

Pretensioners and Injury Risk

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ABSTRACT

In recent years rotary wing aircraft restraint systems that incorporate pretensioners have appeared on the market. While similar systems have been available and used in production automobiles for over 30 years, there have been concerns regarding the potential of injuring occupants should such systems be fielded in aircraft.

This paper provides an overview of the purpose and function of a pretensioner. It discusses the performance enhancements provided by pretensioned restraint systems in ground vehicles. It also discusses the protection offered by pretensioned restraint systems and provides an overview of the literature related to thoracic and other injuries in pretensioned restraint systems. The benefits a pretensioner is expected to provide in fixed and rotary wing aircraft and integration issues will also be discussed.

Based on the research performed and the real world performance of pretensioners in the automotive environment, it is apparent that pretensioners have great potential to decrease the risk of injury to occupants in aircraft without introducing any significant potential for injury as a result of the loads generated by the pretensioner itself.

INTRODUCTION

Restraint pretensioners were introduced in production automobiles over thirty years ago as a means to increase protection offered by seatbelt restraints to occupants. According to the National Highway Traffic Safety Administration (NHTSA), sixty-three percent of all 2002 model year vehicles were equipped with pretensioners. In fact, several manufacturers have started equipping the rear seats of their vehicles with pretensioners. Pretensioners can be integrated into numerous locations

of the restraint system but primarily are integrated into the buckle stalk (Figure 1) or shoulder belt retractor (Figure 2).



Figure 1. Buckle Pretensioner

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Figure 2. Shoulder Belt Retractor Pretensioner

In general, most automotive pretensioners are designed to remove slack, not to generate significant belt forces on the occupant. (Miller, 2005) In fact, a working group which included representatives from Audi, BMW, Mercedes, Porsche and Volkswagen, specified a 2.5 kN (562 pound) limit on shoulder belt pretensioner forces. (He, 1999)

DISCUSSION

Pretensioners improve occupant protection through a variety of ways.

- Pretensioners eliminate webbing slack that can be caused by routing of the restraint or by clothing. (Crandall, 2000)
- By pretensioning the webbing, pretensioners assist in pre-positioning an occupant who maybe out of position by loading the occupant through the webbing prior to occupant motion due to the crash forces. (Walz, 2004 and Muller, 1998)
- The pretensioner increases the initial loading in the webbing which serves to couple the occupant to the vehicle earlier in the crash (Crandall, 2000) thereby improving occupant ride down.
- Pretensioners reduce the spool out of webbing from a retractor, sometimes referred to as film spool during a crash. (Mitzkus, 1984)
- Retractor pretensioners serve to improve the timeliness and reliability of retractor lockup by initially rotating the retractor spool to retract webbing, thereby increasing the time available for the locking mechanism to activate and prevent webbing extraction under the loads of the occupant.

These improvements have numerous effects. As previously mentioned, pretensioned restraints improve occupant crash ridedown. This improved crash ridedown results in a reduction of dynamic overshoot (Miller, 1996),, reducing forces and acceleration experienced by the occupant. Van Rooij (2003) has reported a reduction of both head and chest accelerations and head injury criteria (HIC). This reduction in accelerations experienced by the occupants results in reduced peak seatbelt loads, resulting in lower loads on the occupant from the restraint system.

Van Rooij (2003) also reported that pretensioners reduce an occupant's forward excursion in a frontal or near frontal impact. Specifically, testing has shown a reduction of both head and torso excursions. Additionally Cooper (1997) has also shown that pretensioners reduce both lateral and vertical occupant excursions. This reduced occupant excursion serves to reduce the potential for occupant contact with the vehicle's interior, even if contact still occurs, in most cases the forces of these contacts will be reduced from that which would have occurred without a pretensioner. By preventing or reducing the severity of occupant contact with a vehicle's interior, the potential for contact related injury is reduced.

Thoracic Injury from Belts

A 1998 paper by Foret-Bruno demonstrated a strong correlation between shoulder belt loads and risk of thoracic injury. This study concludes that shoulder belt loads of 8 to 9 kN (1800 to 2025 lbs.) may induce injury and that this risk of injury increases with age. The study further concluded that the risk of high severity injuries due to shoulder belt loading on the thorax is low. The authors found that the thoracic injury mainly fell into the AIS 2 or AIS 3 range. AIS 2 – Moderate injury, generally defined as 2-3 rib fractures or sternal fracture, or AIS 3 – Serious injury, generally 3 or more rib fractures, 2-3 rib fractures with hemothorax or pneumothorax. The thoracic injury risk curves for AIS 2 and greater and AIS 3 and greater reported by Foret-Bruno (1998) are in figures 3 and 4 respectively. Two kilonewtons equates to approximately 450 pounds.

