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LOCOMOTIVE CAB OCCUPANT PROTECTION

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ABSTRACT

The effectiveness of fitting a locomotive cab with a passive inflatable restraint system utilizing inflatable structures, and interior padding to protect the operator has been evaluated for the in-line collision scenario. It is a challenge to design a system that increases protection for the locomotive operator within the cab during accidents, while allowing that operator to react to a specific situation by choosing either to leave or remain in the seat or cab. Numerous strategies have been proposed to increase locomotive cab occupant protection; however, most of these proposals have either required an active response from the cab occupants, e.g., getting into a refuge, or inhibited the potential for fleeing the cab, e.g., seatbelts.

In this study, the occupant protection of a typical locomotive cab interior with a vertical console-stand style control is compared with the occupant protection of an interior modified with the addition of two tube-shaped inflatable structures for secondary impact injury mitigation. The crashworthiness performances of these two interior arrangements are compared for in-line train-to-train collision scenarios that approximate a locomotive-led train collision with another locomotive or cab car-led train.

The analysis uses, as a basis, accident data and information on the crashworthiness performance of the locomotive interior in a train-to-train collision between a standing locomotive-led consist and a moving cab car-led consist conducted on January 31, 2002 at the Transportation Technology Center in Pueblo, Colorado. An analysis model is developed and validated using the full-scale train-to-train test locomotive interior/occupant experiment. The interior/occupant model then serves as a means of interpolating to different crash pulses, and with the alternative protection method using inflatable tube-like structures and interior padding. A range of locomotive operator sizes is investigated, as well as a range of selected initial seating positions for the locomotive operator.

1. INTRODUCTION

In 1992, Congress enacted the Rail Safety Enforcement and Review Act, Public Law 102-365. This act amended the Federal Railroad Safety Act of 1970 to improve general railroad safety operations by reviewing and revising rules based on developed safety data. As part of the Federal Railroad Administration's (FRA) response to improve railroad safety, research and analysis was conducted to determine the benefits and costs of additional locomotive crashworthiness features in providing protection to personnel in locomotive cabs under realistic collision conditions [1, 2, 3]. Studies of railroad accidents have concluded that in the three-year period from 1995 to 1997, 26 locomotive cab occupants were killed and 289 were injured in freight and passenger train accidents in the United States [4].

There were 1.3 locomotive cab occupant fatalities per 100 million train miles, while, during the same time, there were 0.4 highway heavy-truck cab occupant fatalities per 100 million heavy-truck-miles [5]. FRA's policy is zero tolerance for accidents, injuries, or deaths on the nation's rail system.

Included in FRA's locomotive safety research, concepts such as braced collision posts, crash refuges, rotating crew seats, and anticlimbers were evaluated to analyze two aspects of occupant safety, primary injury protection (protection from injury due to structural crushing), and secondary injury protection (protection from injury due to occupant impacting structure or equipment). The evaluation clearly indicated that vehicles with these crashworthiness features can significantly improve crew survivability in the event of a collision.

In 1996, the FRA established the Railroad Safety Advisory Committee (RSAC) to facilitate a transfer of the safety research studies to develop satisfactory rail community solutions on safety regulatory standards. In 1997, the Locomotive Crashworthiness Working Group of the Railroad Safety Advisory Committee (RSAC) formed an Engineering Task

Force to further develop and evaluate safety improvements from modifications to locomotive structural designs. The Task Force developed technical information on baseline and modified locomotive crashworthiness performance in selected collision scenarios [6, 7, 8], developed safer alternatives, conducted research studies, evaluated potential effectiveness, and drafted performance-based standards for freight and passenger locomotives. The committee has drafted recommendations for revisions to Federal regulations and to industry locomotive crashworthiness standards; these recommendations are currently under review by the FRA [9].

The Federal Railroad Administration's Office of Research and Development Occupant Protection Program is continuing studies of locomotive crashworthiness through analysis [10] and full-scale impact tests with passenger and freight locomotives [11, 12, 13]. These studies intend to further develop the technology required to improve the crashworthiness of locomotives.

2. BACKGROUND ON LOCOMOTIVE INTERIORS

There are over 20,000 locomotives in U.S. Class I operation today [14]. Since the service life of a locomotive is typically between 20 and 40 years, the majority of locomotives in use were built before 1980. While successive generations of locomotive cab designs have been developed, there are, in general, two types of operator control layouts used in locomotives: the vertical console-stand style controls and the horizontal console style controls.

