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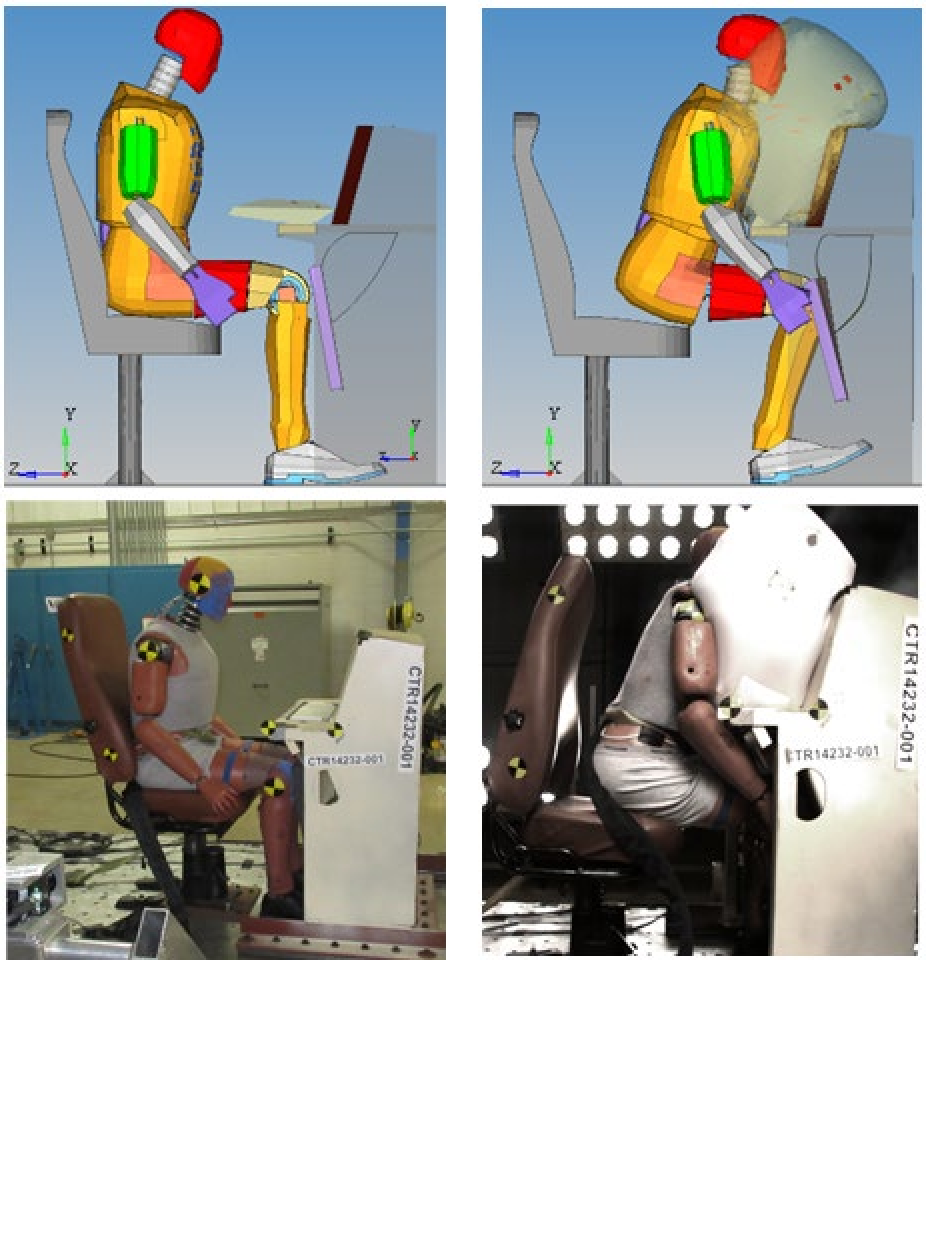
Secondary Impact Protection for Locomotive Engineers – Improved Airbag Design



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14. ABSTRACT

As part of the Federal Railroad Administration's locomotive cab occupant protection research, a Secondary Impact Protection System (SIPS) for locomotive engineers was developed. The system uses an automotive-style passenger airbag and a deformable knee bolster to provide the desired protection – without compromising the normal operating environment and egress.

A prior version of the system was prototyped and tested under a dynamic sled test with a 23g crash pulse and was shown to meet limiting human injury criteria in the Department of Transportation's Federal Motor Vehicle Safety Standards (FMVSS 208) for the head, chest, neck, and femur. Due to marginal performance for the chest injury index, an improved SIPS design was pursued. The major improvements were slightly larger airbag with two additional vents, higher-capacity inflators self-contained within the airbag module, a knee bolster system with thicker knee plate, and brackets shifted toward the front edge of the desk.

Simulations followed by the sled testing confirmed the SIPS successfully met all 11 criteria of the FMVSS 208, demonstrating excellent occupant protection for an unbelted locomotive occupant in a severe frontal collision.

15. SUBJECT TERMS
Airbag, anthropomorphic test device, crashworthiness, energy absorption, finite element analysis, injury indices, knee bolster, secondary impact protection, sled testing

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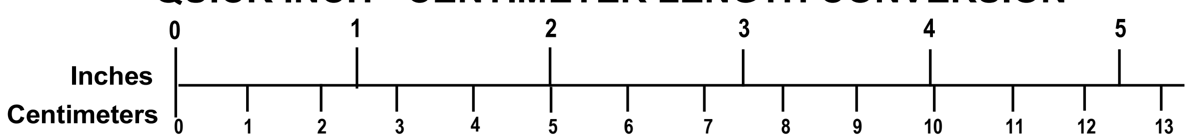
METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH** (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA** (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT** (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME** (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
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 meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE** (EXACT)		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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 Updated 6/17/98

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Executive Summary

As part of the locomotive cab occupant protection research sponsored by the Federal Railroad Administration (FRA) Sharma & Associates, Inc. prototyped and tested a Secondary Impact Protection System (SIPS) for locomotive engineers. The project effort successfully demonstrated the technical feasibility of a secondary impact protection system for the freight locomotive engineer.

The system uses a large automotive-style passenger airbag in combination with a deformable knee bolster to provide the level of protection needed for the locomotive engineer – without compromising the normal operating environment and egress. Computer simulations of an unbelted, 95th percentile Hybrid 3 anthropomorphic test device (ATD) showed that SIPS met the limiting human injury criteria of the U.S. Department of Transportation (DOT) Federal Motor Vehicle Safety Standards (FMVSS 208) for the head, chest, neck, and femur.

Sled testing of SIPS confirmed the simulated performance, and the system successfully met all 11 criteria of the FMVSS 208 standard.

A prior version of the system was prototyped and tested under a dynamic sled test with a 23g crash pulse (DOT/FRA/ORD-19/09) and was shown to meet most of the injury criteria. However, the system showed marginal performance for the chest injury index and indicated potential for an improved airbag design to fully meet all requirements.

To improve the system performance, the updated airbag included two major changes: two vent holes of 30 mm diameter each and a “blaster” designed to act as a cylindrical baffle to redirect about 70 percent of the gas flow toward the airbag panel facing the occupant and also serve as a sacrificial material to protect the main cushion from hot gases exiting the inflators.

1. Introduction

The Federal Railroad Administration (FRA) has performed 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 and corner post structures, which have provided a robust structural cage at the front of the locomotive and increased the survival space for locomotive engineers. These newer standards, laid out in both Federal regulations 49 CFR Part 229 [1] and Association of American Railroads (AAR) standard S-580 [2], have noticeably improved the survivability of locomotive engineers. Full-scale testing with these improved cabs, conducted by Sharma & Associates, Inc. (SA), has demonstrated the safety benefits associated with these newer standards.

1.1 Background

Recent FRA-sponsored research has resulted in the development and demonstration of a Secondary Impact Protection System (SIPS) for locomotive engineers [3]. This system was prototyped and tested under a dynamic sled test with a 23g crash pulse [4] and was shown to meet limiting human injury criteria defined by the National Highway Traffic Safety Administration (NHTSA) in its Federal Motor Vehicle Safety Standards (FMVSS 208) for the head, chest, neck, and femur [5]. The system uses a large automotive-style passenger airbag in combination with a deformable knee bolster to provide the level of protection needed for the locomotive engineer – without compromising the normal operating environment and egress.

The SIPS prototype was based on several airbag geometry configurations' evaluated static deployment and dynamic impactor testing to establish its deployment behavior, i.e., the unfolding pattern, final shape and internal pressure, and overall functioning expected during 23g crash pulse sled testing. To establish the airbag deployment behavior, the unfolding pattern, final shape, and overall functioning expected during the 23g crash pulse sled testing, several airbag geometry configurations were tested through static deployment and impact testing. The system was developed using the design and testing approach used in a successful demonstration for the FRA Technical Report Prototype Design of a Collision Protection System for Cab Car Engineers [6].

Sled testing of SIPS showed that it successfully met 9 of the 11 criteria of the DOT's FMVSS 208 standards [3]. The two criteria that were marginal resulted from the failure of the bag at the time of the maximum internal pressure when the bag was fully engaged between the anthropomorphic test device (ATD), representative of a locomotive engineer, and the engineer's console, causing the ATD to rotate and impact the desk.

The current study is a continuation of the previous study that aimed to improve the occupant protection system. The airbag design from initial SIPS research was the starting point for this fine-tuning. The scope included modifications to bag geometry; the selection of appropriate airbag material for improved permeability; a modified, passive venting system; and the selection and incorporation of an inflator providing sufficient gas for bag inflation during impact and compensation for the desired venting during the crash event.

To achieve these design goals, SA researchers structured the test program to account for design adjustment and fine-tuning throughout the study using component-level tests first, followed by progressively more complex tests, until the final system-level dynamic sled test was conducted. Successful results at each test stage helped improve the probability of success and reduce risk for successive tests. Dynamic finite element analysis (FEA) modeling in LS-Dyna software [7] was the principle engineering tool used in this project, and the measurements made during each test facilitated adjustment, tuning, and correlation of the analytical model as well as the physical prototypes.

1.2 Objective

The objective of this study is to improve the airbag design and its performance to fully meet all the FMVSS 208 requirements. As part of the objective, SA evaluated the design analytically, statically, and dynamically through simulations and component testing prior to successful sled testing with the 23g crash pulse used in the previous effort.

1.3 Overall Approach

The overall approach to accomplish the project objective consisted of the following steps:

- Define the design and performance goal requirements for SIPS.
- Airbag module modifications and new inflator integration
- Non-linear finite element simulations using LS-Dyna
- Static testing of modified airbag module
- Linear accelerator impact testing of the airbag module
- Simulating the finalized airbag design to assess its performance against the FMVSS 208 requirements
- Conduct sled test followed by validation test.

1.4 Scope

The scope includes modifications to the bag geometry, selection of appropriate airbag material for improved permeability, and passive venting system incorporation into the bag to compensate for the desired venting during inflation and decelerating the ATD to meet injury criteria.

1.5 Organization of the Report

This report consists of the following six sections:

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

Section 2: A discussion of the airbag and knee bolster system design requirements

Section 3: A discussion of the airbag and knee bolster system components design and development

Section 4: The component design iterations and through static and dynamic testing to finalize the design followed by sled testing to demonstrate system performance.

Section 5: Overall summary of the effort and recommendations of future research potential

Section 6: References

The report also comprises appendices showing the engineer desk details inclusive of the knee bolster components and the injury limits considered for this project:

Appendix A: Desk Design Drawings

Appendix B: Proposed Injury Limits for 95th Percentile Male ATD

2. Design Requirements

To ensure a successful development and eventual implementation of the envisioned SIPS concept, the design requirements remained essentially the same as the initial SIPS study. The only significant change involved a slight increase in allowable package space under the horizontal desk surface for the airbag module. The design requirements included the following general categories:

- Injury criteria targets for the Hybrid III 50^{th} percentile, unbelted ATD – see Table 2-1.
- Frontal deceleration event: trapezoidal crash pulse presented in Figure 2-1.
- Available packaging space and mounting in the operator's control stand/desk, Table 2-2
- Reaction surface available in the operator's control stand/desk
- Maximize use of commercially available components.

Table 2-1. Design Requirements, Unbelted ATD Injury Criteria Targets

Injury Parameter	Limit, SI	Limit, U.S.	Source
HIC_{15}	700	700	FMVSS 208, S5.1.2(2)
Chest Acceleration, 3 ms Clip	60g	60g	FMVSS 208, S5.1.2(2)
Chest Deflection	63 mm	2.5 in	FMVSS 208, S5.1.2(2)
Neck Peak Tension	4,170 N	937 lbs	FMVSS 208, S5.1.2(2)
Neck Peak Compression	4,000 N	899 lbs	FMVSS 208, S5.1.2(2)
Nij (H3-50 intercepts)			
Nte 50	1	1	FMVSS 208, S5.1.2(2)
Ntf 50	1	1	FMVSS 208, S5.1.2(2)
Nce 50	1	1	FMVSS 208, S5.1.2(2)
Ncf 50	1	1	FMVSS 208, S5.1.2(2)
Femur, Left Max Load	10 kN	2,250 lbs	FMVSS 208, S5.1.2(2)
Femur, Right Max Load	10 kN	2,250 lbs	FMVSS 208, S5.1.2(2)

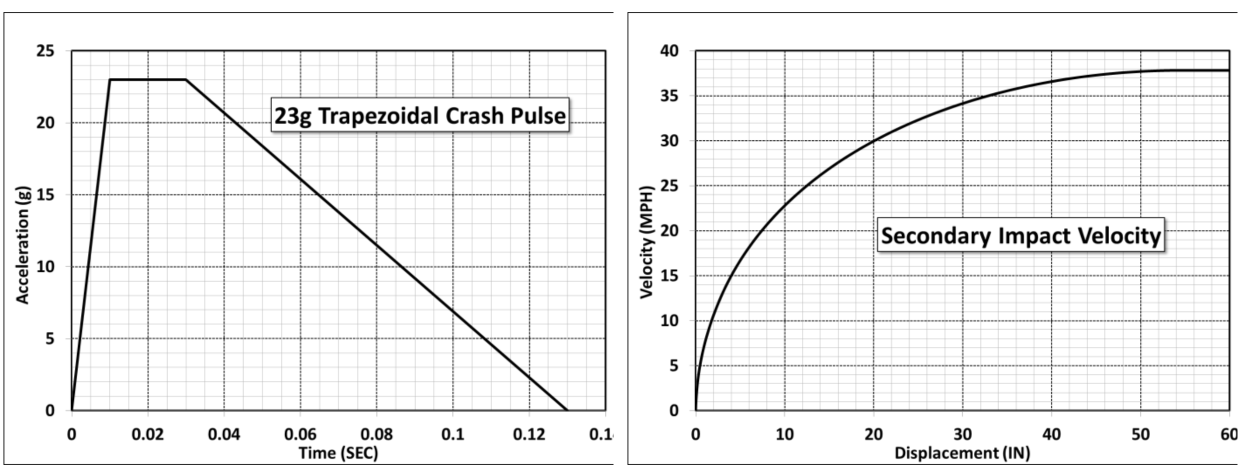

Figure 2-1. Trapezoidal Crash Acceleration Pulse [4] and Secondary Impact Velocity

Table 2-2. Design Requirements, Operator Environment

System or Component	SIPS II Description and Constraints	SIPS I Parameters [3]
Desk	Engineer desk configuration used in SIPS I.	Same
Seat	Standard engineer seat used in SIPS I.	Same
Airbag Module Envelope (w/out mounting flanges)	Length (Y) < 425 mm Width (X) < 150 mm Depth (Z) < 55 mm	Length (Y) < 348 mm Width (X) < 156 mm Depth (Z) < 50 mm
Airbag Cushion Volume	105 +/- 10L	97L
Airbag Cushion Shape	Deployed cushion shape adapted from initial SIPS.	Similar
Airbag Module Mounting	Robustly secured to desk structure.	Same

3. Updated Airbag Design

The airbag module redesign was based on the airbag task guidelines drawn from the conclusion of the previous SIPS study. The initial tasks are listed below. As solutions were implemented, they drove additional design improvements:

- Select a commercially available airbag inflator suitable for the task, with sufficient capacity to provide gas for inflating the bag and compensate for venting.
- Adapt a more robust fabric that will improve the structural integrity of the SIPS airbag to sustain the loads developed during high-energy impacts.
- Switch to non-permeable fabric to allow for fixed, discrete venting with special attention to the size and location of vents.
- Relocate stress concentrations away from high stress areas to ensure desired airbag inflation and deflation behavior.