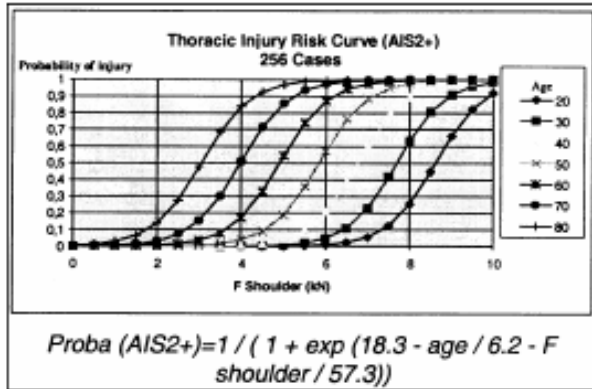


Figure 9. Probabilities of AIS2+ risk according to age and force for the 256 cases

Figure 3. Probability of AIS2+ Injury Curves

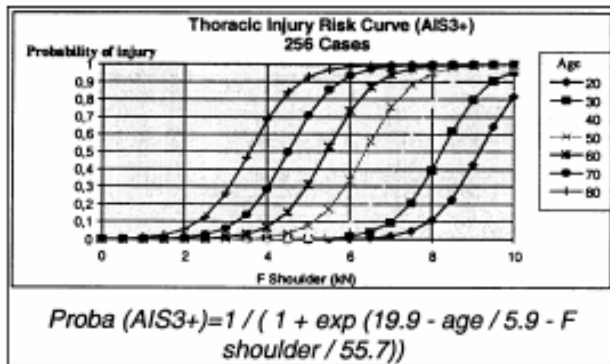


Figure 10. Probabilities of AIS3+ risk according to age and force for the 256 cases

Figure 4. Probability of AIS2+ Injury Curves

The belt loads generated by pretensioners are generally less than 3 kN (675 pounds) which is far less than shoulder belt loads of 8 to 9 kN (1800 to 2025 lbs.) found by Foret-Bruno to cause injury. The pretensioned loads are also far less than the belt loads that occur as a result of occupant loading during a crash. This can be seen in Figure 5 which illustrates the shoulder belt loads measured during a 56 kilometer-per-hour (35 mile-per-hour) frontal crash test. The initial rise in the shoulder belt load to approximately 1500 Newtons is due to the pretensioner, while the much higher loads of over 7000 Newtons is created by the crash forces. This clearly demonstrates that the crash loads far exceed those of the pretensioner. In fact, by incorporating a pretensioner into a restraint, the peak belt loads in a crash are actually reduced. (Zuppichini 1990) With reduced peak belt loading one would expect reduced frequency and severity of injuries due to belt loading on the thorax.

2004 Volvo S40 Driver's Shoulder Belt Loads

Ymin -58.3845 @ 121.15 (ms) Ymax 7147.78 @ 50.1 (ms)

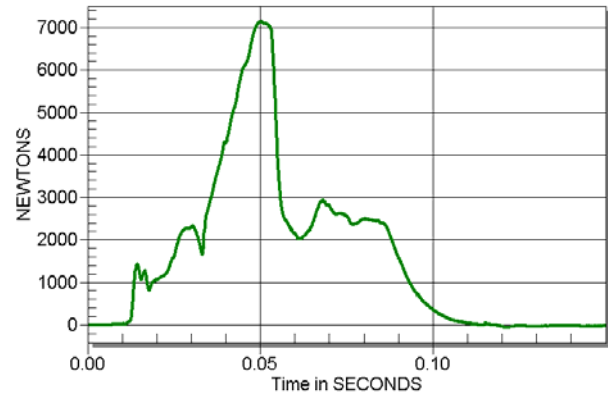


Figure 5. Shoulder Belt Loads in 56 KPH frontal Impact

Since pretensioners have been present in automobiles for over 30 years (Mitzkus, 1984), it was expected that if they were causing injuries to occupants, this would be reported in the literature. A search and review of literature, including that of the Society of Automotive Engineers (SAE), American Association of Automotive Medicine (AAAM), the Stapp conference and numerous other sources found no documented injuries caused by pretensioners. While this lack of literature does not confirm that such injuries are not occurring, it is a strong indicator that if injuries are occurring to occupants as a result of pretensioner loading, it does not occur frequently or result in serious injury.

