etc. The desk top and side sheets were laser-cut, and then pressed into the desired shapes.

The tubes were mitered as called for in the drawings. The structural tubes were then assembled to form the skeleton, and the sheets were welded or bolted in as appropriate to the skeleton. The structure was then painted using contrasting colors for enhanced visibility for the high-speed cameras during the test. Figure 35 shows various views of the assembled and painted desk being readied for final assembly and shipping to the testing facility.

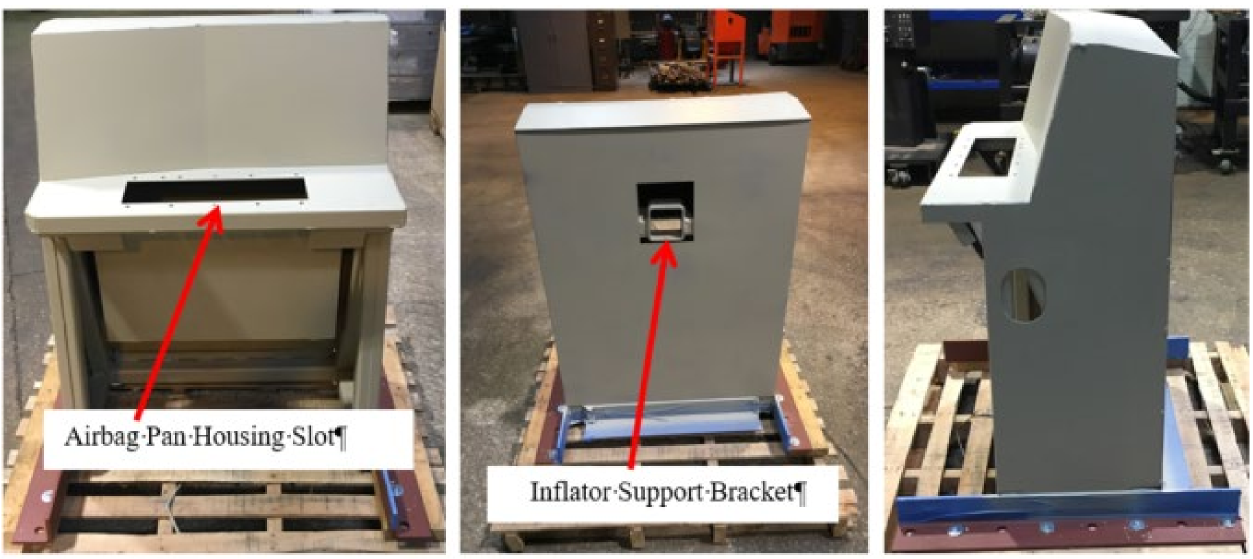

Figure 35. Desk Assembly Showing the Airbag Housing and the Inflator Support Bracket Locations

7.2 Knee Bolster System

The knee bolster system as a concept was retained from the CEPS design. However, the honeycomb layer was removed since it did not contribute significantly to energy absorption in the CEPS sled test. Instead, a 2-inch thick commercial dense foam to minimize a sharp knee force peak was applied to the backing plate using an adhesive, with a vinyl cover applied on the ATD facing side.

The deformable knee bracket was identical to the CEPS. The brackets are made of ASTM standard A36 steel with a minimum yield strength of 36 ksi, a minimum ultimate strength of 50 ksi. The deformable knee brackets were later welded to the baseline cab (Figure 36).

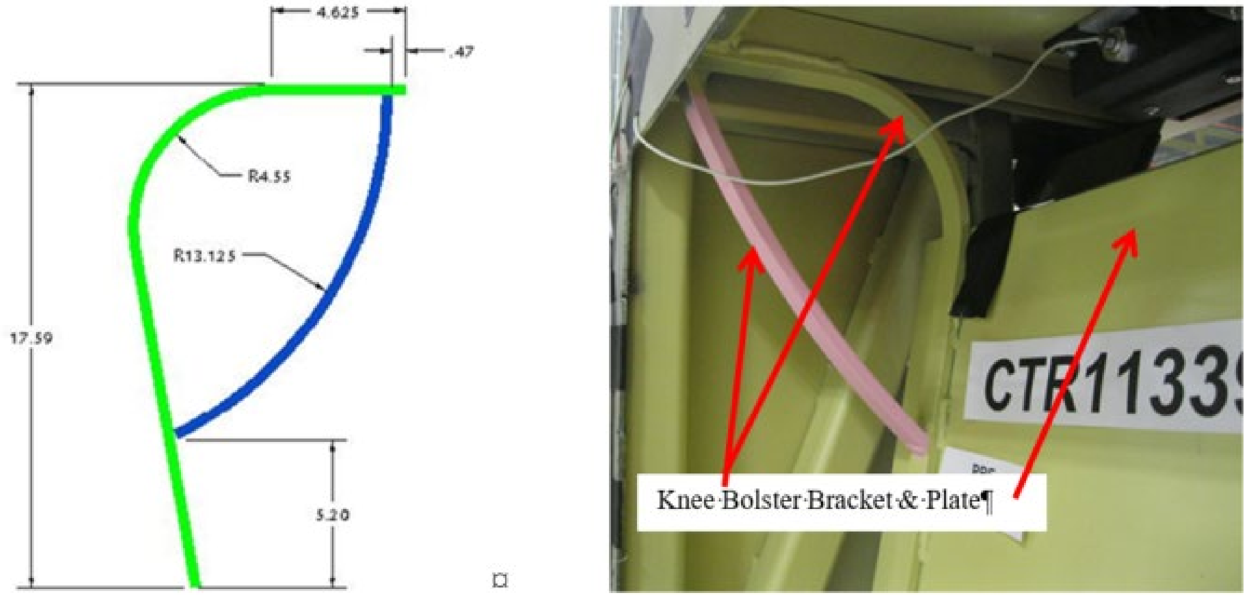

Figure 36. Deformable Bracket—Dimensions and as Installed in the Desk

7.3 Engineer Seat

For the CEPS project, a seat for the test was donated by Southern California Regional Rail Authority (SCRRA), the commuter rail agency in Los Angeles, CA.

This seat had survived the sled tests in the CEPS project and no damage was observed. The same seat as shown in Figure 37 was then used for the SIPS sled testing.

To achieve the desired ATD position relative to the desk, a bracket was bolted to the sled base plate and the seat was then bolted to the bracket.

Figure 37. Engineer Seat Used for SIPS Sled Testing

7.4 Airbag and Inflator

As described in Section 5.2, the airbag design went through several iterations of airbag volume, folding pattern, baffling, venting, and attachment to the pan and attachments to the pan and the port. As listed in Table 3, the final version of the airbag was ITER11 which had a volume of approximately 97 liters, a single reverse roll fold, double baffles with active vents on the back panel, and was attached to the pan with 5 bolts.

The inflator, airbag pan and the inflator mount brackets are shown in Figure 23 and Figure 24. The folded airbag in the pan and attached under the desk is shown in Figure 21.

The final assembly of the desk with airbag and the inflator was completed at the Center for Advanced Product Evaluation (CAPE) testing facilities in Westfield, IN.

8. Sled Test Results

The purpose of dynamic sled testing was to evaluate the system-level performance of the SIPS airbag and knee bolster against key design requirements, including occupant injury measures, when exposed to the 23-g test pulse. These are system level tests, because potential occupant contact surfaces, such as the operator's seat and control stand are present.

8.1 Dynamic Sled Test

Dynamic sled testing has been used for many years within the automotive community to replicate dynamic conditions found in real-world accidents and full-vehicle barrier crash tests. The primary driver for performing sled tests versus full vehicle crash tests is cost. Once a sled test protocol is developed, many tests can be performed with repeatable and reproducible results, without destroying complete vehicles. For these reasons, many regulations that specify the performance of occupant crash protection devices and systems are often written around the performance of sled testing.

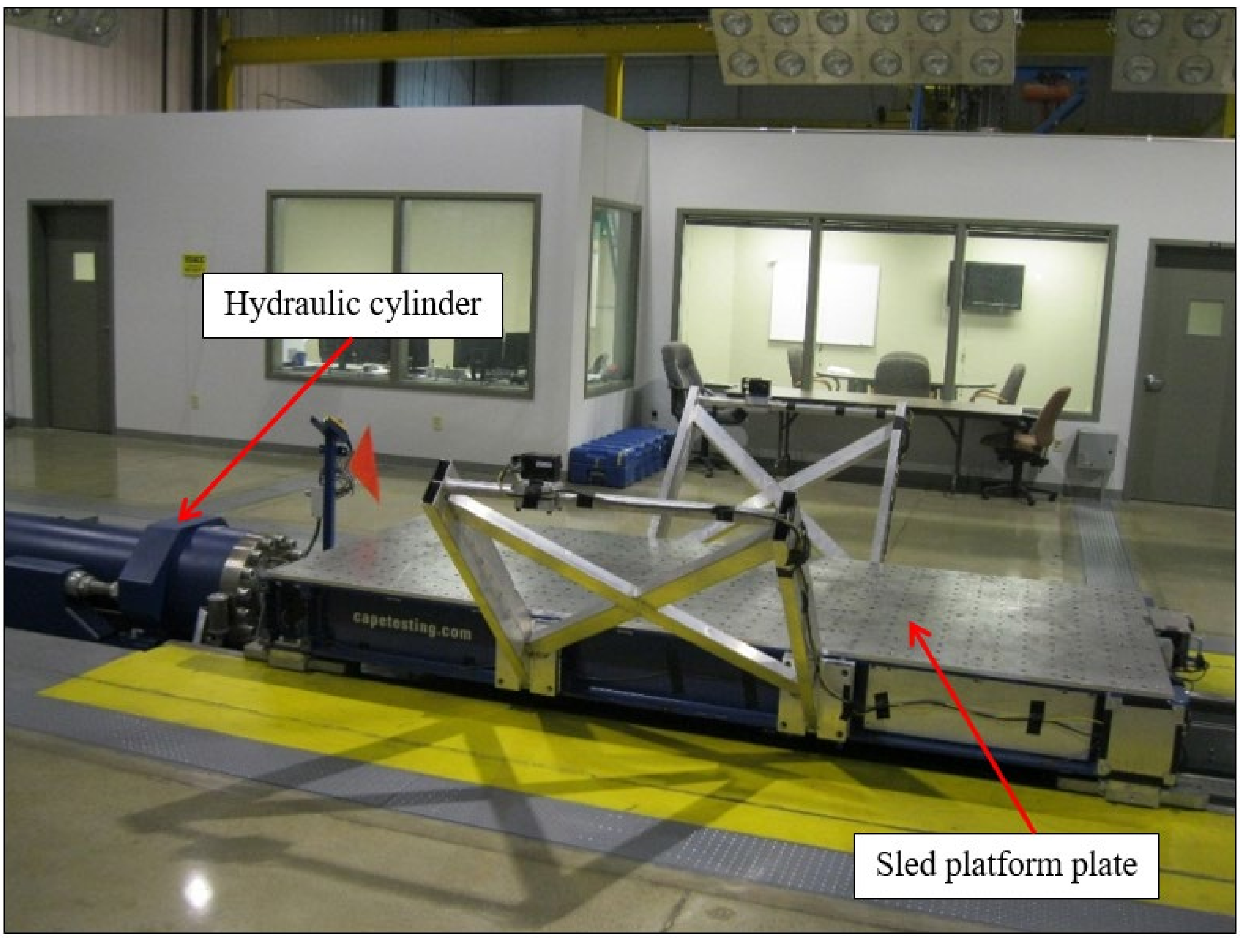

Figure 38. Acceleration Sled at CAPE

Due to the nature of the operation of an acceleration sled, these sleds are often called "reverse firing" sleds. Acceleration sleds can cause confusion among lay persons that find the event to be conducted backwards. Although it is correct that the velocity is in reverse, the inertial forces are in the same direction as a real-world crash or barrier crash test. Acceleration sleds have been accepted by the scientific and engineering community and are preferred over deceleration sleds for some purposes. Figure 38 shows the acceleration sled at CAPE, used to test the SIPS airbag and knee bolster system.

CAPE's acceleration sled uses a hydraulic piston for motive force, and a servo controlled brake system to control the acceleration pulse. At the start of the test, the sled platform is engaged with the piston. The piston is energized with the force necessary to accelerate the sled platform and test articles. The platform is held in place by the servo brake system.

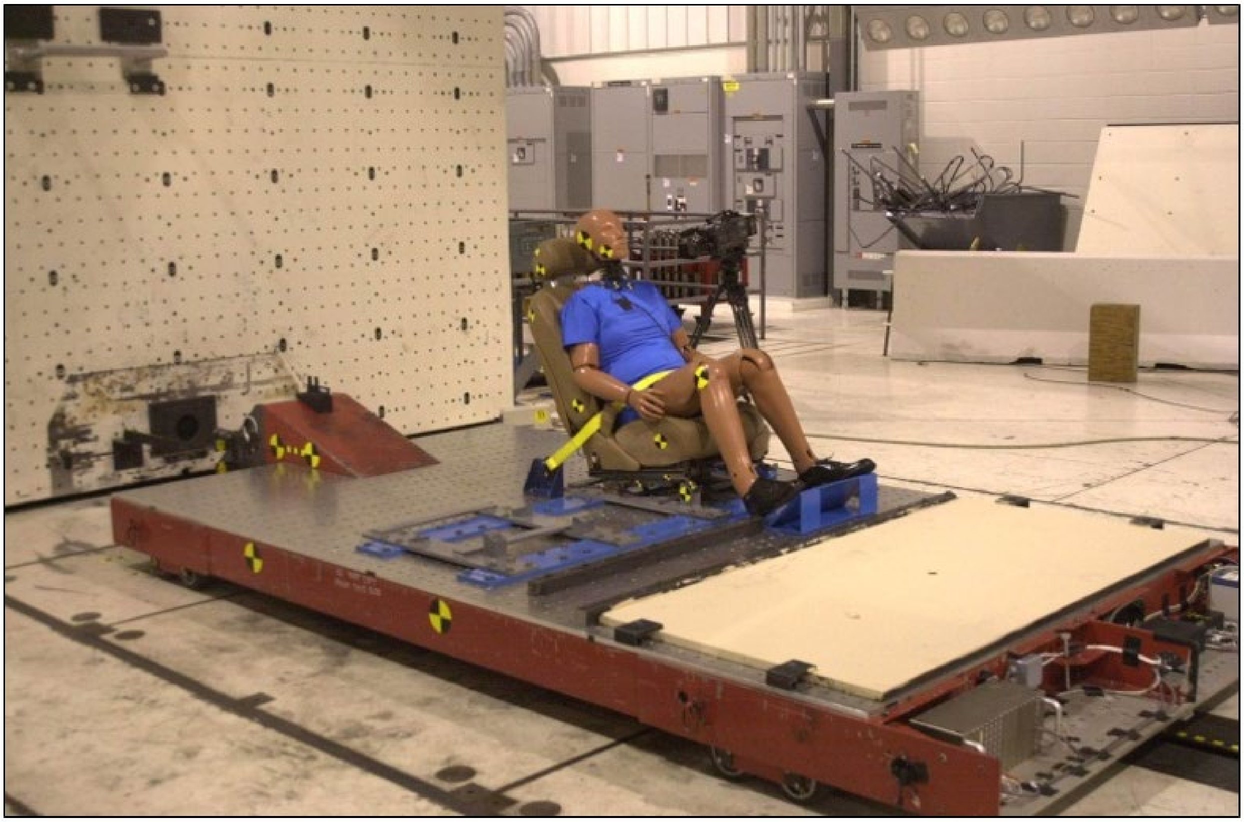

Figure 39. Exemplar Deceleration Sled at CAPE

After the test starts, computer controls modulate the servo brakes to create the intended crash pulse. The hydraulic piston and sled platform are shown in Figure 38. The servo brake system is located underneath the platform and is not visible in Figure 38.

A deceleration sled operates by gradually propelling the sled up to crash speed, allowing the sled to roll freely or slide on tracks, and crash into a mechanism that provides a crash force to decelerate the sled. The measured acceleration experienced by the sled during the deceleration phase of the crash is termed the "crash pulse."

In most cases the sled will bounce backwards (rebound) a small amount after crashing into the deceleration mechanism. This is not necessarily unrealistic since there is likely a small rebound of automobile occupants after a crash occurs.