3.1 Airbag Module

The shape of the module and its attachments to the desk were generally the same as those presented in the initial SIPS study. The most significant difference was that the inflators were self-contained within the module in the SIPS II design, versus the externally protruding cylindrical inflator of the SIPS I design. To accommodate two ADP-3 inflators and a slightly higher-volume cushion (airbag) with thicker fabric, the length of the pan had to be increased by 72 mm. A modest, 5-mm height increase was also necessary. These modifications did not affect any structural components of the desk and still provided clearance for the thighs of the large Hybrid III 95th ATD. Figure 3-1 shows a partially completed SIPS II airbag module. Figure 3-2 and Figure 3-3 show the completed SIPS-II module installed in the desk fixture. The resulting benefits of the new pan design changes were:

- Simpler assembly compared to the previous system
- Fewer parts (see Bill of Materials, Table 3-1)
- Better clamping of cushion to pan
- Larger footprint of cushion onto pan
- Pressure transducer could be mounted externally and ported at a central location into cushion using flexible tubing.
- Enabled features for trigger signal wire and tubing management/protection
- Flexibility of add-on components for shielding and aesthetics

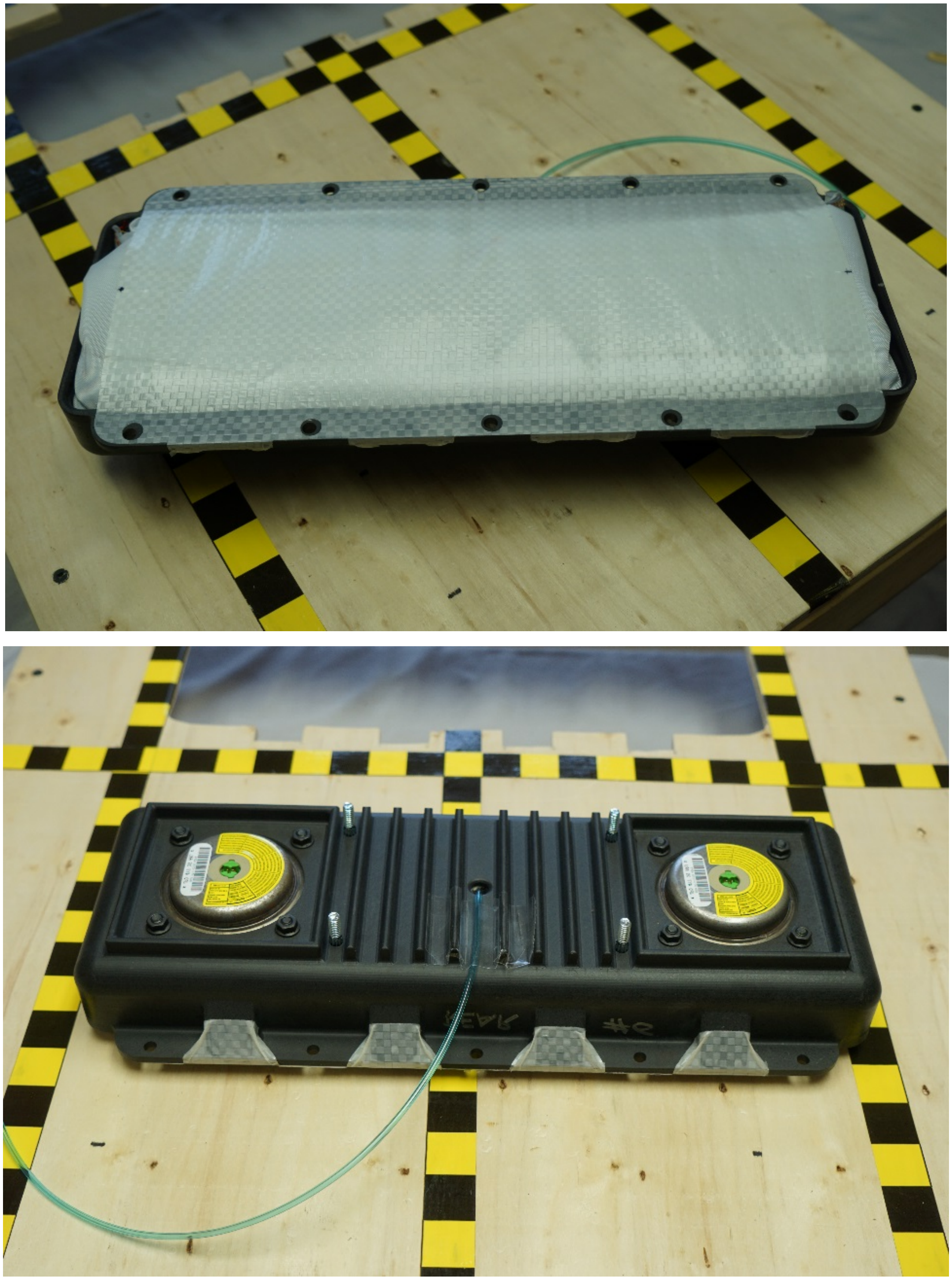

Figure 3-1. SIPS II Airbag Module without Rear Shield

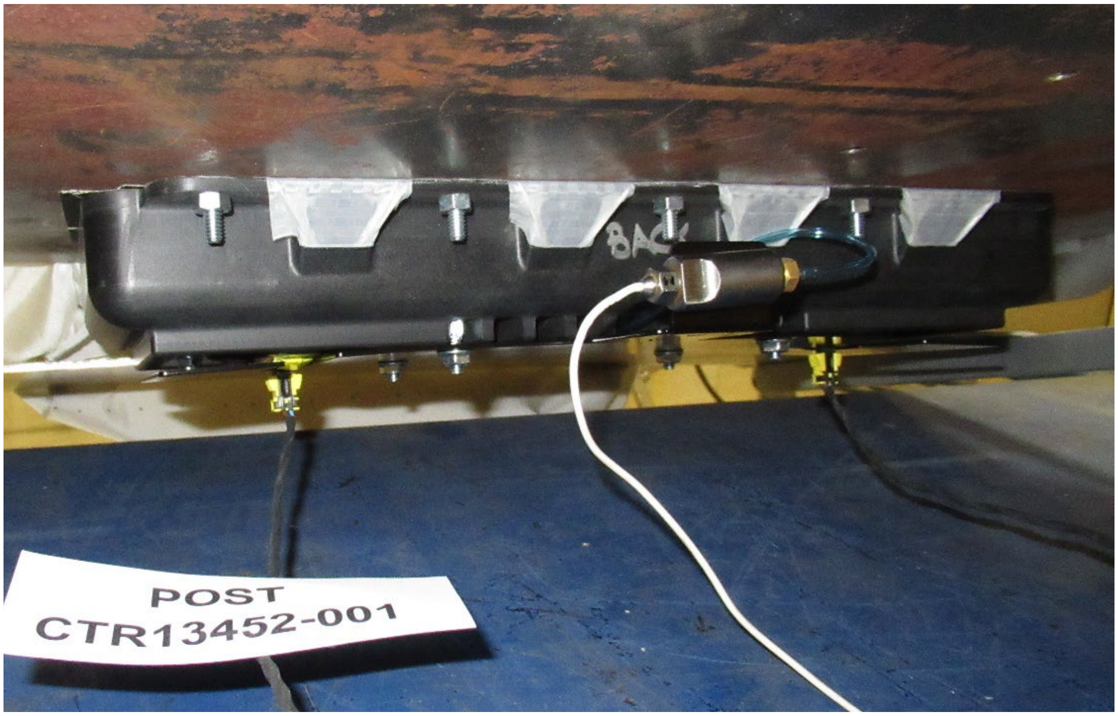

Figure 3-2. Bottom View – Airbag Module Pan and Pressure Transducer

Figure 3-3. Airbag Module Installed to Desk, Showing the Cover

Table 3-1. Bill of Materials for the Final Design

Part Number	Rev.	Description	Qty
181001-200	D	Cushion Assembly	1
181001-020	A	Main Panel, Lower	1
181001-021	A	Main Panel, Upper	1
181001-022	A	Panel, Rear	1
181001-023	C	Side Panel	2
181001-025	A	Tether, Vertical	1
181001-007	A	Tether, Lateral	2
181001-008	E	Reinforcement, Vent	4
181001-013	A	Blast Tube	2
181001-010	A	Pan, Mounting	1
181001-011	A	Cover	1
181001-012	A	Shield, Rear	1
98060A130		Carriage Bolt, 1/4-20	4
94842A101		Flanged Locknut, 1/4-20	4
80295	0	Inflator, ADP-3	2
80303	0	Retaining Ring	2
91310A332		Screw, Hex Head, Class 10.9 M6 x 1.0 Thread x 16 mm Long	8
95108A101		Flanged Locknut, Class 10 M6 x 1.0 mm Thread	8
		Wire Harness	2

The SIPS II airbag module included provisions to mount a pressure transducer to the rear shield. The pan had a hole directly in the center of the back side to allow for fluid communication between the transducer and the expanding space inside the cushion via 1.6-mm ID flexible tubing. These features would not be present in any type of production airbag but provide test data useful for analysis and simulation. These tests used a Meggitt model 8511A-5k piezo-resistive pressure transducer – specifically designed for ballistic applications and commonly used in airbag development.

3.2 Inflator

As mentioned earlier, based on the previous SIPS effort, ample gas output from the inflator was one of the key requirements. The initial SIPS study used a SHI2 inflator that produced inflation energy of approximately 9.2 kJ. It was determined that at least 35 percent more inflation energy would be necessary for the airbag to be able to quickly inflate, and then be able to vent enough gas to manage the high level of kinetic energy being imparted by the large occupant. Another 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. The available package space also limited the selection of commercially available inflators that could be used in this application. The inflator, its attachments, and the bag pack had to fit within the vertical clearance limit.

Given the above parameters and the high complexity of an inflator, various automotive inflators were explored. In North America, there are five manufacturers of inflators. Autoliv, Inc. controls about 40 percent of the global market. Different inflator technologies, as discussed in the beginning of this report, are suitable for different crash-type applications. A stored-gas inflator, for example, expels comparatively cool gases very quickly, making it ideal for side-impact applications which require super-fast responses, both from gas delivery aspects as well as sensing of the event. Conversely, a solid-propellant inflator delivers comparatively hot gas over a longer period, making it more suitable for frontal crash-type applications. For a given amount of gas output, solid-propellant inflators offer the most compact package. As such, the search quickly narrowed to a solid-propellant inflator. The 55-mm desk-to-thigh limitation steered the selection to inflators utilized in steering wheel airbag applications which include a very compact inflator.

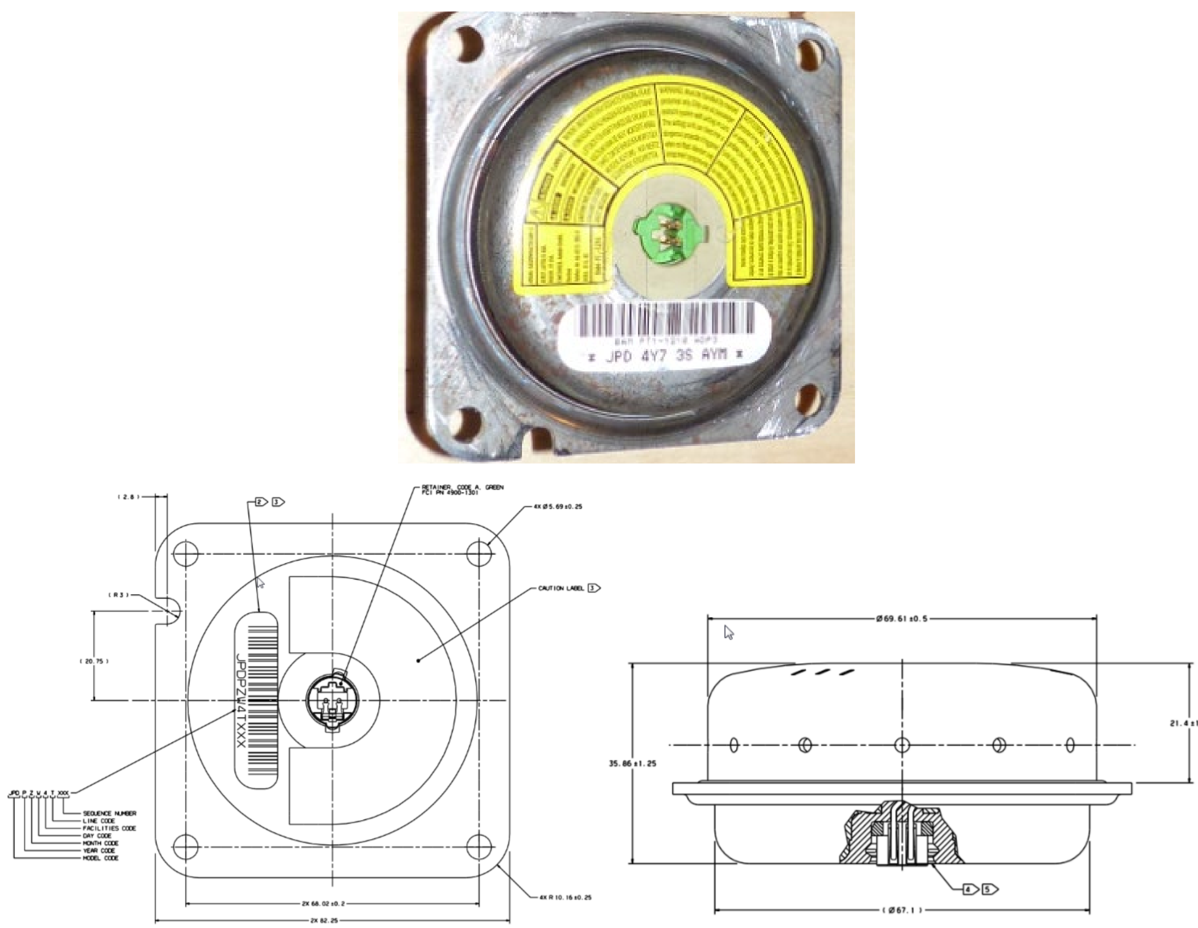

Figure 3-4. Autoliv ADP-3 Inflator

Researchers identified the Autoliv Driver Pyrotechnic-3 (ADP-3) inflator as the best fit for SIPS requirements. This inflator has been in production for over a decade and is capable of inflating a 60L vented cushion. One ADP-3 inflator generates inflation energy of approximately 9.15 kJ – about the same as the SHI2 used in the preliminary SIPS project. The inflator has a toroidal shape commonly referred to as "pancake," and it employs an integral metal flange to attach to the airbag module. The flange is configured in the shape of a square with four attachment holes – one at each corner. The 82-mm size of the square allowed the installation of two inflators into the SIPS II airbag module, thus providing twice the inflation energy, capable of filling a bag up to a volume of 120L. Figure 3-4 shows the ADP-3 inflator.