The vertical console-stand is a tall control placed to the left of the engineer near the center of the cab so that forward vision through a windshield, and right side vision through a window is clear (see Figure 1). The engineer sits facing forward on the right side of the locomotive cab in close proximity to the controls and wall/window, but typically has a large seat zone forward. Egress from the seat requires standing or rotating the seat and moving to the left past the vertical console-stand. The only significant change in this design, which has existed since the 1940's, was the adoption of the clean cab design in the 1970's. The clean cab concept designed out many secondary impact hazards such as protruding parts and sharp edges that can cause injuries to the occupants in collisions and everyday operation.

Figure 1. Typical Engineers Seat Zone with a Vertical Console-Stand Style Controls and Seat

Interiors with the horizontal console style (see Figure 2) have a desk-like control display console in front of the engineer's seat. The engineer still has forward vision through a windshield and right vision through a window, but the area to the left of the engineer in the cab is unobstructed. The horizontal console restricts local movement and position change more than the vertical console-stand, but exiting from the seat only requires rotating the seat.

There are Federal regulations governing locomotive crashworthiness [15], while the Association of American Railroads has safety standards for freight locomotive structural crashworthiness [16], and the American Public Transportation Association (APTA) standards and recommended practices [17] govern the interior and structural crashworthiness of passenger locomotives. Many of the regulations and recommended practices focus on mitigating the effects of occupant secondary impact injury "to the extent possible" through equipment design features such as padded surfaces and rounded corners. In spite of these regulations, standards, and recommended practices, there are a number of features in both interior styles that are potentially injurious to occupants during a collision.

Figure 2. Typical Horizontal Console Style Controls

2.1 LOCOMOTIVE OPERATOR ACCIDENT RESPONSE

Locomotive engineers have been known to respond in different ways, before and during a train accident. Locomotive cab occupants sometimes evacuate the cab if they can see the accident coming in sufficient time. Other times, they choose to remain in the cab and ride out the accident in their seat or crouch/lay down on the floor.

Injuries and fatalities of locomotive cab occupants from prior accidents illustrate the potential risk in any accident. There have been accidents where: the cab occupants survived because they remained in the cab (Glendale, California on January 28, 2000 [18]); the cab occupants evacuated the cab/train, and survived (Clarendon, Texas on May 28, 2002 [19]); the cab occupants were fatally injured because they remained in the cab (Ludowici, Georgia on October 1, 1998 [20]); and the cab occupants were fatally injured because they fled (Near Cajon Junction, CA on February 1, 1996 [21]).

Thus, since these cases show several possible injury outcomes to locomotive operator position, strategies proposed to minimize operator injuries must take into account the position the operator may be in at the time of deployment.

2.2 PREVIOUS RESEARCH

In the 1970's studies were conducted related to the protection of crew members in locomotive cabs [22]. Part of the study concerned itself with the safety aspects of the interior environment, addressing the problem of secondary impact effects on the locomotive occupants. The design recommendations for seating from this research focused on redesigning surfaces and securing interior fittings. A consequence of this and similar studies (in the 1970's) was the adoption of the clean cab design concept in locomotives to avoid protruding parts and sharp edges. This study also analyzed using active restraint devices, including the diagonal shoulder strap and lap belt, and studied the implementation of fixed passive occupant restraint devices, including a deployable passive restraint (airbag), to reduce injury.

In support of a Report to Congress on Locomotive Crashworthiness and Working Conditions [2], alternative protection concepts for the locomotive cab occupants were investigated [1]. Three alternative crash refuges (a safe sturdy area or volume into which crew members can position themselves to be protected from secondary impact or crush) concepts were analyzed:

- **rotating seat**: is a seat where an occupant can rotate and lock in place to face backward prior to a collision with an oncoming vehicle or obstruction,
- **rotating seat which also drops to the floor**: is a seat where an occupant not only can rotate and lock, but can also drop to the floor for better protection, and
- **trench at the rear of the cab:** is a trench located at the rear of the cab that is formed when a lever is pulled and a floor panel drops down to expose a padded space between the cab floor level and sill of the underframe.

Using an analytically derived crash pulse based on an in-line locomotive-to-locomotive collision, simplified models of an occupant and interior were developed and evaluated for each refuge. The analysis results show that all three crash refuge concepts are effective in protecting the occupant against secondary impact injury, but provide limited or no protection against cab crush.

Lap and shoulder belts, airbags, and rotating seats were revisited in another study, published in 2002 [23]. In this study, it was determined that seatbelts would reduce injuries in at least moderately severe accidents; though, concerns about potential inconvenience were noted. The study also determined that airbags can reduce injuries, but could deflect the occupant into a dangerous part of the interior, and suggested that the rotating seat could provide protection if it were rotated in time.