Benefits of Pretensioners

In a 1990 study of 30 mph frontal impacts with Hybrid-III ATDs by Zuppichini (1990) reported the benefits of pretensioned restraints in reducing numerous injury producing parameters. This study reported:

- HIC reduced 17.3 to 42.8 percent
- Chest acceleration reduced up to 11.9 percent
- Shoulder belt loads reduced 200 to 500 N (45 to 112 lbs.)
- Head and chest displacement reduced
- Head velocity reduced

The reduction of head and chest displacement reduces the risk for occupant contact within the interior of the vehicle. Additionally, the reduction in head velocity ensures a reduction in head impact severity if head contact still occurs. The reduction of HIC and chest acceleration directly reduce the risk of injury to those regions while reduction of belt loads reduces the direct loading on the thorax, decreasing the risk of injury.

Similar findings were reported by Walz (2004). Walz reported on NHTSA's analysis of New Car Assessment Program (NCAP) testing of vehicles equipped with lap/shoulder belts with pretensioners which had also been tested prior to the inclusion of pretensioners. Watz found that when pretensioners were added:

- HIC decreased by 150 or 26%
- Chest acceleration decreased by 4.84 g or 9.7%
- Chest deflection decreased 6.46 mm or 20.7%

These findings are very similar to those of Zuppichini (1990).

Systems Approach

In most vehicles on the road today, pretensioners are part of the restraint system and designed to work with the seatbelts and airbags. The addition of a pretensioner supplements or enhances the restraint system and provides for an increased level of protection for an occupant. While the field data from passenger cars indicates a very low risk of injury directly caused by a pretensioner, there are many reports of occupant injury due to airbag deployment. As part of a systems approach to designing and developing an occupant protection system, these, as well as other factors must be considered. The system should be developed to minimize risk in all crashes. One way to reduce the risk of occupant injury caused by airbag deployment in passenger vehicle crashes is to reduce the number of crashes in which airbags deploy. The benefits derived by incorporating a pretensioner into a seatbelt system allows the designers to increase the minimum severity of a crash required to deploy the airbags. This directly reduces the number of crashes in which an airbag will deploy and reduces the exposure of occupants to airbag deployments. Miller (1995) reported that reduced airbag deployment reduces risk of airbag induced injury.

Automotive Verses Aircraft Pretensioners

Data on one production pretensioner developed for use in aircraft was compared to data available on automotive type pretensioners. The pretension forces developed by the aircraft pretensioners, 2225 N (500 pounds) was only slightly higher than what is seen in several automotive systems where peak pretensioner loads are typically in the range of 1800 N (400 pounds). While the aircraft pretensioner does develop slightly higher initial loads than the typical automotive pretensioner, the peak loads of the aircraft pretensioner are still well below the shoulder belt loads seen during a crash. Additionally it is expected that since the occupants of military aircraft are a subset of the general population, in that it excludes the

younger and older extremes, and tends to include generally healthier people, these slightly higher loads would not pose an increase risk of injury from pretensioner loading on the occupant. In fact, 2225 N (500 pounds) equates to a near zero risk of AIS 2 level injury for all age categories under 50 years in the risk curves provided by Foret-Bruno (1998).

Benefits of Pretensioners in Aircraft

The aviation environment provides several increased challenges in protecting occupants over ground vehicles. Generally, the cockpit of an aircraft is a smaller space than the passenger compartment of a car. Passenger cars incorporate passive crash protection in the form of friendlier interiors with such features as flush mounted switches and controls, and interior padding. In many cases this is not practical in an aircraft due to the environments it operates and the requirements of the crew. In addition to harness slack that can be caused by clothing, the aviator also has the potential to increase this slack due to the routing of the harness over body mounted equipment and survival gear. Additionally, numerous aircraft incorporate equipment that requires the operator to be out of the normal upright seated position, usually to lean forward in order to perform mission tasks.

Pretensioners offer benefits that address all of these issues. First, by pretensioning the harness, routing slack caused by body mounted equipment and heavy clothing is minimized. (Mitzkus, 1984) This also assists in pre-positioning an out of position occupant which should improve spinal alignment, increasing an occupant's ability to sustain vertical loads. Additionally, the pretensioner improves the timeliness and reliability of retractor lockup and reduces webbing spool-out. These factors all combine to reduce occupant excursion and increase crash ride down compared to a non-pretensioned restraint system, thereby reducing the risk of occupant contact with the interior of the aircraft and minimizing the loads and accelerations of the occupant during the crash.