The ADP-3 generates a mixture of mostly inert gases through the combustion of the solid propellant stored inside the canister. This specially formulated propellant requires heat and pressure to combust. The initial heat and pressure are provided by a standard initiator, with its own internal combustion initiation train. When compared to a stored-gas or hybrid inflator, such as the device used in the initial SIPS, the ADP-3 inflator produces significantly higher temperature gases. Due to the elevated temperatures, thermal management became a design criterion that had to be taken into account, not only during the event, but post-test as well, when the combusted material heat soaks into the inflator body and surrounding components. This factor had a direct impact on the design and material selection of the cushion and pan, which are discussed later in this section.

Inflator Information and Specifications:

Manufacturer:	Autoliv, Inc.
Model/Family:	ADP-3
Type:	Solid Propellant, Single Stage
Construction:	Steel Body, Hermetically Sealed
Mass:	440 +/- 20 grams
Dimensions:	82 mm x 82 mm x 35 mm (70 mm/67 mm cylinders)
Output:	195 kPa @ 60 ms (60L tank at ambient temperature)

Initiator Characteristics:

Monitor Current:	50 mA current shall not degrade or deploy initiator
All Fire Current:	1.2 A within 2 msec at -40°C to +23°C
No Fire Current:	0.4 A for 10 sec at +23°C to +85°C
Bridge wire Resistance:	2.0 +/- 0.3 ohms
Insulation Resistance:	>1 megohm at 500 VDC for 2 sec
Shunt Resistance:	0.15 ohms max

3.3 Cushion

The design requirements for the SIPS II airbag module included meeting injury criteria for an unbelted Hybrid III 95th percentile ATD during a crash pulse with a 37-mph velocity change. For comparison, FMVSS 208 S5.1.2 [5] requires passenger cars to meet these same injury criteria using an unbelted Hybrid III 50th percentile ATD during a crash test with a 25-mph impact velocity. Compared to the unbelted automotive test requirement, the SIPS II airbag and knee bolster were required to dissipate 297 percent more kinetic energy than equivalent automotive systems. Given this large energy dissipation requirement, the original SIPS cushion was designed using uncoated, permeable fabric to allow the gas to vent through the fabric. The uncoated fabric chosen at the time was a 200 x 200 construction of 470 dtex polyester yarns. In common automotive use today, this modern fabric is comparatively lightweight, allowing for a compact bag pack, with a high-density construction.

The SIPS II airbag cushion carried over the general shape and the cut-and-sew construction of original SIPS cushion, as shown in Figure 3-5. Volume was added to the head contact region (upper-center portion of Figure 3-5) and some volume was removed from the abdominal contact region (lower-left portion of Figure 3-5). The internal, lateral tether design and cushion width also remained essentially the same.

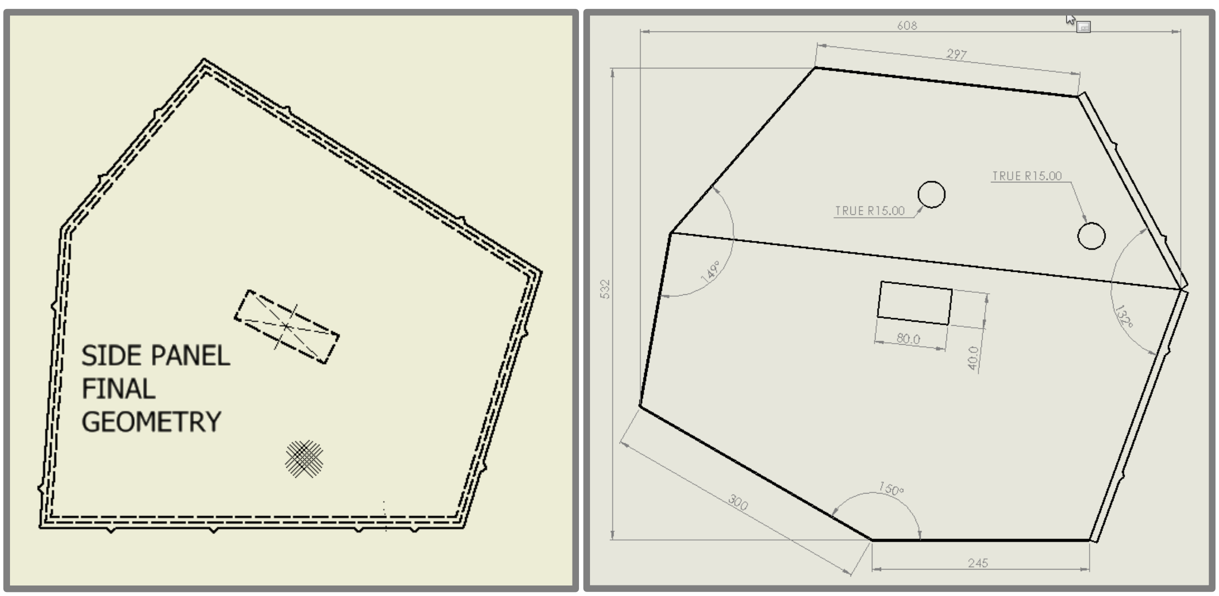

Figure 3-5. Side Panel Geometry Comparison: SIPS left/SIPS II right

To address the design requirements, achieve thermal protection, and better manage structural integrity and system venting, the following changes were implemented relative to the original SIPS:

- Heavier denier fabric commonly used in automotive passenger bags.
- Coated fabric for thermal management and vent tuning with discrete holes
- All new attachment to complement the geometry offered by the ADP-3 inflator. This increased the clamping surface area.
- Reinforcements in high-stress areas

- Added vertical tether "sail" for shape control and gas flow control
- Introduced a "blaster" component inside the cushion to direct gas flow forward during inflation and provide thermal protection.
- Cushion shape was adjusted to remove volume from lower portion that engages ATD abdomen and added volume that engaged ATD head.

The drawback of using a heavier, denier fabric is increased cushion pack volume. Given the stringent dimensional requirements, especially in the vertical direction, the cushion design ended up using two different fabrics – heavier fabric where needed, lighter fabric elsewhere to reduce pack volume of folded airbag. Furthermore, the shift to a non-permeable fabric also increased material thickness due to the silicone coating applied to the woven fabric.

GST Safety Components International remained the chosen fabric supplier. The two different materials procured for the project were:

- FC151K-23602517, 470 DTEX HYO PET 200x200 25GSM SIL CTD
- FC149T-23602517, 585 DTEX HYO PA 175x175 25GSM SIL CTD

To properly position the cushion for engagement with the ATD, the cushion needed to deploy with a significant horizontal vector, toward the ATD. Given the SIPS II module installation under a flat horizontal surface desk surface facing upwards, the SIPS II module design had to alter the gas flow and deploy the cushion's momentum as close to 90 degrees as possible. The design addressed this challenge using two primary methods: an internal blaster and a specialized folding pattern.

Starting with module #002, the SIPS II airbag design included the blaster, which is an internal baffle to direct gas flow. Conceptually, the blaster is an airbag cushion inside the main airbag cushion as shown in Figure 3-6. The exhaust gas from the two inflators ported directly into the blaster. The blaster was sized to provide the initial vertical deployment vector to push the cushion out of the pan. Then, vent orifices in the blaster redirected inflation gases 72 percent toward the occupant, 17 percent toward the back side of the module (towards desk) and 11 percent toward each side. When folded, the blaster lies directly on top of the inflators. It was constructed with two layers of 585 dtex coated fabric, and rip-stop sews served to keep the two layers acting as one – as well as reinforce the area around the aft-facing holes. The blaster worked well, and the inflation trajectory satisfactorily positioned the cushion for ATD contact and also served as a thermal shield in protecting the main cushion from hot gas.

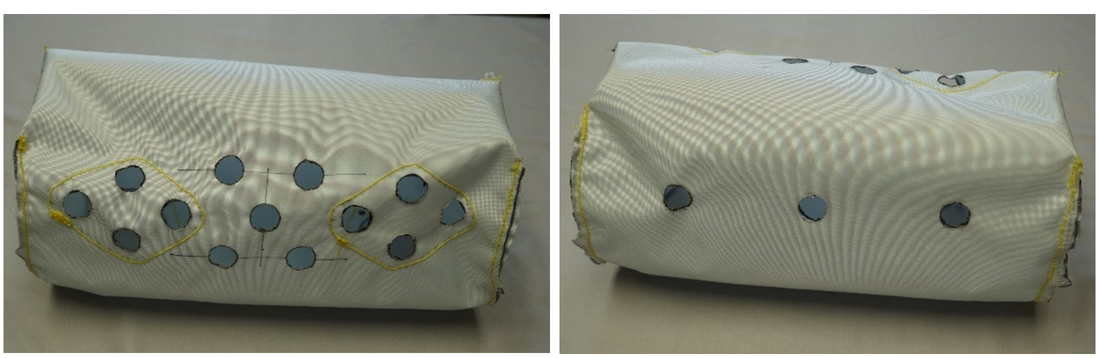

Figure 3-6. Blaster Design Used in Modules #002 through #005

Figure 3-7. The Blaster in Test 001a @ 7 msec

The folding pattern also contributed toward proper inflation trajectory. The single reverse roll folding pattern from the original airbag project was adopted. The physical volumes of the ADP-3 inflators within the pan interior limited bag pack space. To compensate, the folding pattern was developed to shift material toward the central part of the pan, between the two inflators. This sequence was performed prior to the reverse roll and can be seen in Figure 3-8. When coupled with the blaster, the folding pattern described herein produced the desired inflation trajectory.

Figure 3-8. Folding Geometry Prior to Reverse Roll Step

3.4 Pan

The pan is the foundation of the airbag module. In this project, the pan had to be robust to manage the high levels of energy discussed earlier in the report. It also had to be able to withstand elevated temperatures generated by the two pyrotechnic inflators. Its integrated flanges served as structural attachments to the desk, as well as features to which the functional cover could be adhered. There are many advanced plastic resins that withstand temperatures greater than 260°C (500°F), but ultimately glass-filled Nylon 6/6 was used as the best resin for the application. This material is readily available and has good machinability and molding characteristics. Strategically placed ribs and gussets ensured that the pan would retain its integrity during the event.

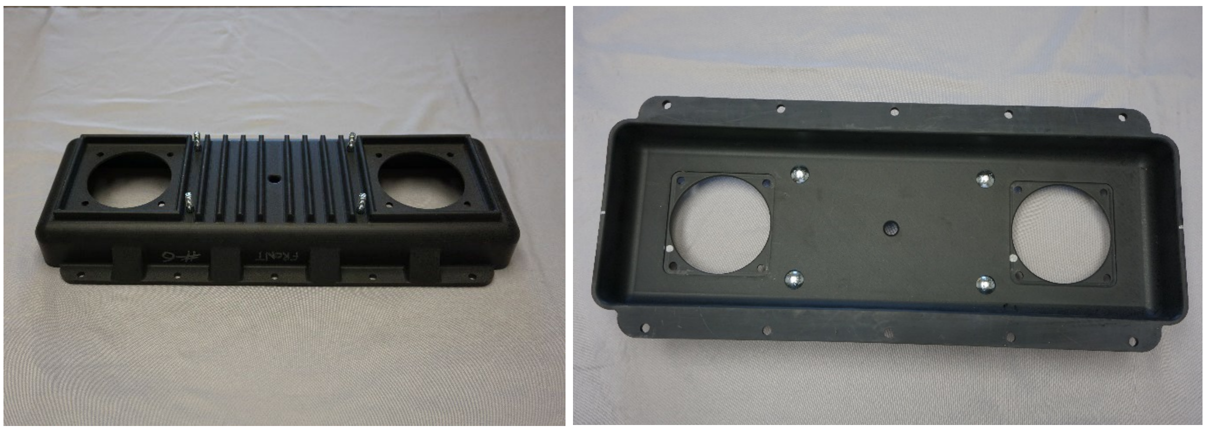

Figure 3-9. SIPS II Airbag Module Pan

3.5 Retainers

The metal retainers work in conjunction with the ADP-3 inflators to form a clamping mechanism which secures the airbag cushion to the pan. The retainers are available for purchase from automotive suppliers and are supplied with four self-clinching #10-32 studs. Researchers discovered during the linear impact testing phase that these automotive, off-the-shelf fasteners were not adequate to manage the high loads generated by the SIPS system. Two of the eight studs broke and separated from the metal retainer. For the dynamic sled tests, a rework procedure was developed and documented. This procedure replaced the #10-32 studs with M6-1.0 hardened Class 10.9 bolts that were threaded into the body of the retainer. Matching flange nuts were also used in these remaining dynamic tests with positive results.

Figure 3-10. SIPS II Airbag Retainer

3.6 Cover

The role of an airbag cover is to contain and protect the folded bag pack until deployment occurs. As discussed in the introduction, covers serve a multitude of roles. Aesthetics is one consideration in an effort to match the color, texture, and feel of the surrounding interior. For the purposes of the SIPS demonstration projects, the cover only served the role of containing the bag pack in its folded state. All covers must offer a means of rapidly and reliably opening when the cushion is pressurized by the inflation gases. For the SIPS study, this was achieved by a series of perforations along the cross-car centerline of the cover. In every test, the tear seam released consistently between 3 and 4 ms after the trigger signal. The cover was attached to the pan flanges by means of a high-strength adhesive, applied by the supplier of the polyethylene cover.

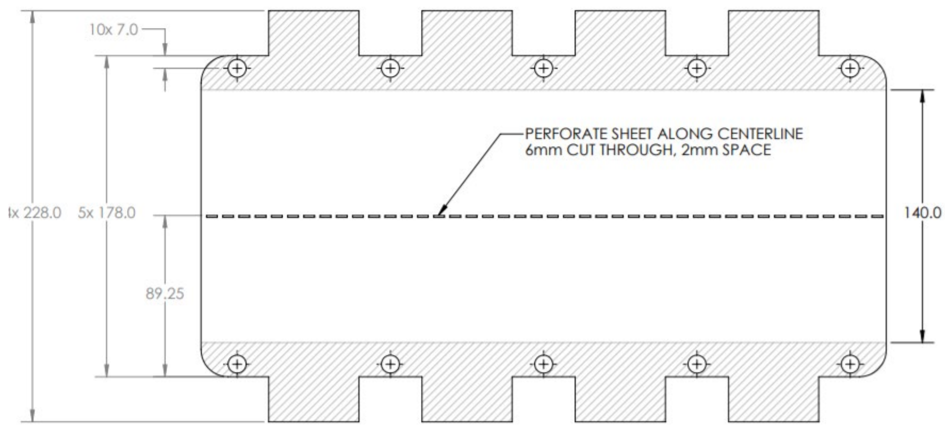

Figure 3-11. SIPS II Airbag Module Cover Sheet

3.7 Rear Shield

The formed sheet-metal shield was a multi-functional closure element. Made of 14 ga (1.92 mm) mild 1008/1010 hot rolled steel and powder coated in black, the shield was the last component to be installed to the module. It was attached to the module via four ¼ - 20 fasteners, lightly torqued to approximately 12 Nm (106 in-lbs). The shield served as:

- Thermal shielding of the inflators. The inflator bodies continue to increase in temperature for several minutes after the test (thermal soaking). This poses a burn risk to a person, such as a test technician, who could accidentally touch the inflator body.
- Thermal sink. Being in direct contact with the inflator bodies, the shield absorbs and dissipates heat. One of the most noticeable benefits of this function was the prevention of the melting of the inflator initiator connectors, which remained intact post-test and were easily disconnected. Melting of these connectors can create a foul-smelling odor.
- Occupant protection. A smooth, uniform surface reduced risk of abrasion and/or damage to the ATD's thighs.
- Wire protection. For automotive vehicles, airbags are expected to have a deployment reliability of 99.999 percent. To achieve such high reliability, the connectors pins are gold-plated, specially designed connectors are specified, and the wiring is carefully routed and protected. The metal shield protects the connectors and the wires from being snagged, severed, stretched, or otherwise compromised. For a commercial application,

the shield would be embossed around the connectors to offer additional protection by fully encapsulating both connectors.