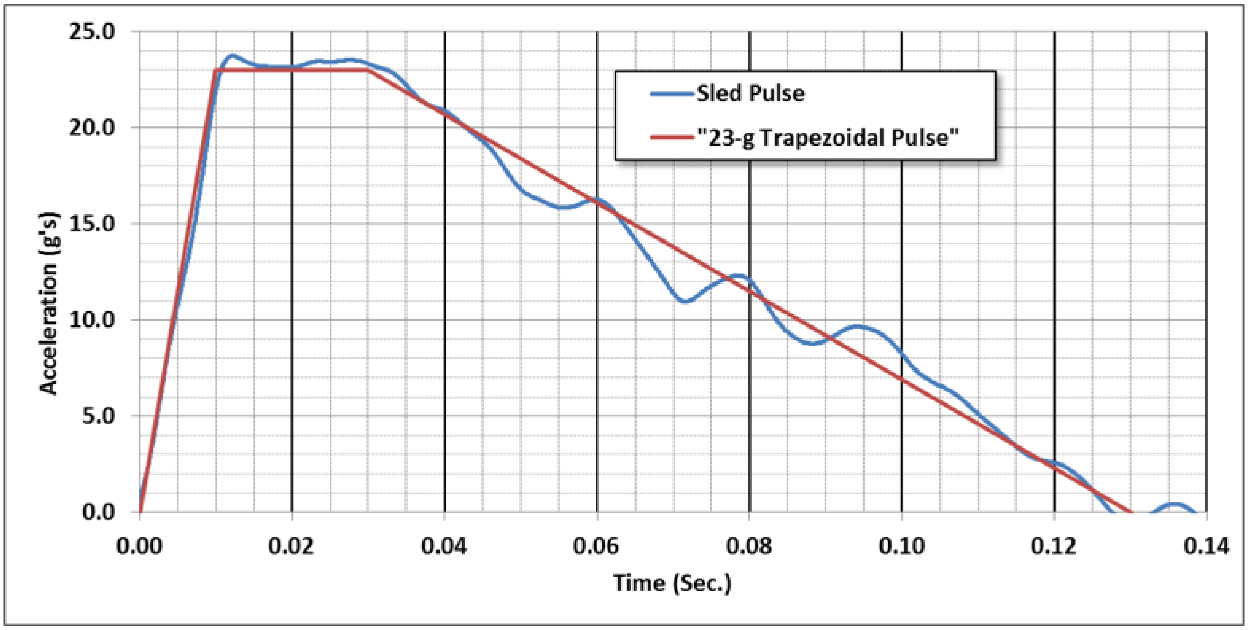

Figure 40. SIPS 23 g Crash Pulse Replication in Sled Test

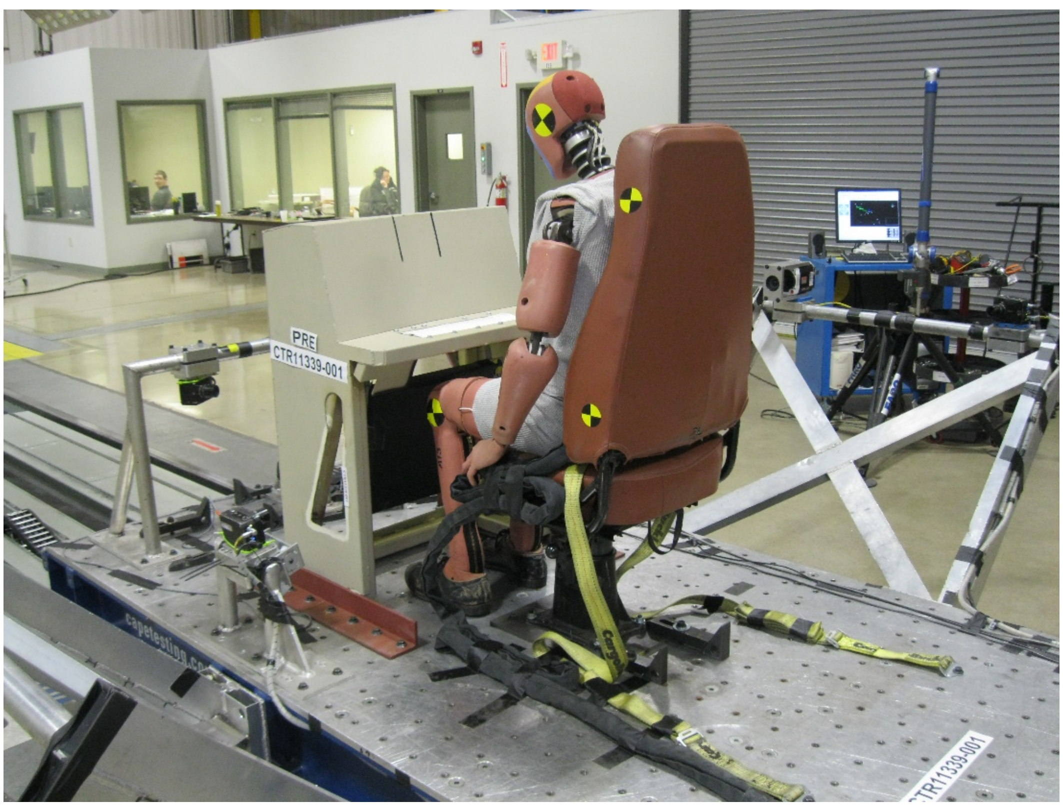

Figure 41. Dynamic Sled Test Setup

During a test with a deceleration sled, the delta V is the velocity at impact plus the rebound velocity, where both velocities are algebraically signed according to their respective directions. Figure 39 shows an exemplar deceleration sled at CAPE. Both the acceleration and deceleration sled designs can replicate a wide variety of crash pulse inputs. For this test series, dynamic sled tests were conducted on an acceleration sled because it can better reproduce the trapezoidal shape of the SIPS test pulse, as shown in Figure 40.

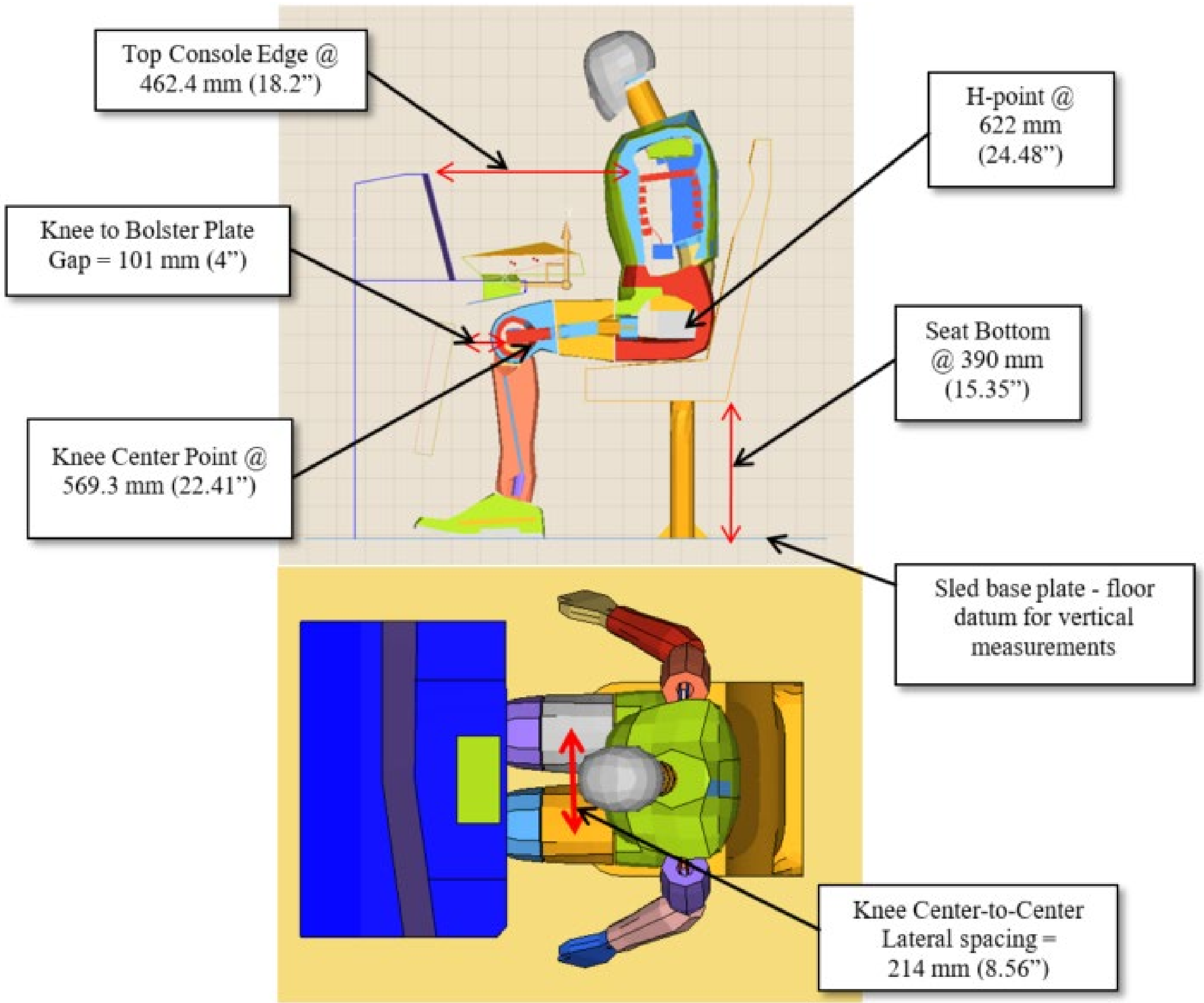

Figure 42. Test Setup—ATD Relative to the Desk

In addition, the initially stationary sled platform enabled more exact pretest positioning of the unrestrained (unbelted) ATD.

For this dynamic test series, a representative locomotive operator's control stand was attached to the sled deck. The SIPS airbag module and deformable knee bolster were installed on the control stand. A locomotive operator's seat was attached to the deck, in the same position relative to the control stand, as was used in the analytical simulation model, Figure 41.

The unbelted, 95th percentile Hybrid III ATD was positioned in the seat, such that the ATD's knees were 4 inches from contact with the deformable knee bolster. Figure 42 shows the pretest setup. The pretest positions of the ATD, relative to targets on the control stand, were measured using a FAROArm®, a portable coordinate measuring machine.

For safety purposes, the ATD was equipped with a tether, whose length was adjusted to not influence the ATD's interaction with the control stand nor with SIPS. Multicolored chalk was applied to the ATD's head, face and knees to help identify contact locations.

8.2 Instrumentation and Data Collection

The dynamic sled test was recorded using six high-speed digital imagers, positioned as follows.

1. Right side view of ATD, on-board imager (2,000 frames/second)
2. Right side oblique view of ATD, on-board imager (1,000 fps)
3. Left side view of knee interaction with bolster, on-board imager (1,000 fps)
4. Left front oblique view of knee bolster, on-board imager (1,000 fps)
5. Oblique view of the right knee bolster bracket (1,000 fps)
6. An overhead view of event, off-board imager (1,000 fps)

The video was recorded at a minimum of 1,000 fps, in accordance with SAE J211-2, Instrumentation for Impact Test, Photographic Instrumentation, except for the first imager which recorded at 2,000 fps to capture more frames for posttest analysis and review.

Reference targets were included in the side view motion plane, enabling the video to be used for motion analysis. A strobe verified synchronization of the video and instrumentation measurements.

Three of the video cameras installed on the sled are shown in Figure 43.

A calibrated 95th percentile Hybrid III ATD included the instrumentation necessary to calculate injury reference values for comparison to the limits. ATD instrumentation included the following measurements:

