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Civil Aircraft Side-Facing Seat Research Summary

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16. Abstract

The Federal Aviation Administration (FAA) has standards and regulations that are intended to protect aircraft occupants in the event of a crash. However, side-facing seats were not specifically addressed when aircraft seat dynamic test standards were developed in the late 1980s. Since then, considerable research has been conducted to increase knowledge about injury risks and mitigation technologies for automotive and aviation applications. Some injury risks such as those to the head, chest, and pelvis are common to both automotive and aviation side-impact scenarios. FAA research has determined that typical side-facing seat configurations could pose additional neck and flailing injury risks. To address these identified risks, the FAA sponsored research to develop neck injury criteria applicable during lateral impacts. This research also evaluated the overall injury risks of the seat configurations identified as having the greatest injury potential. The research included impact tests using postmortem human subjects and the ES-2 test dummy.

In this report, the latest advancements in side-facing seat impact testing technology and biomechanical knowledge are used to identify new testing and injury assessment methods intended to ensure fully side-facing aircraft seat designs provide the same level of safety afforded occupants of forward- and aft-facing seats. The methods identified include: use of the ES-2re test dummy and the injury criteria cited in the automotive safety standards to assess injury, adapting test procedures related to test dummy seating, clothing and instrumentation, applying injury criteria originally applicable to forward-facing seats, reducing flailing injuries by limiting occupant excursion and contact, and applying the new neck injury criteria developed by the FAA-sponsored research.

To determine the effect that implementation of the new criteria could have on approval of typical side-facing seats, the results of research tests with those seat configurations were evaluated using the pass/fail criteria outlined in this report. This evaluation showed that configurations permitting excessive lateral flailing do not pass, and those that limit it by combining effective restraint system geometry with a barrier or inflatable restraint, pass readily. This result indicates that the criteria described in this report can be met by applying current technology.

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This report summarizes the results of a 10-year-long project that involved several organizations and many people.

The project began under the direction of Mr. Steven J. Soltis, FAA Chief Scientific and Technical Advisor for Crash Dynamics; Mr. Van Gowdy, FAA Civil Aerospace Medical Institute (CAMI), Biodynamics Research Team Lead; Mr. Gary Frings, FAA William J. Hughes Technical Center, Aircraft Crashworthiness Program Manager; and the Sponsorship of Mr. Jeff Gardlin, FAA Transport Airplane Directorate Staff.

The research was arranged through the FAA Center of Excellence for Airworthiness Assurance, with the prime contractor being TNO Science & Industry of the Netherlands. The principal TNO researchers were Dr. Jac S. H. M. Wismans and Mr. Mat M. G. M. Philippens. The TNO managers and project engineers responsible for various portions of the project were: Mr. Bachar Aljundi, Dr. Jack van Hoof, Mr. Paul Altamore, Mr. Robin van der Made, and Mr. Roel van de Velde.

The CAMI Biodynamics Research Team accomplished the assessment of injury potential for typical side-facing seat configurations under the direction of Mr. Rick DeWeese (the current Biodynamics Research Team Lead) and Mr. David Moorcoft of CAMI, with the assistance of Mr. Mat Philippens of TNO and Mr. Tom Green of AmSafe Aviation.

Ms. Riske Meijer and Mr. Patrick Forbes of TNO created computer models to analyze test results and support development of experimental setups.

Dr. Paul Begeman and Dr. King Yang conducted the initial Postmortem Human Subject tests at Wayne State University. Dr. Frank Pintar, Dr. Narayan Yoganandan, Mr. Michael Schlick, and Mr. John Humm conducted the remainder of the PMHS tests at the Medical College of Wisconsin (MCW).

Mr. Mat Philippens, in close cooperation with Mr. Rick DeWeese, managed the PMHS test program.

Mr. Allan Abramowitz, FAA Aircraft Crashworthiness Program RPD Manager, served as the Contracting Officer's Technical Representative for the project. He also arranged the follow-on study of lateral neck-bending injury risk directly with MCW. Several individuals provided consultation for this final portion of the project including: Mr. Steven Soltis (now retired), Dr. Jac Wismans (now of Safeteq Inc.), Mr. Mat Philippens (now of TNO Defense, Security and Safety), and Dr. Joseph Pellettiere, the current FAA Chief Scientific and Technical Advisor for Crash Dynamics.

We gratefully acknowledge the hard work, dedication, and cooperative attitude of all of the individuals and organizations that contributed to the success of this project.

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INTRODUCTION

Background

The Federal Aviation Administration (FAA) has standards and regulations that are intended to protect aircraft occupants in the event of a crash. These standards focus primarily on providing protection during frontal and vertical impacts. Side-facing seats were not specifically addressed when these aircraft seat dynamic test standards were developed in the late 1980s. Since then, considerable research has been conducted to increase knowledge about injury risks and mitigation technologies for automotive and aviation applications. This knowledge has led to the development of automotive safety standards addressing side impacts. In the United States, automotive crash tests using the Side Impact Dummy (SID) Anthropomorphic Test Device (ATD) were required beginning in 1995, and testing with the ES-2re 50th percentile male size ATD and SID-IIs 5th percentile female size ATD was phased in starting in 2010.

Current FAA side-facing seat certification requirements are based primarily on the 1995 auto safety standards but also consider aviation-unique injury risks (1). Risks common to both the auto and aviation impact scenario include possible injuries to the head, chest, and pelvis. The perceived aviation-unique risks are neck injury and flailing injuries. The current requirements control these risks using a combination of dynamic tests and design restrictions but fall short of being able to ensure that all side-facing seat configurations provide an equivalent level of safety to forward-facing seats.

In 2005, the FAA applied the latest advancements in technology to conduct an assessment of four common side-facing seat configurations. This assessment used existing aviation safety standards, proposed automotive safety standards, and the available safety research results to determine the risk of injury for each configuration (2). It identified a high risk of neck and flailing injuries in these seating configurations. To address these identified risks, the FAA sponsored research to develop neck injury criteria applicable during lateral impacts (3). This research also evaluated the overall injury risks of the seat configuration identified from the previous study as having the greatest injury potential. Injury reference values were derived for some neck loading conditions, and other neck loading conditions were identified for further study. Some specific injury risks unique to aviation seating configurations were also identified.

Purpose and Methods

In this report, the latest advancements in side-facing seat impact testing technology and biomechanical knowledge from the previously mentioned sources are used to identify new testing and injury assessment methods intended to ensure that fully side-facing aircraft seat designs provide the same level of safety afforded occupants of forward- and aft-facing seats. Since this level of safety is defined by the requirements contained in Title 14 of the Code of Federal Regulations (CFR) Parts 23, 25, 27, and 29 (Subparts 561, 562, and 785 of each), those requirements were used as a baseline for the new or modified test methods or injury assessments (4).

A variety of techniques are cited in this report for evaluating side-facing seat safety. These techniques fall into three categories:

1. Direct measurement of forces, displacements, and accelerations by a test dummy. This is the primary evaluation means cited in both automotive and aviation safety requirements.
2. Quantitative evaluation of occupant kinematics. This can be used to predict potential contact with surrounding structure or injurious articulation of the body. Since derivation of this type of data is quite complex, it is not the preferred method.
3. Qualitative evaluation of occupant kinematics and occupant interaction with restraint system and surroundings. While necessarily the most subjective method of injury evaluation and therefore the least desirable, it is in some cases the only means available to assess injury potential using currently available testing technology. Looking for evidence of lap belt intrusion into the abdomen (submarining) is an example of this type of evaluation.