All of the alternative occupant protection concepts studied were shown to improve protection for select pre-collision operator actions. For example, rotating seats and trenches require active participation of the locomotive cab occupants in their surviving an accident. Accident history indicates that locomotive cab occupants are not always aware of impending accidents, and are sometime unable to actively respond.

To ideally protect a locomotive operator during a collision, a system developed should:

- control/limit occupant injury to survivable levels,
- protect the operator without requiring his or her active response,
- allow the operator to safely egress before, during, and after the accident, and
- provide effective operator protection for a wide range of initial positions and occupant sizes without deflecting the operator into a more dangerous part of the interior.

3. AN ALTERNATIVE STRATEGY FOR LOCOMOTIVE OCCUPANT PROTECTION

In this study, an alternative occupant protection strategy, using a passive inflatable restraint device and a padded wall is analytically evaluated with a vertical console-style control stand and seated occupant in the operator seat. The passive inflatable restraint model represents an inflatable tubular structure.

A relatively new technology, side supplemental inflatable structure devices have been shown to improve safety from occupant side impact head and neck injury in automobile accidents. An inflatable tubular structure consists of a braided synthetic fabric covered tube, which when inflated by an internal bladder expands in diameter, shortens in length, and when anchored at both ends, becomes self-supporting because of skin tension. The structure is stowed laying flat or following a contour in a protective sleeve: the ends are on pivot mounts, and when inflated, the ends deploy in a straight line between mounting points [24].

The inflatable tubular structure is different from an automotive air bag. The tubular structure: operates at pressures much higher than the pressures used in conventional air bags; does not vent after deployment; and retains its position and rigidity through tensile forces. Even after the gas that inflated the tube has cooled, the structure remains sufficiently inflated to provide continuous protection for possible additional impacts during an accident. Because it retains its rigidity and position through tensile forces, it also does not require a bearing surface (such as the console). In addition, it also does not require a storage cover, and does not need to be multi-ply folded in the undeployed state [24].

3.1 IMPLEMENTATION

The locomotive cab seat zone interior/occupant model is shown in Figure 3. This view from the side of a locomotive (wall not shown) depicts the initial seating condition with a 95th percentile male. The console stand is represented with three rectangular-like rigid bodies, the seat is represented with cylindrical-like rigid bodies, and the floor, forward wall, and right wall/window (not shown) are represented with rectangular-like rigid bodies. The travel distances from the seat to the forward wall is 2.0 feet (0.61 m). This model was implemented in MADYMO [25].

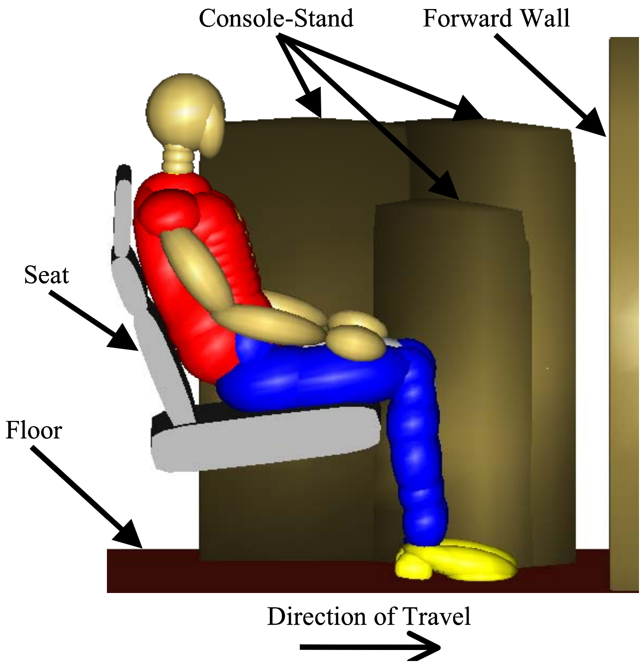

Figure 3. Diagram of Locomotive Cab Interior/Occupant Representation

The modified interior configuration chosen uses two tubular restraint devices and interior padding (see Figure 4). The tubular restraint devices are configured in a "V" to direct the occupant into a position forward of the initial position, protecting all body parts most likely harmed in secondary impacts. The configuration of the padding and tubular structures restrains the occupant's forward motion while providing enough flex to protect the occupant from the energy of the collision.

Padding is sized for the forward wall so that when the occupant travels forward, only the knees and shins contact, while the feet continue under the padding. The padding is modeled with a linear contact stiffness of 250 lb/inch (43,800 N/m) and contact coefficient of friction of 0.5.