1. **Head Acceleration**

   X, Y, Z Accelerometers
2. **Chest acceleration**

   X, Y, Z Accelerometers
3. **Pelvis acceleration**

   X, Y, Z Accelerometers
4. **Upper Neck forces**

   X, Y, Z Load Cell
5. **Upper Neck moments**

   Mx, My, and Mz Moments
6. **Chest deflection**

   Potentiometer
7. **Left and right Femur forces**

   Load Cells

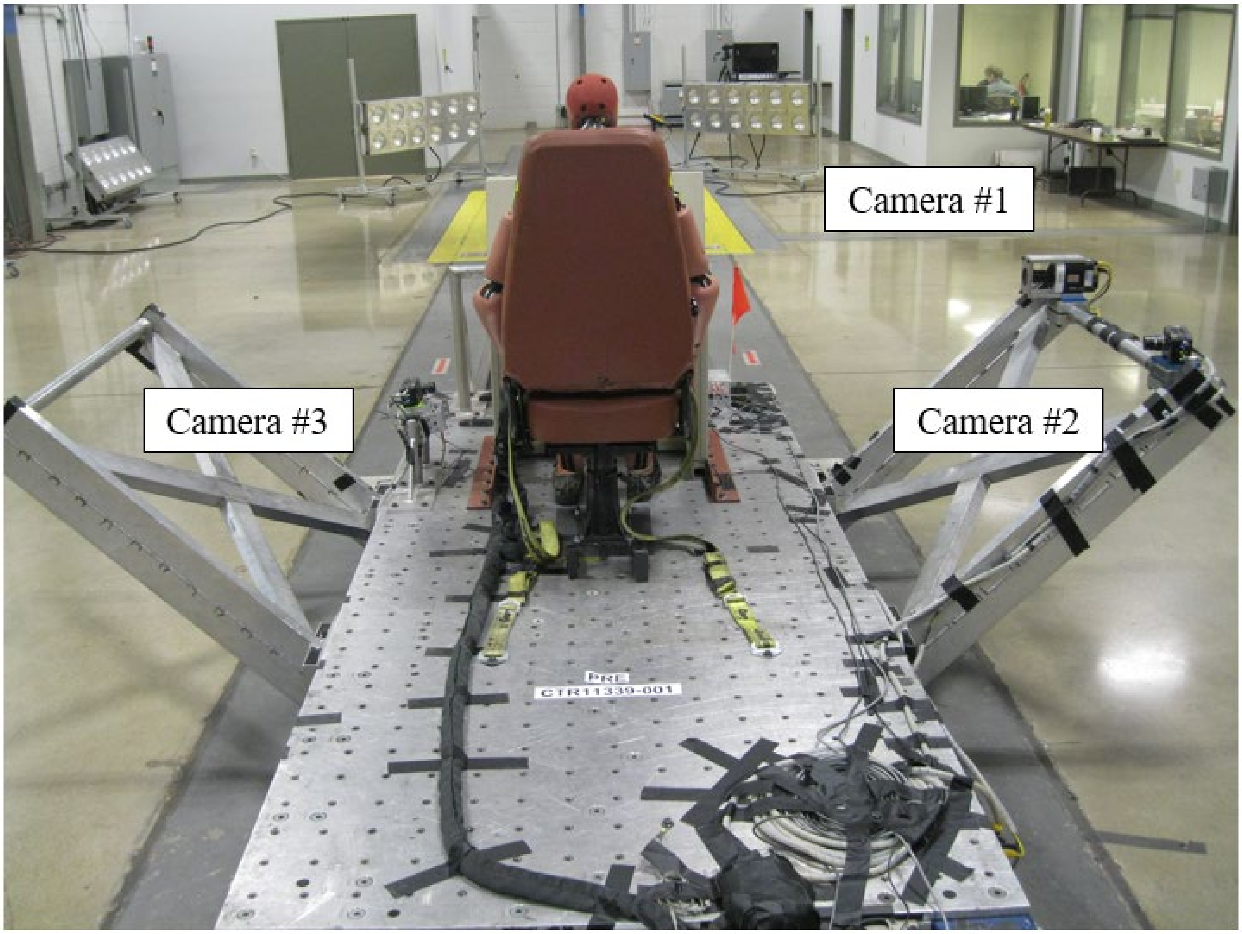

Figure 43. Various Video Camera Locations as Mounted on the Sled

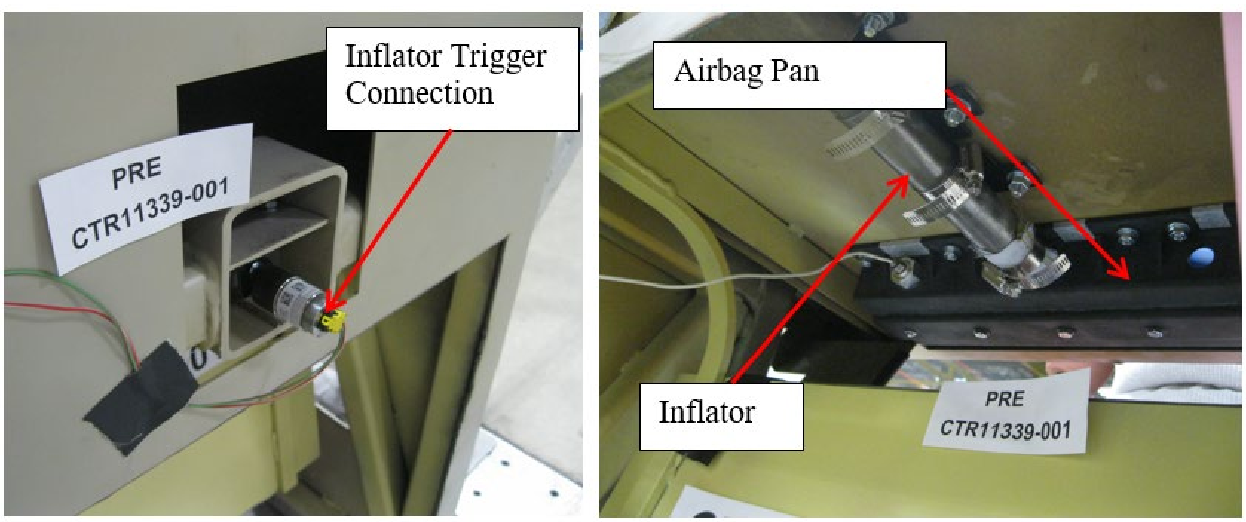

Figure 44. Inflator Firing Trigger Connection

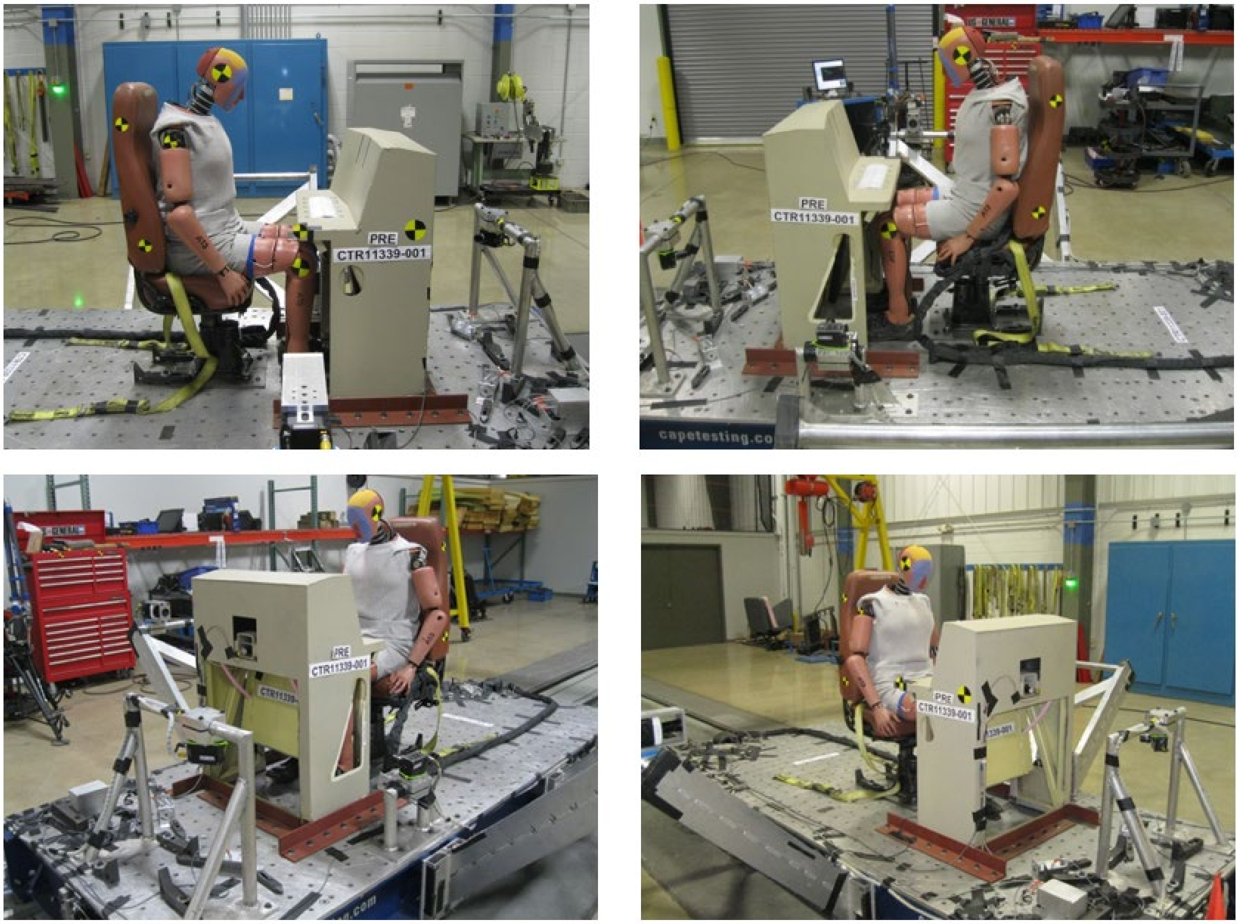

Figure 45. Sled Test Setup—Right and Left Views

Instrumentation also included a pulse accelerometer on the sled platform, a pressure transducer attached to the airbag pan, a contact switch positioned to identify knee contact with the bolster, and a data channel to record the airbag fire signal.

Figure 44 shows the inflator installed in the desk below the console and connected to the airbag pan. Also shown is the electrical connection for the inflator firing trigger.

Figure 45 shows the sled with ATD from various angles and Figure 46 shows the overall sled as set up for testing.

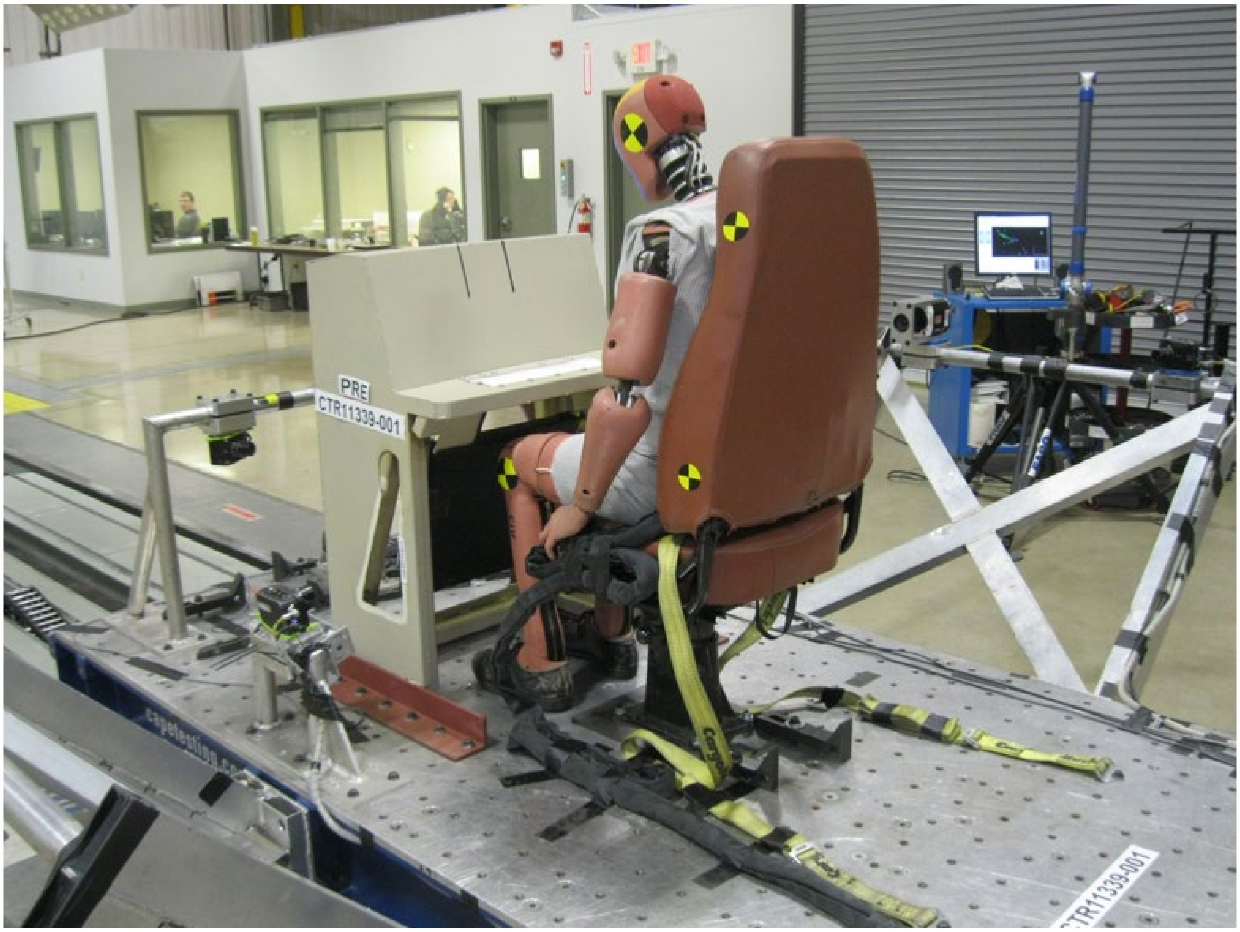

Figure 46. Overall Sled Setup with ATD, Prior to Crash Test

For the crash test, all measurements were made and processed in accordance with SAE J211-1, Instrumentation for Impact Test, Electronic Instrumentation, and calculations were conducted in accordance with SAE J1727, Calculation Guidelines for Impact Testing.

8.3 Sled Crash Test Results

The control system accelerated the sled platform, using the SIPS test pulse shown in Figure 40. The SIPS airbag was deployed 12-ms after time zero by the data acquisition system. This 12-ms delay was chosen as an estimate of the time for a crash sensing system to discriminate between a deceleration event requiring airbag deployment from an event where an airbag deployment is not desired.

Since no crash sensing system exists today for locomotives, the 12-ms delay may or may not be indicative of actual performance in the application.

The dynamic sled test using airbag module 11 was conducted according to plan. CAPE's acceleration sled accurately replicated the crash pulse, (as shown in Figure 40), producing a peak velocity of 60.4 kph (37.5 mph) as shown below in Figure 47.

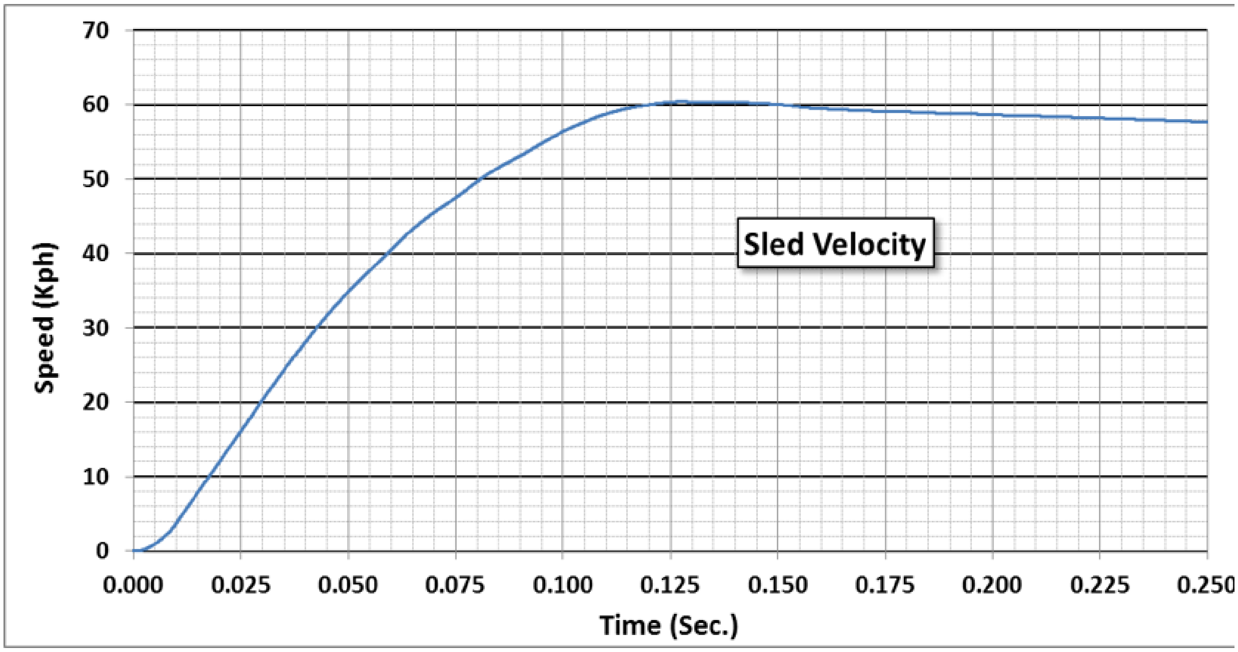

Figure 47. Sled Speed Resulting from the 23 g Trapezoidal Crash Pulse During Test

The deployment signal was sent to the SIPS airbag module at 12 ms and the airbag first appeared in video after an ignition delay of 2.5 ms. The SIPS airbag module deployed symmetrically with good forward trajectory, engaging the head, neck, chest and abdomen of the ATD, beginning at approximately 20 ms. Figure 48 shows the airbag inflating and engaging the ATD as it accelerates relative to the desk. The figure shows the video capture at 0, 30, 45, 60, 70 and 90 ms following the crash event.

Video analysis suggested that the active vents opened at approximately 39 ms, but were at least partially blocked by contact with the desk's reaction surface. The contact switch indicated that the ATD's knees first contacted the knee bolster at 41 ms. At 45 ms, the airbag is well inflated and the ATD had engaged a broad expanse of the well-positioned airbag, as shown in Figure 48.

Between 60–62 ms, a tear in the airbag fabric formed on the lower right-hand side, where the side, bottom and connection panels join. The tear continued to open, and by 70 ms, the data suggested that the SIPS airbag lost all effectiveness, as shown in Figure 48. After 70 ms, the knee bolster and desk structure had to absorb the ATD's kinetic energy without the benefit of the airbag. Once the ATD torso contacted the desk edge, the ATD rotated with the upper body moving up and forward and the chin struck the top of the console.