- Wire management. Routing clips can be directly attached to holes in the shield, allowing wire management transition from the module level to the vehicle level.
- Tubing protection. Unique to a test environment, the pressure tube must be carefully inserted into the cushion, and then with great care protected during a violent crash event. Any damage to the tubing would mean loss of pressure data.
- Pressure transducer attachment. Same to the tubing protection, the pressure transducer must be secured during the entire event. The 90° tab on the aft side served this role.

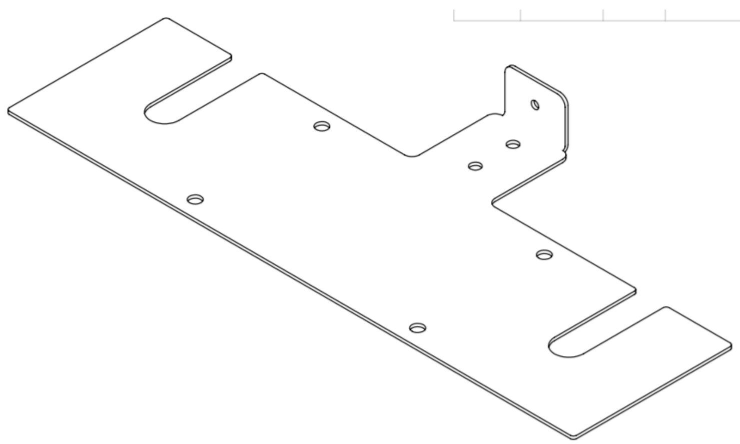

Figure 3-12. SIPS II Airbag Module Rear Shield

4. SIPS II Airbag Design Iterations

Throughout the project, researchers built five SIPS II airbag modules for various design iterations for testing (Table 4-1). Simulations in LS-DYNA were performed to evaluate the cushion inflation and venting changes. The ADP-3 inflator properties were used as input to predict bag behavior at ambient conditions. Prior to building any prototypes, FEA simulations with the new cushion shape and volume were performed to reach a high level of confidence that the given design performed to expectations. Initial simulations were performed with a bag design having two vent holes – one vent hole toward the back edge of each side panel (for this report, when referring to the airbag module, "front" is the face that can be seen by a seated occupant; whereas the "front" of the operator environment is looking forward from the seated position toward the front of the locomotive).

The first three airbag modules employed the 2-vent-hole design of the simulations. Beginning with the second linear impact test (CTR13668-001), all bags had a 4-vent-hole cushion to optimize the system performance. Difference between the side panels with 2-vent-hole versus the 4-vent-hole is shown in Figure 4-1. Simulations were used once again to tune the sizes of the four vent holes. This design change was driven by the need to vent more gas and plastically absorb more energy as demonstrated by the first linear impact test. In this test, as discussed later in this section, the cushion absorbed 20 percent of the kinetic energy of the moving platen. The goal was 50 percent. In the same test, researchers also observed that when loaded, the bag rotated forward and partially folded over the top of the desk. Because of this dynamic interaction of the bag with the asymmetric desk, one vent closed almost completely around 65 msec. The solution was the 4-vent-hole design. Beginning with module #002 through the end of the test phase, there were only two significant design changes:

- Number of vent holes and diameter
- Bag retainer studs (see "Retainers" section)

Table 4-1. SIPS II Airbag Module Design Iterations

Module Serial Number	Test Description	Test Identifier and Date	Design Iteration
#001	Static Deployment 1	CTR13353-001-5/23/2019	Cushion with "throat" attachment to pan; two ø27-mm vent holes (one @ rear of each side panel)
#002	Static Deployment 2	CTR13452-001-6/24/2019	Simplified cushion; removed "throat"; added blaster; larger flaps for thermal protection, 2x ø30-mm vent holes
#003	Linear Platen Impact 1	CTR13496-001-8/31/2019	Two ø30-mm vent holes @ rear of side panels
#004	Linear Platen Impact 2	CTR13668-001-10/18/2019	Four ø27-mm vent holes @ center and rear of side panels
#005	Dynamic Sled 2	CTR14232-001 07/23/2020	Four ø30-mm vent holes @ center and rear of side panels, retainer studs with larger dia. and higher UTS

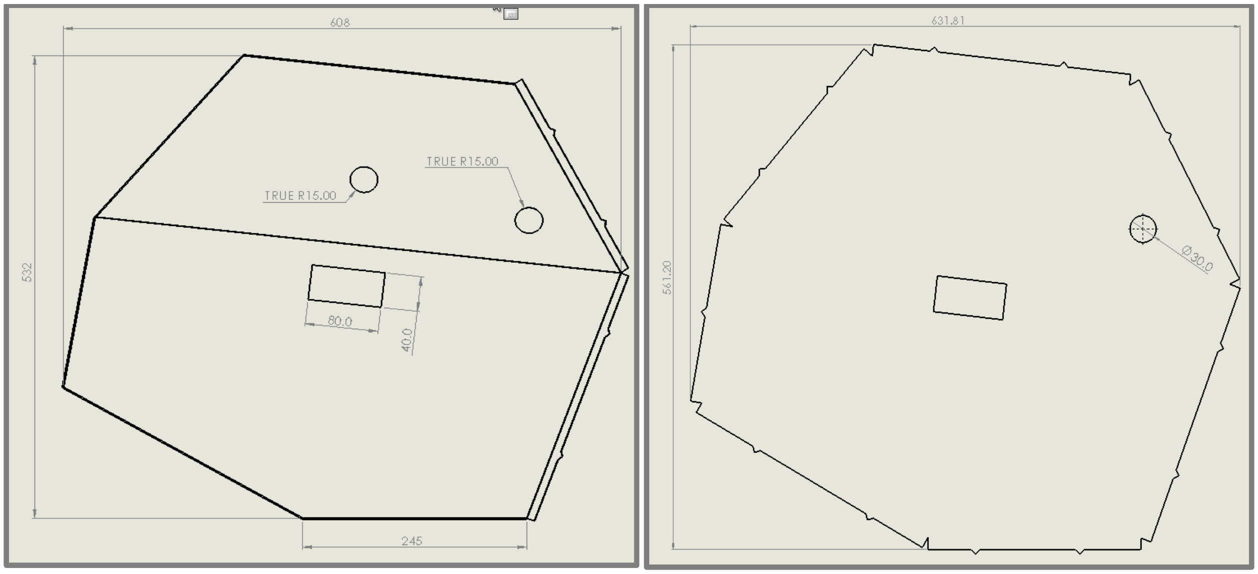

Figure 4-1. Design Iteration of Side Panel: 2-Vent Holes vs. 4-Vent Holes

4.1 Static Deployment Tests

The static deployment tests were conducted to evaluate component-level performance and operating characteristics of the SIPS II airbag module, without external interaction. Data collection was intended to quantify these characteristics and provide information for the tuning of and correlation with the simulation model. In addition, static deployments enabled the assessment of the structural and thermal integrity of the SIPS II module during the deployment alone.

For this test series, researchers mounted a complete SIPS II module to a rigid fixture that simulated the geometry of the operator's control stand/desk. The test procedures used generally reflected the recommended practices from SAE J1630 [8]. The SIPS II modules were deployed using a manually operated electronic switch that also triggered the data acquisition system and high-speed digital imagers, synchronizing them in time. The tests were conducted at ambient temperature, and the SIPS II modules were stored at ambient temperature for no less than 4 hours prior to the test. NHTSA recommends that the standard temperature procedure for the test be between 18.9º and 25.6º C, per Table V2 [12]. Static deployment test setup is shown in Figure 4-2.

The static deployments were recorded using two high-speed digital imagers, positioned 90 degrees apart in the horizontal plane, as a front view and side view. Video was captured at 3,000 fps, in accordance with SAE J211-2 [9]. Reference targets were included in anticipated motion planes, enabling the video to be used for motion analysis. Internal airbag pressure was measured during the deployment at one location. Data was recorded and filtered per SAE J211-1 [10] at 20,000 Hz and included 20 ms of data prior to deployment.

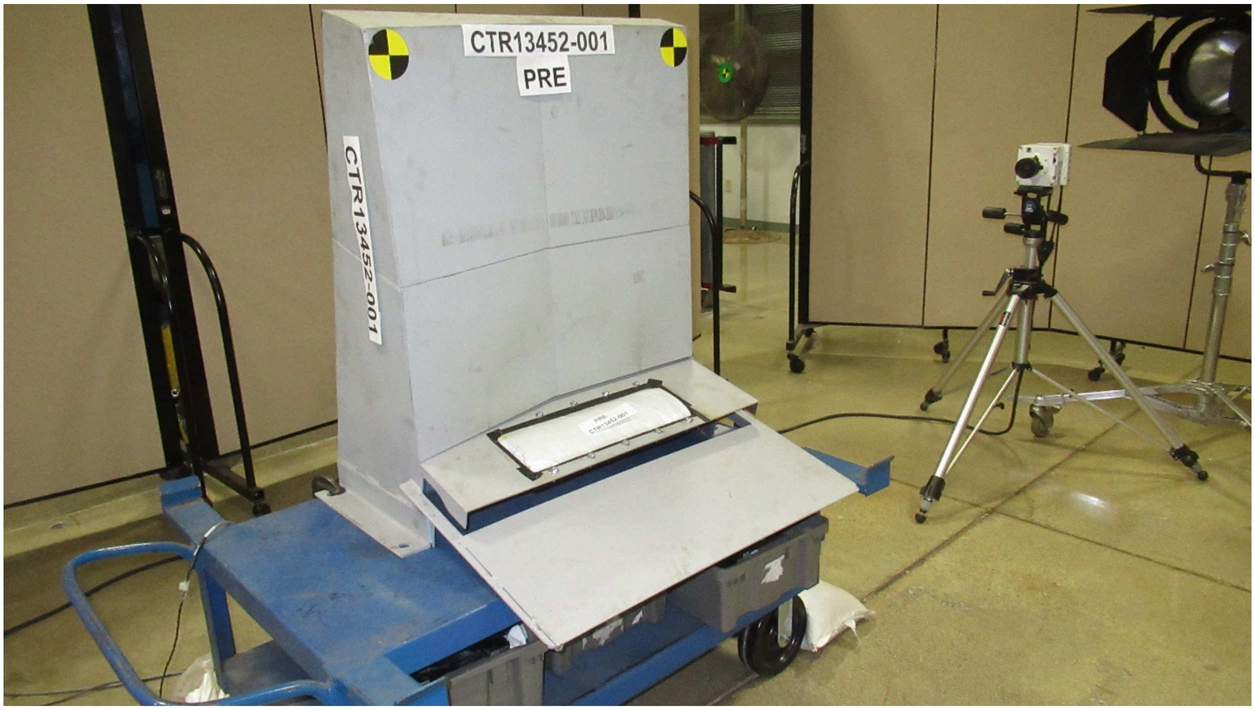

Figure 4-2. Static Deployment Test Setup

Three static deployments were conducted, each providing design guidance when paired with the LS-DYNA FEA simulations:

> The first static deployment (001) of module SN#001 incorporated only a vertical sail tether internal to the cushion for directing gas flow and controlling bag trajectory. The result from this test indicated the presence of high-stress concentration areas in the lower corners of the "recessed" cushion throat, and also showed that not enough gas was being redirected forward to position the bag in front of the occupant early in the event.
>
> The second static test (001a) was that of the blaster only. The blaster was designed to act as a cylindrical baffle that would redirect about 70 percent of the gas flow toward the occupant; it would also serve as sacrificial material to protect the main cushion from hot gases.

The last static deployment test (002) of module SN#002 included a redesigned cushion. The cushion was less complex in design and easier to manufacture. Modifications included:

- The "throat" feature was removed.
- The blaster was incorporated.
- Flap sizes increased for better thermal protection.
- Vent hole size was increased from ø27 mm to ø30 mm.

The test demonstrated significantly improved performance when compared to that of module SN#001 (Figure 4-3). The design goals of trajectory redirection toward the ATD early in the event and enhanced thermal/jetting protection were achieved. Furthermore, there were no structural breaches of any of the components, and the bag pack conformed to the available space inside the pan, even with the addition of the blaster.

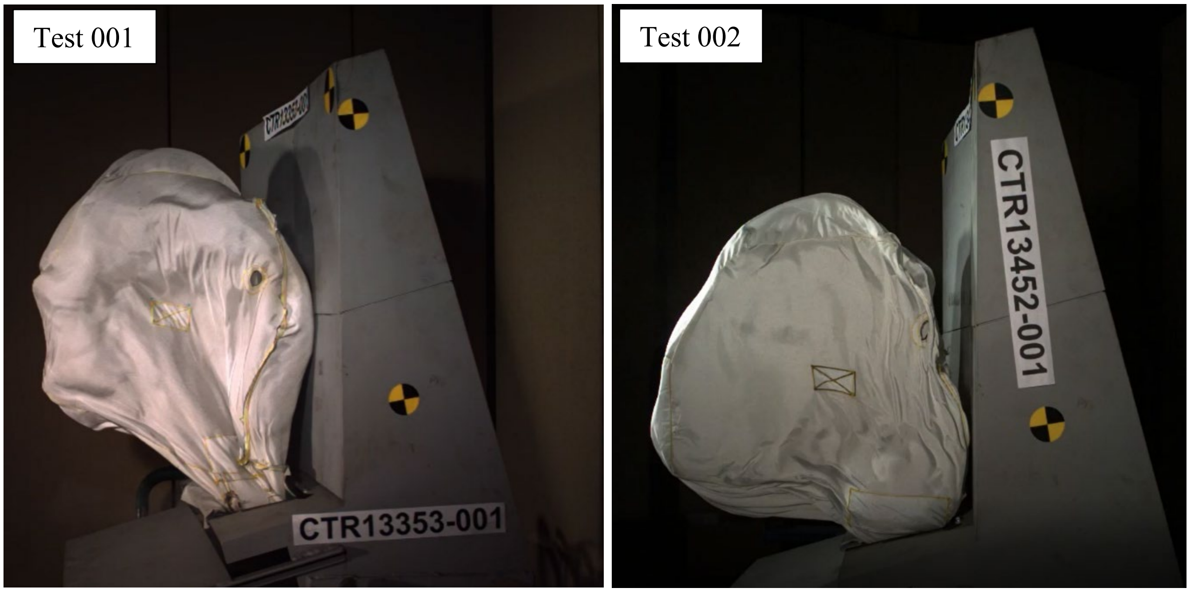

Figure 4-3. Bag Presentation 20 ms – Test 001/Test 002

Once researchers reviewed the hardware, video, and data from test 002, they made the following observations:

- Cushion remained intact – no holes created due to stress or thermal effects.
- Blast tube remained intact – no holes or torn seams due to stress or thermal effects.
- All attachments remained intact.
- Rear shield dissipated heat – connectors not fused to inflators.
- Tear seam worked as intended.
- Pan melted at inflator attachments – compression due to fastener preload.
- Pressure transducer attachments worked as intended with good response.

After these findings it was decided to "freeze" the module and the cushion design and use it for the next set of tests.

4.2 Linear Impact Energy Absorption Tests

The purpose of the linear impact energy absorption test was to evaluate component-level performance and operating characteristics of the SIPS II airbag module interacting with a known body mass at a desired speed. These characteristics included elastic and inelastic energy absorbed by the SIPS II airbag module. Data collection quantified these characteristics and provided information for analytical model tuning and correlation. In addition, these deployments enabled the assessment of the structural and thermal integrity of the SIPS II module, due to both deployment and airbag interaction.

For this test series, researchers mounted a completed SIPS II module 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. The deploying SIPS II module was impacted by a single degree-of-freedom moving platen of defined geometry with a known initial kinetic energy. The platen was propelled using air pressure, and the test was conducted in accordance with recommended practice SAE J2961 [11].

For purposes of the recommended practice, the SIPS II airbag module was considered equivalent to a Class IV passenger airbag module. The fixture was tilted forward at a 15° angle, enabling the linear impactor's body block to travel horizontally. The setup for the linear impact tests is shown in Figure 4-4.

