INJURY CRITERIA FOR SIDE IMPACT DUMMIES

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EXECUTIVE SUMMARY

This document presents the development of injury criteria and associated injury risk curves for the head, thorax, abdomen, and pelvis using the measures from the ES-2re and SID-IIsFRG side impact dummies. The injury criteria development was based on data from cadaveric sled tests and pendulum tests along with corresponding tests with the ES-2re and SID-IIsFRG dummies.

The development of the thoracic injury criteria is presented in detail since NHTSA has conducted tests for this purpose. However, the abdominal and pelvic injury criteria were developed from re-analysis of published data.

The following is a synopsis of the injury criteria and associated risk curves for the ES-2re and SID-IIsFRG dummies.

INJURY CRITERIA AND RISK CURVES FOR THE ES-2re DUMMY

The injury criteria developed using cadaver data for the thorax, abdomen, and pelvis could not be applied directly to the ES-2re dummy since the responses of the ES-2re dummy differed from those of the cadaver for these body regions. Therefore, injury risk curves for the thorax were developed using logistic regression with ES-2re measurements along with cadaver anthropometry as covariates and the cadaver injury outcome as the dependent variable. For the abdomen and the pelvis, the injury risk curves developed from the cadaver data were scaled to represent ES-2re injury measures.

HEAD INJURY CRITERION FOR THE ES-2re DUMMY:

Since FMVSS 201 and the EU Side Impact Directive 96/EC/27 successfully use the head injury criterion, HIC36, to assess head injuries in lateral impacts, HIC36 is suitable for head injury assessment with the ES-2re dummy. HIC36 is defined as

$$\boldsymbol{HIC}36 = \mathbf{max}\left[\frac{1}{\boldsymbol{t}_2 - \boldsymbol{t}_1}\int_{t1}^{t2} \boldsymbol{a}(\boldsymbol{t})\boldsymbol{dt}\right]^{2.5}(\boldsymbol{t}_2 - \boldsymbol{t}_1)$$

$$\textit{\textbf{where } } \boldsymbol{a(t)} \textit{\textbf{ is the resultant head acceleration and }} (\boldsymbol{t}_2 - \boldsymbol{t}_1) \le 36\, \boldsymbol{m}\,\mathbf{sec}$$

Head Injury Risk Curves:

$$\boldsymbol{p}(\boldsymbol{head\ injury}) = \phi\left(\frac{\ln(\boldsymbol{HIC}36) - \mu}{\sigma}\right)$$

where φ is the cumulative normal distribution and μ=6.96352 and σ=0.84664 for AIS 2+ head injuries, μ=7.45231 and σ=0.73998 for AIS 3+ head injuries, and μ=7.65605 and σ=0.60580 for AIS 4+ head injuries.

Values of HIC36 at 25% and 50% risk of head injury for 50th percentile adult male.

Injury Predictor	25% prob. of injury			50% prob. of injury		
	AIS 2+	AIS 3+	AIS 4+	AIS 2+	AIS 3+	AIS 4+
HIC36 Std. Error	600 482 - 745	950 744 - 1212	1400 1122 -1747	1050 896 - 1231	1680 1410 - 1930	2113 1796 - 2465

THORACIC INJURY CRITERIA FOR THE ES-2re DUMMY:

The thoracic injury criteria were developed using data from 42 side impact sled tests with cadavers in 9 different test conditions and corresponding sled tests with the ES-2re dummy.

Thoracic Injury risk curves based on ES-2re Measures for a 45 year old 50th Percentile Male

$$p(AIS3+) = \frac{1}{1+e^{(2.0975-0.0482*\mathbf{max.}\ rib.\ defl.)}}$$

$$p(AIS4+) = \frac{1}{1+e^{(3.4335-0.0482*\mathbf{max.}\ rib.\ defl.)}}$$

$$p(AIS3+) = \frac{1}{1+e^{(1.56-0.0366*\mathbf{max.}\ upper\ spine.\ accel.)}}$$

$$p(AIS3+) = \frac{1}{1+e^{(1.991-0.0254*\mathbf{max}\ lower\ spine\ accl.)}}$$

Maximum rib deflection is the maximum of the three ES-2re measured rib deflections (SAE filter class 180) in mm. Maximum upper and lower spine accelerations are the maximum resultant upper and lower spine accelerations (SAE filter class 180) in gs.

Values of the ES-2re predictor functions at 25% and 50% probability of injury – normalized with respect to a 45 year old person.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum rib deflection (mm) Standard error range	21 mm 0 – 32 mm	48 mm 30 – 70 mm	44 mm 32 – 54 mm	72 mm 54-100 mm
Max. lower spine acceleration Standard error range	36 gs 0 – 59 gs	70 gs 2 – 114 gs	80 gs 54 – 112 gs	130 gs 96 – 170 gs
Max. upper spine acceleration Standard error range	15 gs 0 – 30 gs	46 gs 25 – 65 gs	43 gs 26 – 60 gs	74 gs 58 – 114 gs

ABDOMINAL INJURY CRITERION FOR THE ES-2re DUMMY:

The abdominal injury criterion and associated risk curves were developed from published data by Walfisch (1980). Walfisch conducted cadaver drop tests into rigid and padded armrests. The injury risk curve from the cadaver drop tests is based on the normalized applied force to the abdomen by the arm rest. Using the 42 side impact sled test data series from the Medical College of Wisconsin, a relation was developed between the normalized applied abdominal force in the cadaver sled tests to the corresponding total abdominal force measured in the ES-2re dummy. These two were found to have a one to one correspondence and therefore, the same cadaver injury risk curve could be used with the ES-2re abdominal force.

Abdominal Injury Risk Curves for the ES-2re dummy

$$p(AIS3+) = \frac{1}{1+e^{6.04044-0.002133*F}}$$

$$p(AIS4+) = \frac{1}{1+e^{9.282-0.002133*F}}$$

where F is the normalized applied abdominal force on cadavers or the maximum total abdominal force (sum of forces measured by the anterior, middle and posterior abdominal load cells) in the ES-2re dummy (SAE filter Class 600) in Newtons.

Values of ES-2re abdominal force corresponding to 25% and 50% probability of AIS 3+ and AIS 4+ abdominal injury.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum total abdominal force in ES-2	2300 N	3800 N	2800 N	4400 N

PELVIC INJURY CRITERION FOR THE ES-2re DUMMY:

The pelvic injury criterion was developed by reanalyzing the pendulum impact test data from Bouquet et al. (1998) and the sled test data from Zhu et al. (1993). The applied forces were mass-scaled and age was included in the injury predictor function. A relationship between applied pelvic force on the cadaveric subjects and pubic symphysis force measured in the ES-2re dummy under similar test conditions was applied to obtain injury risk curves based on ES-2re pubic force.

Pelvic injury risk curves based on ES-2re Measures

$$p(AIS2+) = \frac{1}{1+e^{6.403-0.00163*F}}$$

$$p(AIS3+) = \frac{1}{1+e^{7.5969-0.0011*F}}$$

where F is the pubic symphysis force in the ES-2re dummy (SAE filter channel class 600) in Newtons.

Values of ES-2re pubic symphysis force corresponding to 25% and 50% probability of AIS 2+ and AIS 3+ pelvic injury.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 2+	AIS 3+	AIS 2+	AIS 3+
Maximum pubic symphysis force in ES-2	3250 N	6000 N	4000 N	7000 N

INJURY CRITERIA AND RISK CURVES FOR THE SID-IIsFRG DUMMY

The SID-IIsFRG dummy design and instrumentation are significantly different from that of the ES-2re dummy. Therefore, the responses of the two dummies are not scaled representations of each other. As a result, scaling of injury risk curves as done for the Hybrid III family of dummies in the FMVSS No. 208 Advanced Air Bag Final Rule, may not be applicable for the SID-IIsFRG and the ES-2re side impact dummies. To a large extent, the same cadaver tests were considered for the development of SID-IIsFRG injury criteria as that used for the ES-2re injury criteria development presented in the first part of this report. Where possible, tests with the SID-IIsFRG were conducted under similar test conditions as that of the cadaveric tests. The response of the SID-IIsFRG was compared to cadaveric response and if needed, response scaling between cadaveric and dummy responses was conducted. The development of the thoracic injury criteria utilized the same cadaveric sled test data as that used for the ES-2re dummy. The development of abdominal and pelvic injury criteria employed data from published literature.

The Insurance Institute for Highway Safety (IIHS) has initiated a program to rate vehicles in side impact using the SID-IIs side impact dummy. For this purpose, IIHS has provided guidelines for rating the SID-IIs injury measures (IIHS, 2003). The dummy injury measures presented in this document at 25 and 50 percent injury risk to various body regions are, in general, within the IIHS injury measures for good to acceptable rating.

HEAD INJURY CRITERION FOR THE SID-IIsFRG DUMMY:

In the FMVSS No. 208 Air Bag Final Rule, the same head injury assessment value was applied to the 5^{th} percentile female Hybrid III dummy (HIII-5F) and the 50^{th} percentile adult male Hybrid III dummy (HIII-50M). Since the ES-2re head is the same as that of the HIII-50M and that of the SID-IIsFRG is the same as the HIII-5F, the same scaling relations apply as that used in FMVSS No. 208. Therefore, the same injury risk curves for HIC36 as used for the ES-2re can be applied to the SID-IIsFRG head. As a consequence, the point estimates of HIC36 values at 25% and 50% risk of head injury for the SID-IIsFRG is the same as that of the ES-2re dummy.

Values of HIC36 at 25% and 50% risk of head injury for 5^{th} percentile adult female

Injury Predictor	25% prob. of injury			50% prob. of injury		
	AIS 2+	AIS 3+	AIS 4+	AIS 2+	AIS 3+	AIS 4+
HIC36	600	950	1400	1050	1680	2113
Std. Error	482 - 745	744 - 1212	1122 -1747	896 - 1231	1410 - 1930	1796 - 2465

THORACIC INJURY CRITERIA FOR THE SID-IIsFRG DUMMY:

The thoracic injury criteria were developed from 42 cadaver side impact sled tests conducted at the Medical College of Wisconsin (Appendix A) along with twelve sled tests with the SID-IIsFRG conducted under similar impact conditions as the cadaver tests (Appendix H). The injury risk curves for the SID-IIsFRG were developed assuming an age of 56 years (representing the average age of AIS 3+ injured drivers shorter than 5 ft 4 inches) and a chest width of 270 mm (representing the chest width of a SID-IIsFRG dummy). The maximum rib deflection is the maximum of the three SID-IIsFRG thoracic rib deflections (SAE filter class 180). The maximum lower spine acceleration is the maximum resultant lower spine acceleration of the SID-IIsFRG (SAE filter channel class 180).

The maximum normalized thoracic rib deflection of the SID-IIsFRG was similar to the estimated maximum normalized rib deflection of the cadavers in the different test configurations. Therefore, the injury risk curves developed using cadaver normalized rib deflections could be directly applied to the SID-IIsFRG for thoracic injury assessment.

Lower spine accelerations were also used for thoracic injury assessment. Since the lower spine accelerations of the SID-IIsFRG differed from those of the cadavers under similar impact conditions, the injury risk curves developed using cadaver injury measures could not be directly applied to the SID-IIsFRG measurements. Therefore, the injury risk curves developed using SID-IIsFRG lower spine accelerations and the corresponding cadaver injury outcome under similar impact conditions, were used for thoracic injury assessment with the SID-IIsFRG.

Thoracic Injury Risk Curves for the SID-IIsFRG Dummy

$$\boldsymbol{p}(\boldsymbol{AIS}3+) = \frac{1}{1+\boldsymbol{e}^{(5.8627-0.15498*\mathbf{max.}\ \boldsymbol{rib.\ defl.})}}$$

$$\boldsymbol{p}(\boldsymbol{AIS}4+) = \frac{1}{1+\boldsymbol{e}^{(7.7998-0.15498*\mathbf{max.}\ \boldsymbol{rib.\ defl.})}}$$

$$\boldsymbol{p}(\boldsymbol{AIS}3+) = \frac{1}{1+\boldsymbol{e}^{(1.364-0.0212*\mathbf{max.}\ \boldsymbol{lower\ spine\ accel.})}}$$

$$\boldsymbol{p}(\boldsymbol{AIS}4+) = \frac{1}{1+\boldsymbol{e}^{(2.4634-0.021*\mathbf{max.}\ \boldsymbol{lower\ spine\ accel.})}}$$

Values of the SID-IIsFRG predictor functions at 25% and 50% probability of thoracic injury – normalized to a 56 year old female.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum rib deflection (mm) Standard error range (mm)	30.7 mm 27.5 – 33.8	43.2 mm 40.0 – 46.1	37.8 mm 34.8 – 40.5	50.3 mm 47.4 - 54
Max. lower spine acceleration Standard error range	14 gs 0 – 40 gs	65 gs 32 – 84 gs	64 gs 36 – 84 gs	118 gs 97 – 158 gs
	82 gs corresponds to 5% false positive rate			

ABDOMINAL INJURY CRITERION FOR THE SID-IIsFRG DUMMY:

The abdominal injury criterion was developed using the oblique lateral impact test data from Viano (1989) and Viano et al. (1995) and is based on the maximum abdominal deflection measured in the SID-IIsFRG. The maximum abdominal deflection is the maximum of two abdominal ribs' peak deflection (processed by SAE filter channel class 180.)

Abdominal Injury Risk Curve for the SID-IIsFRG dummy

$$\boldsymbol{p}(\boldsymbol{AIS}4+\boldsymbol{abd\ inj.})=\frac{1}{1+\boldsymbol{e}^{8.9798-0.1349(\mathbf{max}\ \boldsymbol{abd\ rib\ defl.})}}$$

Values of the SID-IIsFRG abdominal deflection at 5%, 25% and 50% probability of abdominal injury

Injury Predictor	AIS 4+ Abdominal Injury		
	5%	25% prob.	50% prob.
Maximum abdominal rib deflection (mm)	45 mm	59 mm	67 mm

PELVIC INJURY CRITERION FOR THE SID-IIsFRG DUMMY:

The pelvic injury criterion was developed using the pelvic impact test data from Bouquet et al. (1998). It is based on the sum of acetabular and iliac force (SAE filter channel class 600) measured in the SID-IIsFRG.

Pelvic Injury Risk Curves for the SID-IIsFRG dummy

$$\boldsymbol{p}(\boldsymbol{AIS}2+)=\frac{1}{1+\boldsymbol{e}^{(6.3055-0.001*(\boldsymbol{iliac+acetab.\ force}))}}$$

Values of total iliac and acetabular force corresponding to 25% and 50% risk of AIS 2+ pelvic fracture.

Injury Predictor	25% prob. of fracture	50% prob. of fracture
Maximum Acetabular +Iliac force in SID IIsFRG	5200 N	6300 N

COMPARISON OF INJURY CRITERIA AND ASSOCIATED INJURY ASSESSMENT REFERENCE VALUES (IARVs)

Comparison of Injury Criteria and IARVs for 1) the EU side impact standard Directive 96/27/EC using the EuroSID-1, (2) Side Air bag Out-of-Position Injury Technical Working Group (Joint project of Alliance, AIAM, AORC, and IIHS) using the SID-IIs, (3) Prospoșed SID-IIs IARVs for the IIHS side impact program, (4) NHTSA frontal in-position FMVSS 208 using the HIII-50M and HIII-5F, and (5) Proposed FMVSS 214 upgrade using the ES-2re and SID-IIsFRG.

Body Region	EU 96/27/EC EuroSID1	TWG SID IIs	IIHS SID IIs		FMVSS 208 (2000)		FMVSS 214 proposed	
			Good	Accept	HIII 50M	HIII 5F	ES-2re	SID-IIsFRG
Head	HPC= 1000	HIC15= 779	HIC15= 623	HIC15= 779	HIC15= 700	HIC15 =700	HIC36= 1000	HIC36= 1000
Neck	NA	Nij=1 T=2070 N C=2520 N	T=2.1 kN C=2.5 kN	T=2.5 kN C=3 kN	Nij=1 T=4170 N C=4000 N	Nij=1 T=2620 N C=2520 N	NA	NA
Chest	D=42 mm VC=1.0	D=34 mm, V=8.2 m/s	Davg=34 mm, VC=1 m/s V=6.6 m/s	Davg=42 mm, VC=1 m/s, V=8.2m/s	Chest g =60 gs D=63 mm	Chest g =60 gs D=52 mm	D=35 – 44 mm, T12Ax =82 gs	T12Ax =82 gs
Abdomen	abdF= 2.5 kN	NA			NA	NA	abd F =2.4-2.8 kN	NA
Pelvis	Pubic F=6 kN	NA	Acet F=4 kN, Iliac F=4 kN Iliac+acet F=5.1 kN	Acet F=4.8 kN Iliac F=4.8 kN, Iliac+acet F=6.1 kN	NA	NA	Pubic F = 6 kN	Iliac+acet F = 5.1 kN
Lower Limbs	NA	NA	Thigh F= 2.8 kN, Femur M= 254 Nm	ThighF=3.4 kN Femur M=305 Nm	Femur F=6.8 kN	Femur F=10 kN	NA	NA

Head:
HPC is equivalent to unlimited HIC where t1 and t2 are two times between the initial contact and the last instant of contact. HPC is not computed when there is no head contact.
Neck:
T= maximum neck tension
C= maximum neck compression
Chest:
D= maximum thoracic rib deflection
Davg= average deflection of 5 ribs (thoracic and abdominal) on the SID-IIs
V= rate of deflection
T12Ax = maximum lower spine acceleration
Abdomen:
AbdF= maximum total abdominal force
AbdD = maximum abdominal rib deflection
Pelvis:
Pubic F= maximum Pubic force
Acet F= maximum acetabular force
Iliac F= maximum iliac force
Iliac+acet F= maximum of sum of iliac and acetabular force
Lower Limbs:
Femur F= maximum Axial femur force
Thigh F= maximum anterior-posterior/ lateral-medial femur force
Femur M= maximum anterior-posterior and lateral medial femur moment

INJURY CRITERIA DEVELOPMENT FOR THE ES-2re DUMMY

HEAD INJURY CRITERIA FOR THE ES-2re DUMMY

The morphology of rigid and semi-rigid tissues such as cranium and the falx cerebri impart a different set of initial conditions during lateral impacts in comparison to frontal impacts. Therefore, the injury criterion and the corresponding tolerance in lateral impact may be different from that in frontal impact. The Head Injury Criterion (HIC), used for assessing injury risk in frontal impacts, is based on repeated drop tests of embalmed human cadavers onto rigid and padded surfaces where the impact area was the forehead (Lissner et al. 1960, Hodgson et al. 1977). Though forehead impacts are representative of a frontal impact scenario, the ECE R95 directive and Euro NCAP continue to apply HIC for head injury assessment in lateral impact scenarios.

There is limited lateral head impact data available. McIntosh et al. (1996, 1993) conducted 16 lateral head impacts to unembalmed human cadaveric subjects with rigid and padded surfaces and found that maximum head acceleration was a better predictor of head injury than HIC. The injuries included brain injuries and/or skull fracture. The authors found a 50 percent risk of head injury corresponding to a HIC of 800 and maximum acceleration of 140 gs. More recently, Yoganandan et al. (2003) examined the risk of skull fracture in lateral impacts by conducting ten head drop tests into rigid and padded surfaces. Due to the small sample size from this preliminary study, Yoganandan did not estimate skull fracture threshold levels.

Takhounts et al. (2003) developed an omni-directional brain injury assessment tool called SIMon (Simulated Injury Monitor). It is designed to post process measured dummy head acceleration time histories and provide, via a finite element model of the brain within a skull, the probability of occurrence of two types of serious brain injuries, Diffuse Axonal Injury (DAI) and focal lesions. SIMon automatically compensates for different impact directions by using actual skull and brain geometry within the model. Currently, SIMon is under evaluation by various research groups around the world. More research is needed to better understand head injury tolerance in lateral impacts and for using advanced tools such as SIMon.

Since FMVSS No. 201 and the EU Side Impact Directive 96/EC/27 successfully demonstrated the use of HIC36 for head injury assessment in lateral impacts, HIC36 is suitable for use in FMVSS 214.

HIC36 is defined as in Equation 1.

$$HIC36 = \max\left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a(t)dt\right]^{2.5}(t_2 - t_1) \qquad (1)$$

$$\textit{where } a(t) \textit{ is the resultant head acceleration}$$
$$\textit{and } (t_2 - t_1) \leq 36\, m\sec$$

Hertz (1993) analyzed the head drop test data documented by Mertz and Prasad (1985) using parametric survival methods for doubly censored data assuming a lognormal underlying distribution of failure threshold levels. The injured data were considered left censored and the uninjured data were considered right censored. The resulting injury risk functions are presented in Equation 2 and Figure 1.

$$p(fracture) = \phi\left(\frac{\ln(HIC36) - \mu}{\sigma}\right) \quad (2)$$

where φ is the cumulative normal distribution and μ=6.96352 and σ=0.84664 for AIS 2+ head injuries, μ=7.45231 and σ=0.73998 for AIS 3+ head injuries, and μ=7.65605 and σ=0.60580 for AIS 4+ head injuries.