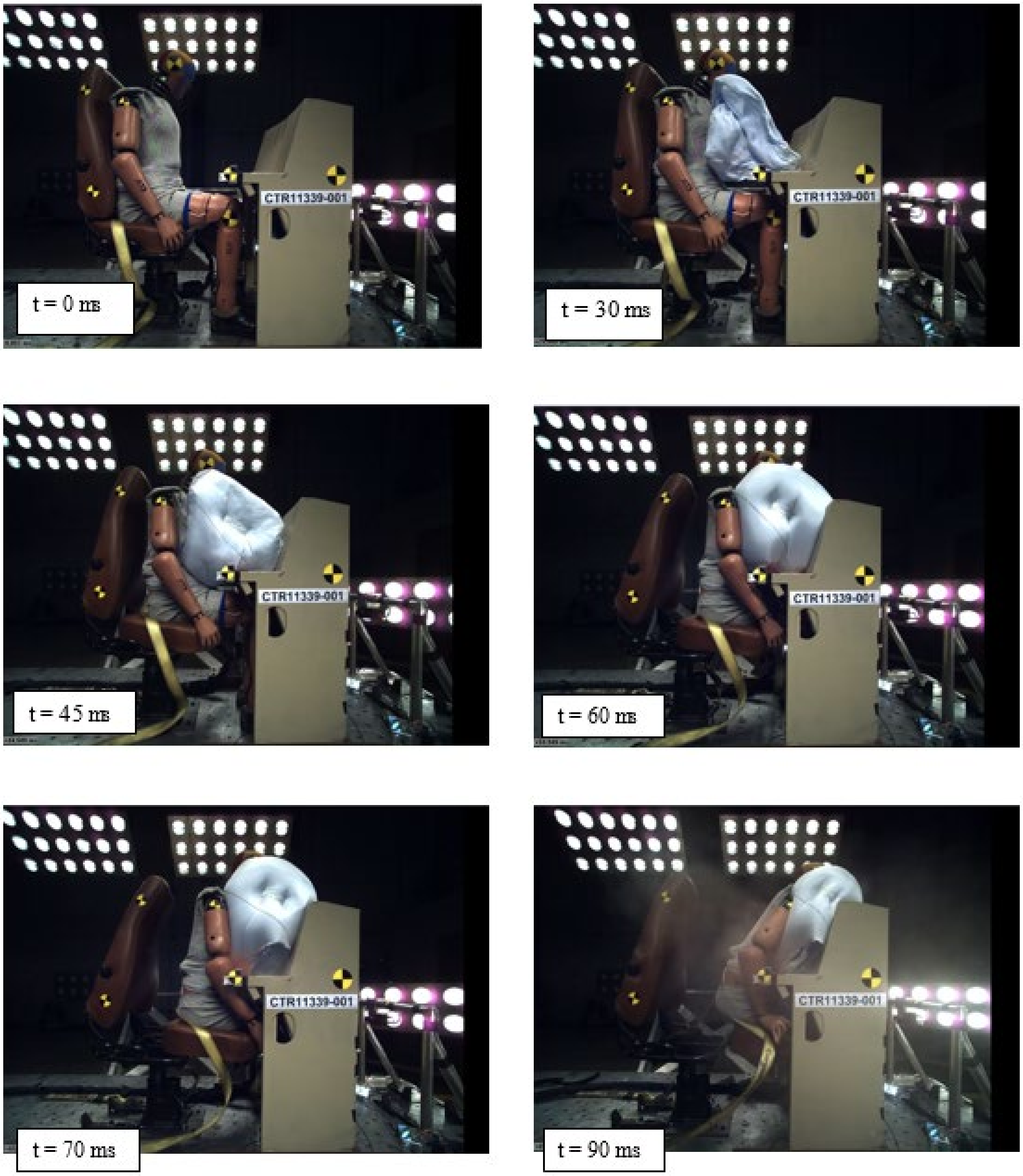

Figure 48. ATD Kinematics from Sled Test

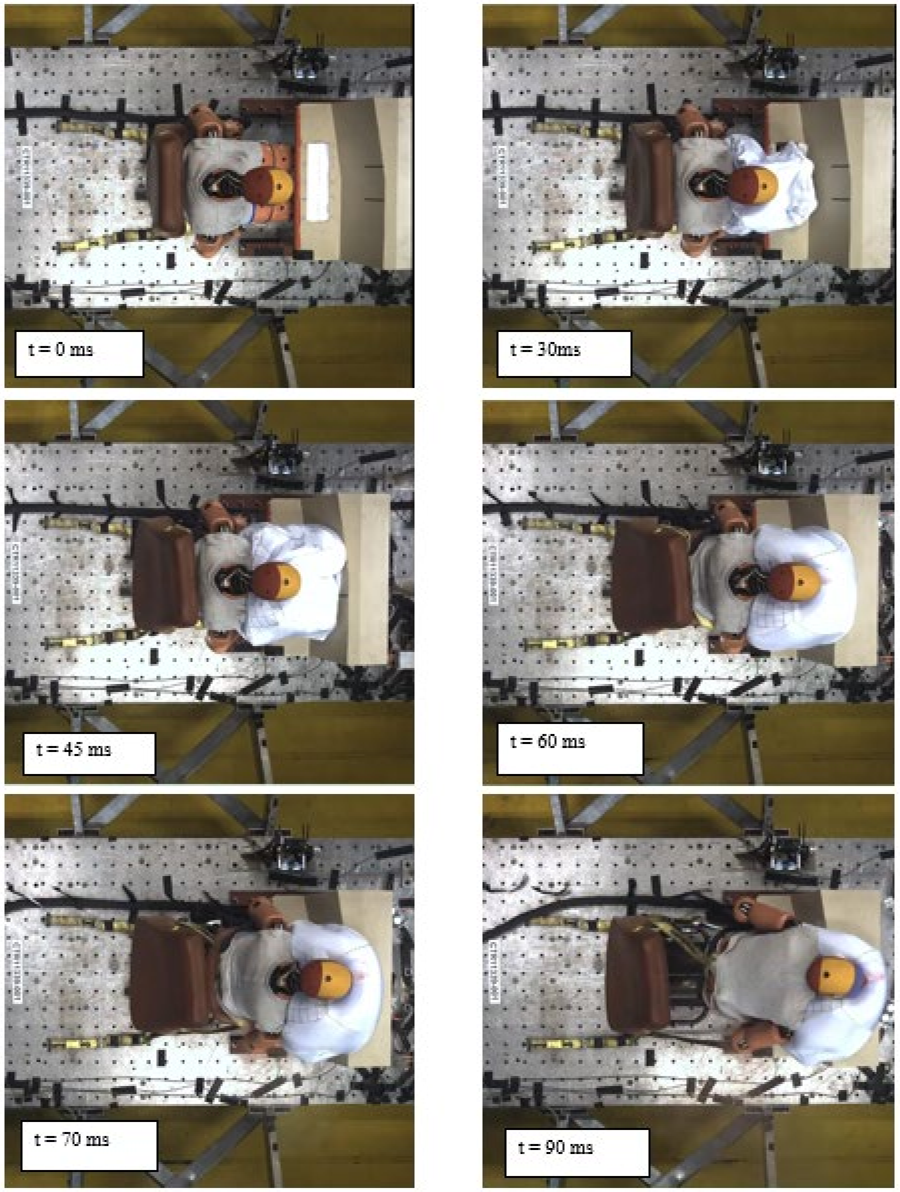

Figure 49. Overhead View of the Sled at 0, 30, 45, 60, 70 and 90 ms

The ATD as viewed from the overhead video camera is shown in Figure 49 at 0, 30, 45, 60, 70 and 90 ms. Plastic deformation of the knee bolster plate and brackets (the pink-colored item) is quite evident comparing the pre-and posttest (also see Appendix D) photographs shown in Figure 50.

Figure 50. Permanent Deformation on the Knee Bolster Plate and Brackets (Left Pretest, Right Posttest)

8.4 Injury indices discussion

ATD injury indices derived from measurements from the sled test (CTR11339-001) are shown in Table 5, compared to the FMVSS 208 limits and the pretest simulation for the final airbag design.

Table 5. Injury Indices—Comparison of Pretest Predictions to Sled Test

Injury Parameter	Index Limit	Injury Indices		
		Pre-test Simulations	Sled Test Value	Sled Test Time (ms)
HIC_{15}	700	91	109	
Chest 3ms (G)	60	32	60/ **(70)****	79
Chest Deflection (mm)	50	55	24.7	253
Femur Left (N)	10,000	6,506	9,157	49
Femur Right (N)	10,000	6,594	9,398	50
Neck Tension (N)	4,170	2,237	**7,883***	111
Neck Compression (N)	4,000	1,245	3,123	97
N_{te}	1.0	0.68	0.74	64
N_{tf}	1.0	0.12	0.99	111
N_{ce}	1.0	0.19	**1.32***	98
N_{cf}	1.0	0.25	0.05	218

* Index exceeding the injury limit. ** For two values, please see Section 8.4.2.

Since the airbag lost structural integrity, some of the injury parameters are elevated due to ATD contact with the sheet metal desk and exceed the injury limit. All maximum injury criteria occurred after the SIPS airbag module lost structural integrity. That suggests that an airbag module that maintains its structural integrity has the potential to dissipate crash energy and reduce injury severity.

As seen in Table 5, two of the neck injury indices, N_t and N_{ce}, which are measures of neck extension and a combination of the neck compression and neck moment were above the targeted limits in the test. A review of the ATD kinematics from the test, presented in Figure 48, highlights the issue. It is seen that the airbag deploys in a trajectory that initially contacts the face/chin area, thereby, loading the neck in extension. It was also seen that in the initial ATD positioning, the neck was leaning forward more than usual.

8.4.1 Head Acceleration

Head acceleration history from the sled test is shown in Figure 51. The HIC_{15} index is calculated based on the acceleration of the head weighted over a 15-ms moving window. As shown in Table 5, the value for HIC_{15} is 109. The value is based on the resultant head acceleration in the x, y and z directions, shown in Figure 52. (For the ATD, the coordinate system follows the right-hand rule, i.e., the x axis is aligned along the sled centerline, the y axis is lateral and the z axis is vertical direction.) Though the acceleration in the z-direction is expected as the ATD contacts the airbag and the head pitches up/down during contact, theoretically there should be no acceleration in the y direction. However, the desk console was not perfectly symmetric relative to the x-axis and the airbag failure also allowed the ATD to slightly rotate, thus creating acceleration in the y direction and this added to the resultant acceleration. In the overhead video shots in Figure 49, the asymmetry of the airbag because of the desk geometry is clearly seen at 60 ms just before the airbag breach. Once the airbag fails the ATD is seen to have rotated to the right. Still, the peak HIC_{15} of 109 is well below the limit of 700.

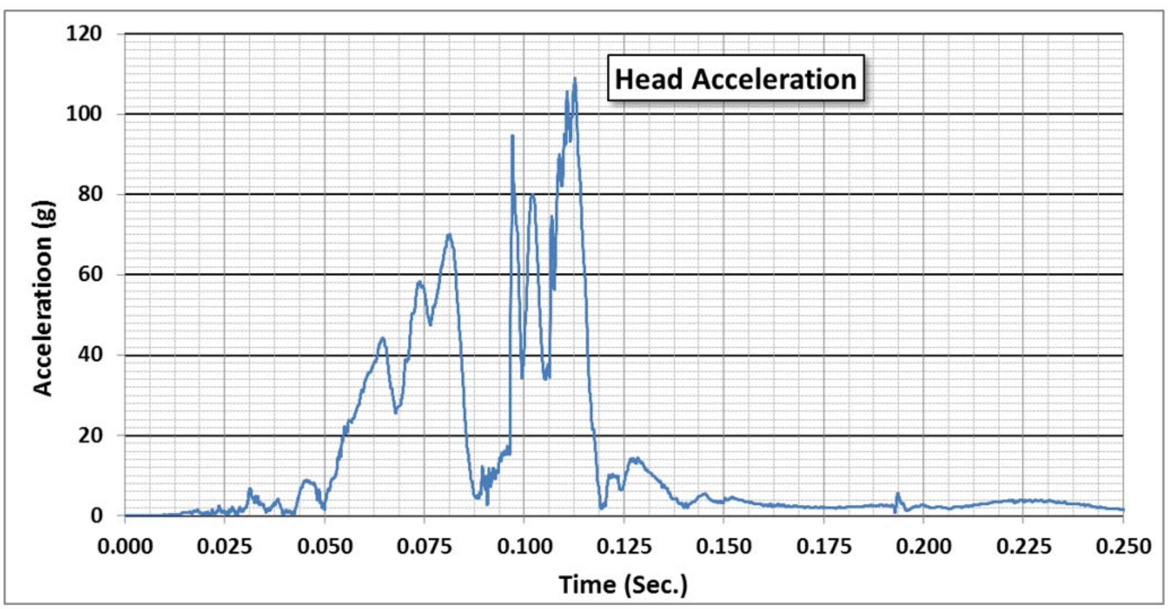

Figure 51. Sled Test Time History—Head Acceleration (Resultant)

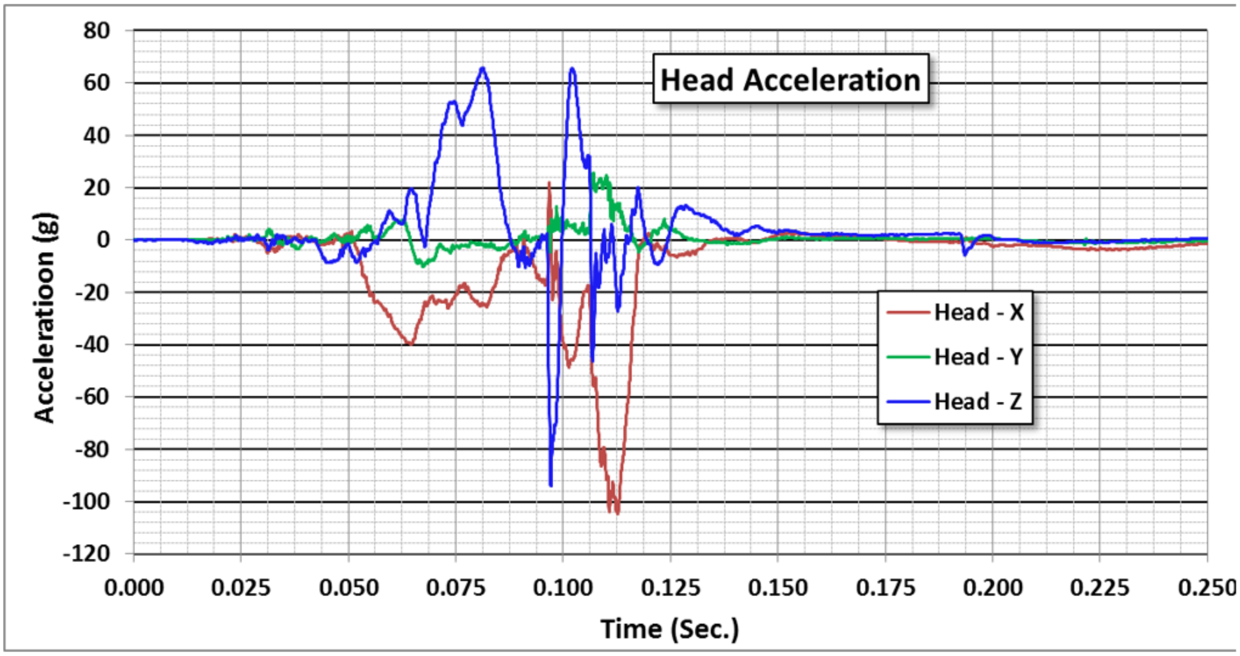

Figure 52. Sled Test Time History—Head X, Y and Z Acceleration

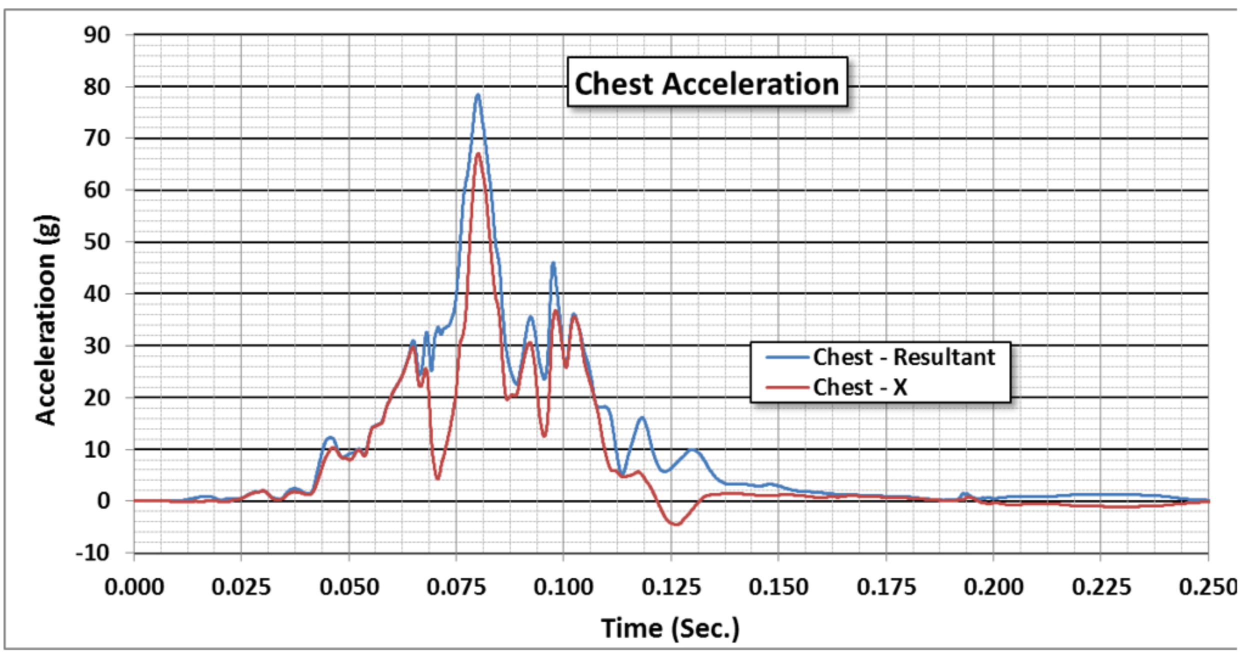

Figure 53. Sled Test Time History—Chest Acceleration

8.4.2 Chest Accelerations

The chest acceleration history from the sled test is shown in Figure 53 The chest injury index limit of 60 is based on a chest acceleration value which is exceeded or sustained within a moving 3 ms window. The pretest simulation chest injury index was predicted to be 32, well below the limit of 60. This value was based on an assumed controlled venting of gas from the airbag to reduce pressure on the chest at the point in time when the ATD is accelerating and contacting the nearly fully deployed or still inflating airbag. A venting system to achieve these characteristics was developed (see Appendix C) based on the simulation results for the gas volume and mass loss during airbag deployment and the ATD interaction with the airbag.

The chest injury index based on the longitudinal (x direction only) acceleration is 60 and equal to the limit. The resultant acceleration based index value is 70 and does exceed the limit value. However, it is obvious that the system needs further improvement to provide the desired response of the airbag to control the chest acceleration to meet the injury index limit.

8.4.3 Femur Loads

Femur loads from the sled test are shown in Figure 54 for both the left and right knee. As seen in Figure 48, the ATD stayed centered and contacted the airbag in an upright and straight position. Both knees experienced the peak load at 50 ms well before the airbag developed the tear at 62 ms. The second peak in the femur load is experienced as the airbag developed the tear and the ATD accelerated forward. However, by then the ATD torso (abdomen) area is in contact with the front edge of the desk and the knees unload completely. It is noted though that both femur loads are below the injury index limit of 10,000 N.