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, noted by the first non-zero measurement of the impactor's accelerometer. The SIPS II airbag module was deployed by the data acquisition system at a predetermined time. The time was chosen such that it would be 79 milliseconds before the platen reached a position 616 mm away from the vertical plane of the fixture, traveling at a target speed of 7.55 m/s. These values were based on 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 and time.

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

Figure 4-4. Test Setup of Linear Impact Test

The guided mass of the impact platen weighed 35 kg, and the flat portion of the interface surface measured 250 mm tall by 700 mm wide. Refer to SAE J2961 for additional details related to the impact platen. The vertical centerline (y-plane) of the platen was aligned with the centerline of the SIPS II airbag module for all tests. The horizontal centerline (z-plane) of the platen was aligned approximately with the centroid of the inflated airbag cushion.

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 the linear motion of the piston attached to the platen.

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

The first linear impact test of module #003, CTR13496-001, met the test parameter conditions derived through simulations:

- 37 ms after airbag deployment, the body block was positioned 358 mm away from the vertical face of the fixture, traveling at 6.36 m/s – closely matching the simulation.
- The body block achieved a maximum velocity of 7.37 m/s in 104 ms.
- The cushion deployed symmetrically, with forward trajectory, decelerating the body block 15 ms after deployment.

- The cushion was in position at 33 ms, and fully developed around 38 ms, when the inflator was fully exhausted.
- The cushion halted the body block's motion without bottoming out; the body block stopped 289 mm away from the fixture.
- The SIPS II airbag module exerted a maximum force of 16 kN after 231 mm of body block penetration.

The SIPS II airbag module absorbed 99 percent of the body block's 995 J of kinetic energy but returned 80 percent of the energy as rebound. The following observations were made from the test:

- Cushion started to decelerate the body block at about 104 ms.
- Inflation trajectory looked good and was nearly symmetrical.
- Cushion construction was robust and showed no seam breach, burning, or tearing of the fabric.
- The internal blaster worked well in directing gases forwardly, as well as in preventing heat/jetting damage to the main cushion.
- The 2x ø30-mm vents were undersized; hence the system managed to absorb only 20 percent of the kinetic energy of the body block.
- The left vent began sealing off due to contact with the reaction surface (desk) at around 45 ms.
- Minimum platen to reaction surface gap reached 289 mm.

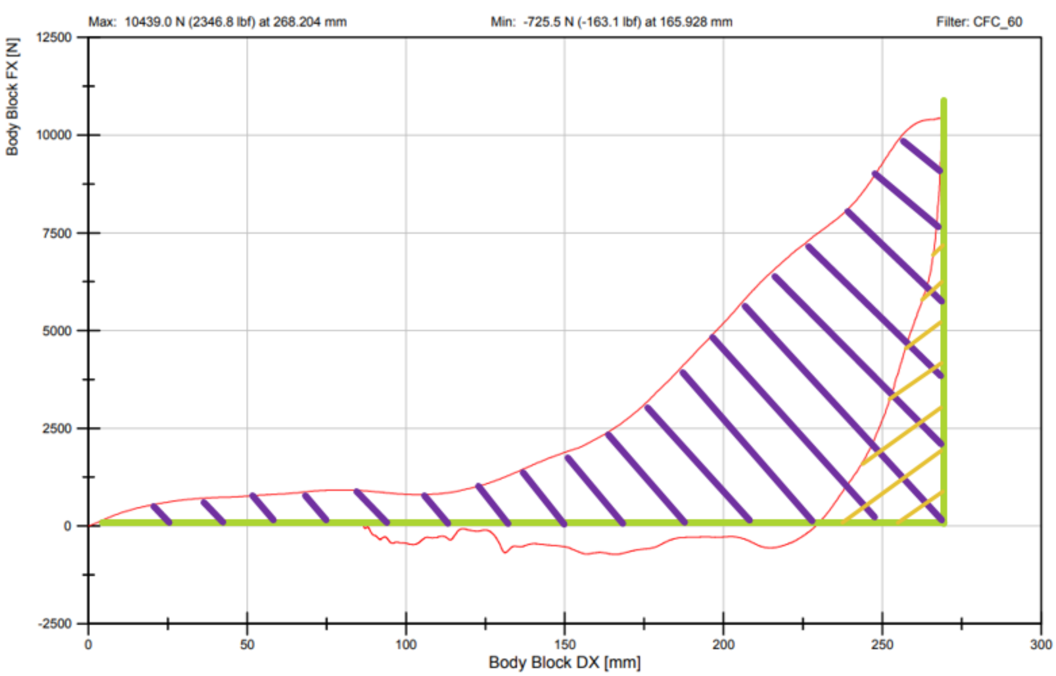

Figure 4-5. Loading and Unloading Elastic Slopes in Test 2

These observations led to increasing the number of vent holes from two to four on module #004 (CTR13668-001) for the second linear impact test – which improved upon the results of the previous test. The test conditions were reasonably close to the target: 12 ms after the airbag deployment, the body block was positioned 505 mm away from the vertical face of the fixture, traveling at 7.56 m/s. The cushion deployed symmetrically, with forward trajectory, decelerating the body block 15 ms after deployment. The cushion was in position at 36 ms and fully developed by 50 ms, when the inflators had exhausted about 95 percent of their contents. The left vent opening was pressed against the fixture at around 40 ms, partially limiting vent effectiveness thereafter. The cushion halted the body block's motion without bottoming out; the body block stopped 235 mm away from the fixture and exerted a maximum force of 10.44 kN.

Figure 4-5 shows the force that the SIPS II 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 10,439 N maximum force was achieved 62 ms after deployment and after the body block penetrated 292 mm into the cushion. The area under each curve represents energy; therefore, the area between the curves represents the energy dissipated by the SIPS II airbag, not returned as rebound.

The results from test 004 provided adequate confidence to proceed with dynamic sled testing. Results from the linear impact testing phase were used as input to refine the occupant simulation model. Simulation iterations were used to further tune vent-hole size prior to sled testing.

4.3 Dynamic Sled Test

The purpose of the dynamic sled test was to evaluate the system-level performance of the updated airbag and knee bolster against key dimension requirements, including occupant injury measures, when exposed to the trapezoidal test pulse. For this test series, the dynamic sled test was conducted on an acceleration-type sled, because it could better reproduce the trapezoidal shape of the test pulse. The sled setup is shown in Figure 4-9, and the desired crash pulse and the sled re-produced pulse are shown in Figure 4-7.

Figure 4-6. Dynamic Sled Test Setup with 95th percentile Male ATD

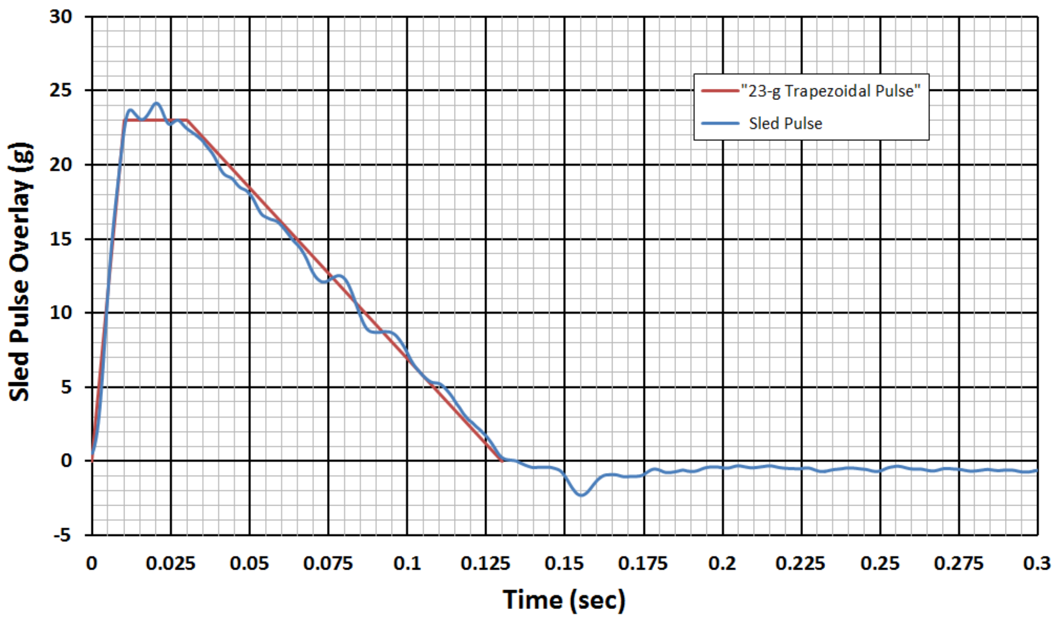

Figure 4-7. Crash Pulse and the Sled Test Acceleration Pulse

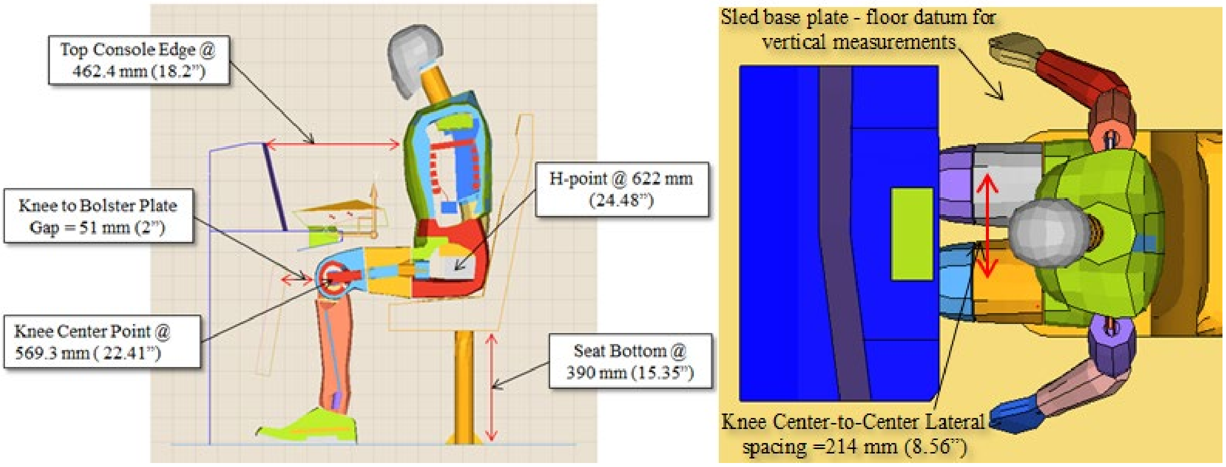

Figure 4-8. Test Setup – ATD Relative to the Desk

In addition, the initially stationary sled platform enabled more precise pre-test positioning of the unrestrained (unbelted) ATD.

For this dynamic test series, researchers attached a representative locomotive operator's control stand 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.

The unbelted, Hybrid III 95th percentile ATD was positioned in the seat, such that the ATD's knees were 2 inches from contact with the deformable knee bolster. Figure 4-8 shows the pre-test setup. The pre-test positions of the ATD, relative to targets on the control stand, were measured using a FARO arm, a portable coordinate measuring machine.

For safety purposes, the ATD was equipped with a tether; its length was adjusted to not influence the ATD's interaction with the control stand or interaction with SIPS. Multicolored chalk was applied to the ATD's head, face, and knees to help identify contact locations in the post-test review.

4.3.1 Instrumentation and Data Collection

For this study, the dynamic sled test was recorded using five high speed digital imagers, positioned as follows:

1. Right-side view of ATD, on-board imager (2,000 fps)
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. Front view of the knee bolster bracket, on-board imager (1,000 fps)
5. 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 post-test 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 4-9.

A calibrated Hybrid III 95th percentile 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

Instrumentation also included a pulse accelerometer on the sled platform, a pressure transducer attached to the airbag rear shield, a contact switch position to identify knee contact with the bolster, and a data channel to record the airbag fire signal. The sled pre-test setup is shown in Figure 4-11.