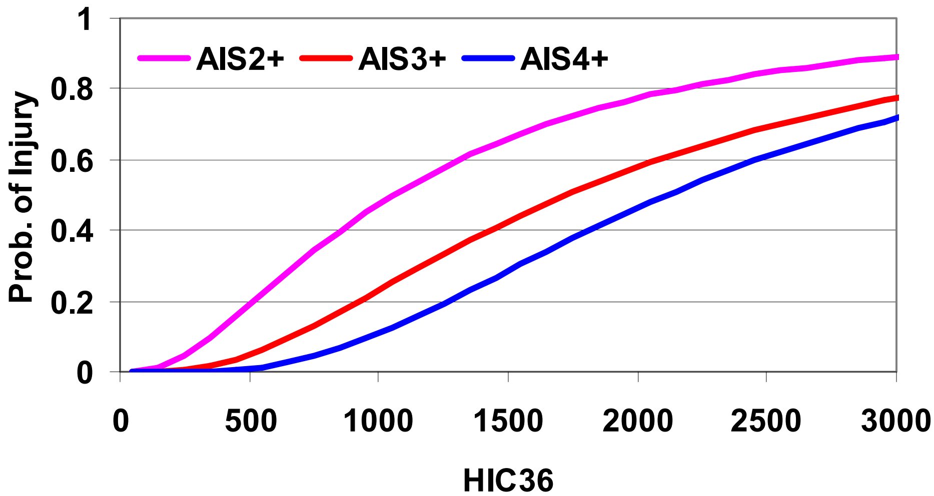

Figure 1. Probability of AIS 2+, 3+, and 4+ head injury as a function of HIC36.

The HIC36 values at 25% and 50% risk of AIS 2+, 3+, and 4+ head injury are presented in Table 1.

Table 1. Values of HIC36 at 25% and 50% risk of AIS 2+, AIS 3+, and AIS 4+ head injury for a 50th percentile adult male.

Injury Predictor	25% prob. of injury			50% prob. of injury		
	AIS 2+	AIS 3+	AIS 4+	AIS 2+	AIS 3+	AIS 4+
HIC36	600	950	1400	1050	1680	2113
Std. Error	482 - 745	744 - 1212	1122 -1747	896 - 1231	1410 - 1930	1796 - 2465

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THORACIC INJURY CRITERIA

INTRODUCTION

Thoracic injury criteria in side impact has been developed and evaluated by various researchers. The Thoracic Trauma Index, TTI, a chest acceleration-based criteria, combined with anthropometric data was developed by the National Highway Traffic Safety Administration (Eppinger, et al., 1984, Morgan et al., 1986) and was included in the FMVSS 214 side impact protection standard in 1990.

Tarriere et al. (1979) analyzed force deflection data of the struck side of the thorax in a series of cadaver lateral drop tests onto an unpadded and padded force plate. They found chest compression to correlate better with thoracic injury than thoracic accelerations. Based on the results from these studies, the EU side impact standard employs a rib deflection injury threshold of 42 mm and a VC threshold of 1.0 m/s.

Lau and Viano (1986) proposed the viscous criteria (VC), a function in time formed by the product of the velocity of chest deformation, V(t), and the instantaneous compression, C(t). Viano et al. (1989) also conducted sixteen lateral impacts to the thorax of whole body cadavers and found that the maximum viscous response, VCmax, and maximum chest compression were significantly better predictors of thoracic injury than spinal accelerations. Logistic regression of this data indicated a 50 percent risk of AIS 3+ thoracic injury with 33 percent of chest deflection with respect to total width and a VC of 1 m/sec.

Cavanaugh (1992) proposed ASA (average spine acceleration) as a predictor of thoracic injury in side impact. ASA is computed as the slope of a line joining 15% and 85% of maximum velocity points on the lower spine velocity curve obtained by integration of the corresponding measured acceleration time history.

Kallieris (1994) conducted forty-two side impact tests with human cadavers in the age range 18 to 65 years located at the near side passenger seat in 90 degree car to car lateral collisions. Analysis of the data indicated age of the subject at the time of death was the best predictor of thoracic injury followed by TTI. Rib deflections, which were computed from rib accelerometer data, were not as good predictors of injury as TTI.

Pintar, et al. (1997) analyzed the data from a series of twenty-six human cadaver sled tests using the Heidelberg type sled system. Pintar proposed the use of TTI*C formed by the product of TTI and normalized chest deflection as a predictor of thoracic injury in side impacts. Kuppa, et al. (2000) analyzed 34 cadaveric side impact sled tests using various statistical techniques such as ANOVA, linear regression, logistic regression, and categorical analysis. The age of the subject was found to influence injury severity significantly ($p<0.05$) while gender and mass had little influence on injury outcome. This analysis indicated that maximum normalized resultant upper spine acceleration was the best individual predictor of injury severity followed by maximum normalized chest deflection and TTI. A model using a linear combination of age, maximum normalized chest deflection, and maximum normalized resultant upper spine acceleration was the best predictor of thoracic injury.

Wang (1989) in an analytical study and Chung (1999) based on lateral pendulum impacts to cadaveric subjects concluded that injury criteria based on stored energy is a better predictor of thoracic injury than is TTI, chest deflection, or VC.

Viano et al. (1995) evaluated the biofidelity of the side impact dummies - EuroSID-1 and the BioSID. Viano et al. correlated the responses of the EuroSID-1 dummy to cadaver responses in similar cadaveric pendulum impact tests published in 1989 and developed thoracic injury criteria that can be directly applied to the EuroSID-1 dummy. According to this injury criterion, a 50% risk of AIS 3+ thoracic injury corresponds to maximum ES-1 measured rib deflection of 57 mm and a VC of 1 m/s.

The current study is an extension of the Pintar (1997) and the Kuppa (2000) studies. The previous two analyses developed injury criteria based on measurements on the cadaveric subject. In order to develop injury criteria for use with the ES-2re, analysis was also conducted using the injury response from the cadaveric sled test data and the physical measurements made on the ES-2re in similar paired sled tests. The resulting injury criteria can be directly applied to the ES-2re without any need for adjustment to account for the differences in measured responses between cadaveric subjects and the ES-2 dummy under similar impact conditions. Such an approach was utilized by ISO, Working Group 6, (ISO, 2003) for developing injury criteria and risk curves for the EuroSID-1.

The current study has an expanded data set of sled tests using cadavers and the ES-2re dummy compared to the Kuppa, et al. (2000) study. This work has already been published at the 2003, Forty-Seventh Stapp Car Crash Conference (Kuppa et al., 2003).

TEST METHODOLOGY

A series of 42 side impact sled tests using fully instrumented human cadaveric subjects and 16 sled tests using the ES-2re were conducted at the Medical College of Wisconsin (MCW). MCW utilized a deceleration sled with a Heidelberg type side impact sled apparatus (Pintar et al., 1997) configured for left side impacts (Figure 2). The test surrogate was seated on a bench at a specific distance away from the impact wall. Due to sled deceleration, the surrogate slides down the bench and strikes the wall surface. Unlike previous Heidelberg side impact sled setups (Cavanaugh et al., 1993, Kallieris et al., 1981), the height of the wall was adjusted such that the shoulder did not contact the wall. This configuration was selected to represent door contact in side impact crashes where the shoulder is above the level of the windowsill for a mid-size male.

The impact surface consisted of four plates configured such that the upper plate impacted the thorax, the middle plate impacted the abdomen, the lower plate impacted the pelvis, and the lowest plate served as a contacting surface for the lower limbs. The four plates were instrumented with load cells to measure the impact force. The impact surface was either a flat wall or offset by 12 cm at the level of the pelvis, the abdomen, or the thorax. The impact surface was either rigid (with no padding) or padded with 10 cm of Ethafoam, LC 200 padding. Four tests were also conducted with door mounted and seat mounted side air bags. Side impact tests were conducted at two speeds (24 km/h and 32 km/h).

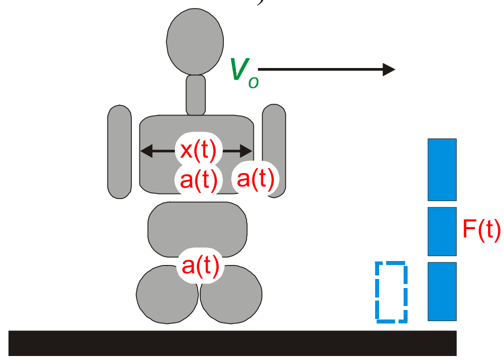


Figure 2. Schematic of the MCW sled test configuration with a pelvic offset.

The detailed description of cadaver preparation and instrumentation, as well as injury assessment is provided in Kuppa, et al. (2000, 2003) and Pintar, et al., (1997). The cadavers were instrumented with triaxial accelerometers fixed to T1 or T2 vertebra, T12 vertebra, and sacrum; uniaxial accelerometers fixed to the left lateral portion of rib 4 and rib 8 to measure medial-lateral accelerations; and a uniaxial accelerometer fixed to sternum to measure anterior-posterior acceleration. Instrumentation on the cadaver also included two 40 channel chest bands wrapped around the chest at the level of the 4th rib and the 7th rib. The load wall was instrumented to measure impact forces at the levels of mid thorax, abdomen, and pelvis.

Immediately after the test, the cadaveric body was radiographed in various directions and angles to assess bony damage. A detailed autopsy was done after each test to assess the trauma to the hard and soft tissues. Autopsy information was used to document the number and location of rib fractures, the possibility of related hemo/pneumo thorax and flail chest, as well as any other soft tissue injury.

The ES-2re dummy was fully instrumented in the corresponding side impact sled tests. The instrumentation on the ES-2re included triaxial accelerometers at the upper spine, lower spine, and pelvis; uniaxial accelerometers at the upper and lower ribs; three rib deflection gauges; and load cells at the abdomen and pubic symphisis.

DATA ANALYSIS

Processing of transducer data and normalization of measurements for the cadavers were conducted in a similar manner as outlined by Kuppa, et al. (2003). Rib and spinal accelerations were filtered with SAE filter Channel Class 180. The thoracic, abdominal, and pelvic force signals were filtered with SAE filter Channel Class 600. Chest displacements were processed with SAE filter Channel Class 180. The acceleration and forces were normalized using the equal velocity-equal stress scaling procedure outlined by Eppinger, et al. (1984) to represent the responses for a 50th percentile male (Equations 3 and 4).

$$acceleration_{norm} = acceleration \times \left(\frac{mass\,(kg)}{75} \right)^{1/3} \qquad (3)$$

$$force_{norm} = force \times \left(\frac{75}{mass\,(kg)} \right)^{2/3} \qquad (4)$$

$$\text{where } mass\,(kg) \text{ is the total mass of subject}$$

TTI for cadavers was computed according to Eppinger et al. (1985) that include the effect of age and mass of the subject. For the computation of TTI, the accelerations at the 4th rib (rlu), the 8th rib (rll), and the lower spine acceleration (spl) were processed using FIR100 filter (Equation 5). The average spine acceleration (ASA) was computed and normalized according to ASA20, defined by Cavanaugh (1993) (Equation 6). ASA20 was computed as the slope of the line joining the points 20% and 80% of maximum velocity on the lower spine velocity curve. ASA20 was used since preliminary data analysis suggested that ASA20 was better correlated to injury than ASA10 or ASA15 as defined by Cavanaugh (1993).

$$TTI = 1.4 \times age + \frac{1}{2}\left(rib_{\max} + spl\right) \times \frac{mass\,(kg)}{75} \qquad (5)$$

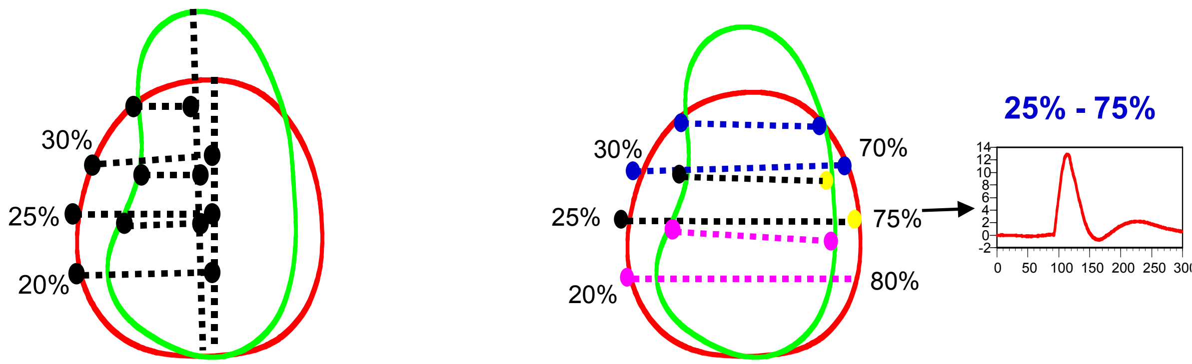
$$\text{where } rib_{\max} \text{ is the } \max.\text{ of } (1.3 \times rlu - 2.02) \text{ and } rll$$

$$ASA = ASA20 \times \frac{age}{45} \times \frac{mass\,(kg)}{75} \qquad (6)$$

TTI_{kernel} was computed as in Equation 5 without the age term (1.4xage). ASA_{kernel} was computed according to Equation 6 with age/45 term set to 1.0.

Full and half thorax deflections were computed using upper and lower chest band data at every millisecond during the impact event as outlined by Kuppa, et al. (2003). The centerline of the spine was considered as the origin of the contour and the sternum was considered to be the point along the band circumference at a distance of 50% of the circumference. Starting at the spine and following the contour in a clockwise direction, and considering the entire circumferential distance as 100%, three locations were marked at 20%, 25%, 30%, 70%, 75%, and 80% of the contour's circumference for each deformation contour. Full thorax deflections were obtained from the distance between 20% and 80% points on the circumference and similarly between 25% and 75% points and 30% and 70% points on the circumference. Half thorax deflections were obtained from the perpendicular distance between the 20%, 25%, and 30% points and the mid-sagittal line joining the spine to the sternum. While computing half thorax deflections, the sternum and spine locations were assumed to remain at 50% and 0% along the contour circumference through out the event. Full and half thorax chest deflections were normalized with respect to initial full thorax width before the impact event at the location of deflection computation.

The full and half thorax rate of deflection (V) was obtained by differentiating the deflections processed by SAE filter Channel Class 180. The Viscous Criterion (VC) was obtained as the product of the rate of deflection (V) and the normalized thoracic deflection. Full and half thorax average normalized deflections, V, and VC were computed for each band as the average of the three normalized deflections, V, and VC, respectively, of each band.



Half Thorax Deflections Full Thorax Deflections

Figure 3. Computation process of half thorax deflections using chest contours developed using chest band data.

Maximum normalized full and half thorax deflections were determined as the maximum among the 6 computed normalized deflections between the two bands. The average normalized full and half thorax deflections for each band was computed as the average of the 3 normalized deflections computed on each band (Figure 3). The average normalized deflection for each subject was determined as the maximum of the computed normalized average band deflection for the two chest bands.

No normalization of data was conducted for the ES-2 measurements. Only the kernels of TTI and ASA were computed for the ES-2re without considering the age and mass of the dummy.

STATISTICAL METHODS

The statistical analysis using the cadaver data was done in a similar manner as that outlined by Kuppa, et al., (2003). The dependent variable in the analysis was the severity of injury sustained by the subject in the form of either, 1) a dichotomous variable: MAIS<3 and MAIS≥3, 2) a dichotomous variable: MAIS<4 and MAIS≥4, or 3) an ordinal variable: MAIS<3, MAIS=3, and MAIS≥ 4. The explanatory variables examined were derivatives of measured mechanical parameters such as accelerations, deflections, and forces, as well as subject characteristics such as age, mass, and gender.

Since the data is doubly censored, analysis was conducted using logistic regression. The goodness of fit and the predictive ability of the model was determined as outlined by Kuppa, et al. (2000). The goodness of fit of the full model was assessed using the p-value of the score statistics. The significance of a covariate in a model was assessed using the p-value of the Wald Chi-square. That is, a lower p-value of the score statistics and the Wald Chi-Square is indicative of a better goodness of fit of the whole model and of a greater significance of the covariate in the model, respectively. The predictive ability of the model was assessed using Goodman-Kruskal Gamma. A Gamma value of 1 indicates perfect predictive ability while a zero indicates no predictive ability of the model. Higher values of Gamma indicate better predictive ability of the model. The predictive ability of the model can also be assessed by the C parameter which is the area under the ROC curve (receiver-operator curve). The C parameter is a function of sensitivity (true positive) and 1-specificity (false positive) of the model. For a given level of the predictor function, the sensitivity is the proportion of injured subjects correctly predicted to be injured, and the false positive rate is the proportion of uninjured subjects wrongly predicted to be injured.

Analysis was also conducted using the injury response from the cadaver tests and the measurements from the equivalent ES-2re dummy tests. When more than one dummy test was conducted for a specific test condition, the dummy measurements from the repeat tests were averaged. The dummy test data were quite repeatable and so the average response was similar to the individual test responses. The subject anthropometric data such as age, gender, and mass were included in these analyses since they may influence the injury outcome.

RESULTS

Figure 4 presents a summary of the cadaver tests conducted in various test conditions. The detailed results of the cadaver side impact sled test data are presented in Appendix A.

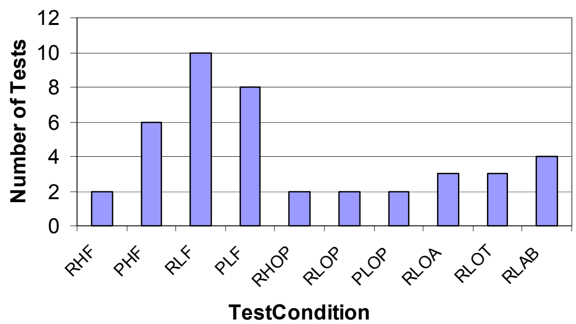


Figure 4. Number of cadaver tests in different test conditions.
RHF: *high speed test (32 km/h) with rigid flat wall,* ***PHF:*** *high speed test with padded flat wall,*
RLF: *low speed test (24 km/h) with rigid flat wall,* ***PLF:*** *low speed test with padded flat wall,*
RHOP: *high speed test with pelvic offset rigid wall,* ***RLOP:*** *low speed test with pelvic offset rigid wall,*
PLOP: *low speed test with pelvic offset padded wall,* ***RLOA:*** *low speed test with abdominal offset rigid wall,*
RLOT: *low speed test with thoracic offset rigid wall,* ***RLAB or ABG:*** *low speed test with air bag on rigid wall.*

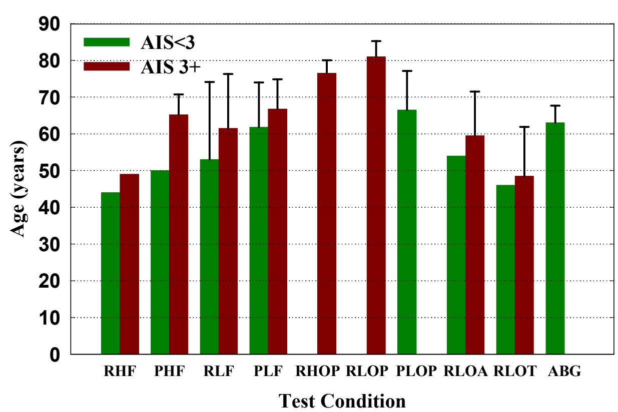


Figure 5. Mean age of subject at the time of death by test condition and injury outcome.

Mean age of subjects in the MCW tests was 61.7±12.8 years. Among the 42 subjects in this test series, 13 were female. Figure 5 presents the mean age of subjects in different test conditions and for different injury outcomes. The mean age of AIS 3+ injured subjects (64.2±12.3 years) is higher than those with no injury or AIS<3 injuries (58.3±13 years). This difference in age was however non-significant due to the small sample size in each test condition.

The injury sustained by the subject was coded according to the Abbreviated Injury Scale (AIS) (1990). The maximum thoracic AIS injury (MAIS) for all the subjects in this test series was due to the number of rib fractures and associated soft tissue injury (hemo/pneumo thorax) or flail chest. Eighteen subjects were uninjured or sustained AIS<3 thoracic injury, 11 subjects sustained AIS=3 injury and 13 subjects sustained AIS≥4 thoracic injury (Figure 6). Two subjects in the abdominal offset tests sustained kidney lacerations of AIS=3 severity which were considered to be abdominal injuries. One subject in a thoracic offset test also sustained a laceration at the superior aspect of the left kidney that was attributed to displaced rib fractures. None of the subjects in this test series sustained liver or spleen injuries. Some subjects in the rigid wall pelvic offset tests sustained pelvic fractures.

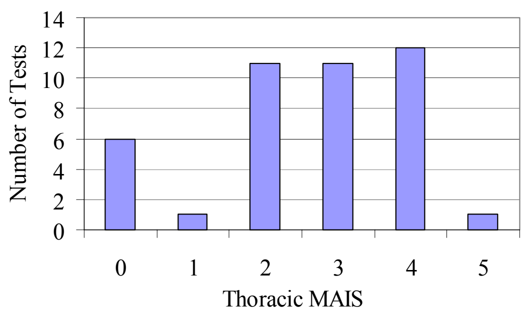


Figure 6. Number of sled tests versus maximum thoracic AIS sustained by the subject.

The number of rib fractures as a function of the corresponding maximum thoracic injury AIS levels sustained by the subjects are presented in Figure 7. The mean and standard deviation of the number of rib fractures at different assigned AIS levels for the 42 subjects are also shown in Figure 7. The number of rib fractures separate AIS levels 0, 1, 2, and 3. However, there is significant overlap in the number of rib fractures between the AIS=3 and AIS=4 injury severities. The mere number of rib fractures was not a good indicator of the severity of injury due to the varied severity of rib fractures (undisplaced or displaced).

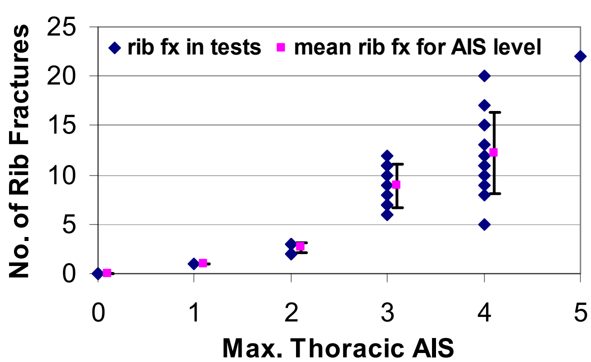


Figure 7. Number of rib fractures for different maximum thoracic AIS.