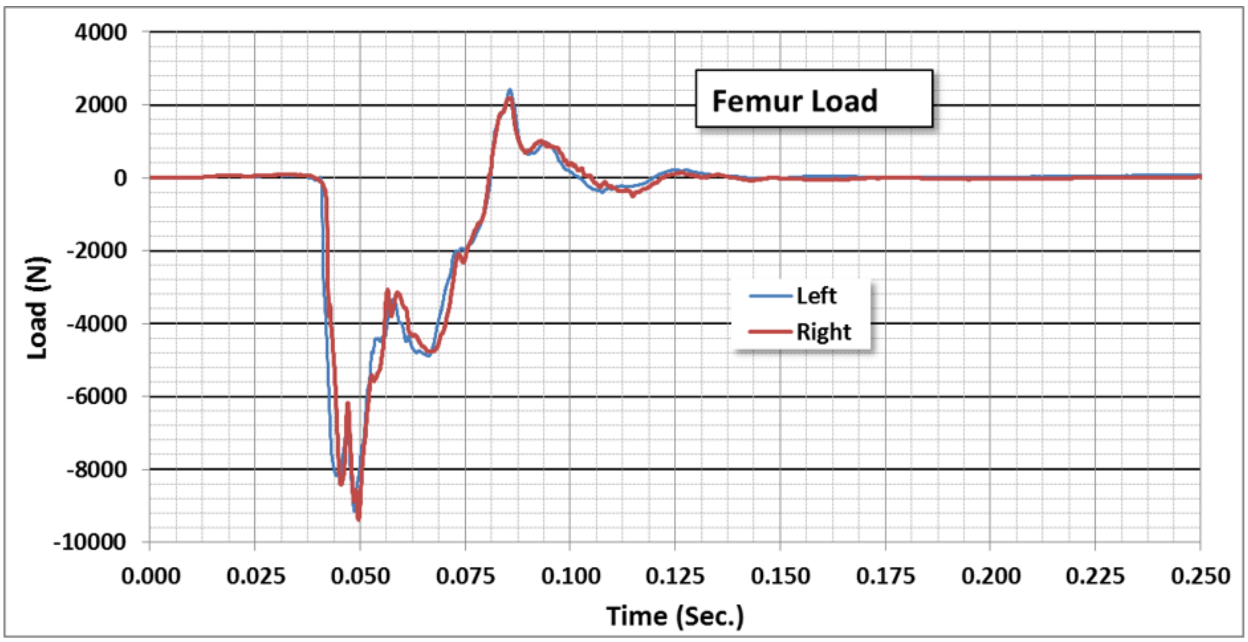

Figure 54. Sled Test Time History—Right and Left Femur Load

8.4.4 Neck Forces

Neck forces from the sled test are shown in Figure 55, Figure 56, and Figure 57 for F_z (along the neck), F_y (lateral direction) and F_x (longitudinal direction.) The neck force F_z is generally the largest of the three due to the head acceleration in the vertical direction. The next highest is the force F_x which would result from the forward/backward acceleration of the head relative to the upper body. The smallest forces seen are in the F_Y direction which would result from head acceleration in the lateral direction such as in a side impact. However, in the sled test, largely all the motion is in x-direction.

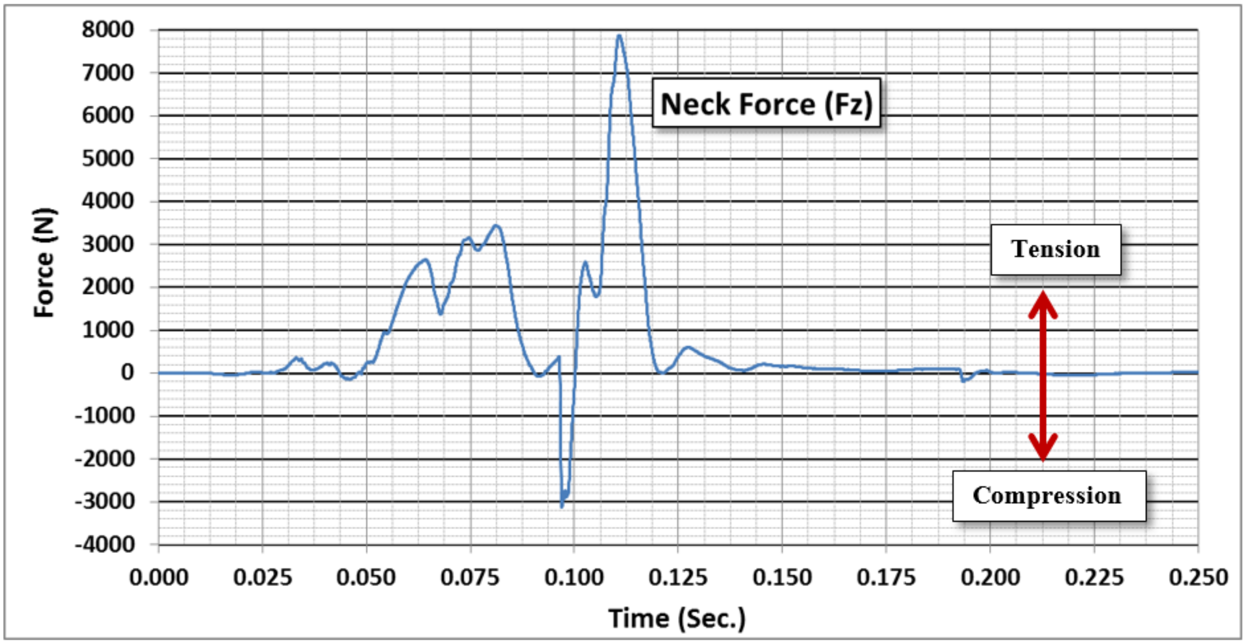

Figure 55. Sled Test Time History—Neck Force (F_z)

Neck force F_z limits are defined in tension and compression. The tension limit (Nt) is 4,170 N and in compression (Nc) it is 4,000 N. As listed in Table 5, the tension limit is exceeded by a significant margin. The F_z value in tension is 7,883 N compared to the limit of 4,170 N. As seen in Figure 55, this value occurs well past the airbag having completely collapsed around 98 ms and the ATD chin hits the desk accelerating the head up creating a high-tension force in the neck.

The compression force limit of 4,000 N is not exceeded and the maximum neck force is 3,123 N which is well below the limit.

So far, we have compared the test measured indices against the values for a 50th percentile Hybrid III male ATD. These are values which have been standardized by the National Highway Traffic Safety Administration (NHSTA). The studies sponsored by the NHTSA have developed indices for the 95th percentile Hybrid III male ATD, as shown in Appendix E [4]. The study recommended peak values of 5,030 N for tension and 4,830 N for compression. The tension value of 7,883 N measured during the test exceeds this higher limit. It should be noted that the maximum tension force in the test occurred after the airbag prematurely collapsed completely and the ATD chin strikes the desk of console.

The neck forces F_x and F_y are shown in Figure 56. The FMVSS 208 does not include any limits for these two forces. Theoretically, with a completely symmetric arrangement of ATD, airbag, desk structure and console surface about the longitudinal axis (x-axis), the F_y force will be zero and the F_x force will be a result of the relative acceleration between the head and upper torso. Relative to the neck force F_z, the F_x and F_y forces are much smaller.

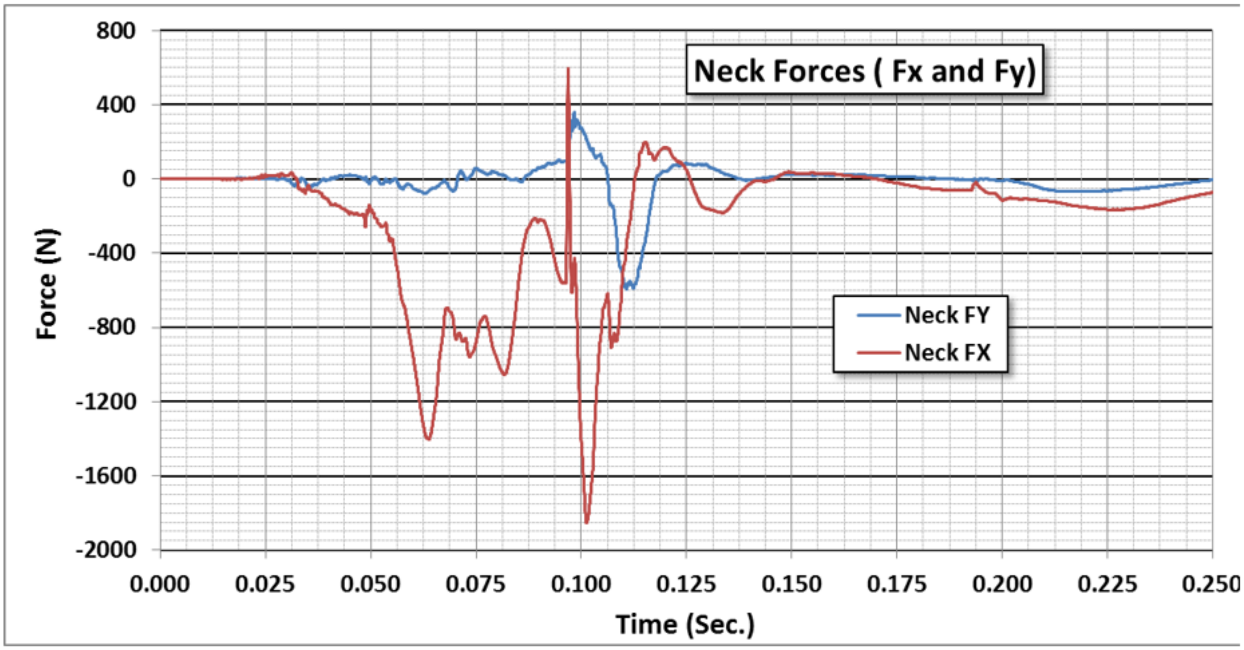

Figure 56. Sled Test Time History—Neck Force F_x and F_y

8.4.5 Neck Injury Indices N_{ij}

The four neck injury indices N_{te} (neck tension, neck extension moment), N_{tf} (neck tension, neck flexion), N_{ce} (neck compression, neck extension moment) and N_{ce} (neck compression, neck flexion) are generated from the neck force F_z (tension/compression) and the neck moment (extension/flexion).

As listed in Table 5, except for the N_{ce}, the other three N_{ij} indices are well within the limits for the 50th percentile ATD. The N_{ce} value of 1.32 is above the limit of 1.0. Although the N_t limit is exceeded even when accounting for the not yet standardized higher limit of 5,030 N, the neck injury criteria of N_{te} is within the limit of 1.0. The N_{ij} limits reported are for a 95th percentile male for intercept values shown in Appendix E, highlighted (light blue) column "Large Size Male."

The time of occurrence for the N_{ce} value of 1.32 is listed in Table 5 as 98 ms and is shown in Figure 57. At this moment, the neck compression force is well below the limiting value, the major contribution to the index comes from the neck moment M_{ocy} generated by the impact of ATD chin on the desk after the collapse of the airbag as discussed in Section 9.

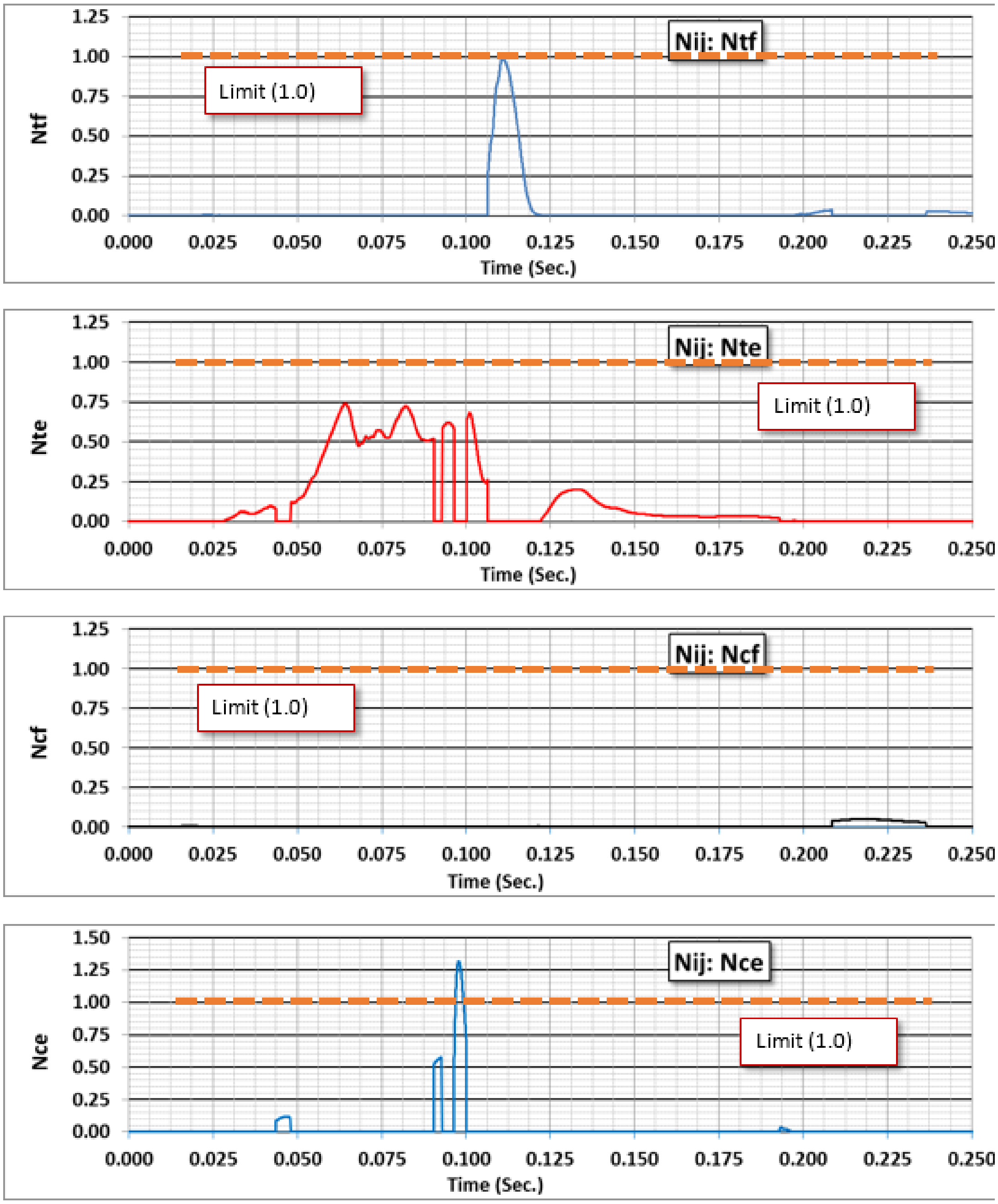

Figure 57. Sled Test Time History—N_{tf}, N_{te}, N_{cf} and N_{ce}

8.5 Airbag Failure Review

The SIPS airbag module 11 used in the sled test was identical in design and construction to module 9 used for the final linear impact test. The airbag pressure as recorded in the linear impact test and the sled test is shown in Figure 58. It is seen that the overall airbag pressure in the sled test generally remained below the pressure recorded in the impactor test up to the point when the airbag tear appeared at approximately 62 ms. At this time, the airbag was pushed by the ATD against the desk/console and the vents even if opened were not exposed. Thus, airbag pressure is slightly higher as the airbag tear quickly grows between 66–90 ms.

Posttest inspection revealed no material or sewing abnormalities. All seams were intact. The tear began where three panels join, forming a stress concentration, and it propagated along the weave of the side panel fabric. The tear occurred on the same side as the pressure transducer attachment, where the material has an additional constraint due to attachment for the transducer.