A common way of deriving quantitative injury criteria is to compare injuries observed during specific loading conditions with measurements made using ATDs exposed to the same loading condition. To aid in this comparison, it is beneficial to have a measurement system to describe the actual injuries. The Abbreviated Injury Scale (AIS) was developed in 1971 to provide a systematic method of characterizing injuries that could be used by physicians, engineers, and researchers. It is updated regularly, with the most recent being the 2008 version. The AIS is an anatomically-based, consensus-derived, global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (5). The AIS characterizes the severity of injury as 1 Minor, 2 Moderate, 3 Serious, 4 Severe, 5 Critical, and 6 Maximal. Injuries are assigned to one of nine numbered body regions as follows:

1. Head (cranium and brain)
2. Face, including eye and ear
3. Neck
4. Thorax
5. Abdomen and pelvic contents
6. Spine (cervical, thoracic, and lumbar)
7. Upper extremity
8. Lower extremity, pelvis, and buttocks
9. External (skin) and thermal injuries

Some examples of neck injuries and their associated AIS injury levels are shown in Table 1.

When sufficient information exists, the probability of a specific severity of injury can be related to a value measured with the ATD. Ideally, injuries that put the safety or ability of the occupant to egress at risk should be prevented during survivable aviation accidents. To achieve this goal, the level of injury as indicated by ATDs during seat qualification tests should be AIS 3 or lower, with some instances of AIS 2 injuries being unacceptable. Each of the quantitative injury criteria cited in §25.562 is intended to provide a specific level of safety for the body region at risk. Several areas of the body were selected for quantitative metrics to provide the overall level of safety sought. These included:

Head: Injuries to the head during an aviation accident are possible if the head comes into contact with any of the various structures in the aircraft. These include locations on the seat, such as the seat back, arm rest, tray table, or any equipment mounted on the seat. The head could also contact a partition, divider, or other aircraft structure. In addition to serious trauma, lesser head injuries that in other environments may not be serious can result in fatality in an aviation accident where rapid egress is important. The Head Injury Criterion (HIC) is used to calculate the risk of a head injury during the tests specified in §25.562. HIC is calculated using the resultant acceleration at the head center of gravity using Equation 1.

$$\mathrm{HIC} = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)\,dt \right]^{2.5} \right\}_{max}$$

Where:
t_1 is the initial integration time
t_2 is the final integration time, and
a(t) is the total acceleration vs. time curve for the head strike, and where (t) is in seconds, and (a) is in units of gravity (g).

Equation 1. Head Injury Criterion

In the implementation of HIC in the aviation environment, the time window for the calculation is unlimited, but begins after the time of head contact. The acceptance value in §25.562 is a HIC value below 1000. Applying a cumulative normal distribution function to the available injury data indicates that a HIC = 1000 is a 23% risk of an AIS-3 or greater (serious) head injury or a 47% risk of an AIS-2 or greater (moderate) head injury (6). This relationship is illustrated in Figure 1. Although this relationship was derived for HIC36 (a version used in auto regulations that limits the evaluation to a 36 msec time window), it is also valid for the aviation version, since the impact cases on which it is based are of short duration, yielding nearly the same value using either method.

Chest: The chest is a major body region that can be injured either from direct impact or from inertial forces. Inertial loading of the chest is a result of rapid deceleration of the occupant and interaction with the restraint system. A stiff restraint that allows large loads to be transmitted directly to the occupant has the potential to cause injury.

Table 1. AIS Severity Level for Neck Injuries (Selected Examples)

AIS Code	Severity	Example - Neck
0	No Injury	
1	Minor	Minor laceration/Contusion
2	Moderate	Spinous process fracture/Trachea contusion/Disc herniation
3	Serious	Atlanto axial dislocation/Dens fracture
4	Severe	Incomplete cord syndrome
5	Critical	Complete cord syndrome (c4 and below)
6	Maximal	Complete cord syndrome (c3 and above)

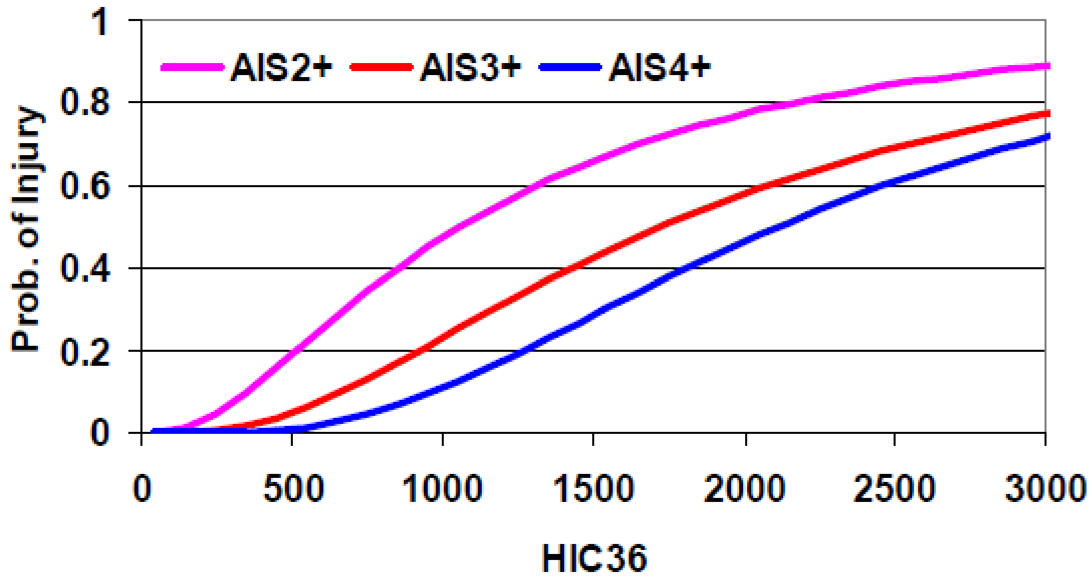

Figure 1. Probability of AIS 2+, 3+, and 4+ Head Injury as a Function of HIC36

Limiting the belt loads is one way to minimize this interaction and limit the risk of injury. In §25.562 tests, a single torso strap load must remain below 1750 lb, which is equivalent to a 50% risk of an AIS-3 or greater chest injury (7, 8). For a combined dual torso strap, the total load must remain below 2000 lb, which is equivalent to a 50% risk of an AIS-3 or greater chest injury (8, 9).

Lumbar: The lumbar spine is at risk for a compression fracture during impacts with a significant vertical component. Providing protection to the lumbar spine may also mitigate heart and aortic injuries, as these were found to seldom occur without an associated head/neck or thoracic injury (10). In §25.562 tests, the lumbar compressive load must remain below 1500 lb. This 1500 lb limit corresponds to approximately a 9% risk of a detectable spine injury. A specific injury severity level was not assigned to the injury cases that form the basis of these criteria (8). These injury cases were from a predominately male military aviator population. This sub-population would be younger and more fit than the general population. As such, a 9% risk of injury to this sub-population should represent a higher level of risk to the general population. Also, a recent examination of spinal injury rates for ejection seats indicates that the actual risk corresponding to seat pan accelerations producing a 1500 lb. load may be greater than the 9% value derived from earlier data (11).

Legs: Protection of the lower extremities is important in aviation impacts since an injury to this body region would severely hinder egress. The leg may be injured either from impact loads of the floor structure, inertial loading of leg flail, or through contact with other items in the cabin. In §25.562 tests, the femur axial compressive load must remain below 2250 lb, which represents a 35% risk of an AIS-2 or greater injury or a 15% risk of an AIS-3 or greater injury to the knee-thigh-hip complex (12).