There are also several other benefits of pretensioners for use in aircraft seen while conducting this study.

- Inertial reels which incorporate pretensioners are very similar in size and shape to non-pretensioned inertial reels. This is expected to make them easily retrofitable into most aircraft in that they should be capable of fitting into the very limited space available for installation.
- If the pretensioner is installed into an aircraft which incorporates a stroking or energy

attenuating seat, the pretensioner integrated into the inertial reel would move with the seat and the occupant.

- Since the pretensioner only tightens the harness, it is expected that the ability to control the aircraft would not be significantly degraded if the pretensioner inadvertently activated. The pretensioner could also be activated prior to a crash to pre-position the occupant.
- Pretensioners reduce body excursions in the forward, lateral and vertical directions, therefore a pretensioner should be initiated in any crash with significant severity.

Incorporation of a pretensioner into an aircraft does not necessarily negate or eliminate the need for a cockpit airbag system. While pretensioners reduce occupant excursions during crashes, they do not eliminate them. Cockpit airbags would still be beneficial when the risk for head impact still exists, even with a pretensioned restraint system. Additionally, occupant crash protection principles state that restraining loads applied to the occupant's body should be widely distributed. This is most effectively accomplished when occupant loads are shared by the harness and an airbag. Applying a systems approach to occupant crash protection indicates that energy managing vehicle structure, energy attenuating seats, energy absorbing padded surfaces, flush-mounted/collapsing controls, restraint harnesses, pretensioner and airbags should all work together as a system to minimize the risk of injury to an occupant.

However, pretensioners can also be used when incorporating or developing an airbag for a specific aircraft is not practical. Due to its ease of integration into the cockpit space, there are some instances where a pretensioner might be practical without an airbag. Some examples include:

- Aircraft with limited console space
- Limited clearance to occupant – insufficient airbag deployment space
- High risk of out-of-position occupants
- Difficult to retrofit airbag into aircraft
- Use of airbag cost prohibitive

In addition to these factors one must also consider the risk of inducing injuries if an airbag system is incorporated into the cockpit. The hazards associated with airbags in automobiles have been well documented. The highest risk of injury is associated with the elderly, very young, unbelted, and small occupants. Airbags also pose a significant injury risk to out-of-position occupants in

passenger cars. Similar findings were presented by McEntire (2001) indicated that early cockpit airbag prototype systems for the UH-60 posed similar types of hazards to out of position occupants. Through redesign of the system, these risks were substantially reduced.

Recently, automotive manufacturers have begun to incorporate a system capable of detecting out-of-position occupants and suppressing or preventing airbag system deployment if an occupant is in the airbag deployment zone. Such a system should be incorporated into a cockpit airbag system, especially if the aircraft's mission requires the occupant to be in the airbag deployment zone. Additionally, un-deployed airbags can pose a hazard to maintainers as well as rescue personnel. While education of the aircraft maintainers as to how to avoid inadvertent airbag deployment is certainly practical, the unfamiliarity with military aircraft by civilian rescue personnel who might respond to a crash will be more difficult to overcome. For this reason, airbag system components should be installed in such a way to minimize the potential for interaction by rescue personnel which could cause an inadvertent deployment.

CONCLUSIONS:

Based on the research performed and the real world performance of pretensioners in the automotive environment, it is apparent that pretensioners have great potential to decrease the risk of injury to occupants in aircraft without introducing any significant potential for injury as a result of the loads generated by the pretensioner itself. While pretensioners and cockpit airbags can be used together, pretensioners offer a means to increase occupant protection even when an airbag can not be incorporated. Because of the pretensioner's low risk of injury, pretensioners should be at the top of a designers list of features when considering methods for reducing an occupant potential for injury from body excursion and restraining loads.

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BIOGRAPHIES

John R. Yannaccone, P.E. is the Senior Engineer for the Forensic Safety Group has over fifteen years experience in the field of occupant protection. His experience includes extensive research and testing of aircraft and automotive equipment and components, as well as design

and development of equipment and aircrew stations for testing the responses of crash dummies and human volunteers. He has conducted crash and sled testing of numerous vehicles including ambulances and has conducted test programs for National Highway Transportation Safety Administration, Nation Institute of Occupational Safety and Health and various branches of the US military. Early in his career, he was employed by the Naval Air Warfare Center – Warminster where is was in charge of the Navy’s Horizontal Accelerator facility. This facility was used to conduct testing on crashworthy seating system, aircraft restraints and restraint system components as well as other aircraft equipment. He has a BS in Mechanical engineering.