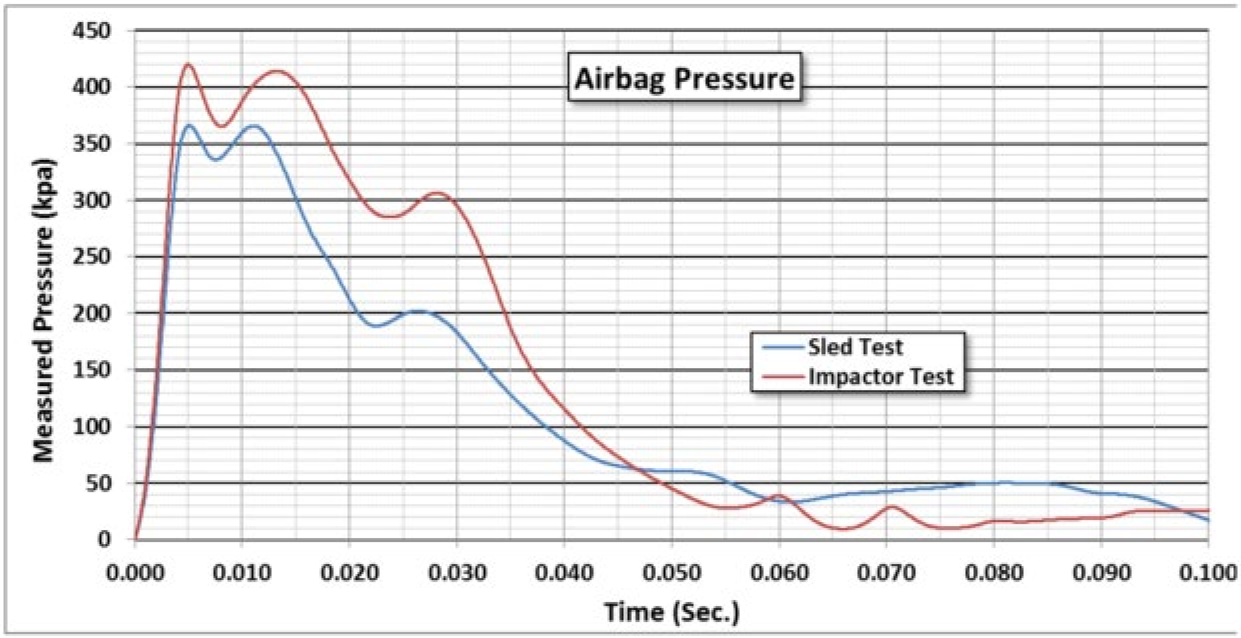

Figure 58. Pressure History Comparison—Sled Test and the Impactor Test

As shown in Figure 59, the bag is attached to the pan with five bolts which are located laterally, symmetric with respect to the pan centerline and the inflator. However, to mount the pressure transducer inside the bag, the hole in the airbag for the transducer is aligned with the hole in the pan side. Once the transducer mounting is complete, it creates constraints on the bag expansion as it reaches near full deployment, thus creating additional fabric stress on that side. Since in both sled tests bag tear occurred on the pressure transducer side, the asymmetry caused by the attachment of the transducer to the bag through the pan wall contributed to the tear. This attachment is shown in Figure 59 (bottom right picture).

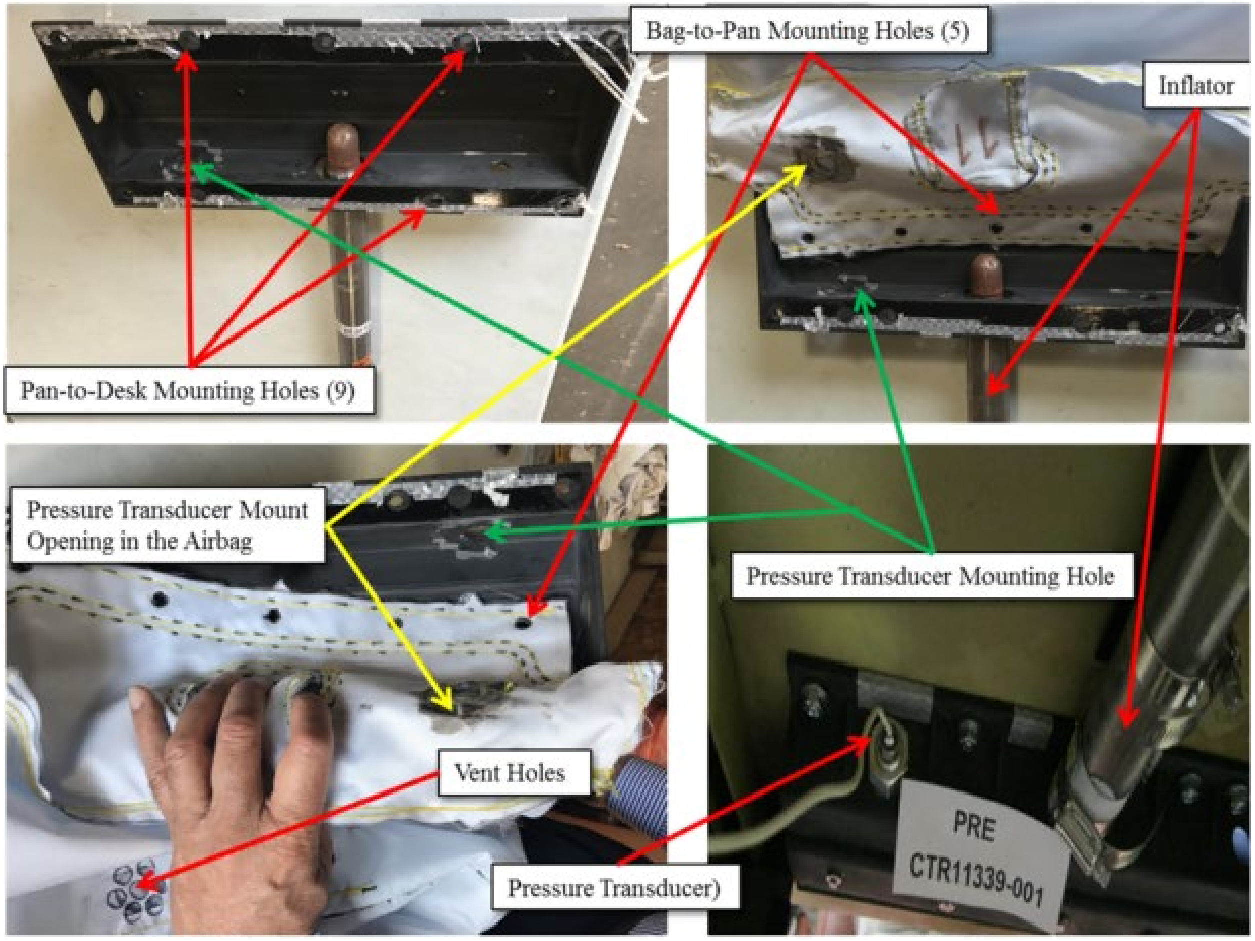

Figure 59. Pan, Air bag, Inflator and Pressure Transducer Assembly Details

It is theorized that relocating the vents to locations where they remain open longer and incorporating an airbag fabric with higher permeability can lower the airbag pressure at the critical time sufficiently to eliminate the airbag tear. However, this will require some redesign of the airbag itself and testing to ensure that design changes result in desirable venting behavior and maintain the injury indices within the limiting criteria.

9. Discussion of the Indices Exceeding the Injury Criteria

Table 5 showed the summary of injury indices from the sled test. There are three injury indices that exceeded the FMVSS 208 criteria: Chest Acceleration 3 ms Clip, Neck Tension (F_z), and N_{ce}. The following discussion suggests that if the airbag had not failed, these criteria would have been met as well.

Figure 60 and Figure 61 show the time histories of the chest acceleration, neck force F_z and neck moment (M_{ocy}) from the sled measurements compared to the LS-DYNA simulated results. The shaded area in these figures indicates the beginning of the airbag tear (around 60–62 ms) through the substantially deflated condition at 90 ms.

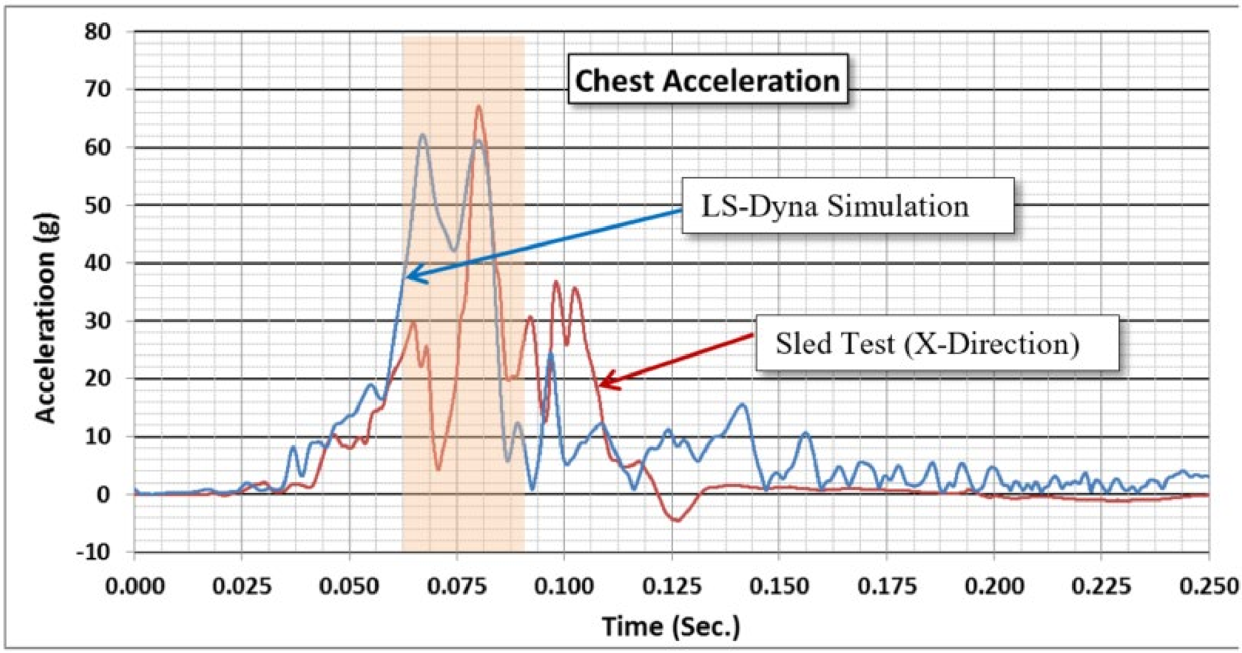

Figure 60. Sled Test and Pretest Simulated Time History—Chest Acceleration

Both the simulation time history and the sled test results of the acceleration show two peaks between 60 ms and 84 ms. The second peak resulting in the high 3 ms Clip for both the sled test and simulation occurs near 78 ms, after which the chest acceleration is much lower.

The first peak in the case of the sled test shows the stiffer airbag behavior just prior to developing the tear and is indicative of the vent not yet being active. The vent was designed to moderate this behavior of the airbag and it appears that the design did not completely function as intended. The LS-DYNA simulation vent is purely analytical and behaves as assumed. This indicates further modification of the vent design is required. The venting feature may also be achieved through use of vents and airbag panels of permeable fabric, unlike the current airbag with coated fabric. However, the coated fabric was chosen due to the use of an under-sized inflator.

Figure 61 shows the neck force F_z and neck moment M_{ocy}. The neck injury indices N_t and N_{ce} exceeded the limit. The peak Nt occurred at 110 ms after the airbag had completely collapsed and the high N_t resulted from the ATD chin striking the top of console.

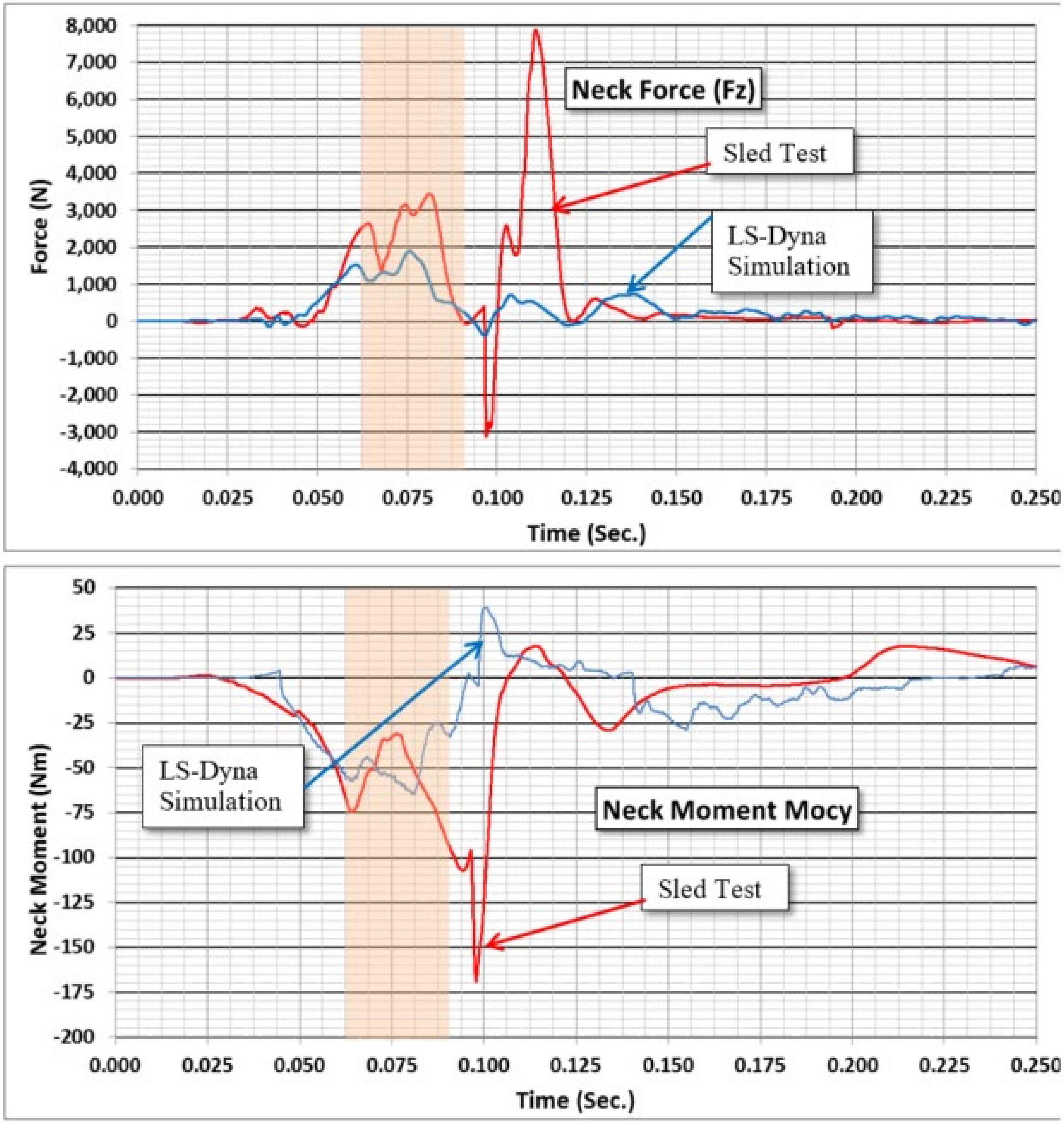

Figure 61. Sled Test and Pretest Simulated Time History—Neck Force (F_Z) and Sled Test Neck Moment M_{ocy}

The maximum N_{ce} occurred at 98 ms when the airbag is near total collapse. At this instant, the ATD is running into the desk with the torso rotating forward, and the chin hits the console, creating compression in the neck, thus forcing the head down generating the high magnitude M_{ocy} (extensive moment). As the simulation shows (and the sled results are trending while the airbag still contains some gas), around 90–98 ms the force F_z and moment M_{ocy} are low enough that they would produce an N_{ce} below the criteria of 1.0. This indicates that an airbag that retained its integrity would have met the N_t and N_{ce} injury criteria.

10. Conclusion

A previous effort supported by the Federal Railroad Administration (FRA) to develop, design and test a Cab Engineer Protection System (CEPS) for commuter cab car engineers showed that a system consisting of an airbag and a deformable knee bolster can provide protection against injuries resulting from secondary impacts experienced by the crew in a collision.

The CEPS concept was adapted with adjustments and modifications for the freight locomotive cab and desk space, i.e., locomotive controls location and layout, and engineer desk geometry. Locomotive collision simulations were conducted using LS-DYNA, an advanced general-purpose multi-physics simulation software package, to ascertain that the acceleration pulse used in the CEPS system was appropriate to further develop the secondary impact protection system (SIPS).

It was established that the crash pulse used for the CEPS system was more conservative than the pulses obtained from the LS-DYNA simulation of locomotive collisions. Therefore, the CEPS crash pulse was chosen for further simulations and developing the SIPS.

RADIOSS®, a leading structural analysis solver for crashworthiness simulations was used to assess the suitability of the CEPS system elements for meeting SIPS needs. The RADIOSS® simulations revealed that to meet the injury criteria in the locomotive desk geometry and space environment, the airbag volume and shape required modification which in turn required a special inflator.

The modified airbag was designed and prototyped. Simple inflation and cold gas testing per SAE J1630 was carried out to study the final deployed airbag shape. Adjustments were made to the airbag geometry by altering tether length and orientation based on the LS-DYNA simulation of the airbag and anthropomorphic test device (ATD), commonly known as a crash test dummy, interaction during deployment.

Once the integrated airbag and inflator system was confirmed to be functional, impactor testing was carried per SAE J2961 procedures to determine the airbag energy absorption. These tests indicated a need for controlled venting to manage the chest injury level that was corroborated by the LS-DYNA simulations.

Once the venting system was integrated into the airbag, the LS-DYNA simulations predicted that the airbag and knee bolster system provide the design target protection against injuries in the freight locomotive environment.