Note that while §25.785 defines a side-facing seat as one mounted at more than 18 degrees with respect to the airplane centerline, this report only addresses seats oriented at 90 degrees. Oblique seats (seats oriented between 18 and 90 degrees) may present other injury risks and may require different (as yet to be determined) criteria to evaluate.

APPLICATION OF IMPROVED TEST METHODS AND TECHNOLOGY

ATD Advancements

As a surrogate for a human occupant, it is necessary for an ATD to provide as human-like (biofidelic) response as possible. The degree of biofidelity provided by the ATD directly affects the accuracy of injury predictions and structural assessments. Therefore, research into advanced ATD technology and impact biomechanics is an on-going effort by many organizations. Application of these advancements can improve the confidence in the safety level of assessments made during aircraft seat impact tests.

Advancements and Research: 14 CFR 25.562 cites the 49 CFR 572(B) Hybrid-II ATD or equivalent for use in dynamic qualification tests of aircraft seats. This ATD was originally designed to evaluate seat and restraint system performance during forward impacts. It was later adapted to also evaluate vertical impacts. It was not designed to provide biofidelity in side impacts and does not have the means to evaluate side impact injury risk (13).

49 CFR 571.214 currently cites the 49 CFR 572(U) ES-2re ATD for use in automotive side impact tests (14). This dummy is the result of many years of research and provides good biofidelity in the automotive impact scenario (15). A set of injury criteria is available for use with this dummy that permits a more specific and accurate assessment of injury than was possible with the SID (16).

The ES-2 also exhibits good biofidelity when used to evaluate typical aviation seat configurations (17). Its biofidelity was assessed for occupants restrained by shoulder/lap belts, as well as rigid barriers/belt systems. In both of these seating scenarios, the ES-2 showed good kinematic agreement with Postmortem Human Subject (PMHS) response for head excursion and torso lateral excursion. This good kinematic agreement led to good agreement of the neck loads and torso and head accelerations.

FAA research cited herein was conducted with an ES-2 build level E2.AI. The version that was adopted in 49 CFR 572(U) was the ES-2re, which differed from this original version somewhat. The ES-2re has a set of rib extensions that extend from the ends of the ribs to the back plate, filling a gap that had existed in the original version. These extensions improved the consistency of the interaction with contoured seat back upholstery common in automobiles (16). Since the back upholstery used in the FAA research test seats was not contoured, it is unlikely that using the ES-2re in these tests would have produced a different response than the original ES-2. This means that neck injury criteria derived using the ES-2 is applicable to the ES-2re as well.

Application to Aviation Side-facing Seats: Just as when used to test automobiles, the enhanced biofidelity of the ES-2re ATD will permit a more accurate and comprehensive evaluation of the level of safety provided by aircraft side-facing seats than was possible using the SID.

Since the combined horizontal/vertical test condition is not likely to produce significant lateral loading when compared to the horizontal test condition, the Hybrid-II ATD or equivalent is still appropriate for use in those tests with side-facing seats. The ES-2re has not been approved by the FAA as an equivalent ATD for use in the combined horizontal/vertical test since its response to vertical loading has not been validated.

Test Procedures

Seating Procedure: The current seating procedure for horizontal dynamic tests, as defined in FAA Advisory Circular (AC) 25.562-1B, does not completely control fore/aft position or angle of the ATD pelvis since the amount of rearward force applied to the ATD while being seated is not specified (18). A modification to this procedure that specifies this force has been shown to produce consistent placement of the ATD in forward-facing seats (19). Using this procedure should improve consistency for all test configurations since pelvic initial position and orientation affects the motion of the entire ATD. Pelvic position can affect the peak lumbar load in combined horizontal-vertical tests and the head trajectory in forward tests. The pelvis and upper torso position can also affect the shoulder belt segment length, which in turn, affects head trajectory. With side-facing seats, the fore/aft position of the ATD also determines what areas of adjacent surfaces are likely to be contacted. To ensure consistent ATD positioning in side-facing seat tests, the modified forward-facing seating procedure was adapted for the ES-2re as follows:

1. Lower the ATD vertically into the seat while simultaneously (see Figure 2 for illustration):
   a. Aligning the midsagittal plane (a vertical plane through the middle of the body dividing the body into right and left halves) with approximately the middle of the seat place.
   b. Applying a horizontal X-direction (in the ATD coordinate system) force of about 20 lb to the torso at approximately the intersection of the midsagittal plane and the bottom rib.
   c. Keeping the upper legs nearly horizontal by supporting them just behind the knees.
2. Once all lifting devices have been removed from the ATD:
   a. Rock it slightly to settle it in the seat
   b. Separate the knees by about 4 inches
   c. Set the head at the approximately midpoint of the available range of Z axis rotation (to align the head and torso midsagittal planes)

Figure 2. ES-2re Positioning Method

d. Position the arms at the joint's mechanical detent that puts them at approximately a 40 degree angle with respect to the torso
e. Position the feet such that the centerlines of the lower legs are approximately parallel to a lateral vertical plane (in the aircraft coordinate system)

The adapted procedure was evaluated to determine its repeatability and ability to reproduce the seated position of a 50th percentile male-size human occupant, as represented by the FAA Hybrid-III ATD. This evaluation consisted of seating an ES-2re and a FAA-Hybrid III three times each on a seat having a zero degree pan angle, a 13-degree back angle, and four-inch thick, soft foam back and bottom cushions. This configuration and cushion matched the seat in the ES-2 evaluation test series (2). Of primary interest was the X location, in the ATD coordinate system, of the head center of gravity (c.g.), knee, and point of applied load. The results are shown in Table 2. Based on these numbers, the adapted procedure positions the ES-2re consistently in the seat; however, it is clear that the upper torso of the ES-2re leans further forward than the FAA-Hybrid III (about 2.2 inches at the head c.g. location). The back plate structure at the rear of the ES-2re spine protrudes further aft than the corresponding area of the FAA Hybrid III. This difference in anthropometry precludes achieving identical initial position for these ATDs unless the ES-2re is forced into position by significantly compressing the back seat cushion. Since applying preload consistently is difficult in practice, the position achieved by the adapted procedure may represent the best compromise between repeatability and biofidelity. Compared to the procedure used for the ES-2 evaluation series (2), the new procedure positions the entire ES-2re ATD about 0.5 inches further forward.

ES-2re ATD Clothing: The clothing and shoes cited in AC25.562-1B are suitable for the ES-2re. The jacket included in the ES-2re's basic construction is sufficient for torso clothing, although a form-fitting shirt may also be used if desired.

ES-2re ATD Lateral Instrumentation: The rib module linear slides are directional, i.e., deflection occurs in either a positive or negative ATD y-direction. The modules should all be installed such that the moving end of the rib module is toward the front of the aircraft. The three abdominal force sensors should be installed such that they are on the side of the ATD toward the front of the aircraft.

ES-2re ATD Maintenance: The ES-2re is a much more complex ATD than the US SID used previously to evaluate side-facing aircraft seats. Calibration of the dummy involves several component and full assembly tests. Between calibrations, it should be inspected frequently for damage. Particular attention should be paid to the rubber neck, since during research tests it was noted that it is susceptible to damage after only a few tests in which the neck was highly loaded (over 700 lb tension and 600 in-lb bending moment) (2).