The load-bearing capability of tubular structure depends upon a number of factors, such as tube dimension and internal pressure. A typical tube would have an inflated diameter of from 4 to 6 in (0.10-0.15 m) and an internal pressure of from 7 to 10 psi (50-70 kPa). The cross section may also be non-uniform in order to tailor the tubular structure for a specific load or packaging profile. The attachment position for the ends of tubular structure depends upon the configuration and geometry of a particular vehicle. A further option is the use of a supplemental net to provide a barrier to align the deployed structure [26].

The modified configuration, shown in Figure 4, uses two 5-inch (0.13 m) diameter tubes that cross forward of the occupant to represent an inflated tube-like passive restraint device. The front ends of the right and left tubes are attached to the forward wall 37 inches (0.94 m) above floor level and 5 inches (0.13 m) from the centerline of the seat. The back ends are attached to the console stand on the left and outside wall on the right 27 inches (0.69 m) above floor level.

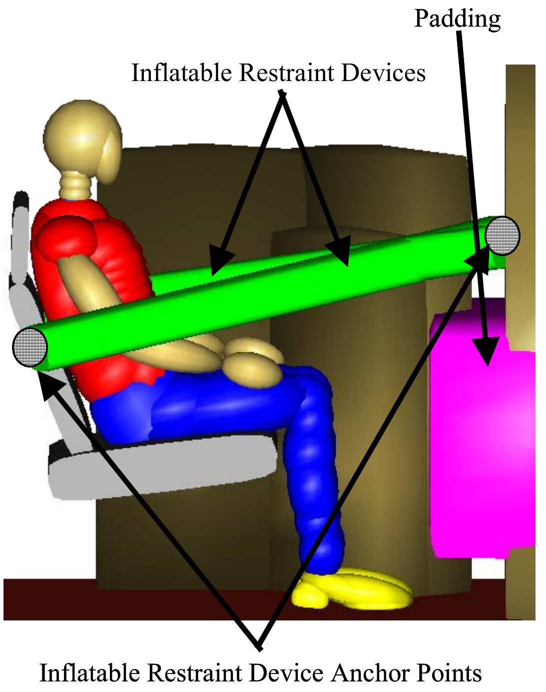

Figure 4. Diagram of Interior/Occupant Representation with Inflatable Restraint Devices and Interior Padding

The curve, contact force versus penetration, shown in Figure 5, approximates the contact interaction characteristic between the occupant and the inflatable tubular structure. The three linear regions in the curve approximate the progressive loading response on the inflatable structure, illustrated in Figure 6. The first region represents a bending of the tube between supports, the second region represents the indentation of the tube skin, and the third region represents the limit of indentation and bending of the tube. The slopes and break points for each region were chosen based on discussion with a designer of the tubes [26], but analysis results show that occupant response was significantly more sensitive to tube orientation than force penetration characteristic.