Statistical Analysis Results

ANOVA analysis was conducted to determine which mechanical parameters were good predictors of injury. Maximum and average normalized full and half thorax deflection were found to distinguish AIS 3+ injuries and AIS 4+ injuries reasonably well. Figure 8 is a plot of mean average half thorax deflections in different test conditions. The deflections are significantly lower (p-value=0.0001) when the injury outcome is AIS<4 than the case for AIS≥4 for all applicable test conditions. The same is true for injury outcome classified as AIS<3 and AIS 3+. For presentation purposes, the normalized deflection was multiplied by the chest width of the ES-2re that is equal to 327 mm. This is the approximate chest width of a 50th percentile male.

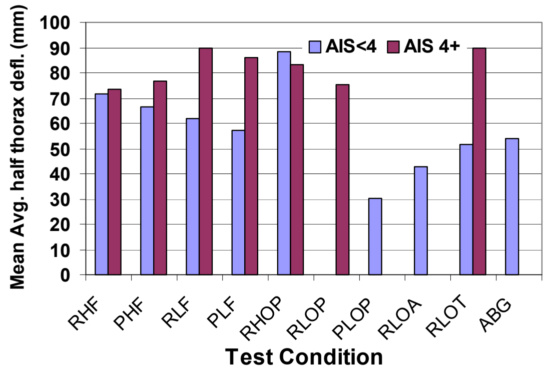


Figure 8. Mean average half thorax deflection in different test conditions and injury outcome.

Similarly, TTI (Figure 9) and resultant upper spine acceleration were also able to separate AIS <3 from AIS≥3 tests indicating that TTI and resultant upper spine accelerations were good predictors of thoracic injury as noted by Pintar (1998) and Kuppa (2000).

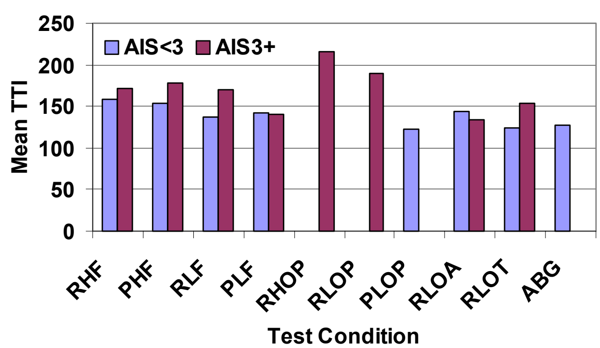


Figure 9. Mean TTI in different test conditions and injury outcome.

In order to study the effects of various parameters simultaneously, parametric regression was conducted on the doubly censored side impact sled test data. Logistic regression analysis was conducted using three different forms of injury outcome as the response (nominal response: AIS<3 and AIS≥3; nominal response: AIS<4 and AIS≥4; ordinal response: AIS<3, AIS=3, and AIS≥4). The age of the subject appears to have some influence on injury outcome as noted in Figure 6 and so, age of the subject was included in all the models. The results of the analysis are presented in Tables 2, 3, and 4. The results indicate that deflections are the overall best predictors of injury. TTI is the next best predictor of injury. Maximum resultant upper spine acceleration and maximum rib acceleration were good predictors of injury as well. Viscous Criterion was a better predictor of AIS 4+ injuries than AIS 3+ injuries. Stepwise and backward regression indicated that a linear combination of age and maximum deflection is the best predictor of injury.

Table 2. Statistical Models and their respective goodness of fit and Predictive ability for injury outcome as a dichotomous variable AIS<3 and AIS 3+

AIS 3+	P-Value				
Models	LR	Score	Wald	Gamma	C
age, peak norm. half thorax Defl	0.0004	0.0013	0.007	0.725	0.86
age, peak norm. full thorax Defl	0.0015	0.003	0.0106	0.675	0.837
age, max. norm avg. half thorax Defl.	**0.0001**	**0.0005**	**0.0051**	**0.745**	**0.873**
age, Vcmax_half thorax	0.0228	0.0532	0.0691	0.477	0.738
TTI	**0.0002**	**0.0007**	**0.0038**	**0.613**	**0.806**
ASA	0.1082	0.1219	0.1385	0.292	0.643
age, TTIkernel (no age term)	0.0002	0.0009	0.0069	0.741	0.87
age, result. Upper spine accel	0.0023	0.0059	0.0183	0.615	0.807
age, ribmax	0.0001	0.001	0.0106	0.697	0.848

Table 3. Statistical Models and their respective goodness of fit and Predictive ability for injury outcome as a dichotomous variable AIS<4 and AIS 4+

AIS 4+	P-Value				
Models	LR	Score	Wald	Gamma	C
age, peak norm. half thorax Defl	0.0001	0.0004	0.0203	0.817	0.908
age, peak norm. full thorax Defl	0.0001	0.0011	0.0215	0.8	0.9
age, max. norm avg. half thorax Defl.	**0.0001**	**0.0004**	**0.0119**	**0.817**	**0.908**
age, Vcmax_half thorax	0.0004	0.0017	0.0205	0.711	0.856
TTI	0.0007	0.0014	0.0071	0.648	0.824
ASA	0.1314	0.1234	0.148	0.252	0.623
age, TTIkernel (no age term)	0.0097	0.015	0.0429	0.633	0.816
age, result. Upper spine accel	0.0006	0.0013	0.0138	0.697	0.846
age, ribmax	0.0324	0.0489	0.0695	0.566	0.782

Table 4. Statistical Models and their respective goodness of fit and Predictive ability for injury outcome as a ordinal variable AIS<3, AIS=3 and AIS 4+

AIS 3, AIS 4+	P-Value				
Models	LR	Score	Wald	Gamma	C
age, peak norm. half thorax Defl	0.0001	0.0001	0.0008	0.687	0.843
age, peak norm. full thorax Defl	0.0002	0.0005	0.0025	0.628	0.814
age, max. norm avg. half thorax Defl.	**0.0001**	**0.0001**	**0.0004**	**0.753**	**0.877**
age, Vcmax_half thorax	0.0018	0.0105	0.0141	0.476	0.737
TTI	0.0001	0.0002	0.0009	0.56	0.778
ASA	0.0655	0.0838	0.0728	0.259	0.627
age, TTIkernel (no age term)	**0.0001**	**0.0005**	**0.0014**	**0.647**	**0.823**
age, result. Upper spine accel	0.0003	0.0017	0.0029	0.564	0.781
age, ribmax	**0.0001**	**0.0004**	**0.0023**	**0.631**	**0.815**

Since the injury predictive models use age, the average age of the driving population involved in side impact crashes was determined using the NASS-CDS database for the years 1993-2001. The mean age of drivers involved in side crashes as a function of height and injury outcome is presented in Figure 10. The mean age of a mid-size driver (5 ft. 4 in. to 5 ft 11.5 in. height) who is uninjured or sustained MAIS<3 injuries is 38 years while that of a mid-size driver who sustained MAIS≥3 injury is about 45 years. Similarly, the average age of a driver who sustained MAIS≥4 injury is also approximately 45 years. Therefore, the injury functions, with age included as a covariate, were normalized by applying an age=45 years in the models.

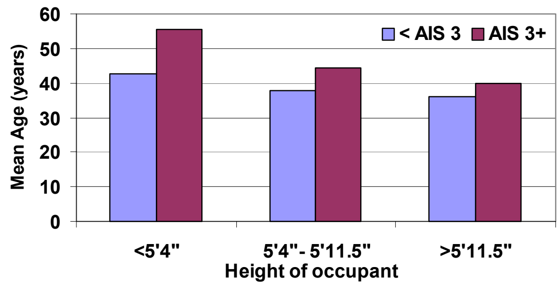


Figure 10. Mean age of small, mid-size, and large drivers involved in side crashes from NASS-CDS (1993-2001).

The results of this analysis were compared to previous published literature. The data of seventeen side impact sled tests (Appendix C) conducted by Cavanaugh et al. (1993) was analyzed using logistic regression. The probability of AIS 4+ injury as a function of age and half thorax deflections using Cavanaugh data is presented in Figure 11 along with the risk of AIS 3+ and 4+ injury from the current study as a function of peak half thorax deflections. The half thorax deflections have been normalized by the full thorax width of each subject. Since the injury risk functions have age as a parameter, an age of 45 years (average age of front seat occupants in passenger cars over age 15 who sustain AIS 3+ injury in a side impact) was used in these risk curves.

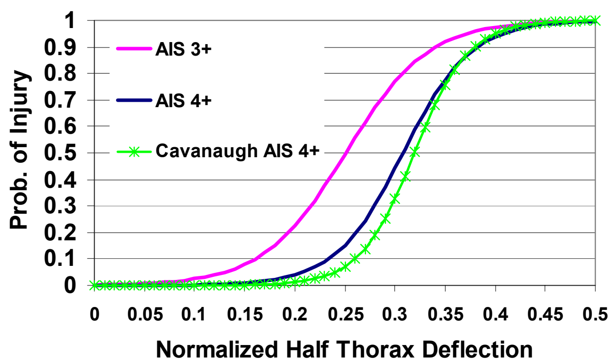


Figure 11. Probability of AIS 3+ and AIS 4+ thoracic injury as a function of peak normalized half thorax deflections.

Viano et al. (1998) conducted pendulum impacts on 16 cadaveric subjects and found that chest deflection and VC were the best predictors of AIS 4+ thoracic injury but none of the measured parameters were significant predictors of AIS 3+ thoracic injuries. The probability of AIS 3+ and 4+ thoracic injury as a function of normalized full thorax deflections from the current study along with the AIS 3+ and AIS 4+ injury risk curve developed by Viano using normalized full thorax deflections are presented in Figure 12.

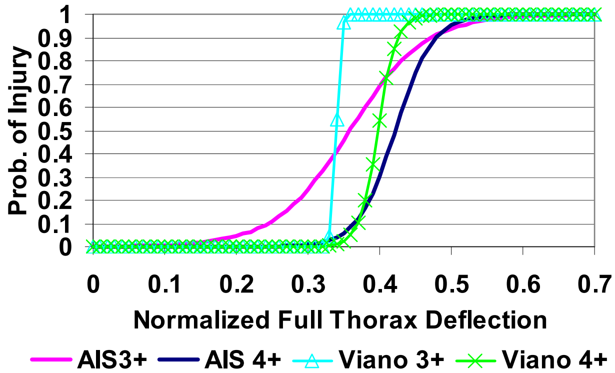


Figure 12. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of normalized full thorax deflections from the current study and Viano (1989).

Kent et al. (2004) conducted survival analysis on doubly censored data. In the current study, logistic regression was used. The data was reanalyzed using survival analysis procedures with Weibull and log-normal as the underlying distributions and subject age as a covariate. In general, the resulting injury risk curves from survival analysis were similar to that developed from logistic regression as shown in Figure 13. Survival analysis does not allow for ordinal dependent variable. Therefore, for consistency in comparison, the logistic regression injury risks curves, presented in Figure 13, were developed using the dependent variable in the dichotomous form of AIS<3, AIS≥3 and AIS<4, AIS≥4.

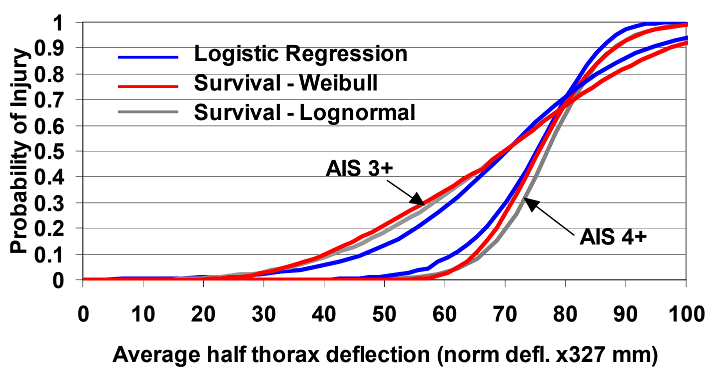


Figure 13. Risk of AIS 3+ and AIS 4+ injury as a function of average half thorax deflection for a 45 year old using logistic regression with logit as the link function, survival methods using Weibull and Lognormal as the underlying distribution.

Since the AIS 3+ and 4+ injury risk curves overlap when the analysis is conducted separately using a dichotomous dependent variable (as in Figure 13), the dependent variable was considered as an ordinal variable – AIS <3, AIS=3 and AIS>3. The probability of injury and standard error corridors as a function of average half thorax deflections, obtained from logistic regression assuming an ordinal dependent variable, for a 45 year old 50th percentile male is shown in Figure 14. The normalized average half thorax deflections were multiplied by the ES-2 chest width of 327 mm and the risk curves were computed for a 45 year old.

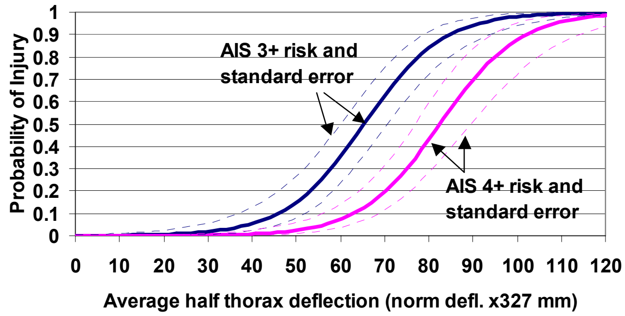


Figure 14. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of average half thorax deflections for a 45 year old 50th percentile male.

The probability of injury as a function of TTI from the current test data is presented in Figure 15. The TTI values of the combined side impact test data reported by Eppinger et al. (1984) and Cavanaugh et al. (1993) were analyzed and injury risk curves were developed as a function of TTI. This combined side impact data is reported in Cavanaugh et al. (1993). The risk curve developed from the analysis of this combined data is also presented in Figure 15. A 25% risk of AIS 3+ injury corresponds to a TTI value of 130 with the risk curve from the current study as well as that from the combined data of Eppinger et al. (1984) and Cavanaugh et al. (1993).

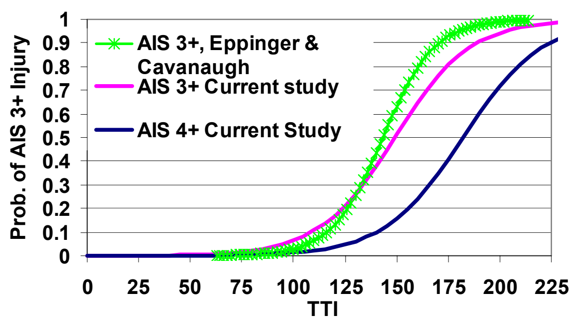


Figure 15. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of TTI from current study and from the combined data of Eppinger et al. (1984) and Cavanaugh et al. (1993).

Kallieris (1994) analyzed 42 cadaveric side impact vehicle crash tests at 40 to 60 km/h closing speed as well as 24 km/h and 32 km/h side impact sled tests. The analysis indicated age of the subject and TTI to be the best predictors of injury. Kallieris found a 25% and 50% probability of AIS 4+ injury was associated with TTI=140 and TTI=155, respectively. In this current study, 25% and 50% risk of AIS 4+ injury is associated with TTI=155 and TTI=180, respectively.

The TTI_{kernel} (by subtracting the age term, 1.4 x age, from the TTI value) from the combined Eppinger et al. (1984) and Cavanaugh et al. (1993) data was also analyzed with age as a separate covariate. The injury risk curves for a 45 year old 50th percentile male based on TTI_{kernel} from the current dataset as well as that derived from the combined data of Eppinger et al. and Cavanaugh, et al. are presented in Figure 16. The AIS 3+ injury risk curves from both data sets are very similar while the AIS 4+ injury risk curves differ.

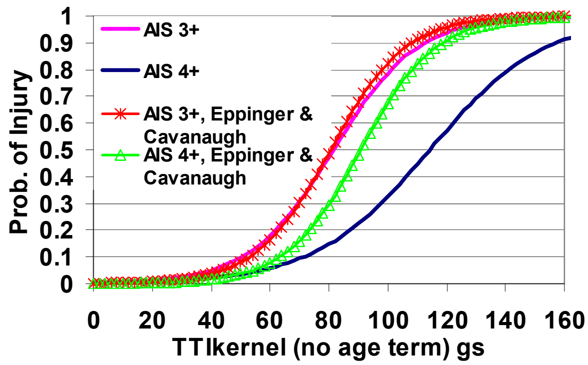


Figure 16. Probability of AIS 3+ and AIS 4+ thoracic injury as a function of TTI_{kernel} derived from the current study as well as from the combined data of Eppinger et al., 1984 and Cavanaugh et al., 1993.

Upper spine acceleration was also found to be a good predictor of thoracic injury for the 42 sled tests conducted at MCW. The risk of thoracic injury as a function of resultant upper spine accelerations for a 45 year old 50^{th} percentile male is presented in Figure 17. The normalized upper spine acceleration data from the 17 cadaver sled tests conducted by Cavanaugh et al. (1993) were also analyzed and the risk of AIS 4+ injury for a 45 year old 50^{th} percentile male is also presented in Figure 17.

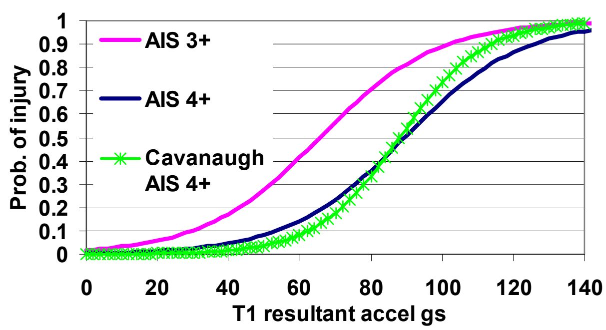


Figure 17. Probability of thoracic injury as a function of resultant upper spine acceleration for a 45-year-old, 50th percentile male from the current dataset and from Cavanaugh et al. (1993) for AIS 4+ injuries.

The logistic regression analysis indicated that normalized deflections, TTI, and resultant upper spine acceleration along with age of the subject as the confounding influence were the best predictors of injury for all forms of injury outcome considered. In addition, the injury risk curves with these parameters, developed using the current data set, compared reasonably well with those derived from other published side impact test data. The injury risk functions are presented in Equations 7 to 12.

$$p(AIS3+) = \frac{1}{1+e^{(9.02937-0.03705\ *age-36.8232*norm.\ avg.\ half\ defl.)}} \quad (7)$$

$$p(AIS4+) = \frac{1}{1+e^{(10.96565-0.03705\ *age-36.8232*norm.\ avg.\ half\ defl.)}} \quad (8)$$

$$p(AIS3+) = \frac{1}{1+e^{(7.2448-0.048657\ *TTI)}} \quad (9)$$

$$p(AIS4+) = \frac{1}{1+e^{(8.7703-0.048657\ *TTI)}} \quad (10)$$

$$p(AIS3+) = \frac{1}{1+e^{(6.4606-0.0544*age-0.061*result.\ up.\ spine\ accel.)}} \quad (11)$$

$$p(AIS4+) = \frac{1}{1+e^{(7.9103-0.0544*age-0.061*result.\ up.\ spine\ accel.)}} \quad (12)$$

The effect of age of the subject was more prominent for the nominal injury response distinguishing AIS 3+ injury than the response distinguishing AIS 4+ injury. The values of selected injury parameters at 25% and 50% probability of AIS 3+ and 4+ injuries for a 45-year-old 50th percentile male are shown in Table 5.

Table 5. Point estimates of cadaveric measured predictor functions at 25% and 50% risk of AIS 3+ and AIS 4+ injury for a 45-year-old 50th percentile male.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Max. average rib deflection	17% or 56 mm	22% or 72 mm	20% or 65 mm	25% or 82 mm
TTI	126	155	150	180
TTI_{kernel}	66 gs	92 gs	82 gs	114 gs
Result. upper spine accel.	48 gs	70 gs	66 gs	90 gs

Sixteen sled tests were conducted in similar test configurations as those of the cadaver tests (Appendix B). For test conditions where more than one ES-2re dummy tests were available, the responses from the tests were averaged. In general, the responses of the ES-2re dummy in repeat tests were quite similar. The injury responses and the anthropometric data (age, gender, mass, and height) of the subjects were taken from the cadaver data and combined with the physical parameters (TTI, ASA, maximum half thorax deflection, spine accelerations, etc.) that are derived from ES-2re measurements in similar condition sled tests. The tests with airbags that were conducted with the cadavers were not repeated with the ES-2re dummy. Consequently, there are only 38 paired cadaver and ES-2re dummy tests conducted in similar test conditions.

The maximum rib deflection was determined as the maximum of the three rib deflections in the ES-2re. The half thorax deflections of the cadavers obtained from the chest band data are external measurements, which includes the skin and flesh deformation. However, the ES-2re deflection gauges measure rib deflection. In order to compare the cadaver and ES-2re deflection responses, the cadaveric normalized half thoracic deflections were multiplied by 327 mm (ES-2re chest width representing 50th percentile male chest width) and an estimated flesh thickness of 10 mm was deducted from the overall half thoracic deflections.

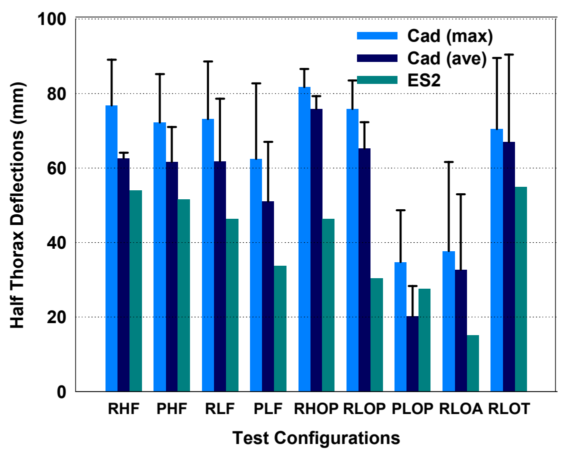


Figure 18. Maximum ES-2re rib deflections and cadaveric maximum and average half thorax deflections (estimated rib deflections) in different test configurations.