Gary R. Whitman has 25 years of experience in aircrew escape, restraint systems, and life support systems. He has led project design, mission analyses, and test and evaluation projects throughout his career. His work has included the design, test, logistics, reliability, risk, maintainability, life cycle costs, vulnerability, producibility, and safety of various projects. He also led the Front Occupant Crash Protection SBIR for the Volpe National Transportation Systems Center to identify methods for protecting front seat occupants in motor vehicles crashes. This effort included analysis of NHTSA’s National Accident Sampling System (NASS) data to identify injury mechanisms and review innovative crash protection technology. Mr. Whitman supported Navy programs, such as: the Survival Technology Restraint Improvement Program, Cats-Eyes Emergency Detachment System, and the Advanced Crashworthy Aircrew Survival System. His responsibilities include investigation of automotive and aircraft mishaps, focusing on the performance of the occupant protection systems and occupant kinematics. He has a BS in Mechanical engineering.

Larry Sicher has over fourteen years of experience in engineering and development in the areas of escape systems, restraint systems, and life support equipment. He participated in engineering, research, development, testing, and evaluation of systems for automotive and aerospace restraint and escape applications. His experience ranges from basic research to hardware development to in-service fleet support. Mr. Sicher conducts evaluations and tests of seating and restraint systems for automobile occupants, crash data analysis, and provides technical support to the U.S. Department of Defense on issues involving military aircrew survivability, emergency oxygen life support systems, escape, and crash protection. Mr. Sicher was responsible

for managing the technical data package verification for the Navy's new Aircrew Integrated Recovery, Survival, Armor Vest and Equipment (AIRSAVE) ensemble, for providing technical support for the Navy's Combat Edge (NCE) program, and for conducting engineering investigations on Navy ejection seat survival kits following aircraft mishaps and fleet failures. He has a BS in Mechanical engineering.

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Pretensioners In Automobiles

- Pretensioners have been in some production automobiles over 30 years
- 63% of model year 2002 equipped with pretensioners

(National Highway Traffic Safety Administration)

- Arbeitskreis (Working Group) Specification limits shoulder belt force from pretensioner to 2.5 kN (562 lbs.) (SAE 1999-01-0080)

– Included Audi, BMW, Mercedes, Porsche & VW



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Where are Automobile Pretensioners?



Buckle

Retractor

72



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Buckle Pretensioner



73



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Retractor Pretensioners



74



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Purpose of Auto Pretensioner

- Removes/eliminates routing slack
(Crandall, IMechE Vol. 214)
- Couples occupant to vehicle earlier in crash
(Crandall, IMechE Vol. 214)
- Tightens (pre-tensions) webbing
- Reduces webbing spool out (Film spool) (SAE 840395)
- Assists in pre-positioning occupant (Walz, 2004)
- Improved timeliness and reliability of retractor lockup
- Generally designed to remove slack, not to generate significant belt forces (Miller, 1995 AAAM)



Effect of Auto Pretensioners

- Reduces dynamic overshoot (SAE 96502)
 - Reduces head and torso excursions
 - Reduces head accelerations and HIC (SAE 2003-01-0500)
 - Reduces chest accelerations (SAE 2003-01-0500)
- Improved occupant crash ride down
- Reduces peak belt loads
- Reduces forward excursion (SAE 2003-01-0500)
- Reduces vertical and lateral excursions (SAE 973347)
- Increased chance of correcting out of position (SAE 980557)