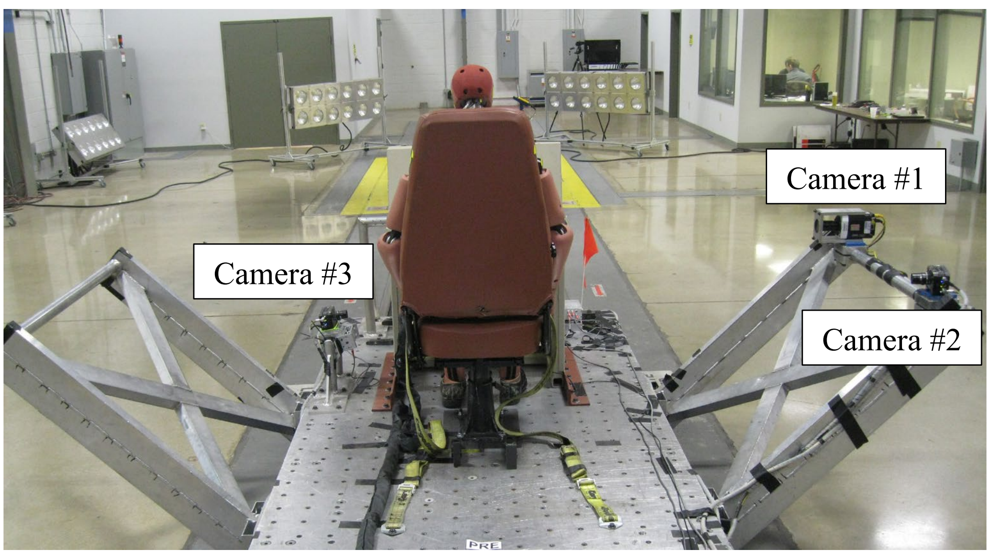

Figure 4-9. Various Video Camera Locations as Mounted on the Sled

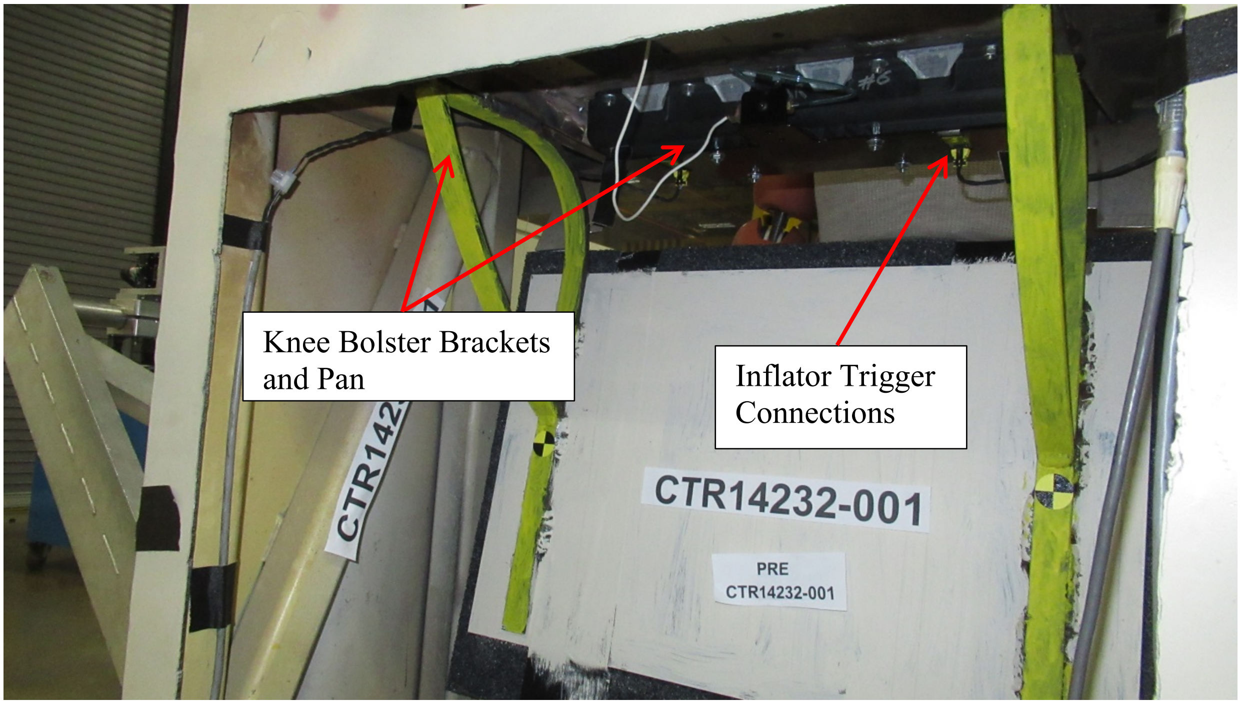

Figure 4-10. Inflator Firing Trigger Connection

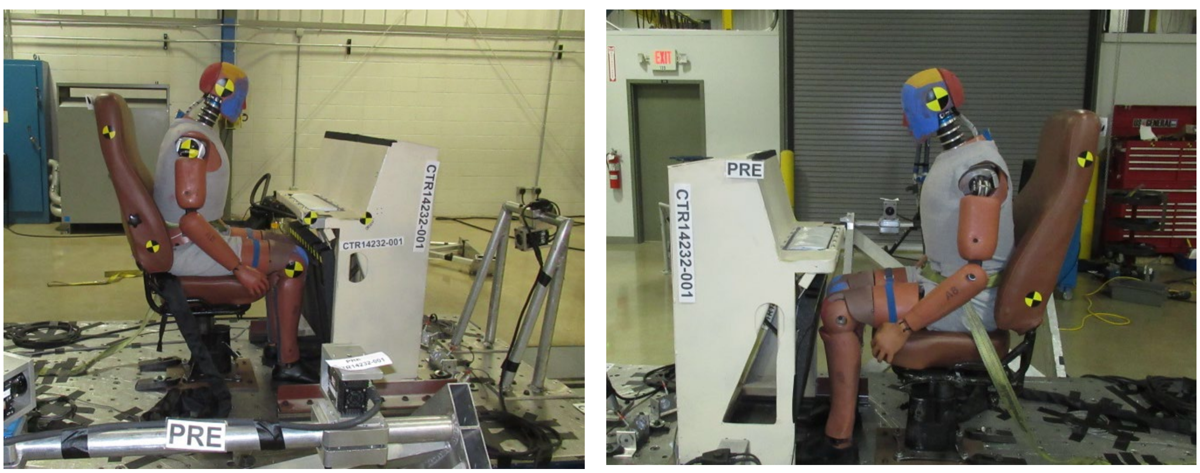

Figure 4-11. Sled Test Setup – Right and Left Views

Figure 4-10 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's firing triggers. Figure 4-11 shows the sled with ATD from various angles.

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.

4.3.2 Sled Crash Test Results

Based on the sled test simulations, the position of the energy-absorbing knee bolster was adjusted on the desk fixture. In addition to that, the knee bolster plate thickness was increased to 0.25 inch.

LS-DYNA simulation of the sled test was conducted using the 23g acceleration pulse shown in Figure 2-1. Figure 4-12 shows the ATD-desk positions and interaction in the simulation for the time frames shown in Figure 4-14 from the sled test.

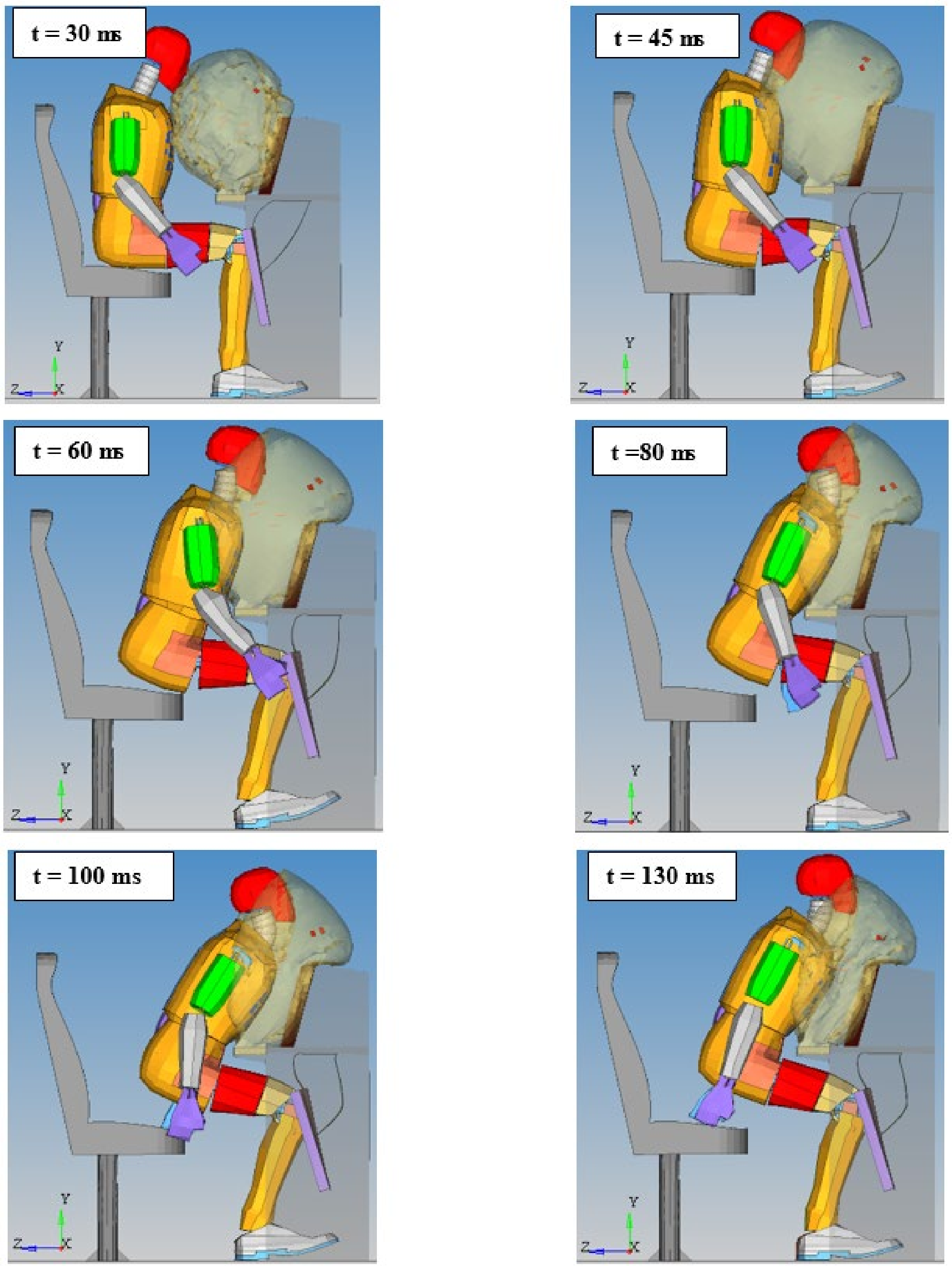

Figure 4-12. ATD Kinematics from LS-Dyna Simulation of the Sled Test

For the dynamic sled test (CTR14232-001), the sled acceleration accurately replicated the crash pulse, (Figure 4-7), producing a peak velocity of 37.7 mph, as shown in Figure 4-13. The deployment signal was sent to the SIPS II airbag module at 10 ms and the airbag first appeared in video after an ignition delay of 4 ms. The SIPS II airbag module deployed symmetrically with good forward trajectory, engaging the head, neck, chest, and upper abdomen of the ATD, beginning at approximately 35 ms. The contact switch indicated that the ATD's knees first contacted the knee bolster at 17 ms. At 45 ms, the ATD chest and head had solidly engaged the well-positioned cushion, as shown in Figure 4-14.

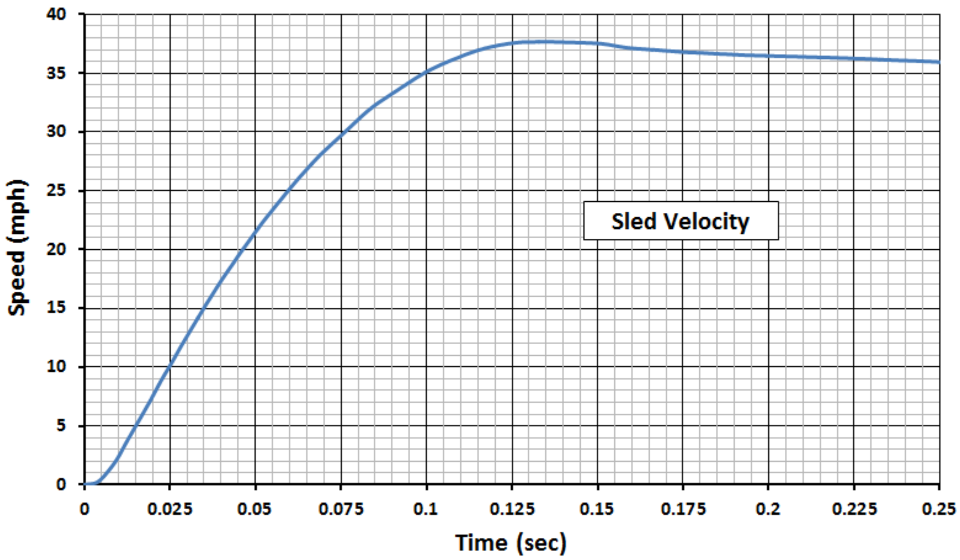

Figure 4-13. Sled Speed Resulting from the 23g Trapezoidal Crash Pulse during Test

Figure 4-14 shows the airbag inflating and engaging the ATD as it accelerated relative to the desk. The figure shows the video captured at 30, 45, 60, 80, 100, and 130 ms following the crash event.

The ATD as viewed from the overhead video camera is shown in Figure 4-15 at 80, 100, 130, and 145 ms. Plastic deformation of the knee bolster plate and brackets is shown in Figure 4-16.

Figure 4-14. ATD Kinematics from Sled Test

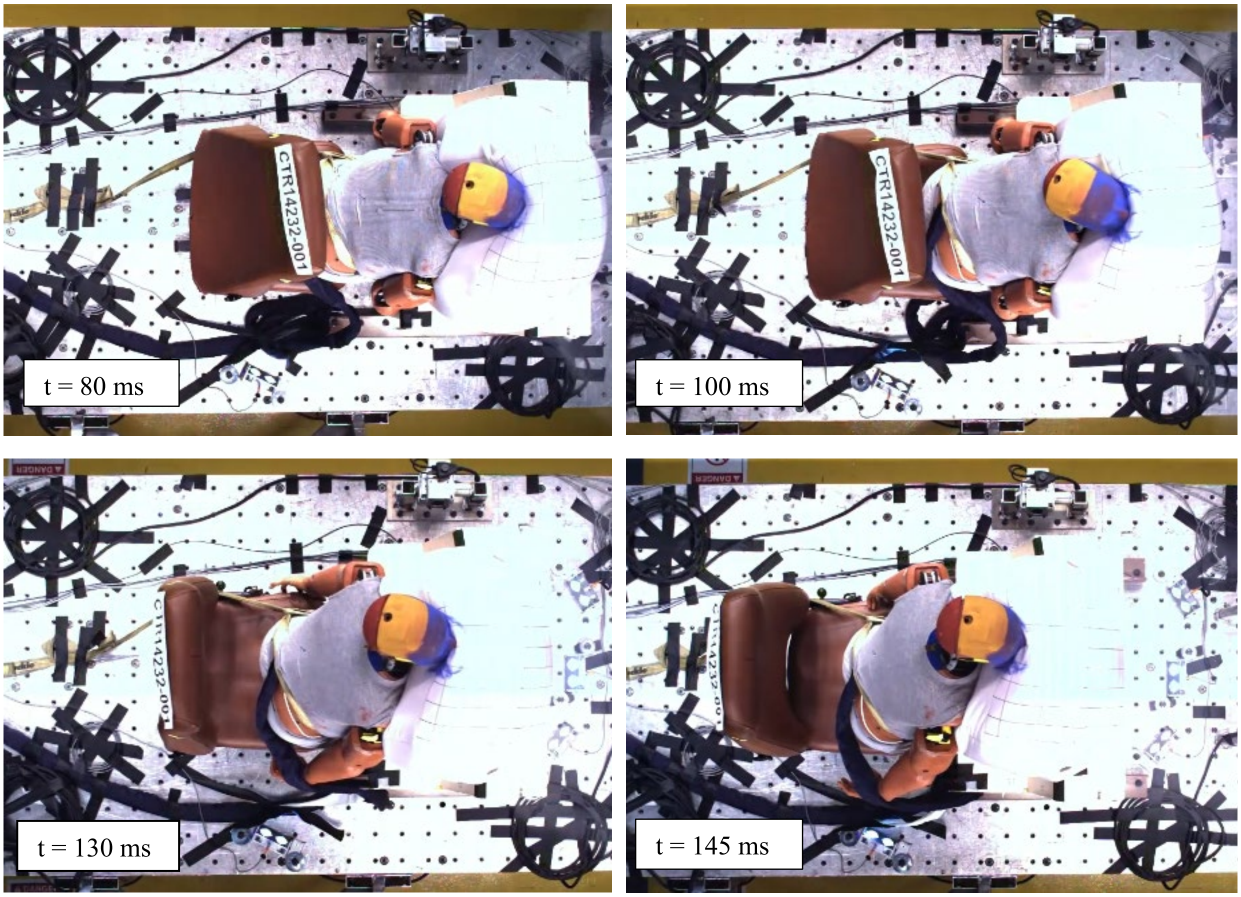

Figure 4-15. Overhead View of the Sled at 80, 100, 130, and 145 ms

Figure 4-16. Knee Bolster Assembly: Left – Pre-test, Right – Post-test (Permanent Deformation)

4.3.3 LS-Dyna Simulation of Sled Test

The LS-DYNA model, shown in Figure 4-12, was built with the HyperMesh preprocessor from the SolidWorks-based CAD geometry of the initial design for the desk and the airbag.

Mid-surfaces were derived from the solid geometry of the desk and stitched appropriately to form the surface geometry for the FE mesh. The surface was then meshed to generate a clean mesh with quadrilateral elements, with a global 20-25-mm characteristic element length throughout the model.

The desk and the chair were modeled with Belytschko-Tsay (BT) shell elements. These are four-node shell elements with multiple through-thickness integration points. The BT element is a computationally efficient element in LS-DYNA and is widely used for crash, impact, and metal-forming applications.

The total number of elements in the model was 18,074; 11,832 for the desk, including knee bolster, and 6,242 for the airbag. A piecewise linear elastic-plastic model was used for the desk and knee bolster (Material Type 24 in LS-DYNA).

To model the airbag in LS-DYNA, the airbag reference geometry was created in HyperMesh based on the solid model design and the final shape of the airbag. The initial shape in the simulation was obtained by scaling down the reference mesh geometry. The leakage was modeled through four vents due to porosity, and the material used for the airbag was MAT_FABRIC in LS-DYNA.

The static airbag deployment tests were used to support and finalize the model used to simulate the sled test for establishing the final ATD and desk positions.

The ATD was imported from the LS-DYNA library and only his position was changed in the current model; material properties and element thicknesses remained the same.

A comparative review of the six time frames showed an excellent correlation between the simulation and test frames in terms of the ATD-desk relative positions and interaction throughout the crash event. Figure 4-17 shows side-by-side comparison between sled test and LS-DYNA simulation for the 80-ms frame.