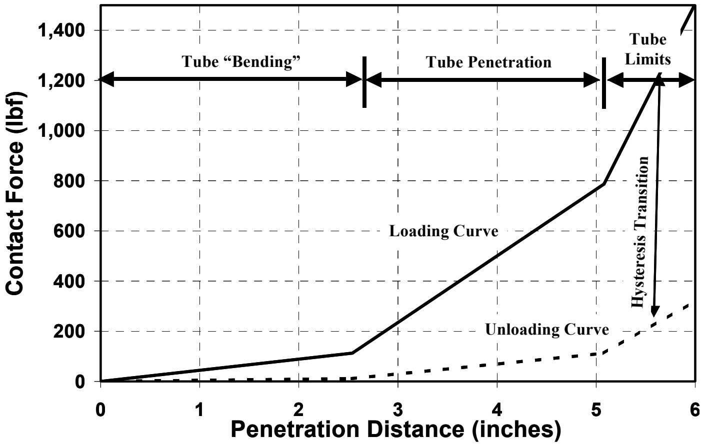

Figure 5. Force Penetration Curve for the Tubular Structure

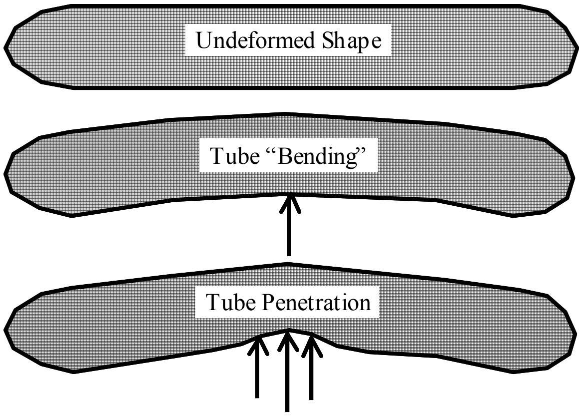

Figure 6. Approximate Response of Inflatable Structure to Increased Loading

The approach used to evaluate the locomotive cab interior is to create successively higher secondary impact velocities (SIV) for the occupant by varying the peak deceleration of a 250 msec duration triangular crash pulse from 1g to 9 g. During a collision, an occupant will gain a velocity relative to the vehicle in the absence of any restraining devices. This secondary impact velocity (SIV) between the occupant and the interior is estimated to provide a loose link between the vehicles collision dynamics and injury severity. The SIV is calculated using simulation results or experimentally measured vehicle accelerations, and is the estimated forward facing unrestrained occupant's velocity relative to the vehicle interior when uninhibited displacement relative to the interior would occur. Figure 7 shows a plot of the SIV from the 1g, 5g, and 8 g triangular crash pulses. Using 2 feet (0.61 m) as the distance an unrestrained locomotive engineer travels before contacting a forward surface, the SIV varies between 2.5 mph and 20 mph (4 kph and 32 km/h). This difference provides a good variation to evaluate the performance of the baseline interior. The modified interior with the inflatable restraint will prevent the occupant from displacing the same distance as without, but that difference will help reduce the injury measures.

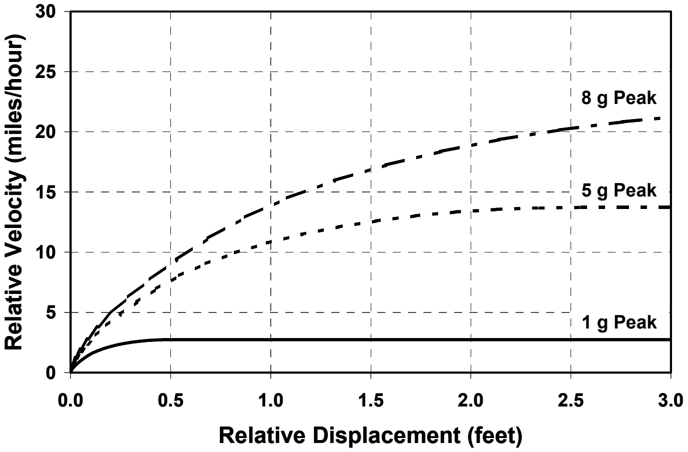

Figure 7. Relative Longitudinal Displacement and Velocity of an Unrestrained Occupant

The alternative protection interior was then simulated with a 95th and a 50th percentile male model and a 5th percentile female model. The 95th and 50th percentile male models were positioned in the same configuration, but the 5th female was positioned with the seat raised 10 inches to account for the shorter upper body. Variation in the initial position of a 95th percentile male was also evaluated for the interior that includes the inflatable structure and padding, to determine how injuries relate to the initial seating position of the occupant. Simulations were run with the 95th percentile male out-of-position by rotating the body about the vertical axis ±15 and ±30 degrees.

Injury criteria relate forces and accelerations to the potential for injury. NHTSA prescribes maximum injury criteria values for the Head Injury Criteria (HIC), the chest deceleration, femur loads, and recently, neck loads [27].) (The HIC calculation includes an average of the acceleration of the head over a prescribed interval. There have been several revisions to this time interval. Currently a time interval of 15 milliseconds is used in the calculation, and this version is referred to as HIC_{15}.) Using the four occupant injury measures of Head Injury Criteria (HIC_{15}), Resultant 3ms Chest Acceleration, Neck Injury (Nij), and femur compression force, the maximum injury criteria for each occupant sizes currently used in the automotive industry are utilized to compare peak injury measures for the simulations.

4. COMPARISON OF CONVENTIONAL AND ALTERNATIVE OPERATOR PROTECTION

4.1 OCCUPANT RESPONSE TO 8 G 250 MSEC CRASH PULSE

To understand how an occupant responds to a crash pulse in the baseline interior, a response is calculated for the forward facing unrestrained 95th percentile male occupant to the 8 g 250 msec crash pulse. The kinematic response is shown in Figure 8. Since nothing prevents the occupant from relative movement forward, the entire occupant travels forward approximately 2 feet (0.6 m), the knees contact the forward wall first, the upper body then pivots about the hips and the head contacts the forward wall, and eventually the occupant comes to rest slumped between the seat and forward wall (not shown). For this interior/occupant simulation, the forward direction velocity of the head just prior to contact with the forward wall is almost 20 mph and after contact is reduced to zero after only 0.02 seconds. In terms of occupant protection, the operator was compartmentalized within the seat zone, but as summarized in the Table 1 for the baseline interior, the large seat zone and rigid forward surface allows motion that causes high injury measures for the head, neck, chest, and femurs.