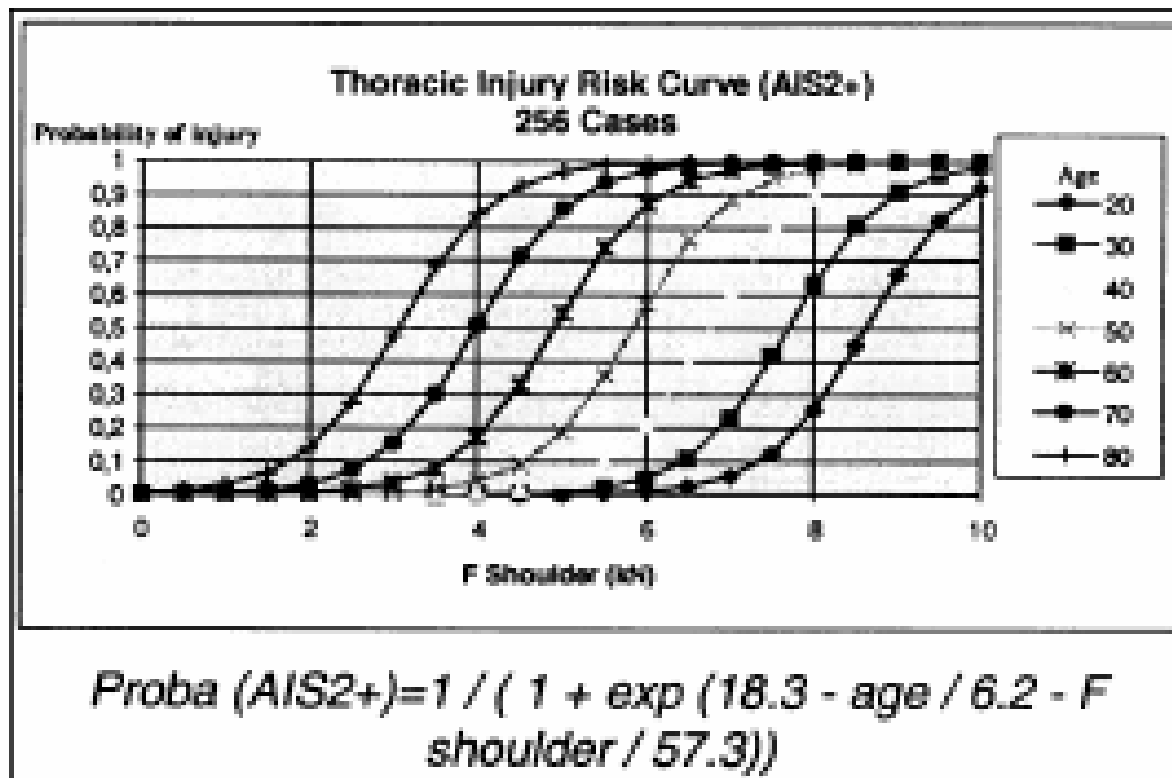


Thoracic Injury from Belts

- SAE 983166
 - Good correlation between shoulder belt loads and risk of thoracic injury
 - Belts loads of 8 to 9 kN (1800 to 2025 lbs.) may induce injury
 - Risk of injury at given load increases as age increases
 - Risk of higher severity injury is less
 - AIS 2 – Moderate – Thoracic injury
 - 2-3 rib fractures, sternal fracture
 - AIS 3 – Serious – Thoracic injury
 - 3 or more rib fractures, 2-3 rib fractures with hemothorax or pneumothorax



Thoracic Injury from Belts



kN	Lbs.
2	450
4	900
6	1350
8	1800
10	2250

Figure 9. Probabilities of AIS2+ risk according to age and force for the 256 cases