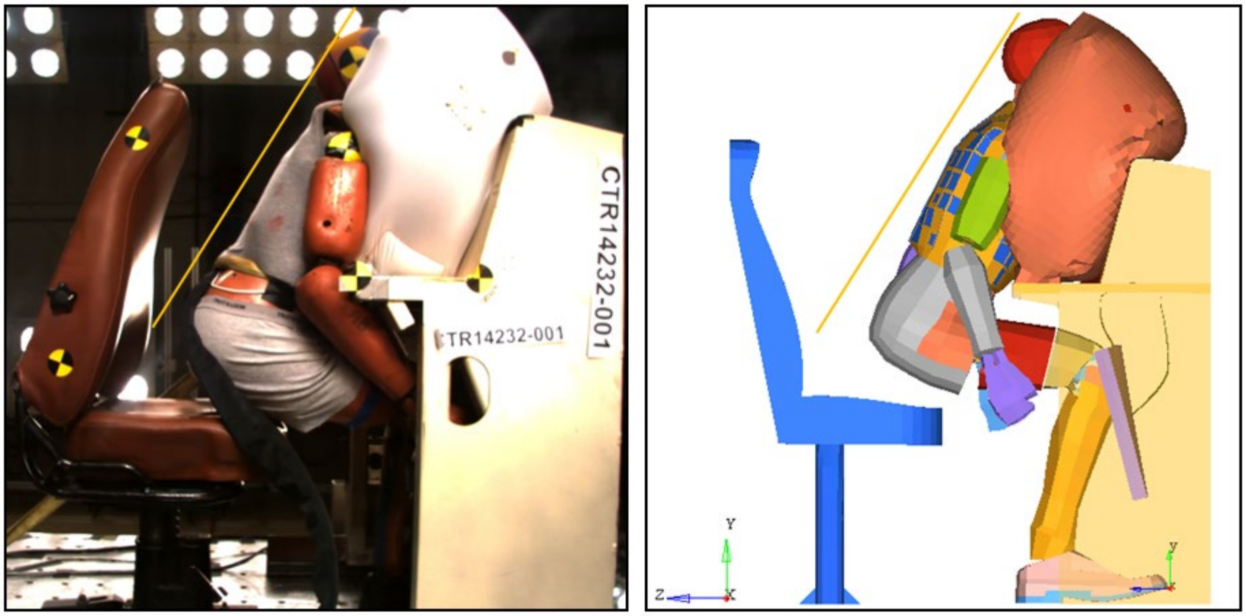

Figure 4-17. Comparison between Sled Test and LS-DYNA Simulation for 80-ms Frame

4.3.4 Injury Indices Discussion

ATD injury indices, based on the measurements from the sled test (CTR14232-001), are shown in Table 4-2, along with the FMVSS 208 limits and the pre-test simulation estimates for the final airbag design.

Table 4-2. Injury Indices – Comparison Pre-test Predictions to Sled Tests

Injury Parameter		Index Limit	Injury Indices	
			Pre-test Simulations	Sled Test Results
HIC_{15}		700	231.3	269
Chest 3 ms (G)		60	56.0	54.1
Chest Deflection (mm)		50	16.0	40.7
Femur Left (N)		10,000	6,980	8,270
Femur Right (N)		10,000	6,870	7,890
Neck Tension (N)		4,170	1,349	3,326
Neck Compression (N)		4,000	728	294
N_{ij}	N_{te}	1.0	0.06	0.60
	N_{tf}	1.0	0.20	0.23
	N_{ce}	1.0	0.09	0.01
	N_{cf}	1.0	0.16	0.09

The sled test met all Injury Assessment Reference Value criteria for the Hybrid III 50th percentile ATD, with good margin for all criteria. These values have been standardized by NHSTA.

NHTSA has developed indices for the 95th percentile male Hybrid III ATD, as shown in Appendix B, but regulations have not been promulgated. The sled test results of Table 4-2 also met all the injury criteria for the 95th percentile male Hybrid III ATD.

Head Acceleration

Head acceleration history from the sled test is shown in Figure 4-18. The HIC_{15} index was calculated based on the acceleration of the head weighted over a 15-ms moving window. As shown in Table 4-2, the value for HIC_{15} was 269, based on the resultant head acceleration in the x, y, and z directions. For the ATD, the coordinate system followed the right-hand rule, i.e., the x axis was aligned along the sled centerline, the y axis was the lateral direction, and the z axis was in the vertical direction. The peak HIC_{15} of 269 occurred in the 58.1–73.1-ms window – well below the limit of 700.

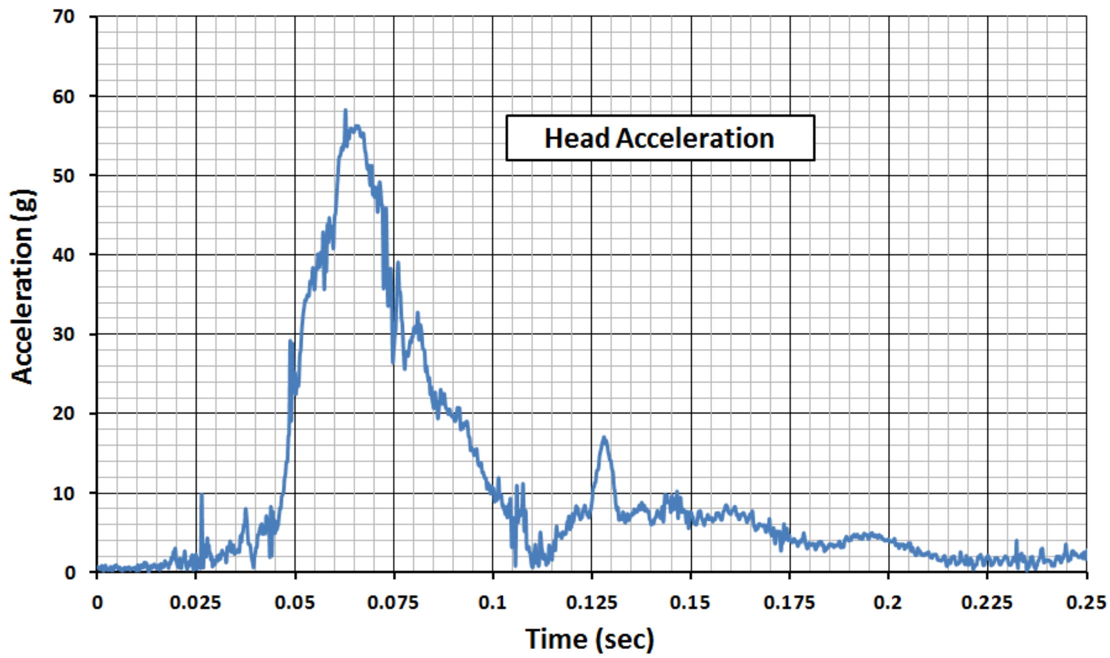

Figure 4-18. Sled Test – Head Acceleration (Resultant) Time History

Chest Accelerations

The chest injury index limit of 60g is based on a chest acceleration value which is exceeded or sustained within a moving 3-ms window. LS-Dyna simulations showed that increasing the knee bolster stiffness and shifting it closer to the dummy would reduce the chest severity index by 10 percent.

The sled test (using Module 005) showed these modifications helped reduce the chest injury index to 54.1g from the 70g obtained in the previous sled test, in which the knee bolster used a thinner knee plate of 0.125 inch. The index 54.1g is within the acceptable value. The chest acceleration history from the sled test is shown in Figure 4-19.

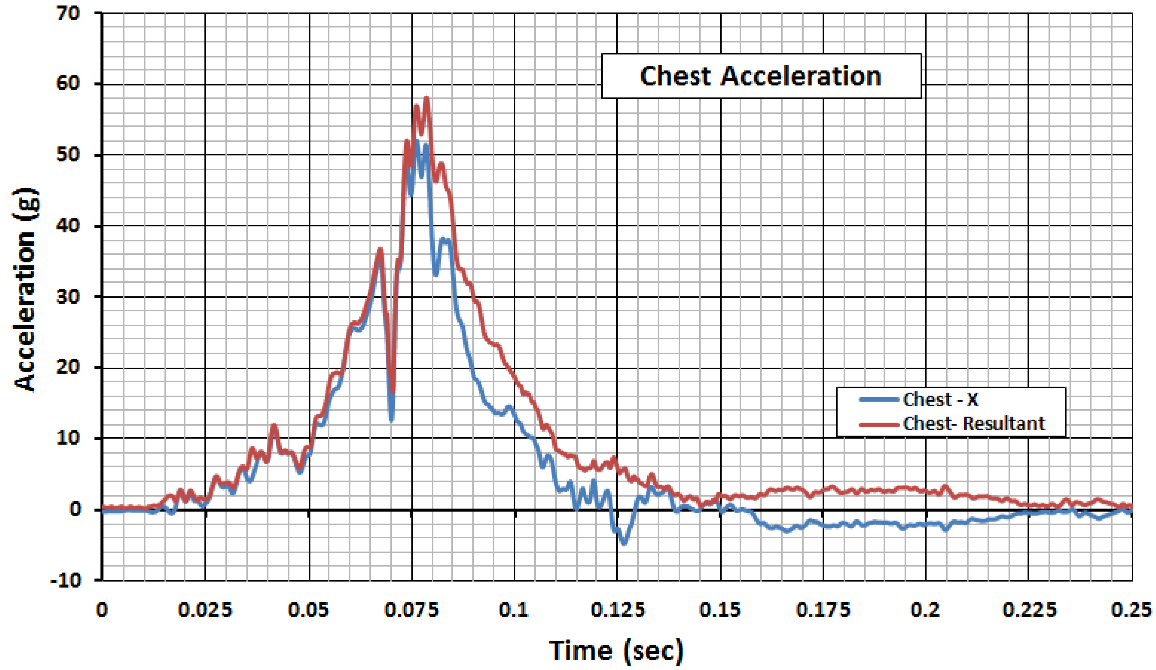

Figure 4-19. Sled Test– Chest Acceleration Time History

Femur Loads

Femur loads from the sled test are shown in Figure 4-20 for both the left and right knee. As seen in Figure 4-14, the ATD stayed centered and contacted the airbag in an upright and straight position. Both knees experienced the peak load at 36 ms. Note that both femur loads were below the injury index limit of 10,000 N (Figure 4-20).

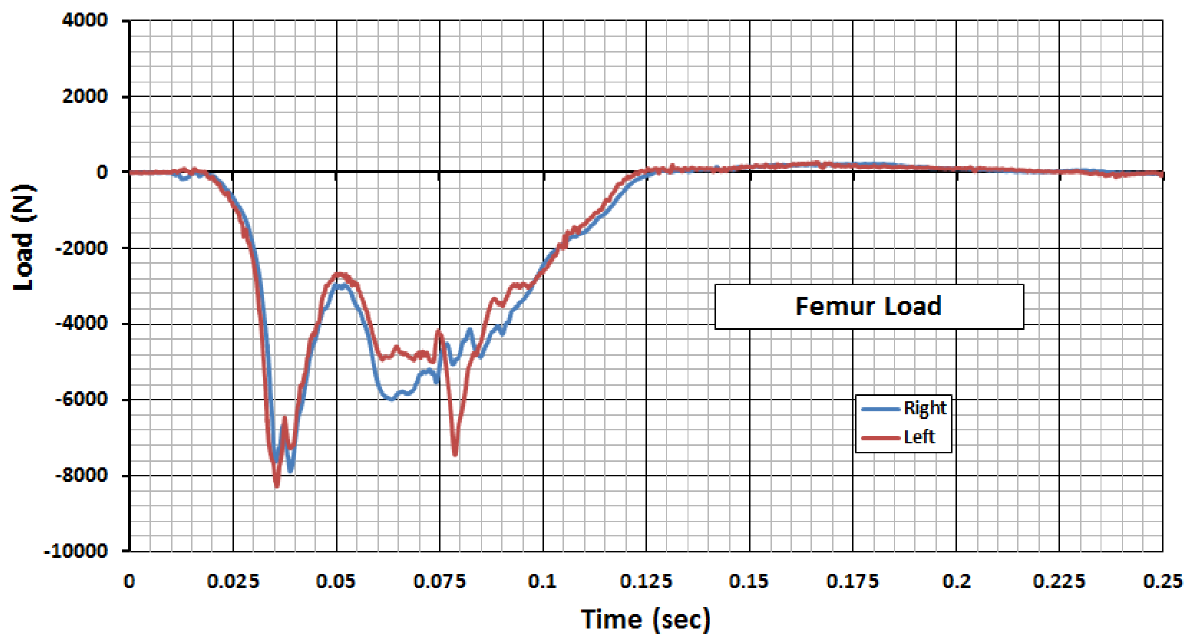

Figure 4-20. Sled Test – Right and Left Femur Load Time History

Neck Forces

Neck forces from the sled test are shown in Figure 4-21 and Figure 4-22 for F_Z (along the neck), F_y (lateral direction), and F_x (longitudinal direction). The neck force F_Z was generally the largest of the three due to the head acceleration in the vertical direction. The next highest was the force F_x which would result from the forward/backward acceleration of the head relative to the upper body. The smallest forces seen were in the F_Y direction which would result from head acceleration in the lateral direction, such as in a side impact.

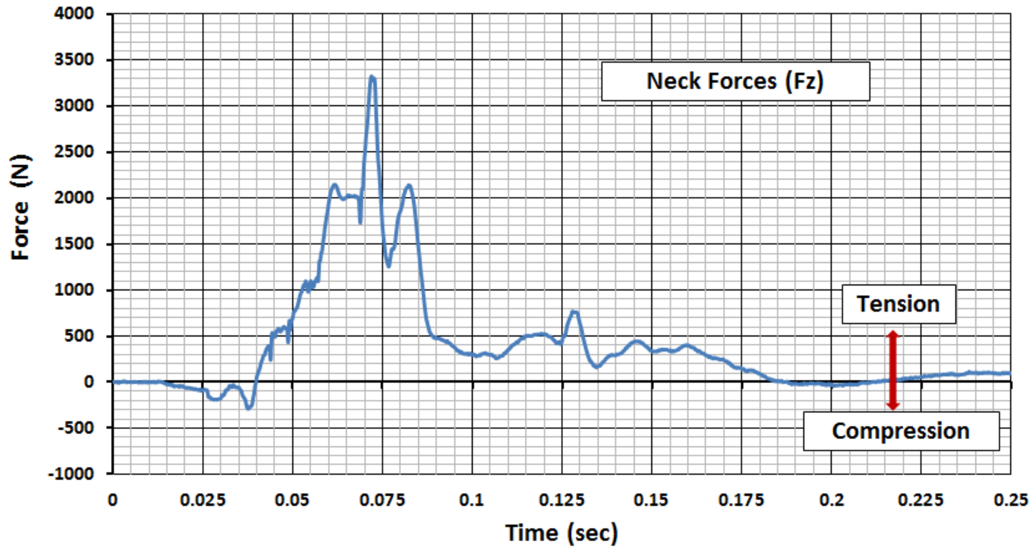

Figure 4-21. Sled Test – Neck Force (F_z) Time History

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 4-2, the measured forces were lower than the tension limits. The F_z value in tension was 3,326 N, compared to the limit of 4,170 N. The neck compression force was well below the limiting value of 4,000 N.