The ES-2re rib deflection responses were significantly lower ($P<0.001$) than the estimated maximum and average rib deflection of the cadavers for similar test conditions (Figure 18). Similarly, the upper spine accelerations of the ES-2re and mean cadaver response were significantly different (Figure 19) while the lower spine accelerations were not significantly different. This implies that injury criteria developed using cadaveric deflection and upper spine acceleration measurements cannot be applied to the ES-2re dummy directly.

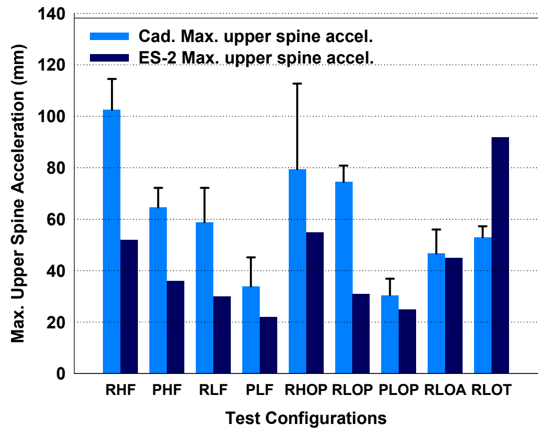


Figure 19. Maximum ES-2re and cadaveric upper spine acceleration in different test configurations.

The ES-2re rib deflections along with the subject age appears to reasonably track the average AIS levels sustained by subjects in different test configurations as is indicated in Figure 20. For similar average age, the maximum thoracic AIS are higher for the test conditions with greater ES-2re rib deflections. This suggests that ES-2re maximum rib deflection measurement may be a potentially good predictor of injury.

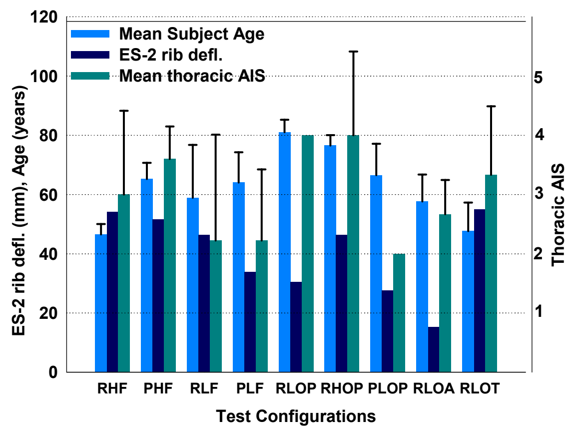


Figure 20. Mean age of subject, maximum ES-2re rib deflection, and mean thoracic AIS injury for different test configurations.

In the logistic regression analysis using cadaver injury and anthropometry information along with the ES-2re measurements, the age of the subject at the time of death was included in all the models since subject age was found to significantly influence the injury outcome ($p<0.05$). Gender and mass of the subject had poor association with injury outcome and were not included in these models. The results of the logistic regression analysis of the ES-2re/cadaver injury data (Tables 6, 7, and 8) indicate that ASA, derived from ES-2re lower spine acceleration, was the best predictor of thoracic injury (AIS 3+ and AIS 4+), followed by maximum rib deflection of the ES-2re. None of the models were significant predictors of AIS 3+ injury ($P<0.05$). The goodness of fit and the predictive ability of all the models were not as good as when cadaveric measured responses were used. Due to the small sample size in some of the test conditions, the average cadaver characteristics and injury response in each group may not be representative of the population. Therefore, variations in cadaver characteristics between groups that could not be accounted for in the injury model, may confound the effect of the ES-2re measured responses on injury outcome, thereby reducing the injury model's predictive ability.

While deflections were very good predictors of injury in the cadaveric test data, the ES-2re measured rib deflections were not as sensitive to changes in the injury outcome. This is partly due to the small sample size of cadaveric test data in some of the test conditions. Due to the small sample size, the differences in occupant characteristics between the various test conditions may have greater influence on the injury outcome than the ES-2re measured parameters. While examining injury criteria for frontal impacts, Kent et al. (2001, 2003) also found similar results in the analysis of cadaver and Hybrid III test data. Kent et al. (2001) found good predictive ability and goodness of fit (P<0.0001) of a model using only cadaver chest deflection and age of the subject. However, when Hybrid III chest deflections were employed Kent et al. (2003), other test characteristics such as restraint system, test speed, driver position, and age, mass, and gender of the subject had greater influence on injury outcome.

Upper and lower spine accelerations of the ES-2re were better predictors of AIS 3+ than AIS 4+ thoracic injury, while ES-2re rib deflections and VC were better predictors of AIS 4+ injury. Unlike the acceleration responses of the cadavers, the ES-2re experienced very little vertical acceleration. Consequently, resultant spinal accelerations of the ES-2re dummy were approximately the same as the corresponding lateral accelerations. Therefore, the analysis was conducted only with lateral accelerations.

Table 6. Statistical models and their respective goodness of fit and predictive ability for injury outcome as a dichotomous variable AIS<3 and AIS 3+ using ES-2re measurements.

AIS 3+	goodness of fit P-Value			Predictive Ability	
Model	LR	Score	Wald	Gamma	C
age, dmax	0.114	0.123	0.152	0.409	0.704
age, Vmax	0.115	0.133	0.164	0.379	0.689
age, VCmax	0.132	0.148	0.177	0.343	0.671
age, TTI	0.089	0.106	0.142	0.36	0.68
age, ASA	0.089	0.099	0.128	0.403	0.701
age, spu	0.091	0.103	0.139	0.367	0.683
age, spl	0.065	0.082	0.116	0.381	0.689
age, ribmax	0.116	0.129	0.163	0.367	0.683

dmax: max. rib deflection, **spu, spl:** max. upper and lower lateral spine accelerations, **ribmax:** max. rib accel., **Vmax:** max. rate of deflection, **VCmax:** max. VC.

Table 7. Statistical models and their respective goodness of fit and predictive ability for injury outcome as a dichotomous variable AIS<4 and AIS 4+ using ES-2re measurements.

AIS 4+	goodness of fit P-Value			Predictive Ability	
Model	LR	Score	Wald	Gamma	C
age, dmax	0.0472	0.0776	0.11	0.474	0.735
age, Vmax	0.1087	0.115	0.139	0.426	0.712
age, VCmax	0.105	0.115	0.141	0.444	0.722
age, TTI	0.141	0.147	0.175	0.389	0.694
age, ASA	0.0283	0.04	0.066	0.506	0.752
age, spu	0.11	0.116	0.151	0.444	0.722
age, spl	0.317	0.322	0.345	0.344	0.671
age, ribmax	0.142	0.146	0.177	0.368	0.683

Table 8. Statistical models and their respective goodness of fit and predictive ability for injury outcome as an ordinal variable AIS<3, AIS=3 and AIS 4+ using ES-2re measurements.

AIS Ordinal	goodness of fit P-Value			Predictive Ability	
Model	LR	Score	Wald	Gamma	C
age, dmax	0.0742	0.063	0.122	0.377	0.688
age, Vmax	0.0844	0.082	0.117	0.346	0.672
age, VCmax	0.096	0.0906	0.132	0.375	0.687
age, TTI	0.076	0.077	0.11	0.321	0.66
age, ASA	0.035	0.038	0.058	0.409	0.704
age, spu	0.0556	0.0674	0.0805	0.357	0.676
age, spl	0.115	0.105	0.164	0.319	0.659
age, ribmax	0.0807	0.091	0.107	0.346	0.672

Injury risk models were also developed by adding other measured parameters to the model with a linear combination of age and deflection. The addition of covariates to this model reduced the goodness of fit and did not improve its predictive ability.

Figures 21 through 23 present the AIS 3+ and AIS 4+ injury risk curves as a function of ES-2re measured maximum rib deflection, ASA, and upper spine acceleration, respectively. Since age is a parameter in all the injury models, the age of 45 years (that represents the average age of AIS 3+ injured drivers involved in side crashes) was used in the models.

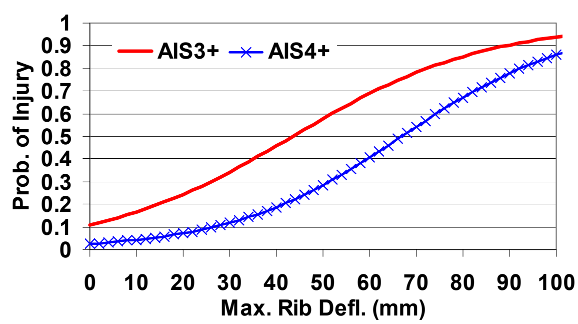


Figure 21. Probability of AIS 3+ and AIS 4+ injury as a function of maximum ES-2re rib deflection for a 45 year old 50th percentile male.

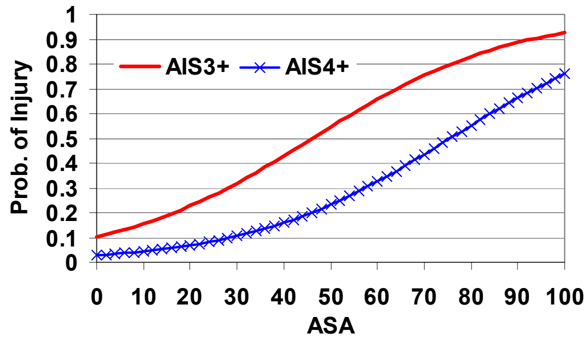


Figure 22. Probability of AIS 3+ and AIS 4+ injury as a function of ES-2re ASA for a 45 year old 50th percentile male.

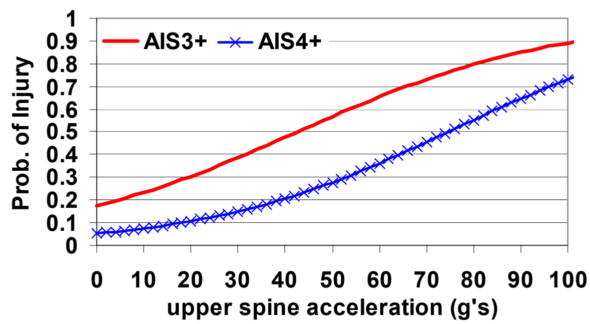


Figure 23. Probability of AIS 3+ and AIS 4+ injury as a function of ES-2re upper spine accelerations for a 45 year old 50th percentile male.

The injury risk curves in Figures 21 to 23 developed using logistic regression with a logit link function present a finite probability of injury at zero values of the injury parameter. This indicates that the goodness of fit and the predictive ability of the model are not good at low values of the injury parameter where no data is available in the current dataset. However, the risk curves are valid within the range of data that corresponds to rib deflection values between 15 to 54 mm, ASA values between 18 and 80 gs, and upper spine acceleration between 20 to 92 gs.

The AIS 3+ injury risk curve based on ES-2re maximum rib deflection for a 45 year old male and corresponding standard error corridors are presented along with the AIS 3+ injury risk curve proposed by the International Standards Organization (ISO) WG-6 (ISO, 2002) for the EuroSID-1 dummy in Figure 24. The AIS 3+ thoracic injury risk curve for the ES-2re from the current study is significantly different than that proposed by ISO for the EuroSID-1.

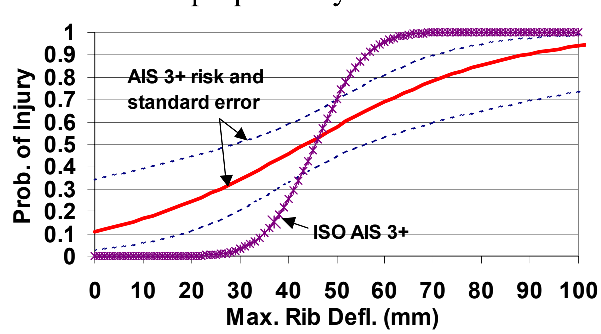


Figure 24. Risk of AIS 3+ injury based on max. rib deflection of the ES-2re dummy from the current study and of the EuroSID-1 dummy from ISO WG-6 (2002).

The test data used to develop the ISO injury risk curves included drop tests, pendulum tests, vehicle crash tests and sled tests with cadavers and the EuroSID-1 dummy. The current study only examined sled test data with cadavers and the ES-2re dummy. The ISO risk curve has been developed using an empirical method called the certainty method. Unlike the statistical methods used in this study, the empirical method employed by ISO cannot evaluate the goodness of fit or the predictive ability of the models. The injury response of the ISO data was categorized into the various AIS levels by the number of fractured ribs unlike the current study that examined number of rib fractures as well as underlying tissue and organ injury. The subject age was taken into account in the ISO analysis by altering the number of fractured ribs sustained by the subject. The current study included subject age as a separate covariate in the regression analysis. These differences in the injury response definitions, analysis methods and the dummy used are some factors causing the differences in the injury risk curves in Figure 24.

Kent et al. (2004) analyzed doubly censored data using survival methods while ISO used the certainty method. The current data set was re-analyzed using these two methods and compared to the injury risk curves developed using logistic regression. Survival analysis was conducted using the Weibull and Lognormal as the underlying distribution. The age of the subject was included as a covariate. The injury risk curves developed from logistic regression using dichotomous dependent variables (AIS<3, AIS 3+ and AIS<4, AIS 4+) were compared with the risk curves from the analyses using survival and certainty methods since they cannot be applied to data with ordinal dependent variables. As with logistic regression, survival analysis also indicated that the predictive ability of the models using ES-2re measurements were not as good as when cadaver measurements were used (p-value>0.01). The piece-wise continuous risk curve from the certainty method was smoothed and is also presented in Figure 25. The injury risk curves developed using logistic regression and survival methods suggest low sensitivity of risk of injury to amount of rib deflection. However, the risk curve from the certainty method is a good S-shaped curve even when age of the subject was not taken into account. This suggests that the certainty method may provide good S-shaped curves even when the data does not show good correlation with injury outcome.

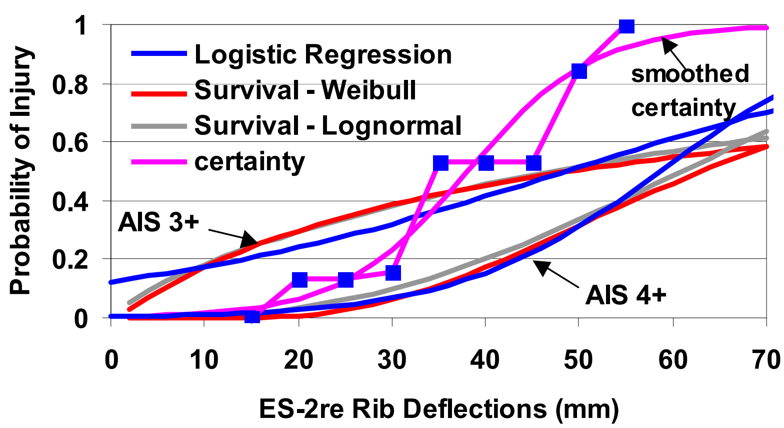


Figure 25. AIS 3+ and AIS 4+ thoracic injury risk curves developed using logistic regression, survival analysis and the certainty method.

The AIS 3+ and AIS 4+ thoracic injury functions based on ES-2re measured maximum rib deflection and ASA are presented in the Equations 13 to 18 along with AIS 3+ injury functions based on upper and lower spine accelerations. The age term in the logit was made constant by applying the age of 45 years. The injury functions therefore represent the probability of injury for the average mid-size male driving population. The point estimates as well as the standard error range of injury parameters at 25% and 50% risk of AIS 3+ and AIS 4+ thoracic injuries for a 45 year-old 50th percentile male are shown in Table 9.

$$p(AIS3+) = \frac{1}{1+e^{(2.0975-0.0482\ *\ \max.\ rib.\ defl.)}} \qquad (13)$$

$$p(AIS4+) = \frac{1}{1+e^{(3.4335-0.0482\ *\ \max.\ rib.\ defl.)}} \qquad (14)$$

$$p(AIS3+) = \frac{1}{1+e^{(2.1633-0.0469 * ASA)}} \qquad (15)$$

$$p(AIS4+) = \frac{1}{1+e^{(3.5428-0.0469 * ASA)}} \qquad (16)$$

$$p(AIS3+) = \frac{1}{1+e^{(1.56-0.0366\ *\ \max.\ upper\ spine.\ accel.)}} \qquad (17)$$

$$p(AIS3+) = \frac{1}{1+e^{(1.991-0.0254\ *\ (\max.\ lower\ spine\ accl.))}} \qquad (18)$$

Table 9. Point values and ranges of the ES-2re predictor functions at 25% and 50% risk of AIS 3+ and AIS 4+ injury – normalized with respect to a 45 year old person.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Max. rib defl. (mm) Std. Error (mm)	21 0 - 32	48 30 - 70	44 32 - 54	72 54 – 100
ASA gs Std. Error (gs)	23 0 - 34	58 38 - 66	46 34 - 58	76 63 – 100
Max. upper spine accel. (gs) Std. Error (gs)	15 0 - 30	46 25 - 65	43 26 - 60	74 58 – 114
Max. lower spine accel (gs) Std. Error (gs)	36 0 – 59	70 2 - 114	80 54 - 112	130 96 – 170

ABDOMINAL INJURY CRITERIA FOR THE ES-2re DUMMY

INTRODUCTION

There is limited abdominal injury data of human subjects in lateral impacts. Walfisch et al. (1980) dropped unembalmed human cadaver subjects from heights of one and two meters so that the right side at the level of the ninth rib struck a rigid or deformable rectangular block simulating the general shape of an armrest (Figure 26). The width of the 'armrest" block was 70 mm, the height varied between tests from 31 to 55 mm, and the length is assumed to have been longer than the antero-posterior dimension of the abdomen at the contact point. Contact velocities were 4.5 m/s for the one meter drop and 6.3 m/s for the two meter drop. Deflection data were determined by film analysis, and deflection was defined as intrusion of the armrest relative to the spine. Among eleven cadaver tests conducted, three of the cadavers in this test series were found to have atrophic cirrhosis resulting in a very stiff liver. Therefore the data for these three tests are invalid. The remaining eight tests were used for the development of performance requirement for the design of the EuroSID-1 abdomen. Due to difficulties in defining an appropriate measure of deflection, force-time data, rather than force-deflection data, were used to define the lateral abdominal response for the upper abdomen. The injury criterion for the EuroSID-1 dummy was developed using this data as well.

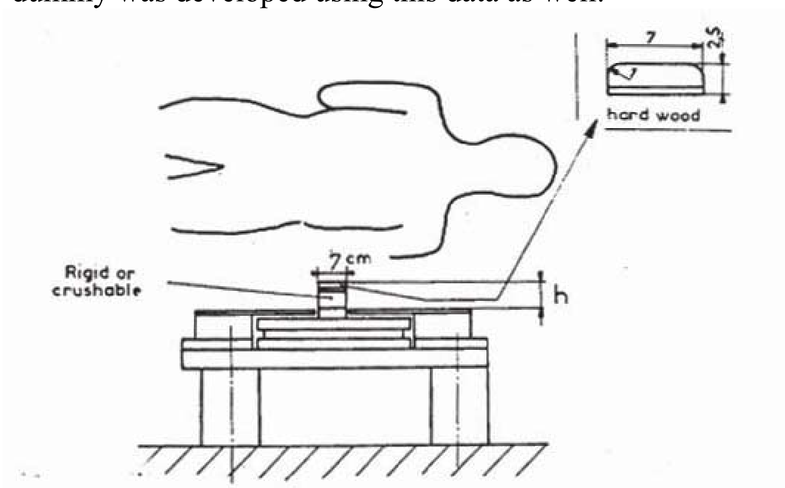


Figure 26. Configuration of cadaver drop tests, Walfisch et al. (1980).

Viano (1989) conducted oblique lateral impacts to unembalmed human cadaveric subjects using a pendulum impactor (Figure 27). In these tests, the 23.4 kg pendulum mass was brought up to impact speeds of approximately 4.5, 6.7, or 9.4 m/s in 50 mm of travel by a pneumatically charged impactor, after which it became a free mass supported only by two cables. The forward motion of the impactor was limited to 400 mm after contact with the subject by a cable tether. The impactor surface was a 152 mm diameter rigid disc with rounded edges. The subjects were suspended upright with hands and arms overhead. To minimize rotation of the torso, the subjects were positioned so that the line of action of the impactor was through the estimated center of gravity of the torso. Instead of a ninety-degree lateral impact direction, each subject was rotated 30 degrees to the left or right depending on the desired impact side. The impactor contacted the subject 75 mm below the Xyphoid process and covered approximately rib six through ten. Deflection data were obtained by analysis of high speed films. Fourteen unembalmed cadavers were subjected to such oblique lateral abdominal impacts. Logistic analysis was applied to the biomechanics responses to identify risk functions for AIS 3+ and AIS 4+ abdominal injury. The analysis results indicated that among acceleration, deflection, rate of deflection, force, and VC, VC was the best predictor of AIS 4+ abdominal injury.