A second response is calculated for the forward facing unrestrained 95th percentile male occupant to the 8 g 250 msec crash pulse, but the alternative operator interior with the padding and inflatable passive restraint is included, shown in Figure 9. Different from the baseline interior kinematics, the occupants relative movement is more limited, none of the body parts contact the forward wall, and after arresting forward motion, the occupant rebounds back into the seat (not shown).

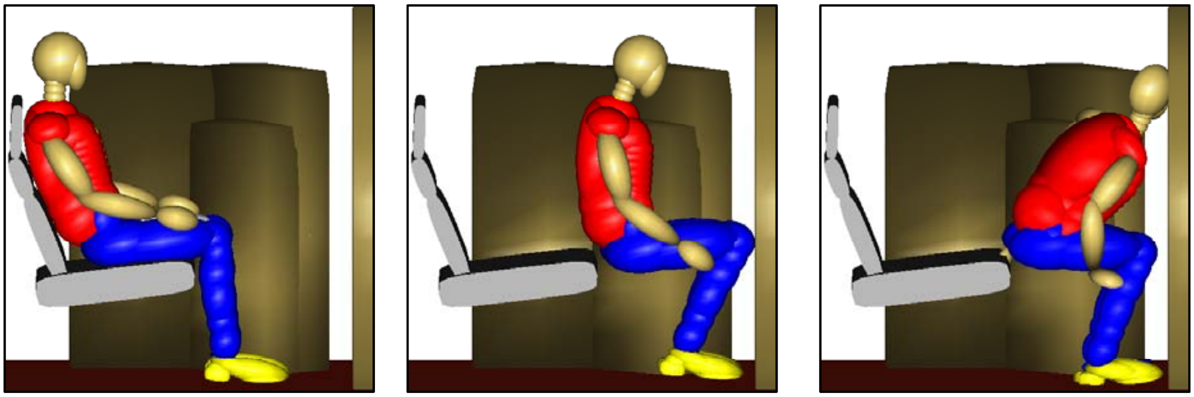
0.0 seconds 0.2 seconds 0.25 seconds

Figure 8. Kinematic Response of 95th Percentile Occupant to the 8 g 250 msec Crash Pulse: Baseline Interior

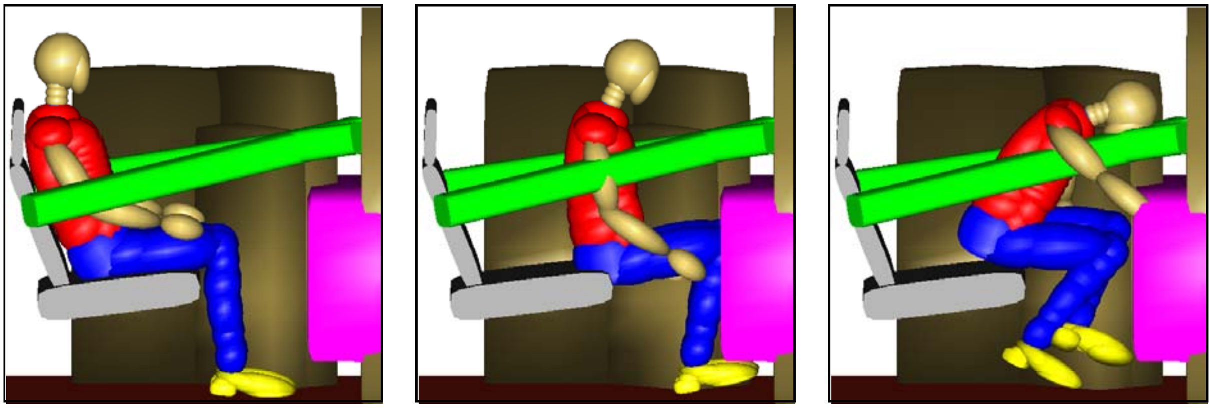
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Figure 9. Kinematic Response of 95th Percentile Occupant to the 8 g 250 msec Crash Pulse: Alternative Interior

The alternative interior effectively decreased the occupant's relative velocity, since, instead of contacting the wall ahead the knees slow to a stop by the padding and torso is penetrating the inflatable restraint. This configuration is also effective in minimizing the relative motion between body parts, e.g. between the head and upper torso. For this interior/occupant simulation, the peak forward direction velocity of the head is around 15 mph, and is reduced to zero over 0.05 seconds. In terms of occupant protection, the operator was compartmentalized within the seat zone by the inflatable restraint, and as summarized in the Table 1 for the alternative interior, all injury measures were reduced to less then 50% of the criteria limits.