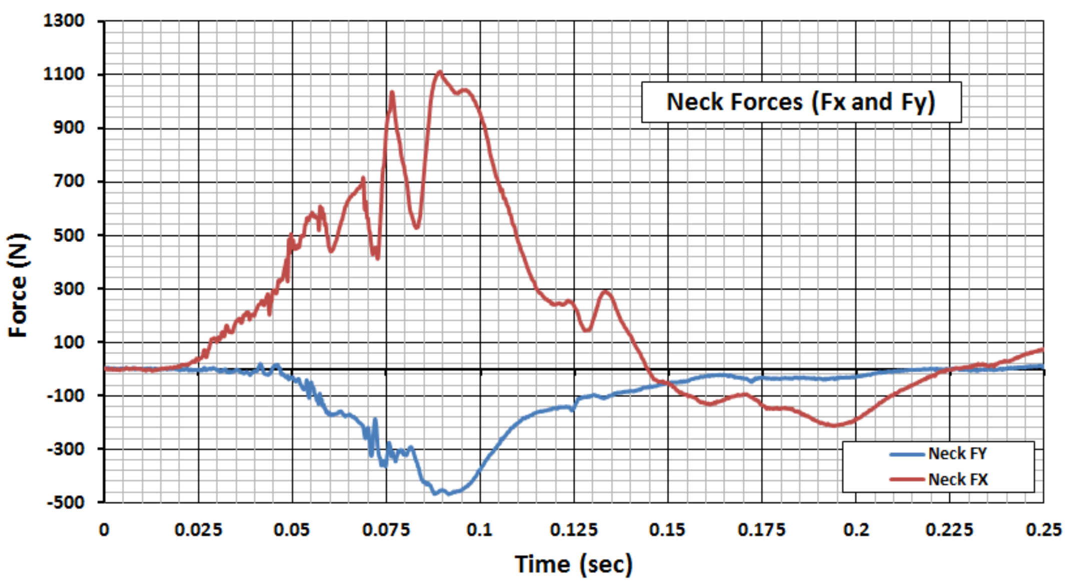

Figure 4-22. Sled Test Time History – Neck Force F_x and F_y Time History

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) were generated from the neck force F_z (tension/compression) and the neck moment (extension/flexion). As listed in Table 4-2, all N_{ij} indices were well within the limits for the 50th percentile ATD (Figure 4-23).

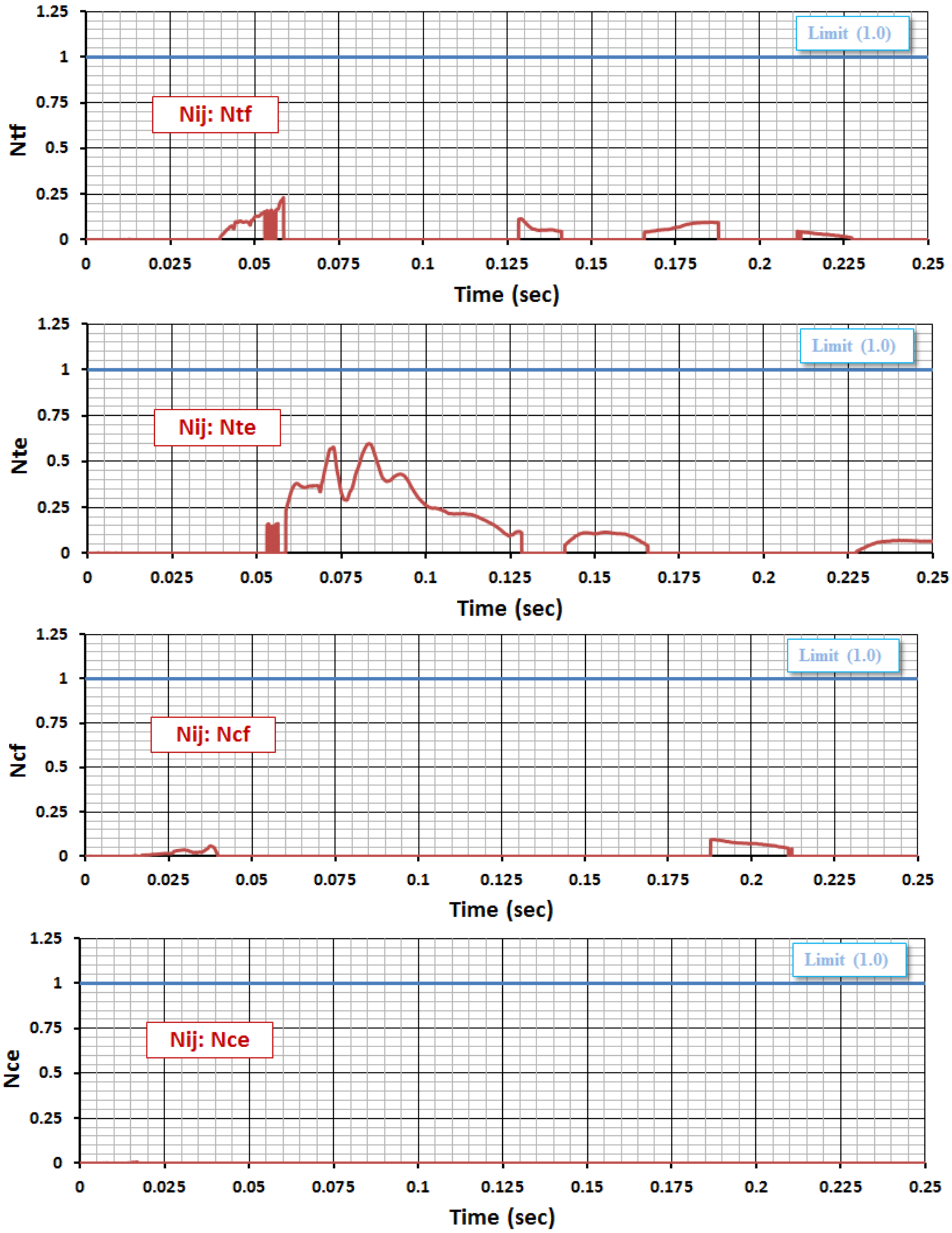

Figure 4-23. Sled Test – N_{tf}, N_{te}, N_{cf} and N_{ce} Time History

5. Conclusion

In this study, SA researchers was developed, prototyped and tested a secondary impact protection system. They improved a system developed under a previous effort to meet all the DOT's FMVSS-208 injury indices for a freight locomotive engineer. The summary and recommendations based on the reported work are as follows.

5.1 Summary

The project successfully demonstrated the following:

- It was technically feasible to develop and implement a secondary impact protection system that protected freight locomotive engineers under moderately severe frontal crash scenarios, where the occupied volume was not significantly compromised.
- The airbag and knee-bolster system prototype developed and tested could be integrated into the locomotive cab layout and space environment.
- The sled tests showed that the system met the injury criteria defined in DOT's FMVSS-208 standards which are also followed in the design of seats, tables, and interior spaces in modern railway passenger equipment in the U.S. and abroad.

5.2 Recommendations

Overall, the study met the objective of demonstrating that a purposefully designed airbag, coupled with an energy-absorbing knee bolster, could provide excellent occupant protection for an unbelted locomotive occupant in a severe frontal crash. The research also demonstrated the opportunities listed below for the future improvement of the system:

- Further gains in occupant protection can be achieved to include everything that contacts the occupant, including the seat and control desk.
- While it positioned the ATD pretest, the seat used in this test series was not designed to contribute to occupant protection. For example, the bottom cushion had no rake angle. A modest rake angle, combined with internal cushion anti-submarine features, would improve occupant presentation to the knee bolster and airbag while improving everyday comfort. Sensing systems that deploy an airbag in a crash could also actuate active components in the seat to improve crash outcome. All these technologies have been commercialized in many on-road vehicles and could be adapted for use in the locomotive environment.
- Simulations can be carried out to estimate the appropriate deceleration magnitudes at which the airbag system would be triggered. Such simulations would also help determine the acceleration pulse levels under which the injury criteria may be exceeded. The sensor would be installed on the locomotive underframe, under the engineer's seat.
- Occupant compartment system-level design must balance the one-time need for crashworthiness improvement with other factors important for everyday use.

6. References

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Abbreviations and Acronyms

APTA	American Public Transit Agency
ATD	Anthropomorphic Test Device
CEPS	Cab Engineer Protection System
CFR	Code of Federal Regulations
DAS	Data Acquisition System
DOT	Department of Transportation
FMVSS	Federal Motor Vehicle Safety Standards
FRA	Federal Railroad Administration
HIC_{15}	Head Injury Criterion (15 ms)
IARV	Injury Assessment Reference Value
KSS	Key Safety Systems
ms	Millisecond
M_{ocy}	Neck Moment
Nt	Neck Tension
Nc	Neck Compression
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
SA	Sharma & Associates, Inc.
SCRRA	Southern California Regional Rail Authority
SIPS	Secondary Impact Protection System
SIV	Secondary Impact Velocity

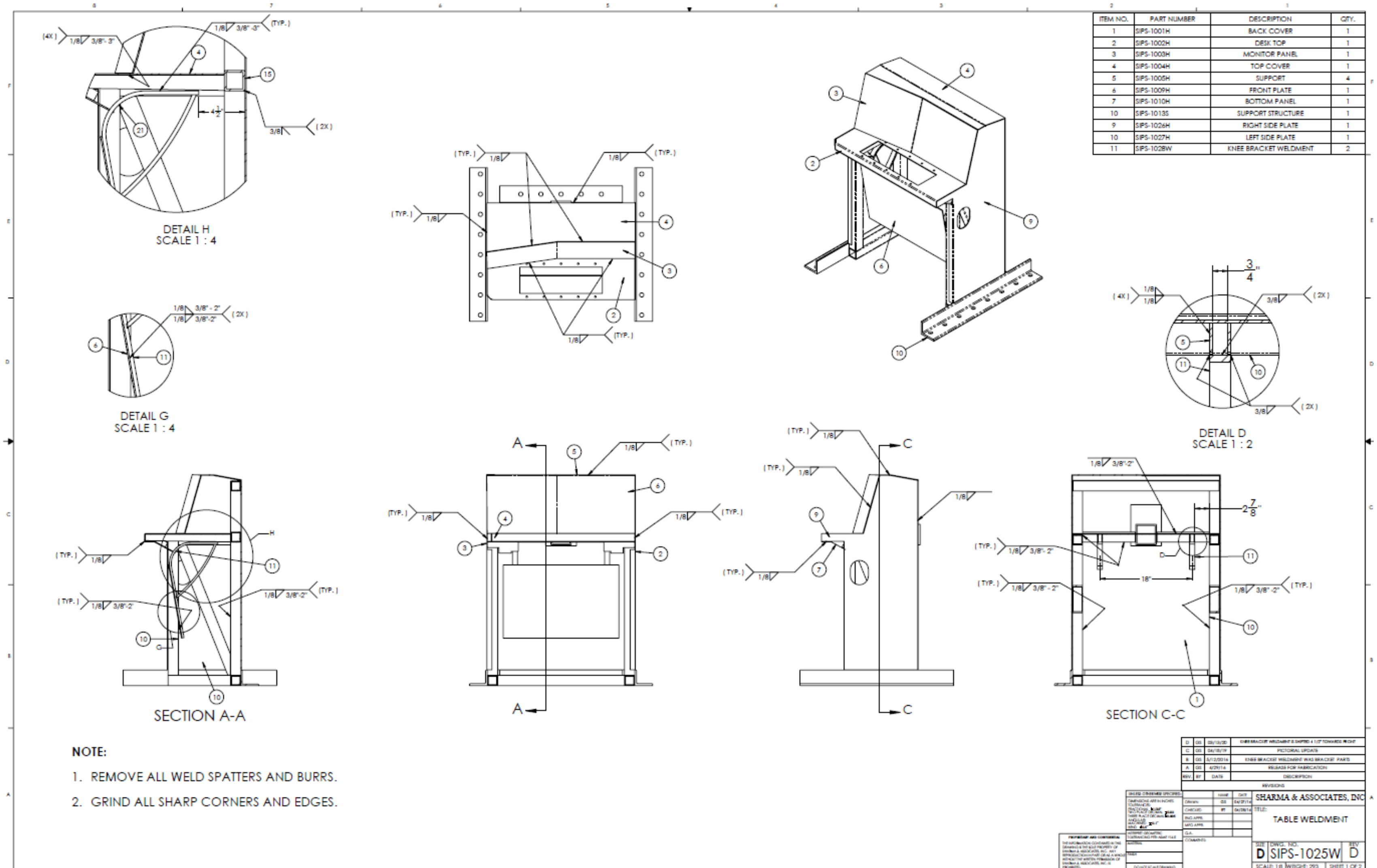

Figure A-1. Support Structure for the Engineer Desk

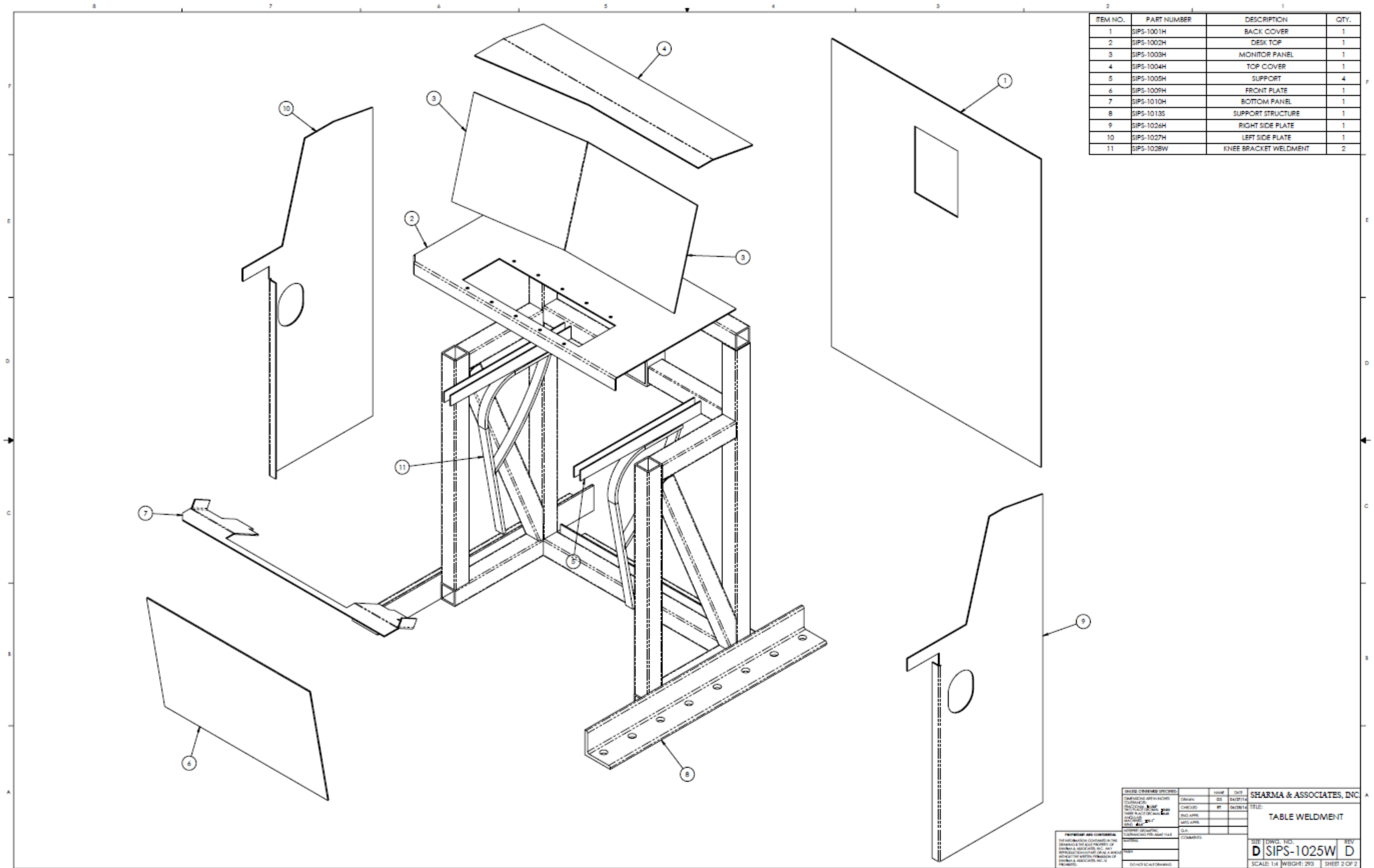

Figure A-2. Support Structure for the Engineer Desk (cont.)

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 (95^{th} 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.

Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II

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