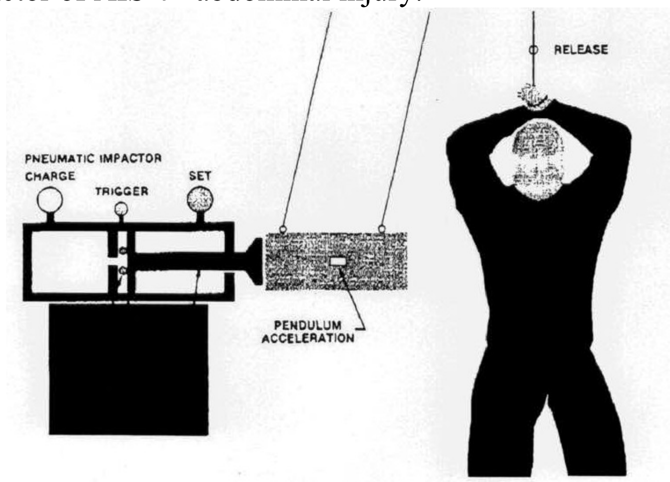


Figure 27. Configuration of abdominal pendulum impact tests, Viano (1989)

Stalnaker and Ulman (1985) analyzed the results of frontal and lateral impacts to animals and found VC to be a viable predictor of abdominal injury. Rouhana (1987) re-examined the Walfisch et al. (1980) cadaver drop test data and recommended the use of the product of abdominal force and abdominal deflection as an injury assessment function rather than force alone as was proposed by Walfisch. Rouhana found that the Viscous Criterion was a good predictor of abdominal injury and therefore recommended a continuous deformation measurement capability into the dummy abdomen.

In the series of the forty-two sled tests conducted at the Medical College of Wisconsin (Appendix A), only two subjects sustained abdominal injuries (kidney injuries). Due to the small sample size of abdominal injuries, an abdominal injury criterion could not be examined with this data set. Therefore, abdominal injury criterion for the ES-2re was developed using published data from Walfisch et al. (1980) and Viano (1989).

DATA ANALYSIS

Since the ES-2re does not have deflection measurements, abdominal injury criteria based on VC or deflection cannot be applied. Therefore, only injury responses based on forces or acceleration are considered here. The cadaver drop test data from Walfisch (1980) (Appendix D) and the pendulum impact tests from Viano (1989) (Appendix E) were reanalyzed for developing abdominal injury criteria.

The age of the subject at the time of death ranged between 45 and 68 years and was found to have poor association with injury outcome in the Walfisch data set. Measured applied force (normalized to represent that of a 50th percentile male according to Equation 4) was found to be a good predictor of injury compared to other measures (log-likelihood p-value=0.004). In the

Viano test data, applied force was a better predictor of abdominal AIS 4+ injury (p-value=0.0035) compared to Cmax (p-value=0.0322). Age of the subject was found to have poor association with injury outcome in the Viano (1989) data set as well. The probability of AIS 3+ and 4+ abdominal injury risk as a function of normalized applied force developed using logistic regression on the Walfisch data set as well as the Viano data is presented in Figure 27. There are only two observations with abdominal injuries in the Viano data set and so the AIS 4+ risk curve from the Viano data set may not be as reliable. The 25% and 50% risk of AIS 3+ abdominal injuries from the Walfisch data set are at a normalized applied force of 2300N and 2800 N, respectively. The 25% and 50% risk of AIS 4+ abdominal injuries from the Walfisch data set are at a normalized applied force of 3800N and 4400 N, respectively.

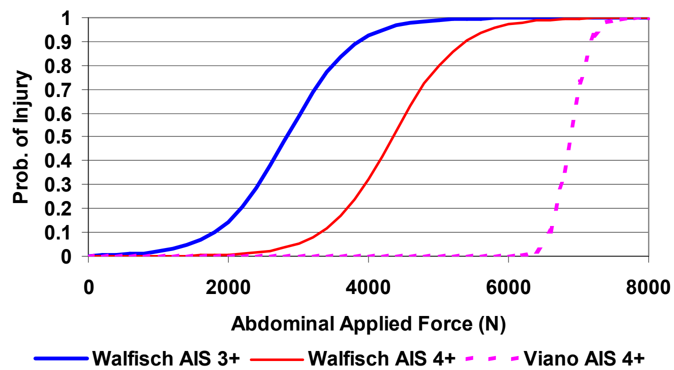


Figure 28. Probability of AIS 3+ and AIS 4+ abdominal injury as a function of normalized (to 50th percentile male) applied force. (Walfisch, 1980 and Viano, 1989).

The ES-2re dummy has 3 load cells in the abdomen – anterior, middle and posterior abdominal load cells. The sum of the forces measured in these three load cells is an estimate of the total load in the abdomen. The abdominal injury risk curves in Figure 28 was developed using applied force on cadaveric subjects. In order to apply the injury risk curves to data measured by the ES-2re abdominal load cells, a relationship between applied force on the cadaver abdomen and the abdominal force measured in the ES-2re dummy needs to be determined. For this purpose, the data from the ES-2re dummy side impact sled tests conducted at MCW (Appendix B) and the data from the corresponding 42 cadaver side impact sled tests (Appendix A) was used. A regression was conducted between the scaled abdominal load wall force (Equation 4) in the cadaver sled tests and the total abdominal load cell force (sum of three abdominal load cell measurements) in the corresponding ES-2re sled tests. Only the tests with male cadaveric subjects whose mass is within the range of 60 to 90 kg were used for this analysis to more closely correspond to the mass of the ES-2re dummy. The average ratio of cadaver applied abdominal force to the ES-2re abdominal force is 1.38±0.66. The regression assuming no intercept indicated that the applied load wall force in the cadaver tests was 93% of the total abdominal force in the ES-2re with an R^2 value of 0.75. Considering the confidence bounds for this regression, it can be assumed that cadaveric applied force is approximately the same as the ES-2re abdominal force measurements. Therefore, the injury risk curves in Figure 28 developed using the drop test data can be used with ES-2re total abdominal force measurements and are presented in Figure 29 and Equations 19 and 20. The point values of total abdominal force measured in the ES-2re corresponding to a 25% and 50% risk of injury are presented in Table 10.

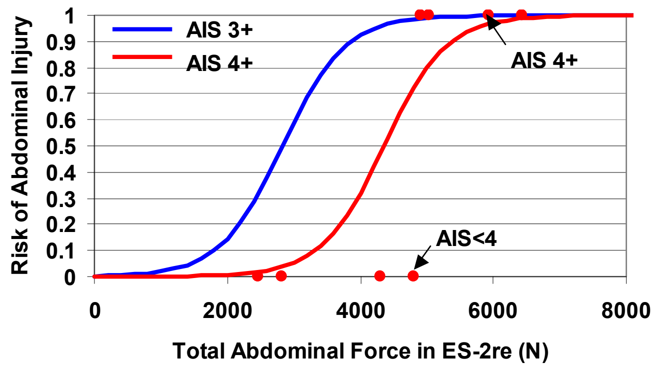


Figure 29. Risk of abdominal injury as a function of total abdominal force measured in the ES-2re dummy.

$$p(AIS3+) = \frac{1}{1+e^{6.04044-0.002133*F}} \quad (19)$$

$$p(AIS4+) = \frac{1}{1+e^{9.282-0.002133*F}} \quad (20)$$

where F is the total applied force on the cadaver abdomen or total force in the ES – 2re abdomen in Newtons.

Table 10. Point values of ES-2re abdominal force corresponding to 25% and 50% probability of AIS 3+ and AIS 4+ abdominal injury.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum total abdominal force in ES-2	2300 N	3800 N	2800 N	4400 N

In the 42 side impact cadaver sled tests, there were 3 abdominal offset tests (SC125, SC126, SC129) of which two of the cadaveric subjects (SC125 and SC126) sustained (kidney) injuries. The ES-2re abdominal force measurement in these two tests was over 9000N. The cadaver in SC130 also sustained a kidney injury however the injury was to the superior aspect of the kidney (collecting ducts) that was due to thoracic loading rather than abdominal loading. The corresponding ES-2re total abdominal force for the rest of the cadaver sled tests where there was no abdominal injury was below 2000 N. This suggests that a limit of total abdominal force in the range of 2300 N – 2800 N (corresponding to 25% and 50% risk of AIS 3+ abdominal injury, respectively) is reasonable.

PELVIC INJURY CRITERIA FOR THE ES-2re DUMMY

INTRODUCTION

Pelvic injuries in side impacts include hip joint injuries, injuries to the soft tissues within the pelvic cavity, and to the pelvic bone. Pelvic injuries consist mainly of fractures resulting from intrusion. Bone fractures may occur at various sites about the pelvic ring, including the acetabulum, the sacro-iliac junction, the pubic symphysis, the pubic rami, and the iliac wing. The pubic rami (the boney area between the symphysis and the acetabulum) is considered to be the weakest part of the pelvic ring, which is where fractures typically occur first.

In the series of 42 side impact tests conducted at the Medical College of Wisconsin (MCW), only three subjects sustained pelvic fractures that were in the rigid wall pelvic offset crash tests. Due to the sparseness of pelvic injuries in this data set, it was not possible to develop a robust pelvic injury criterion with this data set. Therefore, the pelvic injury criteria was developed using published research.

PREVIOUS RESEARCH

Several researchers have carried out cadaver tests to better understand the relationship between pelvic injury tolerance and dummy measurements. Cesari (1980) carried out a series of pelvic impact tests on cadavers using a 17 kg guided hemisphere directed to the greater trochanter (the part of the femur that protrudes from the acetabulum). Based on this data, Cesari (1982) offered a pelvis applied force-based criteria with a 10 kN limit on 50th percentile males.

An acceleration-based criterion was proposed by Haffner (1985). An analysis of several cadaver experiments resulted in two probability of fracture functions that are based on pelvic acceleration measurements. The first was proposed under a stress-based analogy and uses acceleration directly. The second used a strain-based analogy in which pelvic deflections were computed from accelerometer data. For a 50th percentile male of age 40, a Weibull distribution was used to model the probability of pelvic fracture:

Stress-based: $P(Fx) = F(Acc + 40/2)$
143 g gives P(Fx)=20%.

Strain-based: $P(Fx) = F(\text{Defl}/22.5 \text{ cm} + (0.025)*40)$
13.7 mm gives P(Fx)=20%.

Haffner (1985) observed a load path dependency on the measured pelvic accelerations and forces. When lateral loads thru the pelvis were distributed along two paths (such as the iliac wing and the greater trochanter), a much higher acceleration was needed to produce a fracture than if only a single load path was taken. Concentrated pelvic loading can result in fractures occurring at accelerations less than 100 g's. For example, if only the greater trochanter was loaded, pelvic fracture can occur at less than 100 g's. Since NHTSA's tests that were used to formulate the FMVSS 214 requirement of 130 g were based on both load paths, pelvic accelerations at fracture were greater than 100 g.

Cadaver pelvic impact tests using a 23-kg pendulum impactor were reported by Viano (1989). Viano found that lateral pubic ramus fracture correlated with compression of the pelvis, and not with pelvic impact force or pelvic acceleration. Pelvic compression was obtained from high speed film analysis. Viano (1987) recommended a pelvic tolerance limit of 27% pelvic compression.

Cavanaugh (1990) conducted a series of twelve load wall sled tests on cadavers using a set-up very similar to the MCW setup described in the Thoracic Injury Criteria section. The load wall was either a flat rigid or padded wall or with a six inch pelvic offset. Several observations emerged from these tests: 1) Pelvic fractures occur mainly within the pubic rami, which is the most-stressed part of the pelvis, 2) Impactor force correlated well with fracture while pelvic acceleration did not correlate well, and 3) Load tolerance to fracture was found to be mass dependent.

Cavanaugh proposed an applied pelvic force limit of 8 kN (corresponding to 25% probability of fracture) for a load path primarily through the greater trochanter of the femur. On the other hand, Cavanaugh also measured hip deflection via film analysis and found that lateral half-width Vmax*Cmax and compression (or deflection) were better correlates with fracture. Limits of Vmax*Cmax = 2.7 m/s and normalized compression = 36% were offered for a 25 percent risk of fracture.

In a continuation of Cavanaugh's load-wall tests (1990), Zhu (1993) developed an "average force" criteria that was based on the slope of the pelvic momentum trace, in which the force-time history is integrated to yield a nearly linear momentum curve. The slope of the momentum curve is defined as Favg (Average Pelvic Force). Zhu (1993) reported that an average pelvic force of 5 kN and a peak pelvis force of 7.3 kN corresponded to a 25% probability of pelvic fracture.

The ES-2re only has a pubic symphysis force and pelvic acceleration measurement capability and so injury criteria for the ES-2re dummy cannot be based on deflection or rate of deflection measures.

Viano (1995) developed pelvic injury criteria for the EuroSID-1 dummy using 14 pendulum impact tests with cadaveric subjects conducted at Wayne State University. Viano developed pelvic injury risk curves based on pubic force in the EuroSID-1 and pelvic acceleration. Based on these risk curves, a 25% probability of injury was associated with 7100 N of EuroSID-1 pubic symphysis force and 100 gs of pelvic acceleration.

Bouquet (1998) conducted pendulum impact tests to the pelvis at varying energy inputs on eleven unembalmed cadaveric subjects and conducted corresponding impact tests with the EuroSID-1 dummy. The impacting device was a guided linear impactor with a mass of 12 or 16 kg and an impact surface which was a 200X200 mm square. This surface was comprised of two trapezoidal areas in such a way as to be able to disassociate the bearing on the iliac crest from that on the trochanter. Bouquet (1998) combined this data with similar pendulum pelvic impacts at low and high energy levels on 10 cadaveric subjects (Bouquet, 1994). Analysis of this data indicated a 50% risk of AIS 2+ pelvic injury at 7.6 kN applied force and that for AIS 3+ pelvic injury at 11.4 kN. In order to develop a pelvic injury risk criteria based on EuroSID-1 pelvic force measurements, Bouquet developed a relationship between EuroSID-1 pubic symphysis force measurements and corresponding applied pelvic force to the cadavers. Bouquet determined that 50% probability of AIS 2+ and 3+ pelvic injury corresponded to 3.93 kN and 6.16 kN, respectively, of pubic symphysis force measured on the EuroSID-1 dummy.

For the development of pelvic injury criterion for the ES-2re, the test data from Bouquet et al. (1998) (Appendix F) and Zhu et al. (1993) (Appendix G) were re-examined.

DATA ANALYSIS

In the analysis, Bouquet (1998) did not consider the mass of the cadaveric subject, which was found to have considerable influence on the applied force measurement. He also did not consider the age of the subject that influenced injury outcome. Therefore, the Bouquet data (1998) presented in Appendix F was reanalyzed using mass scaled applied force measures (according to Eppinger, et al. 1984) and subject age as covariates in the logistic regression analysis. The force and accelerations were mass-scaled (according to Equation 4) to represent the applied force to a 50th percentile male. The resulting pelvic AIS 2+ and AIS 3+ injury risk curves are presented in Figure 30 and Equations 21 and 22.

The seventeen side impact sled tests (Appendix G) conducted by Zhu et al. (1993) were reanalyzed using logistic regression. Though the pelvic load was mainly applied through the greater trochanter, the force measured at the load wall covered more than just the trochanter and corresponded to a wide pelvic distribution. The measured pelvic force on the load wall was mass scaled according to Eppinger et al. (1984) to represent the force applied to a fiftieth percentile male. Mass scaled applied pelvic force and the age of the subject were included in the regression analysis. The resulting risk of pelvic fracture (AIS 2+) as a function of peak applied force from this analysis, is also presented in Figure 30 where an age of 45 years was used for the risk curves.

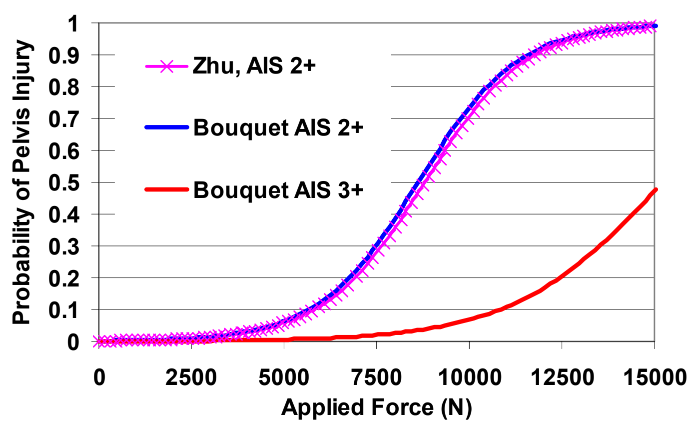


Figure 30. Probability of AIS 2+ and AIS 3+ pelvic injury as a function of normalized pelvic applied force in the Bouquet pendulum impact test series and in the Zhu side impact sled test series using human cadaveric subjects. The risk curves represent the risk of injury to a 45 year old 50th percentile male. Forces have been scaled as per Eppinger et al. (1984).

$$p(AIS2+) = \frac{1}{1+e^{6.804-0.0089*age-0.0007424*F}} \quad (21)$$

$$p(AIS3+) = \frac{1}{1+e^{9.7023-0.04678*age-0.0005*F}} \quad (22)$$

where F is the scaled applied force to the cadaver pelvis in Newtons

The ES-2re dummy is equipped with a load cell at the pubic symphysis to measure pelvic forces. In order to apply the injury risk curves presented in Figure 30 to the ES-2re dummy, the applied pelvic force on the cadaver has to be related to the measured pubic symphysis force in the ES-2re under similar impact conditions. Bouquet (1998) determined such a relationship between the applied force to the cadaveric subject and the pubic force in the EuroSID-1 dummy under similar impact conditions using the data presented in Appendix F. Bouquet's analysis indicated that for subjects with AIS=2 pelvic injury, 28.4% of the applied force on the cadaver was equal to the pubic force in the EuroSID-1. However, Bouquet did not consider mass-scaled applied forces to the cadaver.

The cadaver and EuroSID-1 pelvic force data in Appendix F was reanalyzed using mass-scaled cadaver pelvic force (Equation 4) to obtain a relationship between applied cadaver pelvic force and the corresponding pubic force in the EuroSID-1. The cadaver tests were paired with corresponding EuroSID-1 tests by matching the impact energy of the tests. When more than one EuroSID-1 test was available at an impact energy level, the average responses from these tests was used. Linear regression was conducted using no intercept option (Figure 31) between EuroSID-1 pubic force measurements and normalized applied force to the cadavers. According to the linear regression analysis, this relationship for injured and uninjured subjects is:

*AIS 2+ injured subjects: ES-1 pubic symphysis force=0.455 * (applied force to cadaver pelvis)*
*Uninjured subjects: ES-1 pubic symphysis force=0.22 * (applied force to cadaver pelvis)*

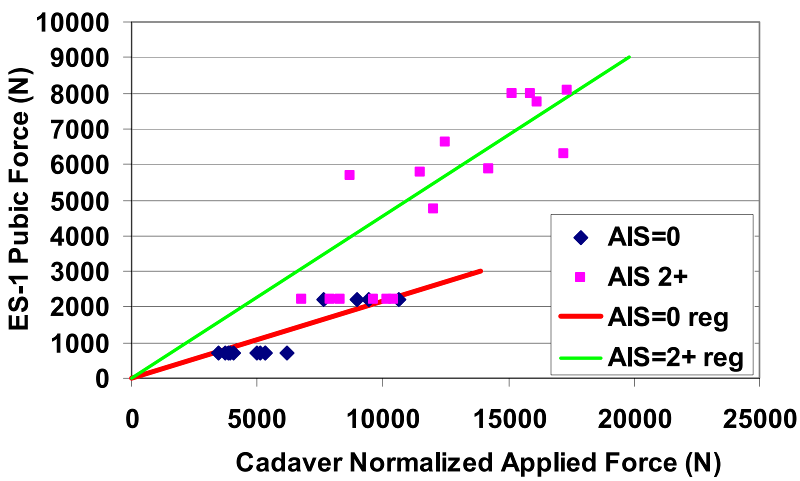


Figure 31. Regression between scaled applied force in cadaver tests to corresponding pubic symphysis force in ES-1 dummy.

Since the pelvis of the ES-2re dummy is essentially the same as the EuroSID-1 dummy, this relationship between applied cadaver force and EuroSID-1 pubic force can be applied to the ES-2re dummy as well. Applying the relationship for AIS 2+ injured subjects (dummy pubic force=0.46*cadaver applied force), the risk curves in Figure 30 are scaled to represent the risk of pelvic injury risk as a function of ES-2re pubic force. The resulting scaled pelvic injury risk curves as a function of ES-2re pubic force is presented in Figure 32 and Equations 23 and 24. Table 11 presents the values of ES-2re pubic symphysis force corresponding to 25% and 50% risk of AIS 2+ and AIS 3+ pelvic injury.

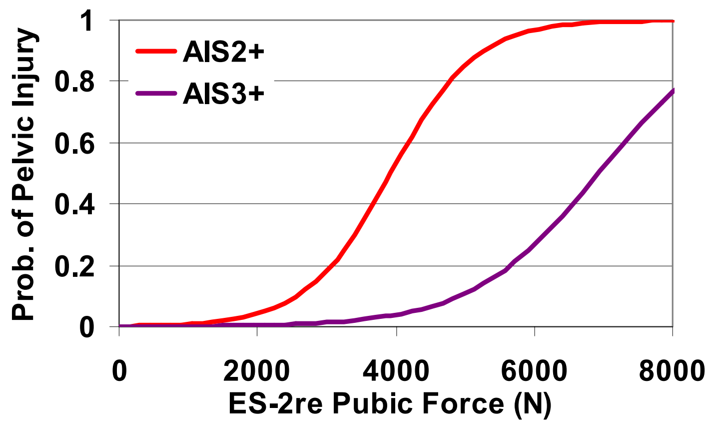


Figure 32. Probability of AIS 2+ and AIS 3+ pelvic injury as a function of ES-2re pubic symphysis force.

$$p(AIS2+) = \frac{1}{1+e^{6.403-0.00163*F}} \qquad (23)$$

$$p(AIS3+) = \frac{1}{1+e^{7.5969-0.0011*F}} \qquad (24)$$

where F is the pubic force in the **ES - 2re** *dummy in Newtons*

Table 11. Point values of ES-2re pubic symphysis force corresponding to 25% and 50% probability of AIS 2+ and AIS 3+ pelvic injury.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 2+	AIS 3+	AIS 2+	AIS 3+
Maximum pubic symphysis force in ES-2	3250 N	6000 N	4000 N	7000 N

INJURY CRITERIA DEVELOPMENT FOR THE SID-IIsFRG DUMMY

THORACIC INJURY CRITERIA FOR THE SID-IIsFRG

Twelve side impact sled tests using the SID-IIsFRG were conducted at the Medical College of Wisconsin (MCW) (Appendix H) under similar impact conditions as those of cadaver tests presented in Appendix A. All test conditions presented in Appendix A were also conducted with the SID-IIsFRG except for the side air bag tests.