Measurement of Inflatable Shoulder Strap Loads: In some inflatable shoulder strap designs, the inflatable portion of the belt starts at the belt guide, so there is not a place to install the webbing transducer that would normally be used to measure the load between the guide and the shoulder of the occupant. Webbing transducers are the preferred means of making this measurement because their use does not require alteration of the system being tested as other types of load instrumentation would. In some FAA research tests with conventional restraints, the strap tension on both sides of the belt guide (upper and lower portion) was measured. From this data, a relationship between the tension in each segment was derived based on the peak load of each segment. Application of this procedure allows an estimate of the tension in the upper portion of the strap to be made by multiplying the ratio of tensions measured on each side of the strap guide by the lower belt segment tension, which is the only available channel in the tests using inflatable belts. The derived relationship is a function of the friction in the belt guide and is only applicable to the specific belt guide design used for that project. When compared with actual measured data, this estimation method provides a

Table 2. ATD Initial Position After Seating (along X-axis with respect to seat reference point)

	ES-2re				FAA-Hybrid III			
Seating Procedure	**Head c.g. (in)**	**Rt Knee (in)**	**Lf Knee (in)**	**Pt of Load App (in)**	**Head c.g. (in)**	**Rt Knee (in)**	**Lf Knee (in)**	**Pt of Load App (in)**
1st Trial	7.2	26.3	26.3	11.0	5.3	26.1	26.0	9.6
2nd Trial	8	25.9	25.8	11.0	5.7	25.7	25.6	9.6
3rd Trial	8	26.2	25.9	11.0	5.7	25.7	25.6	9.6
Average	**7.7**	26.1	26.0	11.0	**5.6**	25.8	25.7	9.6
St Dev	0.5	0.2	0.3	<0.1	0.2	0.2	0.2	<0.1
ES-2 Evaluation Series	**7.2**	25.8	25.6	-	**6.1**	25.1	25.1	-

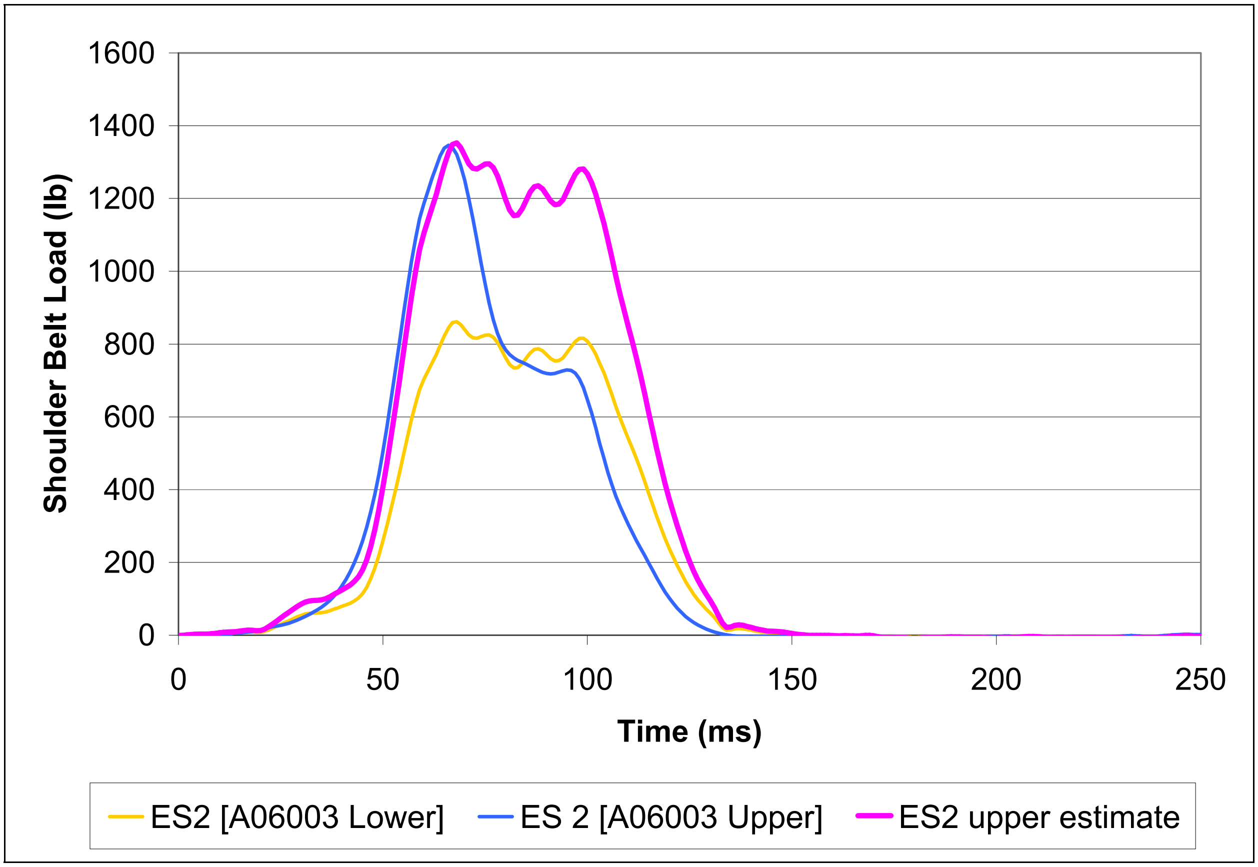

Figure 3. Comparison of Estimated and Actual Shoulder Belt Tension

good match with the actual data up to the peak load, but it diverges significantly after that point (Figure 3). The proportional relationship is only valid during the loading phase, since the frictional characteristics do not remain constant as the belt stops sliding and then reverses direction through the guide.

In tests of side-facing seat configurations that are the worst case for belt loading (rigid seat and belt anchor points), estimated upper strap tension with shoulder belt-mounted airbags is 36 to 47% of the injury criteria limit (2). Tests with conventional belts in the same configurations produced loads between 83 and 99% of the limit. The lower magnitude strap loads in tests with inflatable restraints were not a result of redistribution to the lap belts, since lap belt loads were also 17 to 23% lower than the conventional restraints. In addition, belt impingement data indicate that the airbag distributes the contact force over a larger area than the conventional restraint, further reducing injury risk. These results indicate that side-facing seats using inflatable shoulder belts configured similarly to the systems tested would be unlikely to produce upper strap tension loads in excess of the current injury criteria limit. These data from worst case research test configurations (Tables 3 and 4) may be useful for developing a rational analysis to estimate the shoulder belt load data when direct measurement is not possible because of interference with an inflatable restraint.

Test Protocol and Setup. The most direct way of assessing the safety of any seat installation is to test it in the exact configuration in which it will be installed in the aircraft, including all surrounding interior items that the occupants could interact with. A basic seat design may be produced in several versions or the same seat model may be installed adjacent to a variety of interior items. Rather than test all possible configurations, a rational analysis is often used to select the most critical seat models and interior arrangements for testing. In some cases, the analysis is used to derive the most critical case possible, which can include using rigid representations of the actual interior items. This approach maximizes interior arrangement flexibility. The following general observations are based on results of side-facing seat tests and may be useful for reference when conducting these rational analyses:

- Contact with interior items that are stiff tends to maximize injuries caused by direct contact loading. Using a completely rigid representation of interior items during a test should provide the most critical case for evaluating the potential for those types of injuries.