The alternative interior was also evaluated using the 8 g 250 msec crash pulse, but the 95th percentile male was moved "out-of-position" by rotating the occupant ±15 and ±30 degrees about the vertical axis. For these simulations, the modified interior was shown not to increase the likelihood of injury to the occupant. Results also showed good compartmentalization and kept injury calculations less then 60% of the injury criteria limits. The only noteworthy change was an increase in femur load for the cases when the knees position oriented them to contact the vertical console stand to the left of the occupant.

Table 1. 95th Percentile Male Occupant in Engineer's Seat: Injury Criteria from 8 g 250 msec Crash Pulse

	95th Percentile Injury Criteria [27]	Baseline Interior	Alternative Interior
HIC$_{15}$	700	> 700 (0.27 sec)	88 (0.24 sec)
Neck Nij	< 1.0	>1 (0.27 sec)	0.6 (0.24sec)
Chest 3ms	55 G	52 g (0.28 sec)	18 g (0.2 sec)
Femur (Right/Left)	-2,855 lb (-12,700 N)	-2,061 lb/ -1,830 lb (-9,170 N / -8,823 N) (0.19 sec)	-942 lb/ -1,167 lb (-4,190 N / -5,190 N) (0.18 sec)

The alternative interior was then evaluated with a 50th percentile male and a 5th percentile female occupant using the 8 g 250 msec crash pulse. Injury criteria results for the 50th percentile male were similar to the 95th percentile male. The 5th percentile female injury criteria were slightly elevated, but all below the injury criteria limits, due to lower injury limits compared to similar larger models.

4.2 INJURY MEASURES VARYING CRASH PULSE

To provide a better understanding on the effectiveness of the alternative interior, the baseline and modified locomotive cab interiors were simulated with the 95th percentile and the standard 250 msec duration crash pulse with peak decelerations from 1 g to 9 g. The peak injury measured for the head, neck, chest, and femur was then compared with and without alternative protection from padding and inflatable restraint devices. The results for each injury measure are plotted in Figures 10-13.

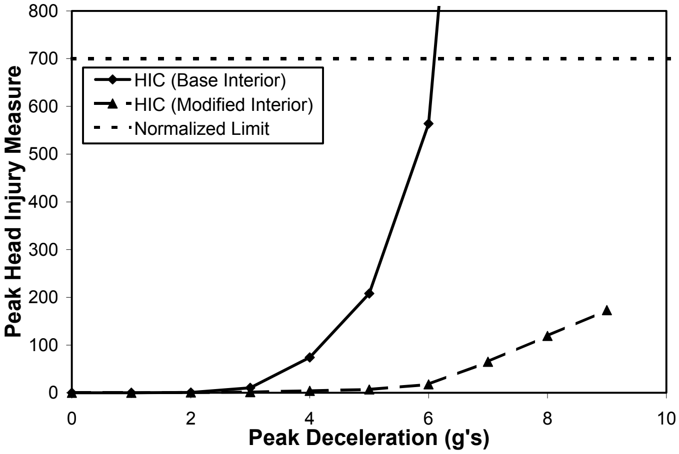

Figure 10. Comparison of HIC Injury Measure With and Without Interior Modifications, 95th Percentile Male

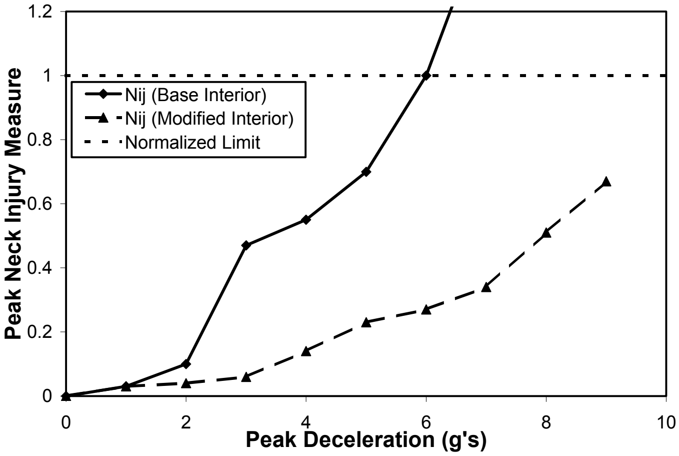

Figure 11. Comparison of Nij Injury Measures With and Without Interior Modifications, 95th Percentile Male

For all the results, the occupant remained in contact with the seat for the 1 g peak. For the baseline interior, as the peak deceleration increased, the occupant would contact the forward wall at successively higher velocities, and the upper body would pivot about the hips at a higher rate, both actions contributing to increasing the injury measures as the peak deceleration increased. The head (HIC) and neck (Nij) injury measures were the most sensitive to the peak of the deceleration. Both crossed the injury criteria between the 6 g and 7 g pulses.