The airbag tethering was modified to open the vent once in the nearly fully deployed position. A subsequent impactor test confirmed the venting system to function as expected.

The SIPS sub-systems, i.e., airbag, inflator and knee bolster, were then assembled into the baseline locomotive cab/desk, and the full system was dynamically tested under a 23-g trapezoidal acceleration pulse used in the development and testing of the CEPS.

During the test at the point of maximum pressure in the airbag at approximately 60 ms, when the ATD was in full contact with the airbag and the airbag was pushed against the vertical surface of the engineer desk, the lateral right side of the airbag developed a tear and the airbag deflated quickly resulting in impact of the ATD head with the desk top surface.

Posttest investigation of the airbag revealed a stress concentration where three panels join. The airbag fabric rip began at this stress concentration point and the tear propagated along one of the seams.

There were several challenges to the implementation of the designed concept. These are outlined below along with recommended solutions.

Bag Size:

A larger airbag would be more amenable to capture the ATD and permit design of optimal venting during deployment and ATD engagement. Since the locomotive engineer is un-restrained (no seat belt permitted), an airbag larger than what would suffice in the automobile environment is imperative. The airbag size was reduced for the test to generate sufficient airbag pressure for the capacity of the available inflator. A larger airbag may include the more highly permeable fabric used by the auto industry in the past as well as the provision of venting holes.

Inflator:

The inflator was not optimal for the system designed for this project. Airbag vendors are not inclined to engage in a limited scope design to make modifications to their products which are optimized for the automobile market. A larger inflator would produce more gas required for the slightly larger airbag (as was originally estimated) and better controlled venting to achieve enhanced ATD interaction around the chest region.

Inflator-To-Bag Connection:

Directing the gas generated by the explosive event in the inflator requires a direct path to the airbag. The limited space under the desk led to mounting the inflator away from the airbag pan, requiring design of an airbag-to-inflator connection.

Limited Testing Samples:

The airbag design engineer and the sled testing facility experts opined that to achieve a stable and optimal design, 15–20 iterations are normally required to implement the design changes necessary to resolve the issues discovered during the sled testing.

In summary, the project successfully demonstrated the following:

- It is technically feasible to develop a secondary impact protection system for freight locomotive engineers.
- The airbag and knee-bolster system prototype can be integrated into the locomotive cab layout and space environment.
- Since the freight railway industry does not have injury criteria, automobile safety performance requirements were chosen for the design and development of this project. The simulations show that the system meets the U.S. Department of Transportation's FMVSS-208 safety performance requirements for automobiles which are also adhered to by the railway passenger equipment supply industry in the United States and internationally.

In the sled testing, the system met 9 of the 11 injury indices listed. It was shown that all 11 injury indices would have been met if the prototype airbag had not prematurely failed at a poor airbag seam design. The project goal was to meet all the criteria at 80 percent of the limit value for all indices. That goal was not met. However, the system as designed and tested is quite promising and with modification to the airbag design and appropriate gas venting the system can easily meet the requirements of providing protection against impact injuries.

10.1 Recommendations

- The SHI2-210/35 inflator produced just enough gas to inflate the 97-liter airbag, leaving a small safety margin. The available inflation gas had to be carefully preserved and then vented at the right time, resulting in a comparatively complex active vent. While the active vent functioned, it was insufficiently developed at the conclusion of the project.
- Future development should be based on a larger output inflator of 5.0 or more moles, to provide an abundance of inflation gas that can be continually vented without requiring preservation of gas that adds complexity to the system. A larger gas supply will also permit the use of larger vents or areas of permeable fabric to improve the proportion of energy absorption of the SIPS airbag.
- While a more effective venting strategy will reduce stress in the airbag, a more robust fabric will improve the structural integrity of the SIPS airbag module to sustain the loads developed during high-energy impacts.
- Fabric made from heavier dtex[3] yarn would be stronger, at the expense of increasing the airbag pack and module size. The automotive trend has been to use lighter weight fabrics, reducing size and weight. Therefore, the SIPS module may need to use a previous generation airbag fabric, if available.
- The fabric tear initiated at a clear stress concentration, where three panels join. These panel connections should be redesigned to move the stress concentrations away from this highly-loaded area.
- Throughout the project, attachment of the pressure transducer influenced the test results and affected the bag attachment to the pan on that end. Future development work should explore alternative means to attach pressure transducer ports, thereby minimizing their influence on the bag performance.

[3] dtex = the mass of the yarn in grams per 10,000-meter length

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Abbreviations and Acronyms

Abbreviations & Acronyms	Definition
AAR	American Association of American Railroads
APTA	American Public Transit Agency
ATD	Anthropomorphic Test Device
BLET	Brotherhood of Locomotive Engineers and Trainmen
CEPS	Cab Engineer Protection System
CFR	Code of Federal Regulations
CAPE	Center for Advanced Product Evaluation
CAD	Computer-Aided Design
DAS	Data Acquisition System
DOT	Department of Transportation
DRD	Design Requirements Document
FMVSS	Federal Motor Vehicle Safety Standard
FRA	Federal Railroad Administration
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
HIC_{15}	Head Injury Criterion
KSS	Key Safety Systems
ms	Millisecond
NHTSA	National Highway Safety Administration
Nc	Neck Compression
M_{ocy}	Neck Moment
Nt	Neck Tension
N_{ce}	Neck Injury Index (compression-extension)
N_{cf}	Neck Injury Index (compression-flexion)
N_{te}	Neck Injury Index (tension-extension)
N_{tf}	Neck Injury Index (tension-flexion)
RSAC	Rail Safety Advisory Committee
SAE	SAE International

Abbreviations & Acronyms	Definition
SIPS	Secondary Impact Protection System
SIV	Secondary Impact Velocity
SA	Sharma & Associates, Inc.
SCRRA	Southern California Regional Rail Authority
SUV	Sport Utility Vehicle
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.

Appendix A.
Brain Storm Session on SIPS Concepts

Table A-1. Concepts—Head and Torso Protection

No.	Deployment/ Technique	Description	Feasibility + Acceptability	Development Time-frame	Likelihood of success	Comment
1	CEPS Style Desk w/remote inflator	Existing CEPS airbag geometry, inflator, and canister.	Medium	Short	High	Desk depth too short for current PAB housing w/inflator. Need remote inflator to use in desk.
2	CEPS Style Desk Reversed w/remote inflator	Existing CEPS inflator, canister, and reverse airbag geometry.	Medium	Short	Medium	Desk depth too short for current PAB housing w/inflator. Need remote inflator to use in desk. Reversed airbag geometry may not bunch against vertical screens as much but may be more beneficial if deployed from vertical surface.
3	Desk Corner (DAB)	Redesign airbag to "squirt" out between the desk horizontal surface and the vertical screen surface at the lower corner.	High	Short	High	Moves housing out of the way for contact to occupant legs and deploys more like a driver airbag directly towards the occupant where needed. No issues with integrated inflator.

No.	Deployment/ Technique	Description	Feasibility + Acceptability	Development Time-frame	Likelihood of success	Comment
4	Between Vertical Screens	Vertical upright deployment expands laterally.	Medium	Medium	High	Need to determine minimum packaging space for airbag door in this configuration to ensure still enough space for screens. No issues with integrated inflator.
5	Top Console Deploy Down	Deployment would occur through a flap on top of the screen console and be deflected downward to fill space between occupant and desk.	Low	Medium	High	Need to ensure the airbag will properly deploy from the furthest distance from the occupant, actively deflected to where needed, and have enough time to fill the available space between desk and occupant. If it misses, occupant will strike desk. No issues with integrated inflator but may need a larger volume airbag due to distance from occupant.
6	Side Writing Pad Deploy Lateral	More like a Side Airbag packaged in the desk below the writing surface. Deployment would be laterally from the horizontal to fill space between desk and occupant.	Medium	Medium	Low	Airbag deploys directly where needed for torso but need to ensure can reach head. Also, need to determine if SAB rolled package can be made large enough volume wise to match our PAB CEPS concept. No issues with integrated inflator.

No.	Deployment/ Technique	Description	Feasibility + Acceptability	Development Time-frame	Likelihood of success	Comment
7	Dual Airbags	One airbag for torso could deploy from desk, another for head could deploy from console out of way.	Medium	Medium	High	Most likely would need two inflators but inquire about possibility of deploying both with one inflator and a manifold.

Table A-2. Concepts—Femur Protection

No.	Deployment /Technique	Description	Feasibility + Acceptability	Development Time-frame	Likelihood of success	Comment
1	Deformable Knee Bolster w/soft Surface Pad	Evolution of the CEPS design without honeycomb.	High	Short	High	Utilize a soft pad on the outside of the steel deformable plate to soften initial knee contact force.

Table A-3. Concepts—Rating and Weight

Weight	Criteria	Comment
5	Injury Index Reduction	Can the concept contribute significantly towards limiting Injury Criteria?
5	Compartmentalization	Can the concept help to keep the operator in his/her seat?
5	Affect Egress	Does the concept allow reasonable egress?
4	Development Timeframe	Is the concept feasible to develop and implement within the time constraints of this project?
3	Simplicity of Design	Does it have complex mechanisms or are there many variables to control?
3	Maintenance	Does the concept increase maintenance time or add new inspection requirements?
3	Comfort & Ergonomics	Is operator comfort or control ergonomics likely to be affected by the concept?
1	Weight Concerns	Will the concept adversely increases the weight of the cab?
1	Material Costs	Are material costs comparable to other concepts?
1	Manufacturing Costs	How easily can the system (desk+ seat+ protection elements) be manufactured?

Notes:

1. See 'Rating Criteria and Weighting' worksheet for details.
2. Rate each combination against each criterion on a scale of 1–5, 5 being highest/best.
3. The weighted sum for each concept will be computed automatically.
4. The weighted sum for each concept will be averaged after getting inputs from all team members.
5. Maximum weighted sum for any concept = 70

Table A-4. Concepts—Rating Table

No.	Head + Torso Protection	Injury Index Reduction	Development Timeframe	Simplicity of Design	Material Costs	Manufacturing Costs	Sum	Rank
	Weighting Value →	**5**	**4**	**3**	**1**	**1**		
1	CEPS Style Desk w/remote Inflator	5	5	5	5	4	69	**1**
2	CEPS Style Desk Reversed w/remote inflator	5	4	4	5	5	67	**2**
3	Desk Corner (DAB)	5	3	4	4	4	61	**3**
4	Between Vertical Screens	4	3	3	4	3	51	**5**
5	Top Console Deploy Down	3	2	3	3	2	41	**7**
6	Side Writing Pad Deploy Lateral	2	3	4	3	2	32	**8**
7	Dual Airbags	3	4	5	2	4	45	**6**
8	OTS Airbag Solution	4	5	4	4	5	60	**4**

Appendix B.
Desk Design Drawings

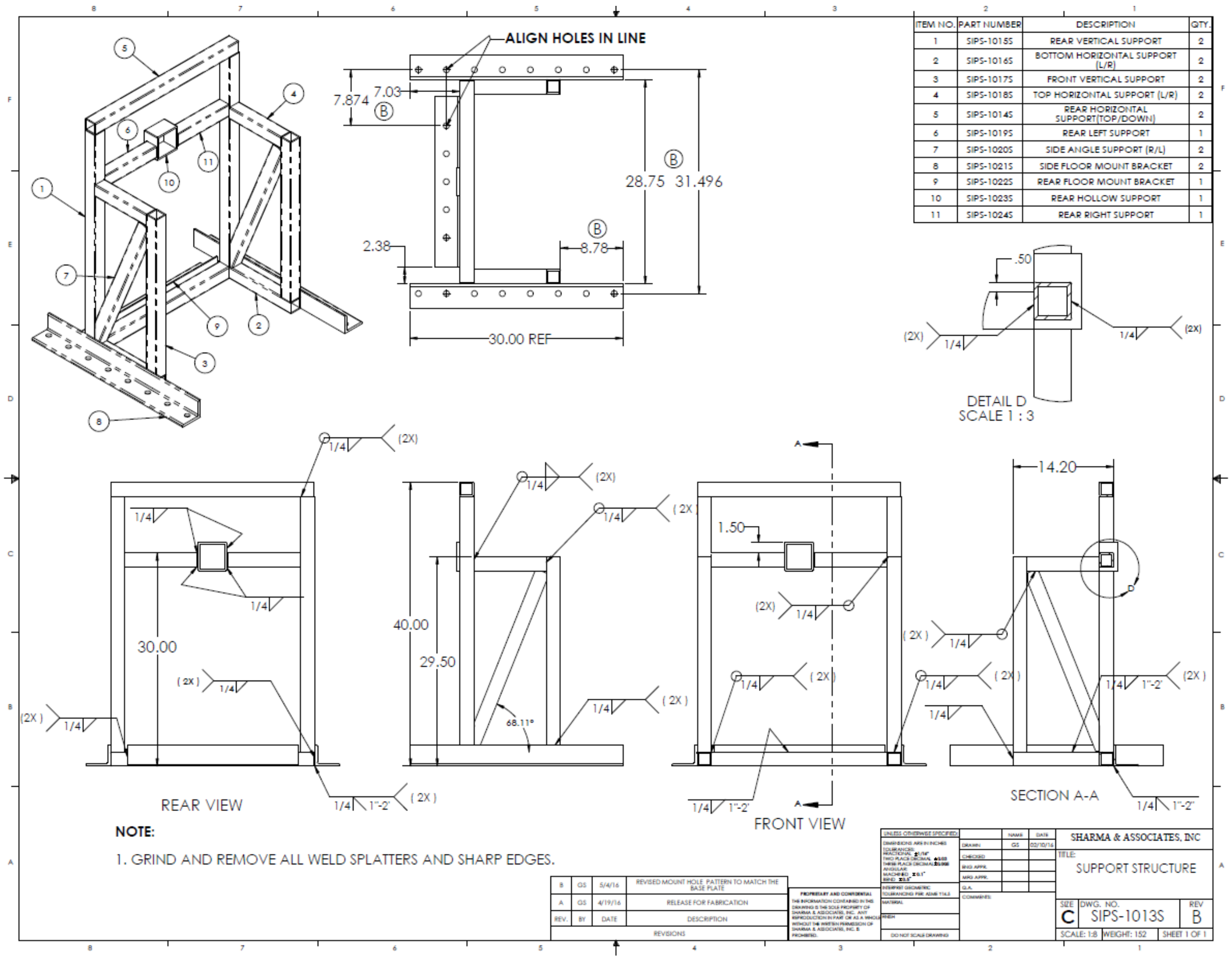
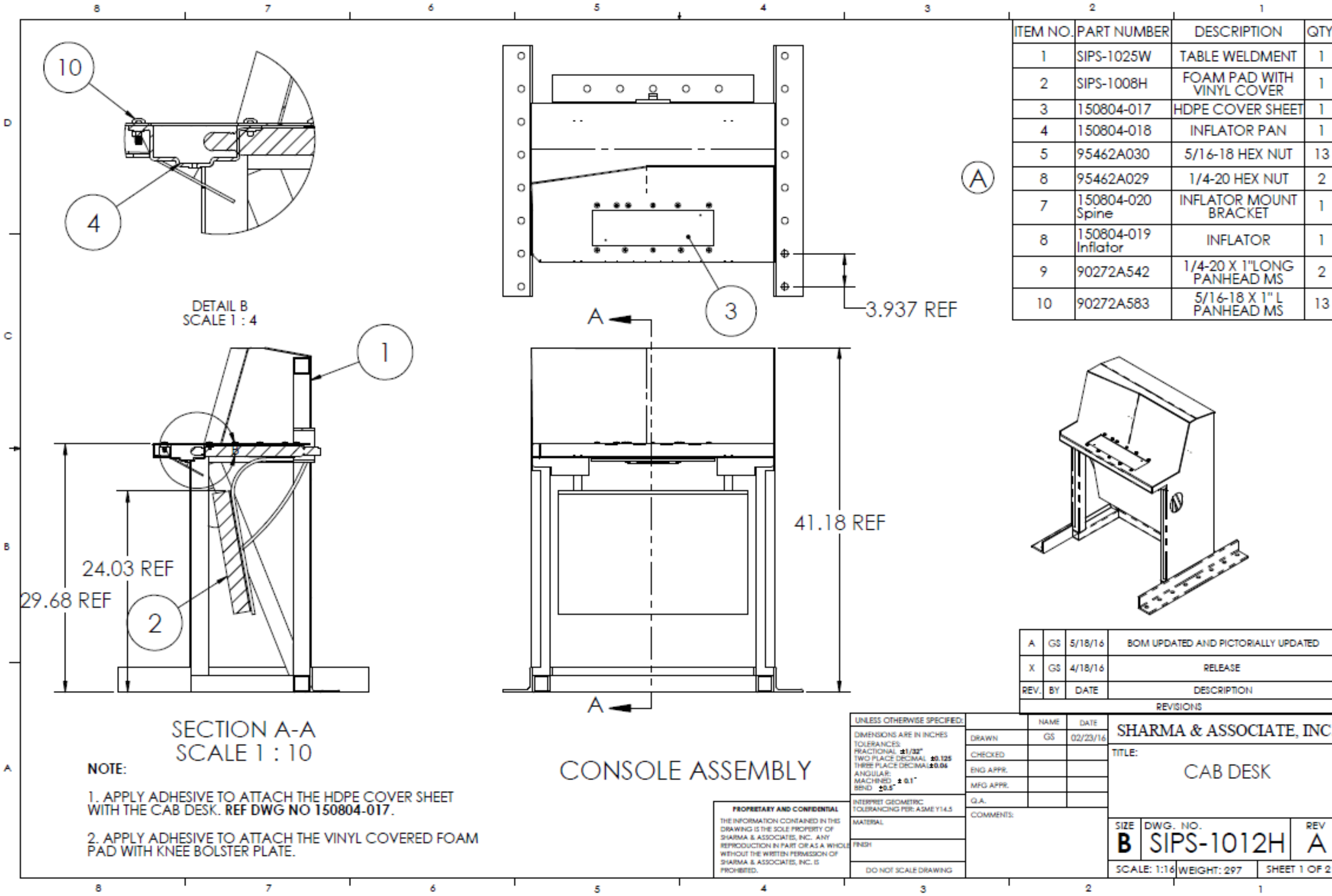


Figure B-1. Support Structure for the Engineer Desk



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SIPS-1025W	TABLE WELDMENT	1
2	SIPS-1008H	FOAM PAD WITH VINYL COVER	1
3	150804-017	HDPE COVER SHEET	1
4	150804-018	INFLATOR PAN	1
5	95462A030	5/16-18 HEX NUT	13
8	95462A029	1/4-20 HEX NUT	2
7	150804-020 Spine	INFLATOR MOUNT BRACKET	1
8	150804-019 Inflator	INFLATOR	1
9	90272A542	1/4-20 X 1"LONG PANHEAD MS	2
10	90272A583	5/16-18 X 1" L PANHEAD MS	13

REV.	BY	DATE	DESCRIPTION
A	GS	5/18/16	BOM UPDATED AND PICTORIALLY UPDATED
X	GS	4/18/16	RELEASE

REVISIONS

Figure B-2. Support Structure for the Engineer Desk (Cont.)