The responses of the SID-IIsFRG in the nine test conditions were compared to the average scaled cadaver responses under similar impact conditions. For this comparison, the cadaver accelerations and forces were scaled to represent those of a 5th percentile female with total mass of 48 kg according to the equal stress-equal velocity method outlined by Eppinger et al. (1984) and presented in Equations 25 and 26.

$$\boldsymbol{acceleration_{norm} = acceleration} \times \left(\frac{\boldsymbol{mass\,(kg)}}{48}\right)^{1/3} \qquad \textbf{(25)}$$

$$\boldsymbol{force_{norm} = force} \times \left(\frac{48}{\boldsymbol{mass\,(kg)}}\right)^{2/3} \qquad \textbf{(26)}$$

$$\textit{\textbf{where mass (kg) is the total mass of subject}}$$

The cadaver half thorax chest deflections were normalized with respect to the initial chest width at the point of measurement. The maximum deflection of the SID-IIsFRG is the maximum rib deflection of the three thoracic ribs. The cadaveric thoracic deflection measurement is external which includes the skin and flesh while the SID-IIsFRG deflection measurements are rib deflections. For comparison purposes, 8 mm was added to the SID-IIsFRG rib deflections to represent the external half thoracic deflection of a 5th percentile female. The SID-IIsFRG estimated external chest deflections were normalized with respect to a chest width of 270 mm.

Figure 33 presents the estimated maximum normalized half thorax external deflections of the SID-IIsFRG and the maximum average normalized half thorax deflection of cadavers for similar impact test conditions. ANOVA analysis suggested that the maximum average normalized half thorax cadaver deflections were not different from that of the SID-IIsFRG under similar impact conditions. While the normalized cadaver deflections were quite similar to the SID-IIsFRG deflections in the flat wall tests, differences in normalized deflections of the SID-IIsFRG and the cadavers in the offset tests were observed. These differences in deflection in the pelvic and abdominal offset tests could be due to geometric positioning of the offset resulting in different loading patterns on the SID-IIsFRG compared to the cadavers.

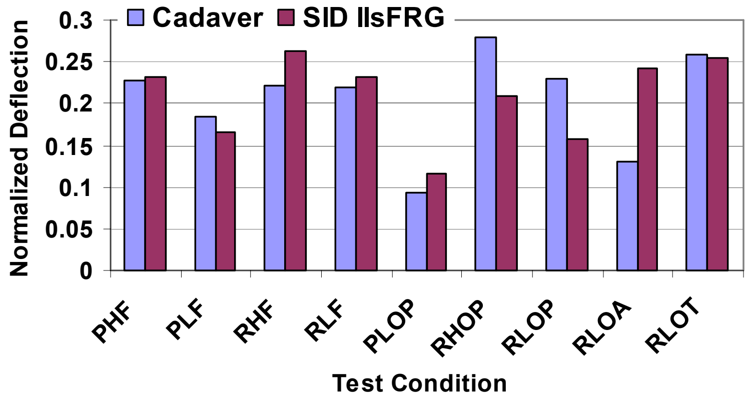


Figure 33. Normalized maximum average half thoracic deflections of cadavers and maximum normalized estimated external half thoracic deflection of the SID-IIsFRG in different side impact test conditions.

Since thoracic deflections of the cadaver and SID-IIsFRG are similar, the injury risk curve with normalized average half thorax deflections as predictor function developed using the cadaver data can be applied to the SID-IIsFRG (Equations 7 and 8).

Since the injury criteria is being developed for small size adult, the average age of the injured (AIS 3+) small size adults involved in side crashes in NASS-CDS for the years 1993-2001 was examined (Figure 10). The average age of AIS 3+ injured occupants of height less than 5 ft 4 inches involved in side crashes is 56 years. Therefore, the thoracic injury risk curves for the 5th percentile female were normalized with respect to an age of 56 years.

In order to represent the thoracic injury risk functions based on cadaver deflections (Equations 7 and 8) in terms of the maximum rib deflection of the SID-IIsFRG, the SID-IIsFRG rib deflection was transformed to represent the normalized cadaver average half thorax deflection by adding 8 mm to represent skin and flesh thickness of a small female and then using a chest width of 270 mm to normalize the total deflection. Equations 7 and 8 were then normalized to represent the injury risk for a 56 year old. The resulting risk functions for a 56 year old as a function of SID-IIsFRG maximum rib deflection (Equations 27 and 28) are presented in Figure 34.

$$p(AIS3+) = \frac{1}{1+e^{(5.8627-0.13638*\mathbf{max.}\ rib.\ defl.)}} \quad (27)$$

$$p(AIS4+) = \frac{1}{1+e^{(7.7998-0.13638*\mathbf{max.}\ rib.\ defl.)}} \quad (28)$$

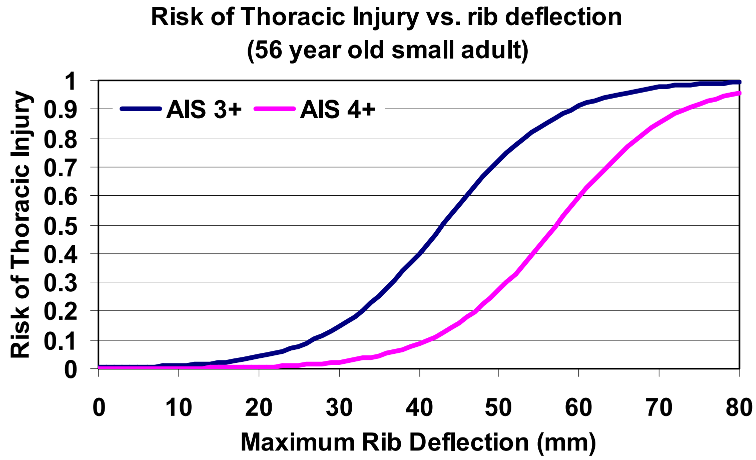


Figure 34. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of peak SID-IIsFRG thoracic rib deflections (maximum of three ribs) for a small adult occupant involved in a side impact crash (mean age of 56 years).

As indicated in the FMVSS 208 final rule (Docket No. 7013), Riggs (1981) found that the bone mineral density in women decreases considerably with increase in age while that of men decreases only slightly (Figure 35). For a 56 year-old person, the average bone mineral density of women is approximately 0.88 times that of men. Since the injury risk curve in Figure 34 was developed using data of predominantly male cadavers, an adjustment needs to be made to account for the lower bone mineral density of females for developing injury risk curves for small size females. The injury risk curves in Figure 34 were scaled by a factor of 0.88 for this purpose. The results are presented in Figure 36 and Equations 29 and 30. According to this risk curve, 38 mm of maximum SID-IIsFRG rib deflection corresponds to a 50% risk of AIS 3+ thoracic injury (Table 12).

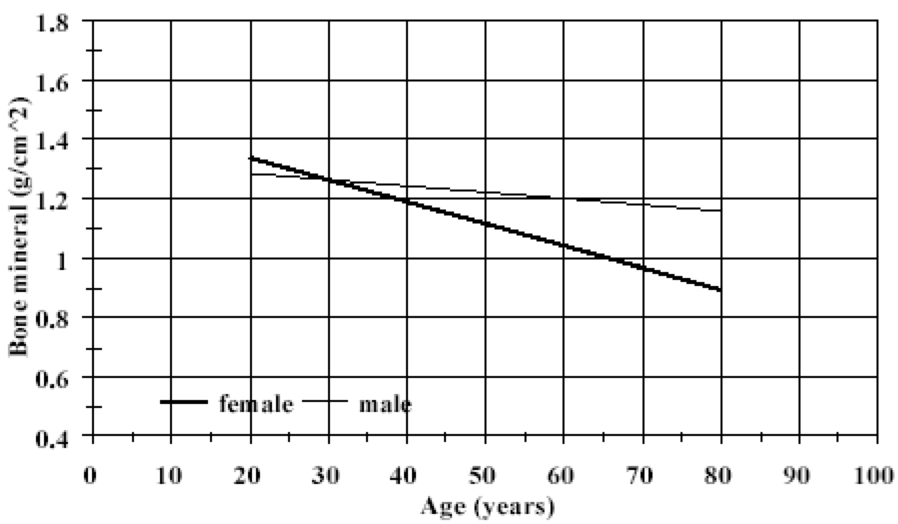


Figure 35. Regression of BMD of lumbar spine on age in 105 normal women and 82 normal men Riggs (1981).

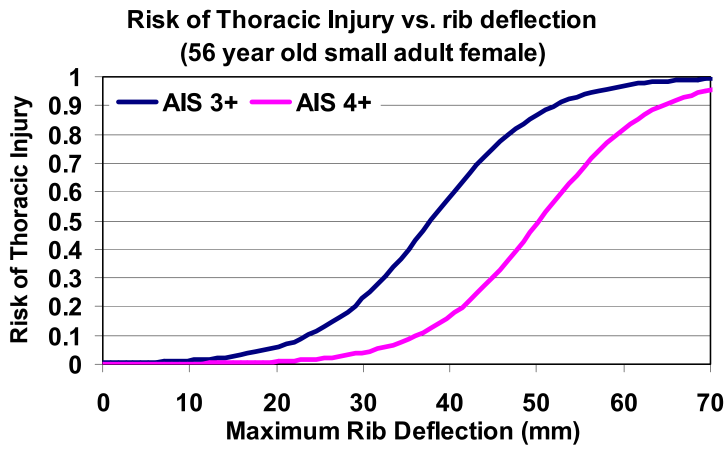


Figure 36. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of maximum rib deflection measured on the SID-IIsFRG for an average small female involved in a side impact crash.

$$p(\boldsymbol{AIS}3+) = \frac{1}{1+\boldsymbol{e}^{(5.8627-0.15498*\mathbf{max.}\ \boldsymbol{rib.}\ \boldsymbol{defl.})}} \qquad \textbf{(29)}$$

$$p(\boldsymbol{AIS}4+) = \frac{1}{1+\boldsymbol{e}^{(7.7998-0.15498*\mathbf{max.}\ \boldsymbol{rib.}\ \boldsymbol{defl.})}} \qquad \textbf{(30)}$$

The data from the 42 side impact sled tests conducted at MCW (Appendix A) indicated that upper spine acceleration was a better predictor of injury than lower spine acceleration. However, a reanalysis of the combined cadaver data from Eppinger, et al. (1984) and Cavanaugh et al. (1993), presented in Appendix I, indicated that lower spine acceleration was a reasonably good predictor of thoracic injury (Wald p-value<0.001). The accelerations in the Eppinger data were mass scaled to that of a 5th percentile female (according to Equation 25) and injury risk curves were developed using the age of the subject and T12 lateral acceleration as the covariates. The resulting equations were normalized to a 56 year-old (average age of small occupants with AIS 3+ injuries in side crashes) and are presented in Figure 37 and Equations 31 and 32.

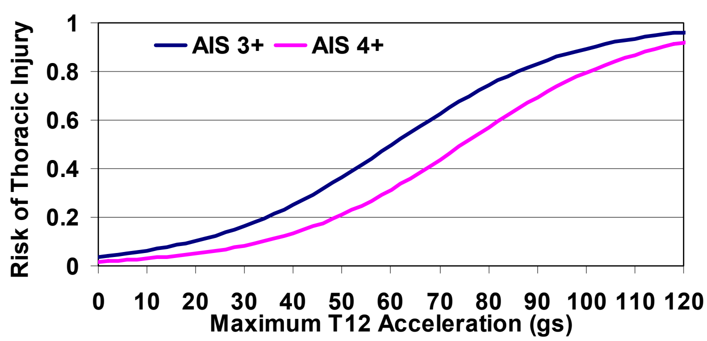


Figure 37. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of normalized T12 acceleration (Eppinger, et al., 1984 data mass scaled to represent a 5th percentile female accelerations). An age of 56 years old was taken to normalize the data to that of a short driver involved in a side impact crash.

$$p(AIS3+) = \frac{1}{1+e^{(10.5127-0.13*age-0.0536*T12Accel.)}} \quad (31)$$

$$p(AIS4+) = \frac{1}{1+e^{(11.2875-0.13*age-0.0536*T12Accel)}} \quad (32)$$

Table 12. Point values of 5th percentile female predictor functions at 25% and 50% probability of thoracic injury – normalized with respect to a 56 year old person.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum rib deflection (mm) for small size female occupant	31 mm	43 mm	38 mm	50 mm
Max. lower spine result. accel. (g's) for 5th female occupant	40 gs	54 gs	60 gs	74 gs

Comparison of the lower spine acceleration of the SID-IIsFRG and the cadaver under similar impact conditions using ANOVA indicates that there are some differences in lower spine responses (Figure 38). Some of the response differences in the offset tests may be due to differences in the geometric positioning of the offset, which results in differences in the loading patterns between the SID-IIsFRG and the cadavers. Due to these differences, it may not be possible to directly apply the lower spinal acceleration limits derived from cadaver measurements for injury assessment with the SID-IIsFRG.

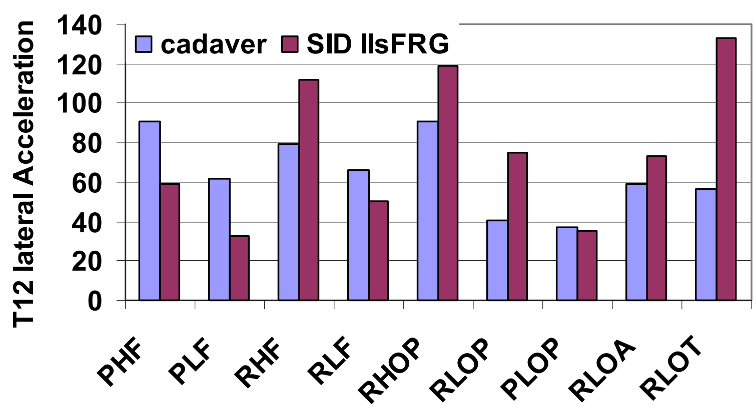


Figure 38. Mean T12 lateral acceleration measured in the cadaver (mass-scaled to a 5th percentile female) and SID-IIsFRG in different impact conditions

ANALYSIS USING CADAVER INJURY RESPONSES AND SID IIsFRG MEASUREMENT

Analysis was also conducted using the SID-IIsFRG mechanical responses along with the subject injury information and anthropometric data similar to that done with the ES-2re. Tables 13, 14, and 15 summarize results of the analysis.

Table 13. Statistical models and their respective goodness of fit and predictive ability for injury outcome as a dichotomous variable AIS<3 and AIS 3+ using SID-IIsFRG measurements.

AIS 3+	goodness of fit P-Value			Predictive ability	
Models	LR	Score	Wald	Gamma	C
age, dmax	0.0109	0.016	0.0365	0.531	0.764
age, Davg	0.0357	0.0446	0.0674	0.483	0.741
age, Vmax	0.0261	0.0399	0.0652	0.513	0.755
age, Vavg	0.0675	0.0819	0.112	0.431	0.714
age, VCmax	0.0827	0.0956	0.127	0.384	0.689
TTI	0.0587	0.0843	0.1179	0.404	0.7
ASA	0.0353	0.0502	0.0822	0.428	0.711
age, rspu	0.0589	0.0779	0.1188	0.388	0.693
age, rspl	0.0294	0.0445	0.0787	0.445	0.722
age, spl	0.0303	0.0445	0.0783	0.439	0.719

dmax: max. rib deflection, **Davg:** Average rib deflection, **spu, spl:** max. upper and lower lateral spine accelerations, **rspu, rspl:** max. resultant upper and lower spine acceleration, **Vmax:** max. rate of deflection, **VCmax:** max. VC.

Table 14. Statistical models and their respective goodness of fit and predictive ability for injury outcome as a dichotomous variable AIS<4 and AIS 4+ using SID-IIsFRG measurements.

AIS 4+	goodness of fit P-Value			Predictive ability	
Models	LR	Score	Wald	Gamma	C
age, dmax	0.1893	0.2121	0.2415	0.316	0.657
age, Davg	0.035	0.047	0.074	0.47	0.74
age, Vmax	0.135	0.138	0.17	0.441	0.72
age, Vavg	0.0616	0.0703	0.105	0.492	0.745
age, VCmax	0.217	0.227	0.252	0.355	0.676
TTI	0.0828	0.0869	0.146	0.561	0.779
ASA	0.0497	0.0532	0.0818	0.518	0.758
age, rspu	0.1947	0.1971	0.2357	0.357	0.678
age, rspl	0.0697	0.0735	0.1066	0.473	0.736
age, spl	0.0688	0.0731	0.1041	0.471	0.734

Table 15. Statistical models and their respective goodness of fit and predictive ability for injury outcome as a ordinal variable AIS<3, AIS=3 and AIS>3 using SID-IIsFRG measurements.

AIS 3, AIS 4+	goodness of fit P-Value			Predictive ability	
Models	LR	Score	Wald	Gamma	C
age, dmax	0.0291	0.0328	0.0548	0.375	0.687
age, Davg	0.0248	0.0247	0.0465	0.409	0.704
age, Vmax	0.0436	0.0423	0.0782	0.397	0.698
age, Vavg	0.0551	0.0492	0.0972	0.382	0.69
age, VCmax	0.1031	0.1031	0.14	0.322	0.66
TTI	0.0606	0.0561	0.116	0.412	0.705
ASA	0.0236	0.0289	0.0453	0.437	0.718
age, rspu	0.0773	0.0823	0.1197	0.356	0.677
age, rspl	0.0253	0.0316	0.0494	0.419	0.709
age, spl	0.025	0.0314	0.0475	0.412	0.705

Tables 13 to 15 indicate that the best predictors of injury are lower spine acceleration, ASA, and peak and average rib deflection. Average rib deflection (Davg) is the mean of the peak deflection of the three thoracic ribs. Maximum deflection (dmax) is the maximum of the peak deflection of the three thoracic ribs. Thoracic injury risk curves were developed using logistic regression. Age of the subject was included in all the models and the risk functions were normalized to a 56 year old.

Since most of the subjects in the Medical College of Wisconsin tests were male, the derived injury risk curves are mainly applicable to male subjects who are known to have better bone quality than females. Therefore, a factor of 0.88 (from Figure 35) was used to account for the greater vulnerability of female compared to male subjects for the same scaled injury measure. The equations for the injury risk curves presented in Figures 39 to 42 are provided in Equations 33 to 40. The point values of SID-IIsFRG injury measures at 25% and 50% risk of thoracic injury derived from these equations is presented in Table 16.

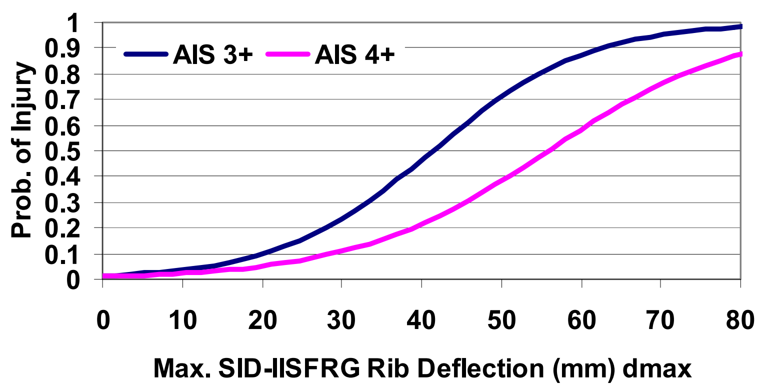


Figure 39. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of SID-IIsFRG maximum thoracic rib deflection normalized for a 56 year old female.

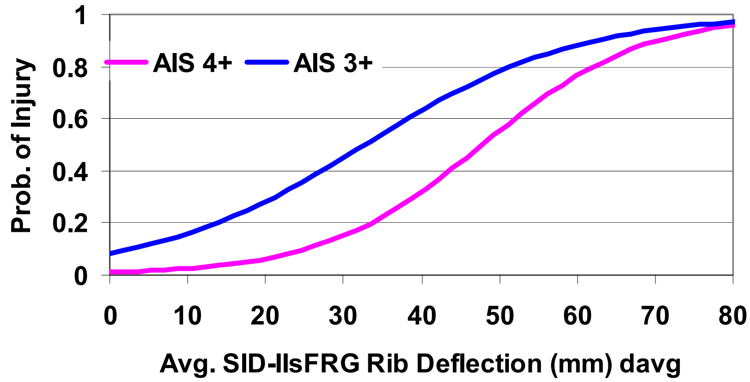


Figure 40. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of SID-IIsFRG average thoracic rib deflection normalized to that for a 56 year old female.

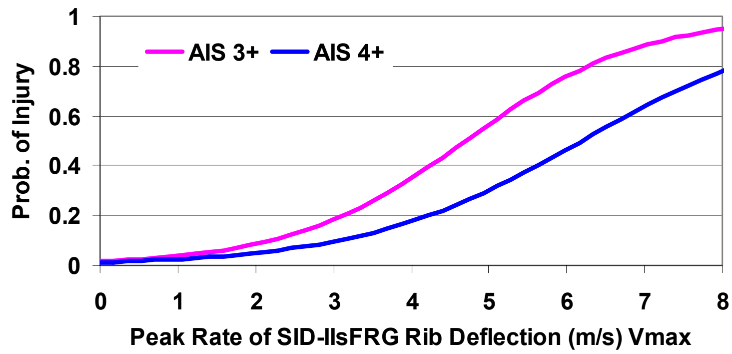


Figure 41. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of SID-IIsFRG maximum thoracic rib rate of deflection normalized for a 56 year old female.