Table 3. Shoulder Strap Tension From Rigid Side-Facing Seat Research Tests

Test Configuration and Number	Restraint Type	Lower Shoulder Strap Tension (lb)	Upper Shoulder Strap Tension (lb)	Upper/Lower Strap Tension Ratio	Estimated Upper Shoulder Strap Tension (lb)	Percentage of Tension Limit for Upper Shoulder Strap
Center						
A05066	Conventional	1113	1735	1.56		99
A05068	Conventional	1094	1705	1.56		97
A05067	Inflatable	491	-----		765	44
A05070	Inflatable	526	-----		820	47
ArmRest						
A05075	Conventional	995	1529	1.54		87
A05076	Conventional	948	1458	1.54		83
A05073	Inflatable	410	-----		630	36
A05074	Inflatable	418	-----		642	37

Table 4. Lap Belt Tension From Rigid side-Facing Seat Research Tests

Test Configuration and Number	Restraint Type	Right Lap Tension (lb)	Left Lap Tension (lb)	Percentage Reduction in Lap Tension for Inflatables
Center				
A05066	Conventional	2882	959	
A05068	Conventional	2971	1043	
A05067	Inflatable	2285	591	23
A05070	Inflatable	2385	591	17
ArmRest				
A05075	Conventional	1401	-----	
A05076	Conventional	1419	-----	
A05073	Inflatable	1166	-----	17
A05074	Inflatable	1150	-----	19

- Contact with interior items that do not have sufficient stiffness to support the occupant will tend to increase injuries due to restraint interaction and occupant flailing, as well as increasing seat structural loading when compared to contacting more rigid items. Omitting contactable interior items during a test should provide the most critical case for maximizing seat structural loading and for evaluating the potential for injuries caused by restraint loading and flailing.
- Contact with interior items that are not homogenous with respect to stiffness may produce a combination of contact, restraint, and flailing injuries. If only a portion of an item is stiff, then it could create concentrated loading on some parts of the body and allow excessive flailing of other body parts. Using a completely rigid representation of only a portion of the item may be a critical case for evaluating injury potential of such an item during a sled test. For instance, a wall that is very stiff up to the armrest level and quite flexible above it could be represented by a completely rigid lower section and by omitting entirely the upper section.
- The stiffness properties of interior components likely to be struck by seat occupants are usually a consideration in determining critical test cases. For side-facing seat configurations where an occupant is seated next to a forward wall, the most likely head contact point is directly related to the occupant's sitting height. The impact area observed during tests with a 50th percentile male-size occupant can be combined with anthropometry data to determine the vertical dimensions of the wall area most likely to be struck by a range of occupant sizes. If the contact area of the side of the head is defined as the top of the head to the chin, then the mid point of that area coincides with the height of the eye point (and the head c.g.). Figure 4 illustrates the relationship between the center of the 50th percentile male's impact area and the upper and lower bounds of the likely impact area for a range of occupants. The bounds illustrated correspond to the height of the top of the 95th percentile male's head and the height of the 5th percentile female's chin. (20).

APPLICATION OF IMPROVED INJURY CRITERIA

14 CFR 25.562 Injury Criteria

Compliance with the injury criteria cited in §25.562 is intended to provide a specific level of safety. Since these criteria were originally developed to evaluate occupant safety in forward impacts, they were reviewed for applicability to side-facing seat safety.

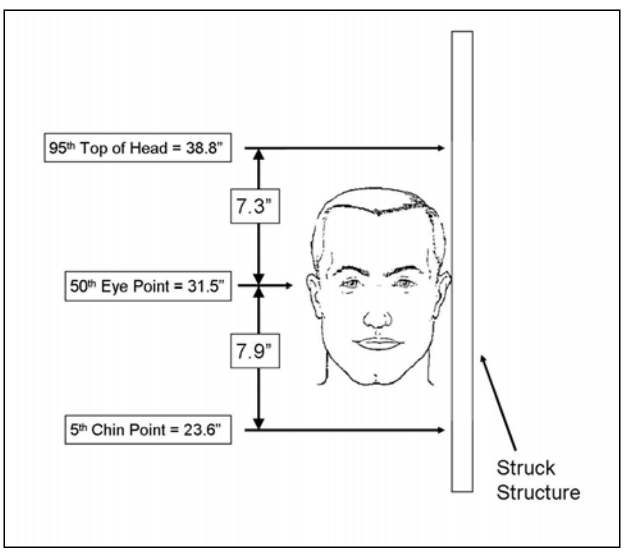

Figure 4. Head Contact Area for a Range of Occupants

Upper Torso Strap Loads: In forward-facing impacts, upper torso strap loads correlate with both internal injuries and skeletal fractures (rib and clavicle) (6). The load limits in the current regulations are intended to limit injury risk to a 50% chance of an AIS-3 injury. FAA-sponsored research indicates that both of these types of belt-induced injuries are also a risk in side-facing seats. In two impact tests with the occupants seated next to an armrest, wearing three-point restraints, both of the occupants received multiple rib fractures (AIS 2), one occupant received a clavicle fracture (AIS 2), and one received a carotid artery intimal tear (AIS 3) (3).

This series of tests, conducted at the Medical College of Wisconsin (MCW), also yielded shoulder belt load data (previously unpublished). The test configuration required for this series precluded measuring the belt load at the shoulder, which is the specified measurement point for injury evaluation in FAA regulations. However, load data was measured between the strap guide and the inertia reel assembly. Since this MCW test configuration used the same belt guide design as in the previously discussed FAA inflatable restraint tests, the same scaling factor and procedure were used to estimate the belt load at the shoulder, based on the available load data.

The estimated shoulder belt loads produced during the PMHS tests, as well as matching ES-2 tests, are shown in Figure 5. As can be seen, the estimated shoulder belt loads for these tests with the ES-2 ATD are about 25% lower than the current criteria for single-strap loads (1750 lb). This lower load is consistent with the lower severity injuries (AIS 2-3) observed in the matching PMHS tests. Therefore, the upper strap load limits in the current regulations remain a useful indicator of injury potential for side-facing seats when measured using the ES-2 ATD. However, the absolute value of the shoulder belt loading produced by the ES-2 is significantly higher (60% higher) than the loads generated by the PMHS in this loading condition.