Thoracic Injury from Belts

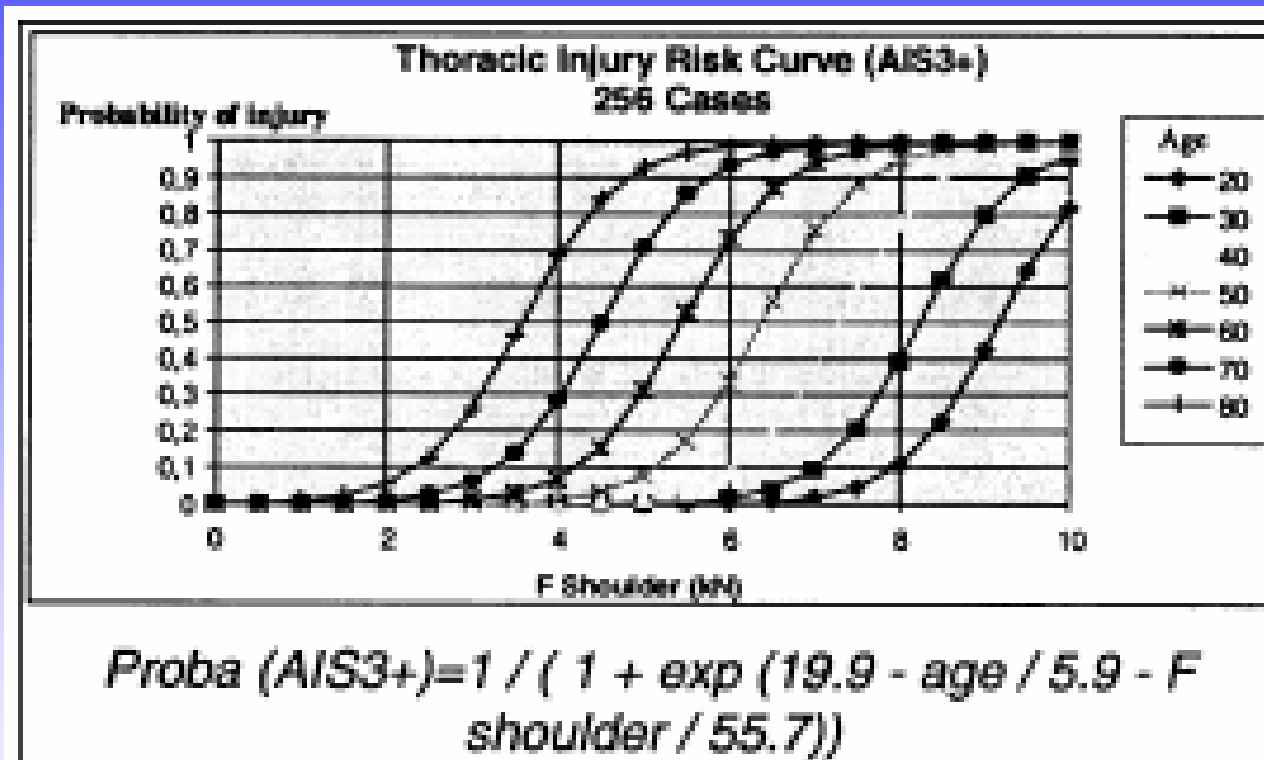


Figure 10. Probabilities of AIS3+ risk according to age and force for the 256 cases

kN	Lbs.
2	450
4	900
6	1350
8	1800
10	2250



Injuries Related to Pretensioners

- Pretensioners in vehicles over 30 years
(SAE 840395)
- Review of literature – no documented injuries from pretensioners
(SAE, AAAM, Stapp etc.)
- Pretensioner belt loads less than those generated during crash
- Use of pretensioners reduces peak belt loads in crash
- Aircraft pretensioner shoulder belt loads of 2220 N (500 pounds)
 - Probability of AIS 2 injury less than 5% for all age groups under 60 years



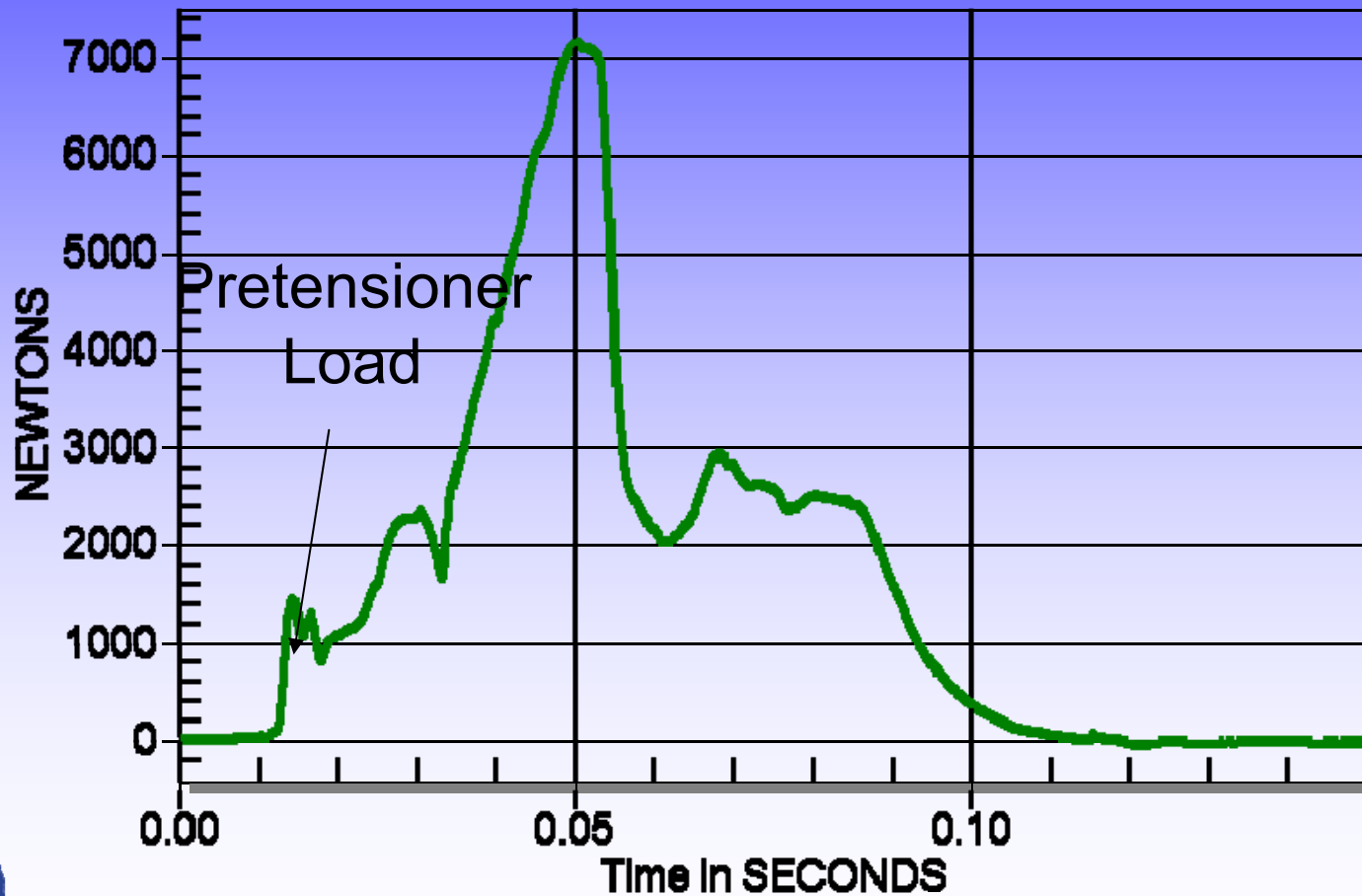
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Belt Loads in NCAP Test