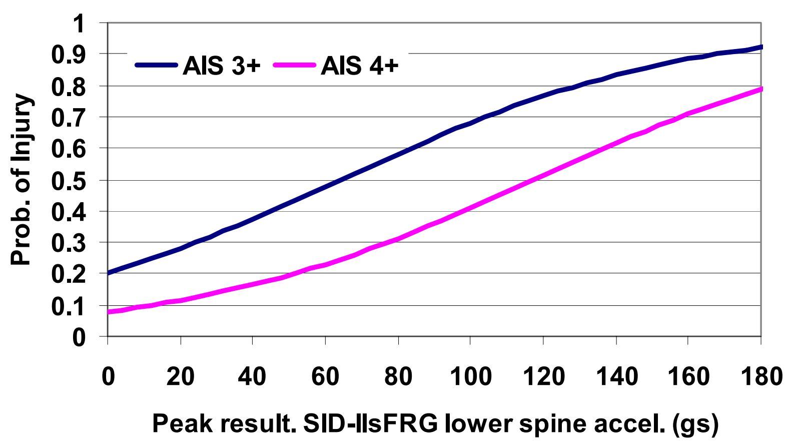


Figure 42. Risk of AIS 3+ and AIS 4+ thoracic injury as a function of SID-IIsFRG maximum lower spine acceleration normalized for a 56 year old female.

The thoracic injury risk models using SID-IIsFRG measures had better goodness of fit and injury predictive ability than the models developed using ES-2re measures, but worse than those using cadaver measures. Since the SID-IIsFRG deflections were similar to the cadaver deflection under similar impact conditions, the injury risk curves using cadaver deflections presented in

Figure 36 and Equations 29 and 30 can be used for determining thoracic IARVs for the SID-IIsFRG.

Since the SID-IIsFRG lower spine accelerations are not the same as those of the cadavers under similar impact conditions (Figure 38), the injury risk curves developed using the SID-IIsFRG measured lower spine accelerations (Figure 42) should be used for injury assessment with the SID-IIsFRG. Lower spine accelerations may not have a causal relationship with thoracic injury but are good indicators of the overall loading to the thorax. Spinal accelerations may be used to detect severe loading conditions that are undetected by the unidirectional deflection measurements. An analysis was conducted to determine the sensitivity and false positive rate (1-specificity) at different levels of lower spine acceleration. For this purpose, a receiver-operator curve (ROC) was made (Figure 43) using the AIS 3+ injury risk curve in Figure 42. The ROC is a plot of false positive rate along the x-axis and the sensitivity along the y-axis. Figure 44 is a plot of false positive rate as a function of the SID-IIsFRG lower spine acceleration. Maximum lower spine acceleration of 82 gs is associated with a five percent false positive rate and a 60% risk of AIS 3+ thoracic injury.

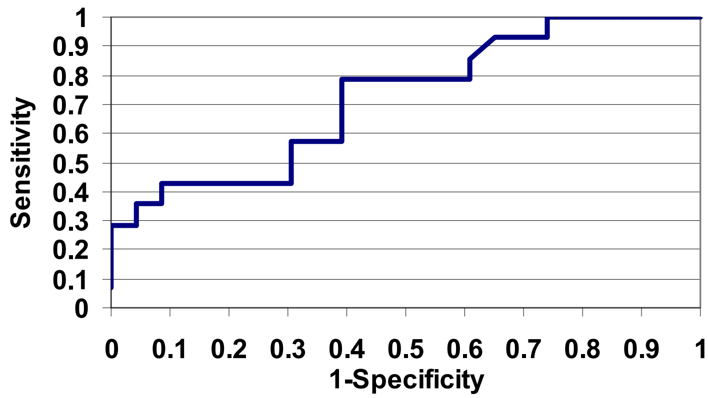


Figure 43. Receiver-Operator-Curve for SID-IIsFRG lower spine Acceleration as a predictor of AIS 3+ injury for a 56 year old female.

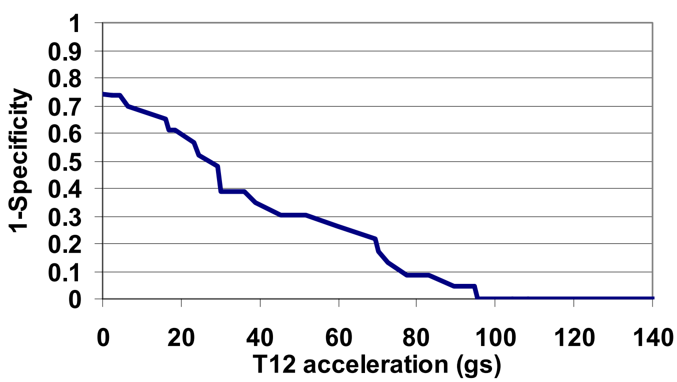


Figure 44: SID IIsFRG lower spine acceleration vs. false positive rate, normalized for a 56 year old female.

$$p(AIS3+) = \frac{1}{1+e^{(4.3092-0.1041*\max.\ rib.\ defl.)}} \quad (33)$$

$$p(AIS4+) = \frac{1}{1+e^{(3.9692-0.0717*\max.\ rib.\ defl.)}} \quad (34)$$

$$p(AIS3+) = \frac{1}{1+e^{(2.3239-0.0683*average\ \ rib.\ defl.)}} \quad (35)$$

$$p(AIS4+) = \frac{1}{1+e^{(4.6322-0.0969*average\ \ rib.\ defl.)}} \quad (36)$$

$$p(AIS3+) = \frac{1}{1+e^{(4.1404-0.881*V\max)}} \quad (37)$$

$$p(AIS4+) = \frac{1}{1+e^{(4.3427-0.7011*V\max)}} \quad (38)$$

$$p(AIS3+) = \frac{1}{1+e^{(1.364-0.0212*spnl)}} \quad (39)$$

$$p(AIS4+) = \frac{1}{1+e^{(2.4634-0.021*spnl)}} \quad (40)$$

Table 16. Point values of the SID IIs predictor functions at 25% and 50% probability of thoracic injury – normalized with respect to a 56 year old person.

Injury Predictor	25% prob. of injury		50% prob. of injury	
	AIS 3+	AIS 4+	AIS 3+	AIS 4+
Maximum rib deflection (mm) for small size female occupant	31 mm	41 mm	41 mm	56 mm
Average rib deflection (mm) for small size female occupant	18 mm	36 mm	34 mm	48 mm
Max. rib deflection rate (m/s) for small size female occupant	3.5 m/s	4.7 m/s	4.7 m/s	6.2 m/s
Max. lower spine result. accel. (g's) for small size occupant	16 gs	64 gs	64 gs	116 gs
	82 gs corresponds to a 5% false positive rate.			

ABDOMINAL INJURY CRITERIA FOR THE SID-IIsFRG

Most previous research indicated that abdominal deflection and the Viscous Criterion are better predictors of abdominal injury than is abdominal force (Viano, 1989, Rouhana et al., 1987, Stalnaker et al., 1985). Since the SID-IIsFRG has abdominal deflection measurement capability, injury risk curves were developed based on maximum abdominal deflection and VCmax.

Injury risk curves were developed using pendulum impact cadaver test data from Viano (1989). Viano found that maximum normalized full abdominal deflections were poor predictors of AIS 3+ injuries but good predictors of AIS 4+ injuries (Figure 45). The abdominal deflections were normalized with respect to the full abdominal width of the subjects.

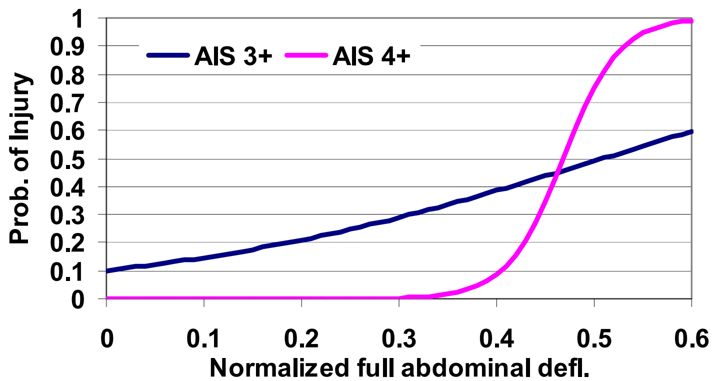


Figure 45. Risk of AIS 3+ and AIS 4+ abdominal injury as a function of maximum normalized full abdominal deflection measured on the cadaveric subject.

Viano (1995) developed a relationship between the external full abdominal deflection of cadaveric subjects and the abdominal rib deflection of the BioSID. Arbelaez et al. (2002) applied this relationship to the SID-IIs along with an abdominal deflection scale factor of 0.788 (corresponding to the ratio of half chest width of the SID-IIs to that of the BioSID. The resulting relationship between SID-IIs peak abdominal deflection and cadaveric normalized abdominal deflection is presented in Equation 41.

peak norm. cadaver abdomen deflection = 0.21 + 0.003877 x SIDIIs peak abdomen deflection (mm) (41)

Using this equation, the abdominal injury risk curve using SID-IIsFRG rib deflections are presented in Figure 46 and Equation 42.

$$p(AIS4 + abd\ inj.) = \frac{1}{1 + e^{8.9798 - 0.1349(peak\ abd.rib\,defl.)}} \qquad (42)$$

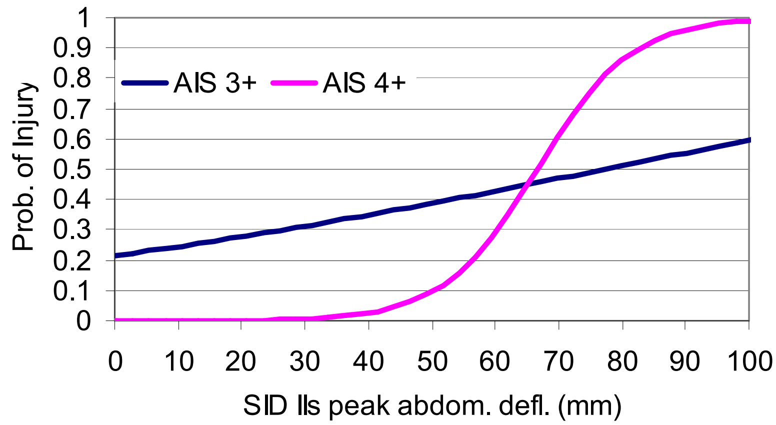


Figure 46. Risk of AIS 3+ and AIS 4+ abdominal injury as a function of maximum abdominal rib deflection of the SID-IIsFRG.

Since AIS 4+ injuries are quite severe, IIHS applies a 5% risk of AIS 4+ abdominal injury. This corresponds to 45 mm of peak abdominal deflection (Table 17). IIHS also employs the viscous criterion to assess thoracic and abdominal injury risk. Viano et al. (1995) provided abdominal injury risk curves based on VC that are presented in Figure 47. However, NHTSA is currently not considering using VC for injury assessment since displacements were better predictors of thoracic injury than was VC and since the process used to compute VC may have numerical errors.

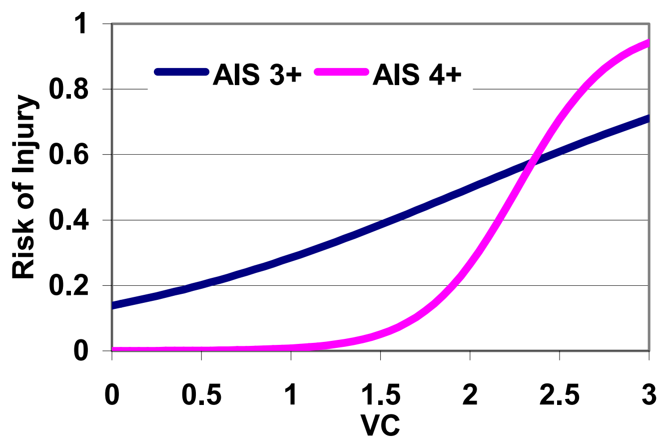


Figure 47: Risk of AIS 3+ and AIS 4+ abdominal injury as a function of VC (Viano, 1989).

Table 17. Point values of the SID IIs maximum abdominal deflection at 5%, 25% and 50% probability of AIS 4+ abdominal injury, Viano (1989).

Injury Predictor	AIS 4+ Injury		
	5%	25% prob.	50% prob.
Maximum abdominal rib deflection (mm)	45 mm	59 mm	67 mm

PELVIC INJURY CRITERIA FOR THE SID-IIsFRG

The pelvic injury criteria for the SID-IIsFRG was developed using the cadaver test data from Bouquet et al. (1998) by scaling the normalized force to that of a 5th percentile female according to Equation 26. The pelvic loads in the impact tests by Bouquet et al. (1998) were distributed over a wide area that included the iliac crest and the greater trochanter of the cadavers. Therefore, the normalized applied pelvic force in these cadaver tests was assumed to be equal to the sum of the forces in iliac wing and acetabulum of the SID-IIsFRG under similar impact conditions.

The risk of AIS 2+ pelvic fractures based on the total force measured on the SID-IIsFRG pelvis (acetabulum + iliac wing) was developed and is presented in Figure 48 and Equation 43. The age of the subject was taken to be 56 years. Twenty-five percent risk of pelvic fracture corresponds to 5200 N of the sum of acetabular and iliac force measured on the SID-IIsFRG (Table 18).

$$\boldsymbol{p(AIS\,2+)} = \frac{1}{1+\boldsymbol{e}^{(6.3055-0.001*(\boldsymbol{iliac+acetab.\ force}))}} \qquad \textbf{(43)}$$

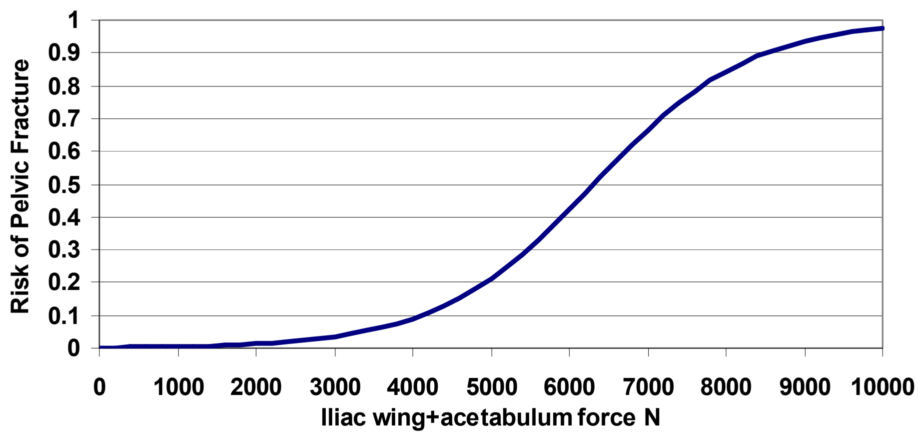


Figure 48. Risk of AIS 2+ pelvic fracture as a function of iliac wing + acetabular force in the SID-IIsFRG.

Table 18. Point values of total iliac and acetabular force of the SID-IIsFRG corresponding to 25% and 50% risk of AIS 2+ pelvic fracture.

Injury Predictor	25% prob. of fracture	50% prob. of fracture
Maximum Acetabular +Iliac force in SID IIsFRG	5200 N	6300 N

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APPENDIX A. SIDE IMPACT CADAVERIC SLED TEST DATA CONDUCTED AT THE MEDICAL COLLEGE OF WISCONSIN

tstref	tstcfn	sex	age	mass	width	MAIS	fxrb	rbfx	thx_f	abd_f	pel_f	Hdmax	Hdavg	HVmax	HVC	Fdmax	Fdavg	FVmax	FVC	HVavg	HVCavg	FVavg	FVCavg	TTI	ASA	spu	spl	rspu	rspl	rlu	rll	pel
			yrs	kg	mm				N	N	N			m/s	m/s			m/s	m/s	m/s	m/s	m/s	m/s		gs	gs	gs	gs	gs	gs	gs	gs
SC101	RLF	M	73	89	330	4	7	15	5554	1925	3464	0.357	0.329	17.3	5.3	0.477	0.435	35.1	8.9	4.48	0.48	6.96	0.41	187	51	49	48	50	50	101	113	.
SC102	RLF	M	27	72	316	0	0	0	6939	2795	8639	0.255	0.208	7.9	1.3	0.364	0.302	12.2	2.1	6.43	0.88	10.3	1.4	85	16	60	58	62	58	43	.	75
SC103	RLF	M	55	76	336	3	7	11	4975	5314	3372	0.243	0.212	6	1.4	0.394	0.350	7.3	1.9	5.51	1.01	6.74	1.52	160	26	49	51	50	57	183	112	55
SC105	PLF	M	70	71	324	0	0	0	3498	1970	5618	0.114	0.104	3.3	0.3	0.176	0.163	5.2	0.5	2.87	0.24	4.78	0.46	154	72	23	68	24	70	37	62	32
SC106	PLF	M	56	64	288	2	2	2	.	1678	4949	0.198	0.183	3.3	0.4	0.3	0.283	4.4	0.9	3.11	0.33	4.11	0.79	125	27	23	76	23	76	23	57	35
SC107	PHF	M	50	93	359	2	3	3	13033	3139	6893	0.176	0.173	8.6	1.1	0.299	0.267	16.8	1.1	6.13	0.81	14.78	0.95	154	45	51	54	54	56	135	174	57
SC108	RHF	M	44	83	336	2	3	3	16338	3888	9905	0.239	0.219	7.1	1.9	0.395	0.364	10.9	2.2	6.68	1.44	10.16	1.83	158	51	94	62	94	90	88	140	76
SC109	RHF	F	49	62	317	4	5	5	7225	3668	19104	0.292	0.225	10.9	2.3	0.41	0.346	9.7	2.1	8.57	1.46	9.2	1.85	172	34	111	74	117	87	135	125	60
SC110	RLOP	M	78	88	340	4	8	13	3657	559	10838	0.279	0.245	5.5	0.9	0.359	0.324	8.3	1.4	4.77	0.72	7.15	1.1	189	33	79	35	80	38	139	44	54
SC111	RLOP	M	84	76	309	4	8	15	3944	643	14413	0.246	0.215	5.1	1.1	0.335	0.301	6.9	1.4	4.25	0.81	5.89	1.06	.	.	70	.	71	.	84	114	65
SC112	RHOP	M	79	93	373	3	10	12	4395	2393	21071	0.27	0.270	3.9	1	0.37	0.370	7.2	1.2	3.16	0.42	6.33	0.75	202	71	56	54	57	55	132	106	66
SC113	RHOP	M	74	77	320	5	15	22	7447	2250	19336	0.291	0.255	6.8	1.5	0.412	0.376	11.8	2.6	6.44	1.29	10.93	2.2	231	125	103	103	112	109	142	164	67
SC114	PHF	M	63	100	345	4	12	17	7946	3757	8512	0.239	0.218	4.1	0.9	0.417	0.384	9.3	2.6	4.03	0.7	8.21	2.14	209	78	65	87	73	92	.	201	63
SC115	PLF	M	72	66	335	4	8	10	4160	2301	5190	0.32	0.264	5.3	1.2	0.409	0.356	6.7	1.5	4.56	0.96	6.21	1.23	142	34	46	29	49	34	63	111	37
SC116	PHF	M	67	76	329	3	7	11	7487	3525	8663	0.271	0.226	5.3	1	0.412	0.332	8.8	2.1	4.49	0.74	7.39	1.72	170	63	73	93	74	112	60	130	51
SC118	PLOP	M	74	51	293	2	3	3	3482	758	9067	0.107	0.075	2.5	0.1	0.191	0.148	4.1	0.4	2.48	0.14	3.4	0.3	129	28	26	31	27	32	44	65	23
SC117	PLOP	M	59	73	324	2	2	2	3049	653	7429	0.167	0.110	2.3	0.3	0.27	0.195	4.6	0.9	1.81	0.15	3.96	0.59	116	37	35	33	36	33	46	.	30
SC119	PLF	F	75	42	284	3	8	11	3691	2187	7869	0.214	0.185	4.7	0.8	0.318	0.259	6.6	1.3	3.77	0.64	4.89	0.87	153	30	42	51	48	53	81	106	35
SC120	RLF	F	67	74	300	0	0	0	4997	3095	5945	0.215	0.189	5.5	0.8	0.374	0.317	9.2	2.2	4.97	0.64	8.33	1.8	164	46	52	63	54	66	102	95	41
SC121	RLF	M	86	67	295	3	6	9	5744	3414	8972	0.235	0.215	5.2	0.8	0.364	0.325	6.7	1.7	4.58	0.6	6.47	1.25	195	33	47	41	47	50	183	67	46
SC122	PLF	M	79	53	266	1	1	1	4133	2018	7893	0.203	0.148	4	0.6	0.305	0.253	6.2	1.2	3.16	0.36	5.05	0.87	155	23	33	38	34	39	92	111	35
SC125	RLOA	M	68	81	335	3	7	10	4256	8083	4744	0.074	0.066	3.4	0.2	0.117	0.103	4.4	0.4	2.8	0.14	3.79	0.3	150	41	39	41	44	47	121	115	42
SC123	PLF	M	62	63	296	3	6	7				0.254	0.195	4.4	0.7	0.352	0.284	5.8	1.6	3.37	0.47	4.82	1.21	.	.	.	.	.	.	.	.	.
SC126	RLOA	M	54	90	340	2	3	3	3891	7236	3413	0.144	0.135	4.7	0.5	0.2	0.186	5.3	0.9	4.37	0.41	4.96	0.71	143	43	44	61	52	64	115	130	88
SC127	RLOT	F	58	71	347	4	9	11				0.254	0.248	7.6	2.5	0.331	0.314	10.4	4	7.5	2.23	9.24	3.58	.	.	.	.	.	.	.	.	.
SC129	RLOA	F	51	52	278	3	6	8	1704	6905	2847	0.22	0.190	7.9	0.8	0.33	0.300	9.8	1.9	4.92	0.58	7.4	1.41	119	23	57	50	61	52	70	99	62
SC130	RLOT	M	39	66	302	4	7	9	9163	734	10035	0.3	0.300	3	1	0.377	0.350	3.7	1.5	4.89	0.54	3.81	0.59	153	16	48	56	50	57	59	.	95
SC128	RLOT	F	46	69	313	2	2	2	9329	532	7787	0.184	0.158	9	1	0.25	0.220	12.2	1.9	7.93	0.87	10.56	1.57	124	11	56	41	63	49	90	94	41
SC124	RLF	F	45	63	289	0	0	0	4773	2725	9350	0.217	0.152	6.7	1	0.329	0.221	6.4	1.6	4.96	0.6	5.22	0.97	121	17	82	45	82	53	156	167	58
SC131	RLF	M	48	75	332	4	7	8	2992	2735	5456	0.293	0.256	17.6	3.9	0.431	0.391	26	11.8	13.94	3	22.91	9.5	167	22	77	66	77	89	163	278	47
SC132	PHF	M	65	73	332	4	7	12	8682	3759	7745	0.281	0.262	6.1	1.1	0.406	0.366	6.7	2.7	5.64	0.96	6.47	2.04	178	54	56	91	61	95	89	161	56
SC133	PHF	M	73	74	339	4	11	20	9025	3584	8556	0.274	0.224	4.6	0.9	0.421	0.343	6.2	2.8	4.26	0.75	5.6	2.08	180	56	71	62	77	64	129	194	51
SC134	PHF	F	58	62	291	3	6	6	6504	4303	9153	0.268	0.213	11.5	2	0.411	0.365	16.1	6.9	9.75	1.63	13.3	4.97	153	51	58	57	77	64	114	46	44
SC135	RLF	F	56	64	298	4	7	11	3769	1990	7339	0.266	0.239	6	1.2	0.407	0.332	6.4	1.7	5.21	0.98	5.57	1.32	142	57	48	59	49	60	121	102	46
SC136	PLF	F	54	61	298	2	3	3	3046	1634	6012	0.275	0.235	4.2	0.8	0.384	0.320	4.8	1.5	3.61	0.57	3.99	1.08	133	16	22	37	22	38	92	166	51
SC137	RLF	F	73	50	280	2	3	3	3896	2648	10891	0.207	0.177	11.9	2	0.332	0.278	15.5	3.2	10.45	1.55	14.07	2.7	181	81	66	80	72	84	114	111	57
SC138	PLF	F	58	48	288	3	6	6	3404	2528	6254	0.195	0.180	3.8	0.5	0.26	0.242	4.5	0.9	3.47	0.39	4.14	0.75	125	43	31	62	36	64	72	133	.
SAC101	ABG	F	61	65	312	0	0	0	5112	1680	9229	0.154	0.120	3	0.2	0.229	0.200	3.6	0.5	2.52	0.14	2.75	0.38	111	16	22	18	27	46	28	46	53
SAC102	RLF	M	51	61	318	3	6	7	8343		10686	0.208	0.170	5.4	0.6	0.337	0.280	5.6	1.5	5.08	0.52	5.3	1.22	166	50	52	65	54	70	133	141	64
SAC103	ABG	M	60	102	339	0	0	0	7690		3758	0.232	0.160	8.2	1.5	0.293	0.220	9	2	5.33	0.77	6.56	1.17	137	58	27	46	43	47	72	49	58
SAC104	ABG	M	61	69	312	2	3	3	4280	1930	9998	0.284	0.230	6.5	1.2	0.384	0.320	9.5	2	6.06	0.93	8.5	1.62	116	23	22	36	26	37	29	43	60
SAC105	ABG	M	70	101	330	2	2	2	3078	2358	7226	0.16	0.150	8	0.9	0.272	0.230	12.2	3	7.06	0.8	10.44	2.06	146	37	28	47	33	50	26	40	51