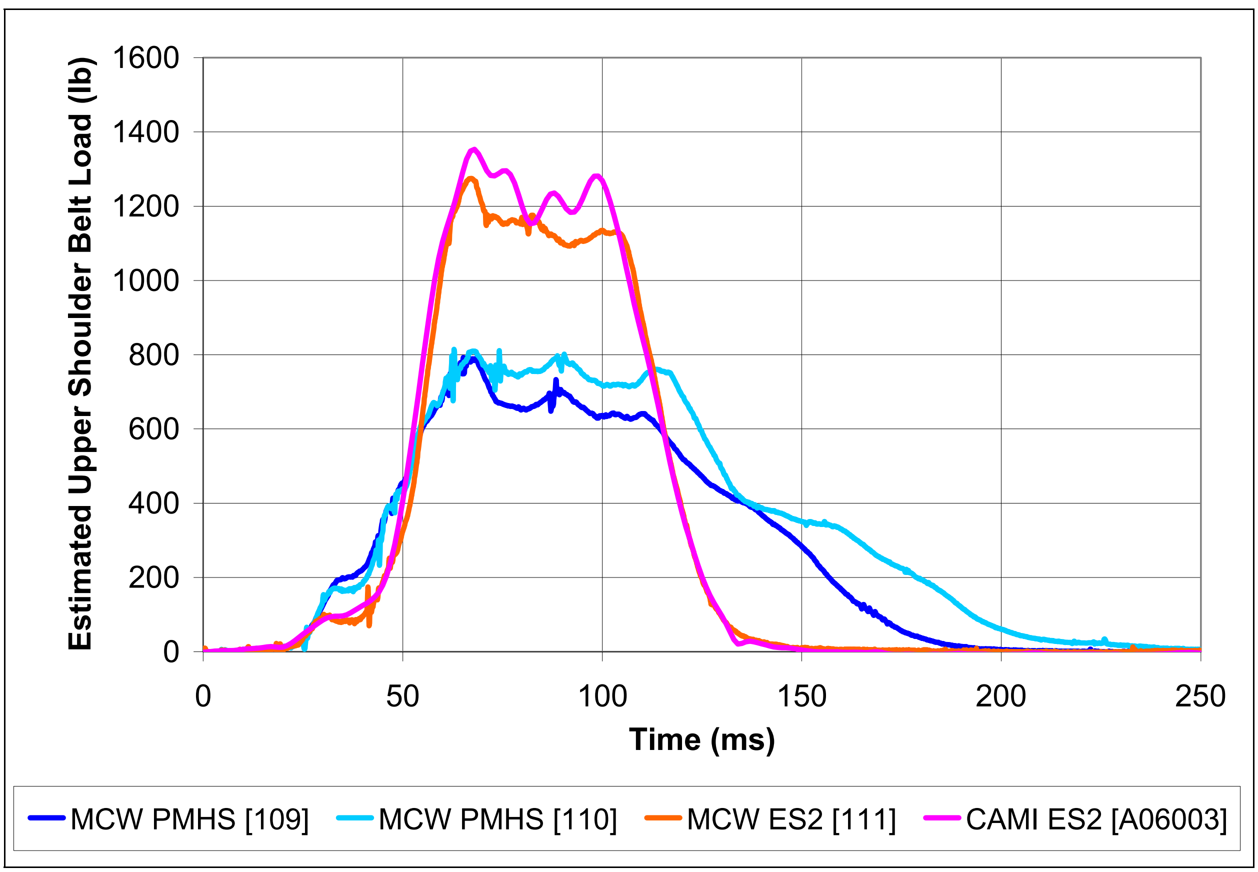

Figure 5. Comparison of PMHS and ES-2 Shoulder Belt Tension

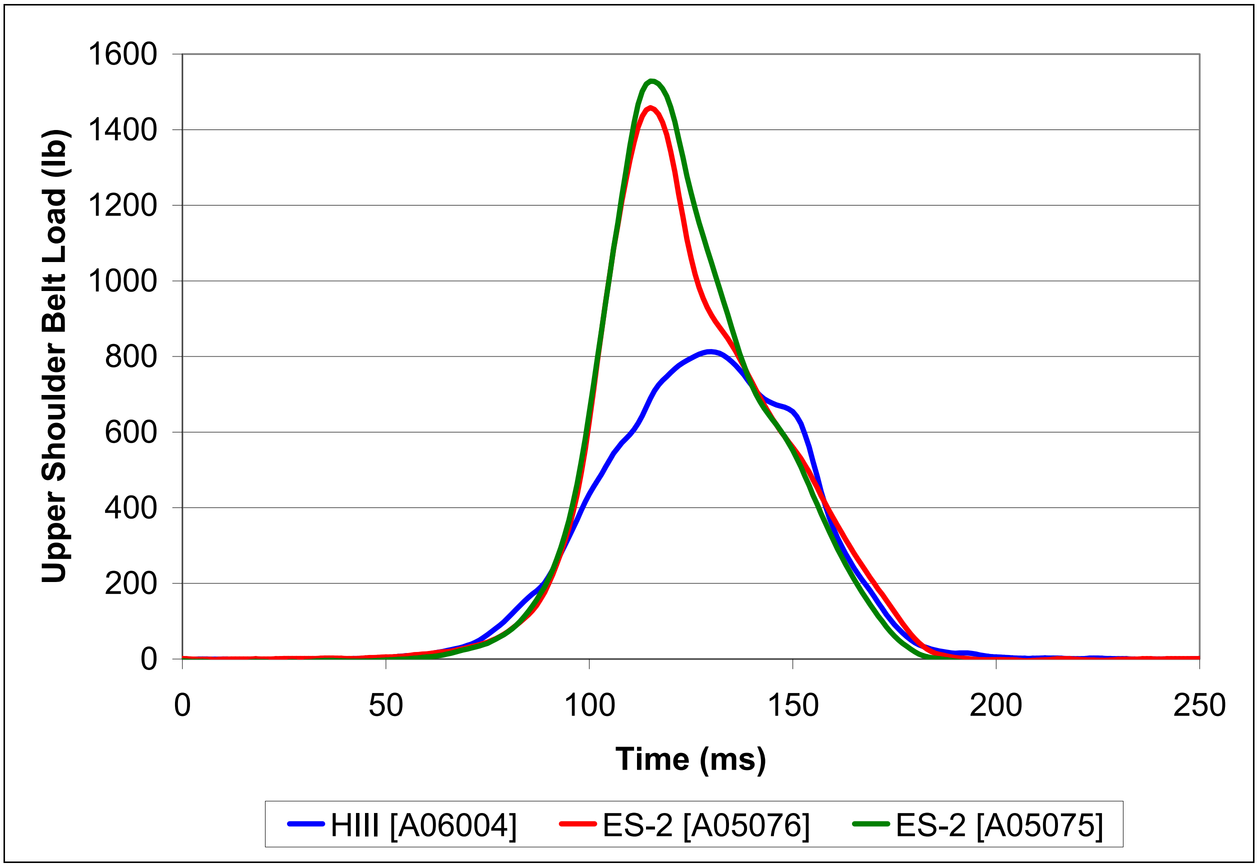

Figure 6. Comparison of FAA Hybrid-III and ES-2 Shoulder Belt Tension

A test with the FAA Hybrid-III in the same seat configuration as the ES-2 tests was also conducted at CAMI for reference. As can be seen in Figure 6, the measured upper shoulder strap load for this Hybrid-III ATD was about 45% lower than the ES-2 value, which means that using the existing pass/fail criteria to evaluate shoulder strap loads generated by the FAA Hybrid-III would underestimate the potential for injury in this loading condition. The peak load generated by the Hybrid-III, however, is similar to PMHS load. This biofidelity in regard to belt loading means that when used for structural evaluation of side-facing seats, forward-facing ATDs should generate realistic upper torso restraint loads.

Lumbar Compressive Load: 14 CFR 25.562 reduces the risk of spinal injury by limiting the lumbar compressive load measured by the Hybrid-II ATD, or equivalent to1500 lb. No evidence is available to indicate that applying a combined load to the spine in the Y-Z plane versus the X-Z plane alleviates the risk of spinal injury, so this criterion is still applicable to the evaluation of side-facing seats.

HIC: Although originally derived to evaluate injury risk in forward impacts, the HIC has also been used to evaluate impacts to the side of the head as well. As such, HIC is currently cited in 49 CFR 571.214 as one of the pass/fail criteria for the ES-2re ATD. Therefore the current 14 CFR 25.562 requirement limiting HIC to less than 1000 is applicable to aircraft side-facing seat evaluations using the ES-2re ATD (6).