2004 Volvo S40 Driver's Shoulder Belt Loads

Ymin -58.3845 @ 121.15 (ms) Ymax 7147.78 @ 50.1 (ms)



81



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Do Pretensioners Work?

- 1990 study of 30 mph frontal impacts with Hybrid-III ATD (SAE 905139)
 - HIC reduced 17.3 to 42.8 percent
 - Chest acceleration reduced up to 11.9 percent
 - Head and chest displacement reduced
 - Shoulder belt loads reduced 200 to 500 N (45 to 112 lbs.)
 - Head velocity reduced
- NHTSA analysis of NCAP testing of vehicle where were added (Walz, 2004)
 - HIC decreased by 150 or 26%
 - Chest acceleration decreased by 4.84 g or 9.7%
 - Chest deflection decreased 6.46 mm or 20.7%



Pretensioners

- Part of the system – works with belts and airbags
- Supplements/enhances restraint system – provides increased protection
- Increases minimum severity where airbags must fire. This reduced:
 - Number of crashes where airbags deploy
 - Reduced airbag deployment and reduces risk of airbag induced injury (Miller, 1995 AAAM)



Auto vs. Aircraft Pretensioner

- Shoulder belt forces slightly higher in aircraft system compared to automobiles
- Aircraft pretension loads still well below harness crash loads
- Aircraft pretensioner loads well below allowable shoulder loads for “younger” adults



Pretensioner Benefits in Rotary Wing Aircraft

- Removes routing slack caused by body mounted gear and heavy clothing (SAE 840395)
- Removes routing slack
- Tightens (pre-tensions) webbing
- Reduces webbing spool out (Film spool)
- Improved timeliness and reliability of retractor lockup
- Assists in pre-positioning occupant
- Improves spinal alignment

85



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Pretensioner Benefits in Rotary Wing Aircraft (cont)

- Easily retrofitable
- Fits in very limited space
- Is not expected to degrade ability to operate aircraft
- Moves with stroking seats to maintain proper position of harness on occupant
- Pretensioner provides increased protection in all crash vectors



Do You Still Need an Airbag?

- Short answer – YES, if head contact possible
- Systems approach allows for load sharing between harness and airbag
- Pretensioners reduce but do not prevent occupant excursion
- Harness, pretensioner, airbags and seat all work as system to reduce injury risk
 - Can reduce peak belt loads (SAE960502)



Additional Pretensioner Applications

- Can be used when airbags not practical
 - Easily integrated into occupant space
 - Limited console space
 - Limited clearance to occupant
 - High risk of out-of-position occupants
 - Difficult to retrofit airbag
 - Use of airbag cost prohibitive



Airbag Hazards in Autos Well Documented

- Airbags increase risk to:
 - Out of position occupants
 - Improperly restrained occupants
 - Elderly and very young
 - Small occupants
 - Maintainers
 - Rescue personnel



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