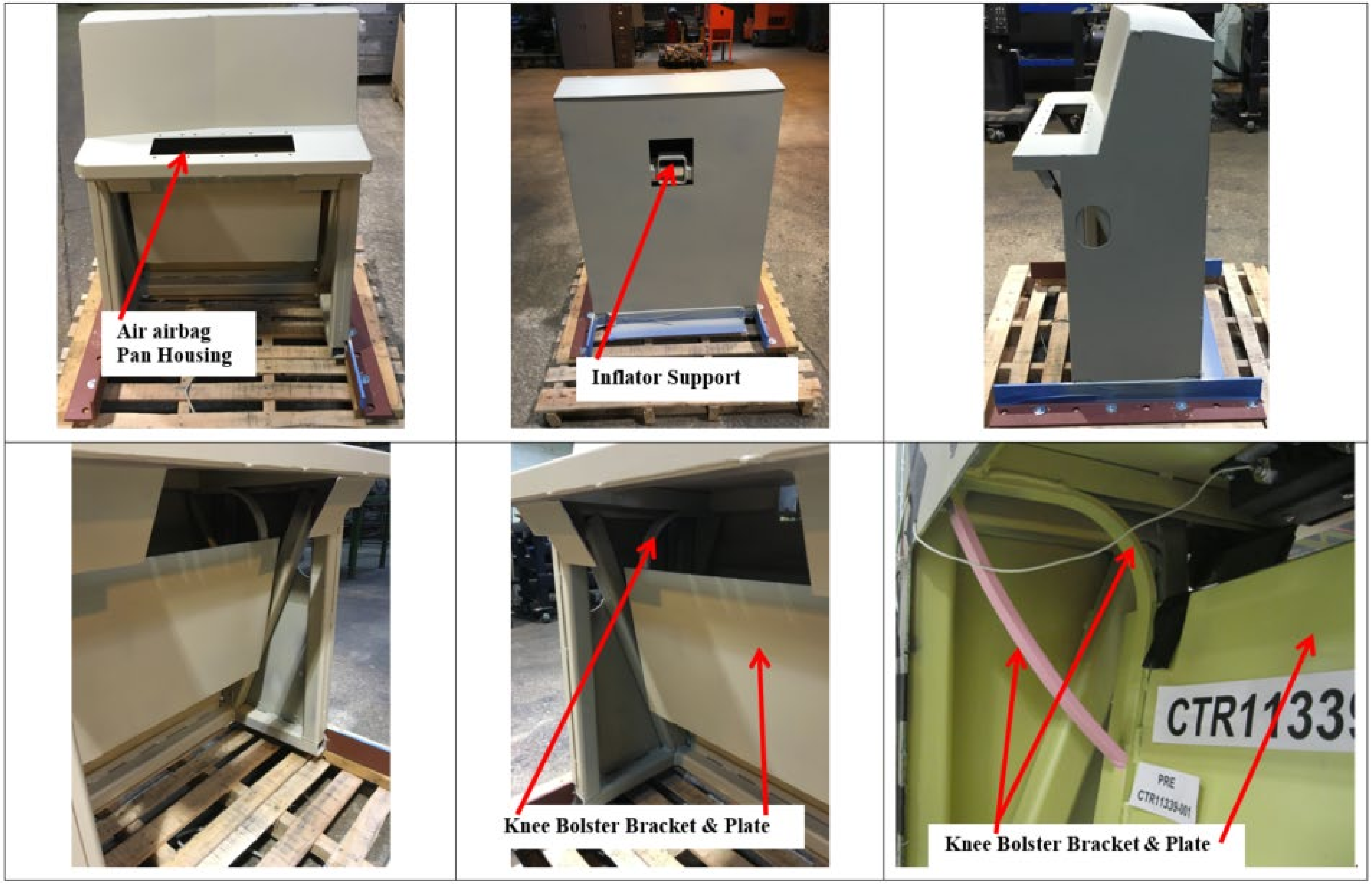
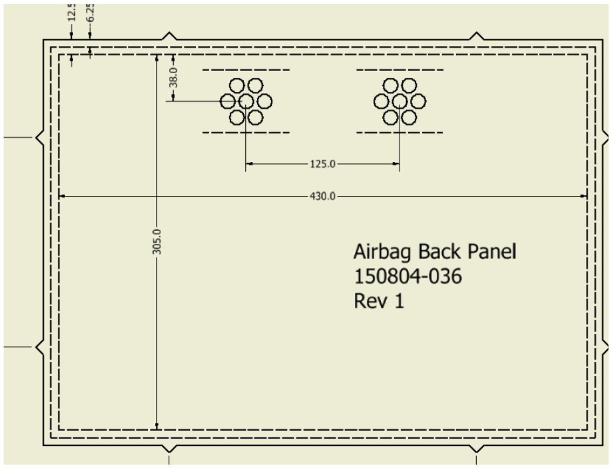


Figure B-3. Engineer Desk Assembly

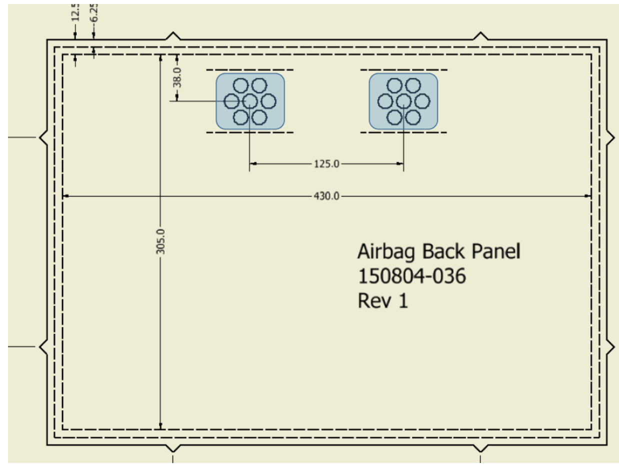
Appendix C.
Airbag Venting Mechanism

Airbag Venting Mechanism

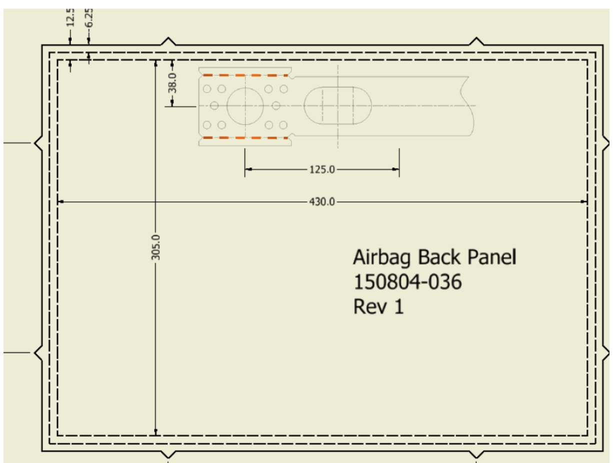


Back panel includes two vents. Hex vent hole pattern assures that fabric valve will not push through.

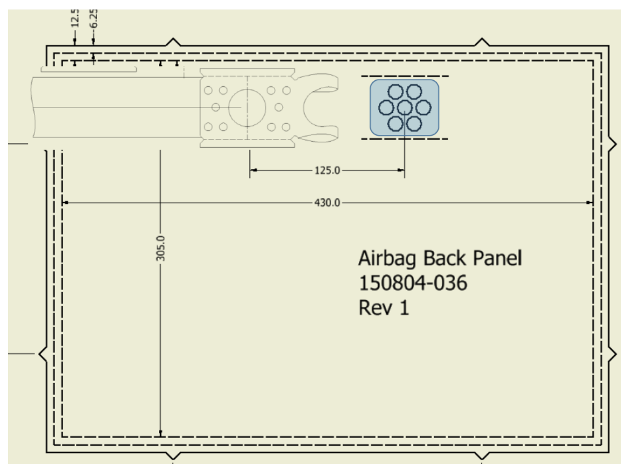
Airbag Venting Mechanism



Adhesive/sealant application helps to seal vent initially and holds fabric tether in place during assembly, folding and initial phase of deployment.

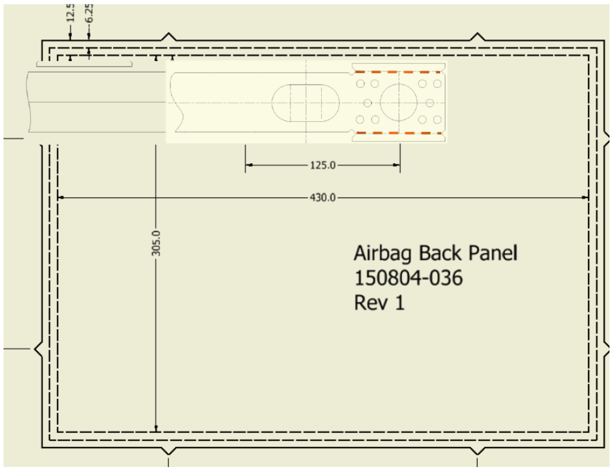


New fabric vent piece sewn in place with holes aligned overtop the hex vent pattern.

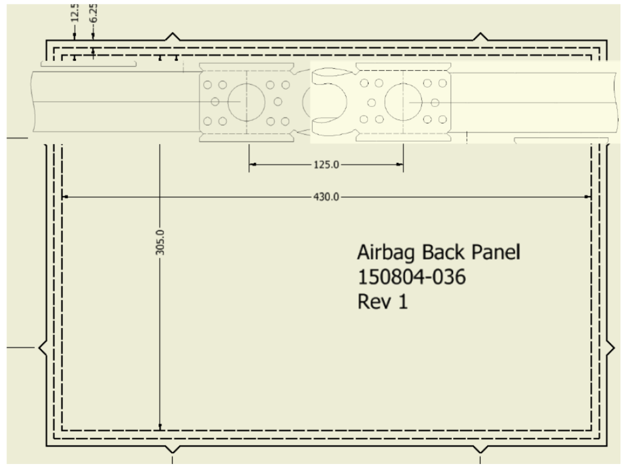


Fabric tether/valve inserted between back panel and top vent. Once in place, it is pressed into adhesive/sealant.

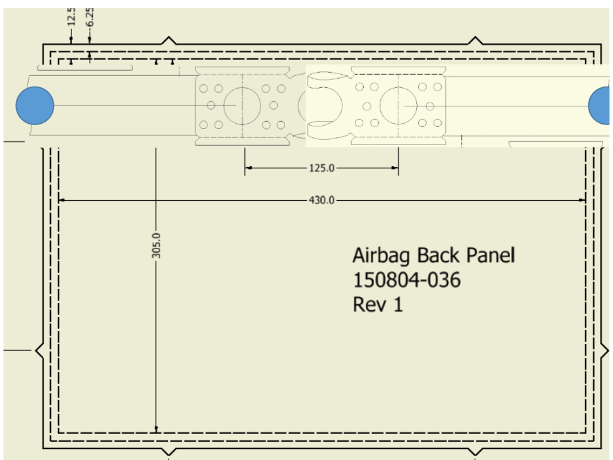
Airbag Venting Mechanism **Airbag Venting Mechanism**



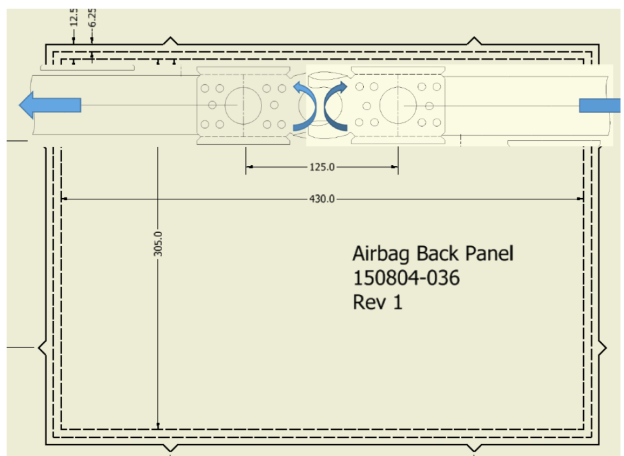
Second fabric vent piece sewn to back panel, with vent hole aligned with hex vent pattern on back panel.



Fabric tether/valve inserted between back panel and vent. Once in place, is pressed into adhesive/sealant.



Back panel sewn into airbag assembly. Before final sew internal tether ends are sewn to side panels at the lateral tether locations.



During deployment, expanding airbag puts tether in tension. Bond with adhesive/sealant is broken and the tethers translate through the vent panel. Slots in tethers open the vents.

Appendix D.
Knee Bolster View from Sled Test

Figure D-1. Knee Bolster Plate and Bracket View at 0, 30, 45, 60, 70, and 90 ms

Appendix E.
Proposed Injury Limits for 95th Percentile Male ATD

Table SES-1: Summary of Recommended Injury Criteria for the Final Rule

Recommended Criteria	**Large Sized Male§**	**Mid-Sized Male**	**Small Sized Female**	**6 YO Child**	**3 YO Child**	**1 YO Infant**
Head Criteria: HIC (15 msec)	700	700	700	700	570	390
Neck Criteria: Nij	1.0	1.0	1.0	N/A	N/A	N/A
In- Position Critical Intercept Values						
Tension (N)	8216	6806	4287			
Compression (N)	7440	6160	3880			
Flexion (Nm)	415	310	155			
Extension (Nm)	179	135	67			
Peak Tension (N)	5030	4170	2620			
Peak Compression (N)	4830	4000	2520			
Neck Criteria: Nij	N/A	N/A	1.0	1.0	1.0	1.0
Out-of-Position Critical Intercept Values						
Tension (N)			3880	2800	2120	1460
Compression (N)			3880	2800	2120	1460
Flexion (Nm)			155	93	68	43
Extension (Nm)			61	37	27	17
Peak Tension (N)			2070	1490	1130	780
Peak Compression (N)			2520	1820	1380	960
Thoracic Criteria						
1. Chest Acceleration (g)	55	60	60	60	55	50
2. Chest Deflection (mm)	70 (2.8 in)	63 (2.5 in)	52 (2.0 in)	40 (1.6 in)	34 (1.4 in)	30* (1.2 in)
Lower Ext. Criteria: Femur Load (kN)	12.7	10.0	6.8	NA	NA	NA

§ The Large Male (95th percentile Hybrid III) is not included in the final rule, but the performance limits are listed here for informational purposes.

* The CRABI 12 month old dummy is not currently capable of measuring chest deflection.

Figure D-2. Proposed Injury Limits for 95th Percentile Male ATD