Femur Axial Force: The intent of the femur axial force limit in §25.562 is to reduce the chance of leg injuries that could impede egress after an emergency landing (21). The orientation of side-facing seats makes exceeding the load limit during a forward impact very unlikely. However, in tests of aircraft side-facing seats, human subjects have sustained serious leg injuries that would not only have impeded egress but could also be life threatening (3). The nature of the injuries indicates that they were caused by torque applied to the femur (likely created by the inertial force of the unrestrained lower leg). The test protocol for that project (which was focused on neck injury) did not include measuring the PMHS femur torque or the specific rotation angle that causes injury. However, if the upper leg's axial rotation with respect to the pelvis is limited to the normal static range of motion, then the risk of injury should be low. That range of motion for a seated occupant's internal and external rotation ranges from 18 degrees for the least flexible persons (the male population's 5th percentile rotation value) to 45 degrees for the most flexible persons (the female population's 95th percentile rotation value) (22). ATD tests in the same seat configuration as the PMHS tests showed that the ES-2 leg will rotate at least 60 degrees in this loading scenario (2). In the absence of an available criteria relating rotation angle to a specific risk of injury, limiting upper leg axial rotation with (respect to the pelvis) to 35 degrees from the nominal seated position (approximately the 50th percentile range of motion for both genders) should also limit the risk of serious leg injury. One means of determining the amount of relative upper leg rotation is by observing the amount of lower leg flailing in high-speed video of the dynamic tests. Since the lap belt tends to prevent significant lateral rotation of the pelvis, the motion of the lower leg with respect to its initial position is sufficient to derive the upper leg relative rotation with respect to the pelvis.

Restraint Contact: §25.562 requires that restraints remain on the shoulder and pelvis of the occupant during impact. AC 25.562-1B clarifies this requirement by stating they must remain on the shoulder and pelvis when loaded by the occupant. This pass/fail criterion is necessary to protect the occupant from serious injury that could be caused by lap belt contact forces applied to soft tissue or by ineffective restraint of the upper torso caused by the restraint sliding off the shoulder. In forward-facing seats (the type specifically addressed by that AC), occupant motion during rebound and any subsequent re-loading of the belts is limited by interaction with the seat back. The term "rebound" in this context is used to denote the period during the test when the occupant reverses direction of travel and the belt loading drops to zero. So, for a forward-facing seat, disregarding the belt position after rebound is a reasonable limitation on the injury evaluation period. However, in a side-facing seat subjected to a forward impact, the restraint system may be the only means of limiting the occupant's rearward motion. In this case, the rebound energy is likely to be much less than the initial loading, so the tension produced in the belts during rebound should also be much less. But, it is still important for the lap belt to remain on the pelvis since soft tissue injuries can occur at relatively low loading levels. Sliding of the upper torso restraint off the shoulder during rebound is unlikely to be a direct source of injury, however, as with forward-facing seats, if the motion of the occupant during rebound would cause significant contact with surrounding structure (whether caused by the upper torso restraint coming off the shoulder or not), then it may be necessary to assess the injury potential of that contact.

Additional Injury Criteria

The top level requirement of §25.562 is "to protect each occupant during an emergency landing condition." Meeting this requirement for side-facing seats requires injury assessments beyond those specifically cited in §25.562. This is because side-facing seats can load occupants in unique (and potentially injurious) ways that do not occur in forward-facing seats. The following criteria are useful to evaluate the level of safety provided by side-facing seats.

49 CFR 571.214 Injury Criteria.The injury criteria cited in §571.214 for use with the ES-2re ATD were reviewed for applicability in aviation impact scenarios. All of the requirements were found to be useful for evaluating the safety of typical aircraft side-facing seats (2). For each of these criteria, the relationship between the probability of injury and a value measureable by the ES-2re has been defined. These criteria and the associated risk of sustaining a specific level of injury are summarized below:

- *Head Injury.* HIC36 limited to 1000, evaluated for the entire duration of the test. This version of HIC differs from the one cited in §25.562 in that it limits the maximum time window to 36 milliseconds. The aviation version, which has an unlimited time window, is equally valid for use with the ES-2re since both versions are based on the same impact injury data. Limiting HIC to 1000 limits the injury risk to a 23% chance of an AIS-3 or a 47% chance of an AIS-2 head injury (6).
- *Ribs.* Lateral deflection of any rib module is limited to 1.73 inches. This limits the injury risk to a 50% chance of an AIS-3+ chest injury (23).
- *Abdomen Force.* Limited to a combined load (from all three load cells) of 562 lb. This limits the injury risk to a 33% chance of an AIS-3+ abdominal injury (23).
- *Pubic Symphysis Force.* Limited to 1350 lb. This limits the injury risk to a 25% chance of an AIS-3+ pelvis injury (23).

Lateral Neck Injury Criteria. Extreme lateral bending of the neck has been observed during tests of typical aircraft side-facing seats. To address this potential for injury, the FAA sponsored research that developed the following neck injury criteria for use with the ES-2re (3):

- *Neck Tension.* FAA research findings established a strong correlation between neck tension applied by inertial forces during lateral impacts and neck injury. An injury risk curve was developed for tension forces measured by the ES-2. An axial neck tension limit of 405 lb represents a 25% risk of an AIS-3 or greater neck injury.

- *Neck Moment.* Initial FAA research did not produce high lateral moments in the absence of tension. This loading condition was of interest because in some tests, the potential injury mitigation technology (inflatable restraint systems) has produced relatively high bending loads with little tension (2). The PMHS test associated with the highest moment recorded during the initial research did not produce significant neck injury. This indicated that the onset of injury was likely greater than the 673 in-lb measured by an ES-2 ATD subjected to the same test conditions (3). To investigate further, a follow-on project was conducted to assess the load case consisting of low tension and high lateral moments. The highest bending moment produced at the occipital condyles of the PMHS during that follow-on research was 651 in-lb. This load did not result in a detectable injury. A comparison between ES-2 and PMHS response when loaded in the same manner and at the same severity indicates that this load corresponds to a 1018 in-lb moment measured by the ES-2 (24). Therefore, a value of 1018 in-lb lateral bending moment (as measured at the occipital condyle location of the ES-2) can be considered a threshold, below which neck injury is not expected.
- *Neck Compression.* FAA-sponsored research focused on loading conditions that were most likely to occur in typical side-facing seat installations. The investigated conditions did not produce neck compressive loads; however, this load case cannot be ignored since some seat configurations that have nearby structure could produce neck compression during lateral impacts. The tension and compression limits cited in §571.208 for use in forward tests of automobiles are very similar (tension = 937 lb and compression = 899 lb). If the lateral bending of the neck reduces its tolerance to compression loading in the same manner and to the same degree that it reduces the tolerance to tension loading, then applying the same limit specified for tension loading during side impact to compression loading should provide a similar level of safety for this loading condition.
- *Neck Shear.* Analysis of the PMHS results did not reveal as strong a correlation between neck shear and injury as it did for tension loading. This is because, as with neck lateral moment, the research method did not produce high shear forces independent of tension loading. So, for the serious injury cases, it is unknown whether the injury was caused by the shear force, the tension force, or the combined effect of both. On the other hand, an upper limit at which severe injury would occur obviously exists. A conservative load limit can be based on the injury risk curve that was developed for resultant shear (Fxy) forces measured by the ES-2. A limit on the neck shear load of 185 lb represents a 25% risk of an AIS-3 or greater neck injury. While this limit is conservative, the degree of conservatism is unknown.