With the padding and inflatable restraints added, all the injury measures were less than 50% of the injury criteria maximums when less then an 8 g peak was simulated. This improvement significantly reduces the likelihood of injury to the occupant.

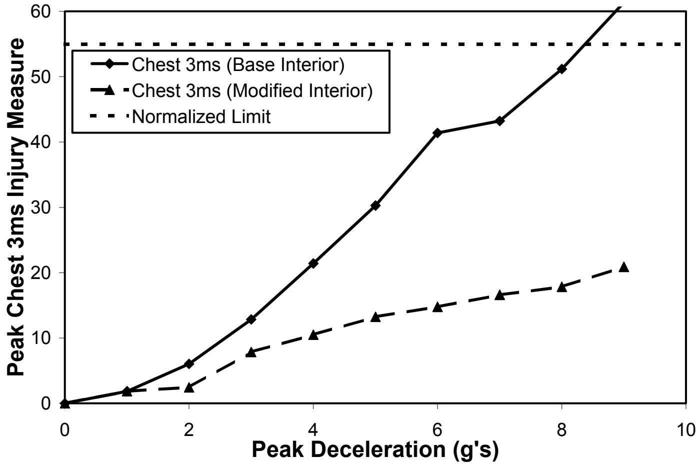

Figure 12. Comparison of Chest 3ms Injury Measures With and Without Interior Modifications, 95th Percentile Male

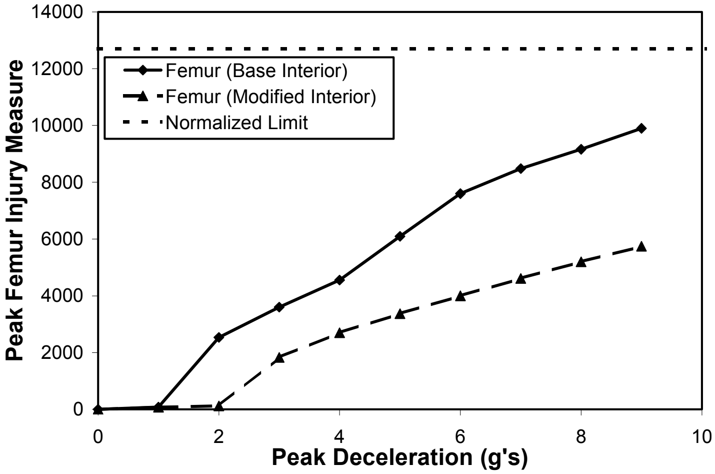

Figure 13. Comparison of Femur Injury Measures With and Without Interior Modifications, 95th Percentile Male

5. SUMMARY AND CONCLUSIONS

A strategy was proposed for protecting locomotive operators during accidents, using two inflatable tubular structures attached to the cab interior form a "V" when deployed, and a deformable pad attached to the front wall. This strategy offers many advantages:

- it compartmentalizes and limits the locomotive operator's relative motion, consequently reducing the likelihood of torso, neck, and head injury
- it reduces femur injury by providing enough padding at the knees
- it is effective for a range of occupant sizes and a range of locomotive operator initial positions.
- it overcomes two significant drawbacks to previously proposed strategies for increased locomotive cab operator protection:
  - it allows the operator to freely leave the cab at anytime before, during, and after an accident.
  - it does not require the operator to actively participate in his or her own protection by getting into a trench, or by pulling a lever to activate a rotating seat.

Future studies include development and testing of an engineering model design of this concept, similar to the steps taken to develop seats with lap and shoulder belts for rail passengers. As part of this development, detailed design requirements are enumerated, including requirements for attachment strength, constraints on the uninflated location of the inflatable structures, constraints on inflated location, definition of activation requirements, etc. The configuration of the inflatable structures described in this paper has not been optimized, but should be optimized as part the engineering model development. To complete the development of the design, and measure its performance, sled testing or inclusion of an example in fullscale impact testing of rail equipment should be performed.

The concept described in this could be applied to the conductor's seat in the locomotive cab, as well as the dead-head seat that is present in many locomotive cabs. This concept may also be effective for passenger rail cab car operators.

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