Occupant Support Criteria. Unless well restrained, occupants of side-facing seats can experience large excursions and flailing that can be a source of injury. These types of injury risks are not likely in forward- and aft-facing seats. The following additional qualitative criteria are needed to evaluate (and limit) the occupant's excursion and flailing in order for the seat system to provide the same level of safety as forward- or aft-facing seats:

- *Pelvis Excursion.* AC 25.562-1B clarifies the intent of §25.562(c)(7) by requiring the primary load path between the occupant and the seat attachments remain intact. If inertial loads cause the occupant to load a seating surface during the impact event (including rebound), then that surface is a primary load path. As such, excursion of the load-bearing portion of the occupant's pelvis beyond the bottom seat cushion supporting structure is a loss of load path, having the same effect on the occupant that a structural failure would. The area under and around the ischial tuberosities on the bottom of the pelvis bear much of a seated occupant's vertical load (25). The area of the cushion under the ATD having the greatest effect on performance is defined in AC 25.562-1B as a 5-inch deep by 8-inch wide rectangular area that is 3 inches forward, 2 inches rearward, and 2 inches sideward of each buttock reference point (18). The corresponding area on the bottom of the pelvis is the principal load-bearing area and can be used when evaluating whether the load path between the ATD and seat pan is maintained.
- *Head and Neck Support.* TSO-C127a (26) and SAE AS8049b (27) require that aft-facing seats have sufficient height and stiffness to support the occupant's head and spine. Providing this support is intended to reduce spinal injuries when occupant inertial forces cause it to load against the seat back. Some side-facing seat configurations have been found to produce loading that causes the occupant's head to flail beyond the top of the seat back. Ensuring the seat has sufficient height and stiffness to support the head and spine is one way to prevent the potentially injurious spine loads that could be created by excessive articulation. Of the common seating configurations tested by the FAA, the ones that resulted in flailing beyond the seat back also produced upper neck tension and shear forces exceeding the injury limits suggested in this report (2). This finding implies that excessive rearward articulation of the neck is unlikely in common seating configurations if upper neck forces are below the suggested values. Therefore, in side-facing seat tests, the intent of the requirement to provide sufficient rearward (with respect to the occupant) support for the spine and head can be met by limiting the magnitude of neck loads. Applying either of these approaches to side-facing seats (providing spinal support or limiting neck loads) would

provide the same level of safety afforded occupants of forward- and aft-facing seats.

- *Upper Torso Support*. Serious injures, including spinal fractures, have been observed in tests that produce lateral flailing over an armrest (28). The ES-2re's abdominal force measurement has been shown to correspond to injuries resulting from horizontal impact on that area. Limiting the loading in this area may prevent some of the injuries produced when occupants flail over the armrest structure, but this criterion was not intended to evaluate spinal or internal injuries caused by excessive lateral bending of the occupant, as those types of injuries were not observed in the typical automotive side impacts that formed the basis of the criterion. In the automotive side impact tests, the occupants are typically fully supported through the vehicle door and window. While there is currently no criteria relating the amount of lateral flail to a specific risk of injury, if lateral flexion is limited to the normal static range of motion, then the risk of injury should be low. This range of motion is approximately 40 degrees from the upright position (22). Ensuring that lateral flexion does not create a significant injury risk is consistent with the goal of providing an equivalent level of safety to a forward- or aft-facing seat, since that type of articulation does not occur to occupants of those seats during forward impacts.
- *Body-to-Body Contact Limitation.* Currently, there is no standard means to assess the specific injury risk for the contact between occupants that can occur during impacts. Since these types of contact do not occur to occupants in forward or aft-facing seats, one means to ensure that the same level of safety is provided is to prohibit contact between the head, pelvis, torso, or shoulder area of one ATD with the adjacent seated ATD's head, pelvis, torso, or shoulder area. Contact during the rebound phase would be unlikely to cause significant injury due to the much lower energy of those contacts.
- *Occupant Retention.* Another consideration in evaluating restraint systems is that §25.561 (a) and (b) requires the occupant be protected from serious injury when inertia forces are applied in all six orthogonal directions, as defined in paragraph (b)(3) (reference 4). So, if application of those loads could be expected to move the occupant in such a way that it was not supported by the seat bottom or back, or that the belts would interact in a manner considered injurious by the criteria in §25.562, then the seat would not be in compliance with the intent of §25.561. Essentially, a seat and restraint system that only restrains the occupant safely when loaded in the forward or vertical directions defined in §25.562 would not meet the intent of §25.561.

CONCLUSIONS

Current aircraft side-facing seat certification requirements are based on 1990s technology and science and are not adequate to ensure all side-facing seat configurations provide an equivalent level of safety to forward-or aft-facing seats. Advances in test methods, ATDs, and injury assessment techniques have been made since those requirements were drafted. These advances have been used to develop test methods, testing technology, and injury criteria that provide an improved means of determining the level of safety provided by fully side-facing aircraft seats.

Many of the criteria described in this report are significantly different from those previously used to evaluate side-facing seats (29). To determine the effect that implementation of these new criteria could have on approval of typical seating configurations, the results of the CAMI ES-2 test series (2) were evaluated using the pass/fail criteria outlined in this report. This evaluation showed that configurations permitting excessive lateral flail do not pass, and those that limit it by combining effective restraint system geometry with a barrier or inflatable restraint pass readily. Table 5 summarizes this evaluation for three configurations that incorporate effective injury mitigation strategies. This result indicates that the criteria described in this report can be met by applying current technology.

The research summarized in this report focused on impact conditions that are purely lateral with respect to the occupant. However, these findings may also be applicable to impact scenarios that deviate from lateral to some extent. If an oblique impact results in occupant kinematics and loading that is similar to a lateral impact, then it follows that the lateral impact criteria could be applicable in that case. Once an angle of impact is determined to be sufficient to cause the kinematics and loading to deviate significantly, then additional criteria (as yet to be determined) may be necessary to properly evaluate that seat configuration.

Table 5. Evaluation of Typical Side-Facing Seat Configurations Using New Injury Criteria

Body Location	Criteria	Seated Mid-Couch, with Infl. Shoulder Strap and Body-centered Restraints (A05067) (A05070)	Seated Next to Full Wall with Conv. Shoulder Strap and Body-centered Restraints (A05065)	Seated Next to Armrest with Infl. Shoulder Strap and Body-centered Restraints (A05073) (A05074)
Head	HIC < 1000	Pass	Pass	Pass
Neck	Tension < 405 lb Compression < 405 lb Bending < 1018 in-lb Shear < 186 lb	Pass Pass Pass Pass	Pass Pass Pass Pass	Pass Pass Pass Pass
Shoulder	Belt load < 1750/2000	Pass*	Pass	Pass*
Abdomen	Σ front, mid, rear < 562 lb	Pass	Pass	Pass
Chest	Rib deflect < 1.73 in	Pass	Pass	Pass
Pelvis	Pubic Symphysis < 1350 lb	Pass	Pass	Pass
Leg	Flail < 35 deg	Pass	Pass	Fail**
Retention / Support	(1) Pelvis excursion: The load bearing portion of the bottom of the ATD pelvis shall not translate beyond the edges of its seat's bottom seat cushion supporting structure. . (2) Upper Torso support: The lateral flexion of the torso must not exceed to 40º from the normal upright position during the impact.	Pass Pass	Pass Pass	Pass Pass
Body to body contact	No head, pelvis, torso, or shoulder contact allowed	Pass***	N/A	N/A

* Direct measurement of inflatable shoulder strap tension is not feasible in most installations. Research tests comparing inflatable shoulder restraints with conventional restraints indicate that inflatable restraints tend to lower tension loads significantly.

** This configuration did not have a structure to restrain the lower legs, resulting in excessive flailing.

*** Although these tests did not include a second occupant, the excursion of the ATD was such that prohibited contact with an adjacent occupant would have been unlikely.

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