Tstcfn: test configuration:--R=rigid, P=padding, H=32km/h impact, L=24 km/h impact, F=flat wall, OP=pelvic offset, OT=thoracic offset, OA=abdominal offset ABG=air bag; **Rbfx:** number of rib fractures; **width**: average of chest width at 4th and 8th rib; **MAIS:** maximum AIS of thoracic injury, **thx_f:** norm. max. thoracic wall force, **abd_f:** norm. max. abdominal wall force, **pel_f:** norm. max. pelvic wall force, **Hdmax,Fdmax:** half and full thoracic deflections (normalized with respect to chest width), H**Vmax, FVmax:** Max velocity derived from half and full thorax deflections, H**VC, FVC:** Max. VC derived from half and full thorax deflections, **TTI:** computed as in Eppinger, 1984., **ASA:** ASA20 computed and normalized as in Cavanaugh (1993), **spu and spl:** norm. lateral upper and lower spine acceleration (g's), **rspu, rspl:** norm. resultant upper and lower spine acceleration (g's), **rlu, rll:** norm. left upper and left lower rib acceleration (g's), **pel:** norm. pelvic acceleration (g's).

Note: The test speed of SC112 was 27.5 km/h which is lower than the other high speed tests.

APPENDIX B. ES-2RE SLED TEST DATA CONDUCTED AT MEDICAL COLLEGE OF WISCONSIN

																	Upper rib			Middle Rib			Lower Rib		
tstno	tstcfn	thx_f N	abd_f N	pel_f N	ABDF N	PELF N	TTI	ASA g's	spu g's	spl g's	rspu g's	rspl g's	pel g's	rpel g's	rlu g's	rll g's	dmax (mm)	Vmax (m/s)	Vcmax (m/s)	dmax (mm)	Vmax (m/s)	Vcmax (m/s)	dmax (mm)	Vmax (m/s)	Vcmax (m/s)
SD254	PHF	9107	3458	11915	1847	3075	52	44	39	49	39	49	59	59	46	69	49.2	2.45	0.63	53.8	2.49	0.71	48.9	2.50	0.48
SD261	PHF	8197	3542	10900	2005	2403	53	44	34	48	35	49	60	62	36	49	43.5	2.04	0.48	49.3	2.19	0.59	47.8	2.43	0.48
Avg.	**PHF**	**8652**	**3500**	**11407**	**1926**	**2739**	**53**	**44**	**36**	**49**	**37**	**49**	**59**	**61**	**41**	**59**	**46.3**	**2.25**	**0.56**	**51.6**	**2.34**	**0.65**	**48.3**	**2.47**	**0.48**
SD260	**PLF**	**4628**	**2064**	**6806**	**1207**	**1596**	**31**	**27**	**22**	**31**	**22**	**31**	**37**	**38**	**24**	**25**	**26.9**	**1.24**	**0.12**	**33.5**	**1.60**	**0.20**	**33.8**	**1.67**	**0.23**
SD255	PLOP	2818	1042	9566	601	2499	38	16	25	28	26	28	36	37	29	43	28.7	1.35	0.19	22.7	1.10	0.12	15.7	1.24	0.06
SD256	PLOP	2782	1150	9367	605	2586	34	16	24	27	25	27	36	37	31	36	26.6	1.35	0.17	22.0	0.98	0.11	17.6	1.24	0.07
Avg.	**PLOP**	**2800**	**1096**	**9466**	**603**	**2543**	**36**	**16**	**25**	**28**	**26**	**28**	**36**	**37**	**30**	**40**	**27.6**	**1.35**	**0.18**	**22.4**	**1.04**	**0.12**	**16.6**	**1.24**	**0.07**
SD262	RHF	13928	5773	17871	4177	5226	153	79	57	105	59	105	137	137	110	193	NA	NA	NA	NA	NA	NA	53.8	7.76	2.02
SD263	RHF	13084	6176	18396	4157	5274	153	76	48	106	50	106	131	131	95	193	NA	NA	NA	NA	NA	NA	54.3	7.81	2.06
Avg.	**RHF**	**13506**	**5975**	**18134**	**4167**	**5250**	**153**	**78**	**52**	**105**	**54**	**106**	**134**	**134**	**102**	**193**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**54.1**	**7.79**	**2.04**
SD259	**RHOP**	**8550**	**919**	**28321**	**732**	**6923**	**140**	**39**	**55**	**100**	**57**	**102**	**142**	**142**	**104**	**177**	**46.4**	**4.91**	**1.02**	**34.4**	**5.16**	**0.79**	**24.1**	**4.31**	**0.46**
SD252	RLF	9090	2638	13583	1804	3586	81	46	30	61	31	61	78	78	64	105	41.1	3.44	0.62	47.2	5.49	1.21	43.8	5.14	1.12
SD253	RLF	9076	2615	13688	1889	3633	82	47	30	64	31	64	84	85	66	107	39.8	3.49	0.62	45.7	5.58	1.22	43.8	5.25	1.13
Avg.	**RLF**	**9083**	**2627**	**13636**	**1847**	**3610**	**81**	**47**	**30**	**62**	**31**	**63**	**81**	**81**	**65**	**106**	**40.4**	**3.47**	**0.62**	**46.4**	**5.54**	**1.22**	**43.8**	**5.20**	**1.13**
SD250	RLOA	969	16952	6756	9439	1571	102	18	46	96	46	96	67	67	108	152	14.6	2.48	0.11	4.9	1.28	0.03	12.3	2.19	0.09
SD251	RLOA	1196	16783	6472	9205	2042	108	17	43	93	44	93	75	75	127	146	15.8	2.77	0.13	4.6	1.17	0.03	9.5	1.68	0.06
Avg.	**RLOA**	**1082**	**16867**	**6614**	**9322**	**1807**	**105**	**18**	**45**	**94**	**45**	**95**	**71**	**71**	**117**	**149**	**15.2**	**2.63**	**0.12**	**4.7**	**1.23**	**0.03**	**10.9**	**1.94**	**0.08**
SD257	RLOP	3896	465	16133	582	3812	60	34	31	42	31	42	76	76	59	71	30.2	2.87	0.40	22.1	2.43	0.24	12.8	2.02	0.10
SD258	RLOP	4028	462	16355	681	NA	61	26	32	43	32	44	79	79	54	73	30.8	2.84	0.40	22.0	2.42	0.24	13.3	2.19	0.12
Avg.	**RLOP**	**3962**	**464**	**16244**	**632**	**3812**	**61**	**30**	**31**	**43**	**32**	**43**	**77**	**78**	**56**	**72**	**30.5**	**2.86**	**0.40**	**22.1**	**2.43**	**0.24**	**13.0**	**2.11**	**0.11**
SD248	RLOT	24323	490	6962	923	1757	201	65	91	99	92	99	65	66	426	332	NA	NA	NA	NA	NA	NA	54.8	8.10	1.41
SD249	RLOT	25349	493	7586	695	1725	199	70	93	103	93	103	58	58	393	343	NA	NA	NA	NA	NA	NA	55.2	8.09	1.40
Avg.	**RLOT**	**24836**	**491**	**7274**	**809**	**1741**	**200**	**67**	**92**	**101**	**93**	**101**	**61**	**62**	**410**	**338**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**55.0**	**8.10**	**1.41**

Tstcfn: test configuration:--R=rigid, P=padding, H=32km/h impact, L=24 km/h impact, F=flat wall, OP=pelvic offset, OT=thoracic offset, OA=abdominal offset; **thx_f:** maximum thoracic force, **abd_f:** max. abdominal force, **pel_f:** max. pelvic force, **ABDF:** total ES-2re abdominal force, **PELF:** ES-2re pubic symphysis force, **dmax:** max. upper, middle, and lower rib deflection, **Vmax:** Max velocity derived from dmax, **VCmax:** Max. VC derived from d,ax, **rlu, rll:** left upper and left lower rib acceleration (g's), **spu, spl, pel:** lateral upper spine, lower spine, and pelvic accelerations, **rspu, rspl, rpel:** resultant upper and lower spine and pelvic accelerations, **TTI:** computed as in Eppinger, 1984 without the age term, **ASA:** ASA20 computed as in Cavanaugh (1993). NA: not available

APPENDIX C. SIDE IMPACT CADAVER SLED TEST DATA PUBLISHED BY CAVANAUGH ET AL., (1993)

tstno	MAIS	Age	TTI	Dmax	chswd	VCmax	ASA10	cmax	T1y	T12y
1	5	60		181	438	4.8		0.41	131	
2	5	64	196	122	414	3.3	65.5	0.29	48	102
3	5	37	209	137	570	4.5	57	0.24	145	126
4	4	69	221	100	390	1.7	52.7	0.26	40	70
6	4	60	217	88	380	1.1	43.6	0.23	130	88
5	4	67	156	80	390	1	23.6	0.21	63	84
7	4	66	172	98	468	1.3	28.8	0.21	64	42
8	5	64		125	408	2.6	29.5	0.31	54	51
10	2	60	175	81	426	1	21.1	0.19	46	95
11	2	54	138	69	370	0.7	23.3	0.19	58	51
13	4	62		81	442	0.9		0.18	54	
15	0	43	126	103	404	1.3	27.6	0.25	46	52
17	2	65	220	95	430	1	19.5	0.22	58	67
9	5	61	167	111	400	1.6	41.1	0.28	73	75
12	5	68	161	109	378	2	46.3	0.29	74	66
14	4	60	176	95	416	1.1	36.8	0.23	57	88
16	4	58	198	99	338	2.1	35.2	0.29	48	74

Tstno: test number (Cavanaugh, 1993), **MAIS:** maximum AIS level injury, **Age:** age of subject at time of death, **TTI:** TTI computed according to (Eppinger, 1984), **Dmax:** maximum half thorax deflection in mm by film analysis, **chswd:** full thorax width of subject in mm, **VCmax:** Maximum VC in m/s, **ASA10:** average spine acceleration, **cmax:** normalized chest deflection, **T1y:** normalized lateral T1 acceleration, **T12y:** normalized lateral T12 acceleration.

APPENDIX D. CADAVER DROP TESTS, WALFISCH ET AL (1980)

tstno	age	sex	width mm	rbfx	AIS	force (N)	normforce	forcenatp	relpen+defl
205	62	F	242	3	0	1600	2820	2700	0.28
206	66	M	310	9	4	5350	5040	4700	0.48
209	54	M	290	4	4	3800	4910	4900	0.36
210	61	M	290	4	3	4150	4300	3850	0.355
211	46	M	260	0	0	1700	2460	2250	0.51
213	67	M	340	8	3	4900	4810	3300	0.16
215	52	M	280	7	5	5100	6430	5800	0.34
217	55	M	325	11	5	5000	5930	6000	0.29
212	45	F	220	5		1500	2110	1900	0.266
219	68	F	290	12		1950	2490	2250	0.183
216	56	M	295	11		4200	5580	4850	0.38

age: age of cadaveric subject at the time of death, **sex:** subject gender, **width:** abdominal width in mm at the 9th rib level, **rbfx:** number of rib fractures sustained**, AIS:** AIS category of injury, **force:** Measured applied force in Newtons, **normforce:** Applied force normalized – mass scaled to represent that for a 50th percentile male, **forcenatp:** Normalized force at time of maximum penetration**, relpen+defl:** normalized deflection (relative to the half abdomen width at the 9th rib level) of the abdomen which includes the penetration of the armrest and the abdominal deflection obtained from film analysis.

APPENDIX E. CADAVER ABDOMINAL PENDULUM IMPACT TESTS, VIANO (1989)

Run #	Cadaver #	Impact Side	Age (years)	Mass (kg)	Sex	Waist Breadth (cm)	Impactor Speed (m/s)	Pend Force (kN)	VC_max m/s	Def_max cm	C_max %	Total Fractures #	MAIS
6	947	R	38	56.25	Male	25.5	6.79	3.67	1.17	10.4	36.1	4	3
8	954	R	66	56.25	Male	25.5	6.73	3.06	1.37	12.1	37.7	7	3
10	RNY2	R	64	61.69	Male	33	6.75	4.17	1.14	11.3	33.9	0	0
12	956	R	40	76.2	Female	33.5	7.06	3.95	1.37	11.9	37	2	2
15	993	R	49	70.76	Male	31.5	8.1	4.89	1.73	13.4	43.2	0	0
19	986	R	29	70.3	Male	28	5.1	2.37	0.55	8.3	25.4	0	0
20	986	L	29	70.3	Male	28	9.8	7.36	2.04	12	43.1	9	4
23	047	L	62	83.91	Male	34.5	5.5	2.73	0.87	12.7	35.8	0	0
24	047	R	62	83.91	Male	34.5	5.4	2.29	1.01	14.5	41.3	0	0
28	047	R	62	83.91	Male	34.5	9.9	6.89	2.42	17.3	48.2	0	0
30	008	L	52	53.07	Female	29.5	5.1	3.2	1.04	10	36.1	0	0
34	063	R	64	48.54	Male	34	9.8	6.87	2.67	15.7	48.8	6	4
42	UOM2	L	64	75.76	Male	34.5	3.82	1.99	0.55	9.6	26.3	1	1
43	UOM2	R	64	75.76	Male	34.5	3.8	1.86	0.58	9.9	26.9	4	3

APPENDIX F. PELVIC IMPACT TEST DATA WITH CADAVERIC SUBJECTS AND THE EUROSID-1 DUMMY, BOUQUET ET AL. (1998).

						Cadaver Measured parameters							ES-1 Measured Parameters			
tstno	AGE yrs	SEX	WEIGHT kg	mass kg	velocity m/s	energy J	AIS	applied force	Norm. Appl. Force N	deflec tion	VC	accel g	Applied Force N	pubic symph force N	energy (J)	accel g
LCB01	65	M	54.5	12	11.4	774	2	13940	17247	50	1.12		24325	6292	778	128
LCB02	53	F	78	16	9.91	786	3	8930	8700	89	1.78	84	20450	5685	794	115
LCB03	80	F	30	16	10	803	3	7720	14221	67	1.54	105	20500	5884	803	114
LCB04	93	F	43	12	10	600	3	8300	12027	75	1.55	82	15770	4763	606	110
LCB05	84	M	42	12	13.4	1077	3	11790	17354	61	1.53	107	33160	8053	1079	188
LCB06	77	M	67.5	12	13.7	1120	3	15090	16188	71	1.8	115	34080	7736	1120	192
LCB07	72	M	82	16.2	11.5	1073	3	16120	15189	66	1.04	86	33170	7961	1028	184
LCB08	66	M	59	16.2	11.8	1118	3	13520	15865	68	1.22	136	33170	7961	1028	184
LCB09	65	M	66	16.2	9.47	725	2	10590	11532	56	1.64	79	20475	5784	799	114.5
LCB10	69	M	56	12	10.4	645	0			67		72	15770	4763	606	110
LCB11	71	M	71	12	11.8	834	3	12040	12488	65	1.77	97	24995	6638	857	152.5
MRB01	76	M	82	23.4	3.5	143	0	5640	5314	31.8	0.26		3147	690	137	
MRB03	57	M	76	23.4	3.4	135	0	6220	6165	28	0.23		3147	690	137	
MRB05	66	M	69	23.4	3.41	136	0	3670	3880	32.7	0.2		3147	690	137	
MRB07	69	M	52	23.4	3.43	138	0	4160	5311	21.2	0.18		3147	690	137	
MRB09	78	M	54	23.4	3.29	127	0	4010	4992	28.8	0.21		3147	690	137	
MRB11	38	M	86	23.4	3.34	131	0	4270	3898				3147	690	137	
MRB13	63	M	60	23.4	3.35	131	0	3000	3481	24.5	0.16		3147	690	137	
MRB15	69	F	59.5	23.4	3.26	124	0	3210	3746	32.4	0.27		3147	690	137	
MRB17	81	M	82	23.4	3.22	121	0	4310	4061	36.4	0.26		3147	690	137	
MRB19	70	M	70	23.4	3.26	124	0	4920	5152	28.3	0.23		3147	690	137	
MRB02	76	M	82	23.4	6.74	532	2	8400	7915	60.6	0.75		10330	2220	517	
MRB04	57	M	76	23.4	6.5	494	2	10550	10457	38.8	0.65		10330	2220	517	
MRB06	66	M	69	23.4	6.77	536	2	9120	9641	54.6	0.56		10330	2220	517	
MRB08	69	M	52	23.4	6.46	488	2	6520	8323	56.7	0.95		10330	2220	517	
MRB10	78	M	54	23.4	6.5	494	2	8150	10146	56.9	0.86		10330	2220	517	
MRB12	38	M	86	23.4	6.64	516	0	9840	8982				10330	2220	517	
MRB14	63	M	60	23.4	6.44	485	2	5840	6777	54	0.66		10330	2220	517	
MRB16	69	F	59.5	23.4	6.57	505	0	6540	7632	50.8	0.8		10330	2220	517	
MRB18	81	M	82	23.4	6.57	505	0	10040	9460	46.7	0.63		10330	2220	517	
MRB20	70	M	70	23.4	6.43	484	0	10180	10659	38.2	0.52		10330	2220	517	

APPENDIX G. LATERAL IMPACT SLED TEST DATA FROM ZHU ET AL. (1993).

Test No.	wall	speed (m/s)	age years	sex	mass kg	lamda	Normalized Response				MAIS
							pelvic gs	VCmax	Fmax (kN)	average force (kN)	
1	pelvic offset	8.9	60	M	70.5	1.02	81.7		12.17	7.45	2
2	pelvic offset	9.1	64	F	49.5	1.15	50.7		11.27	7.14	3
3	pelvic offset	10.5	37	M	70	1.02	99.6	4.2	16.52	9.95	2
4	unpadded	9.1	69	M	57.6	1.09	62.9	0.9	12.92	6.68	2
6	unpadded	9	60	M	61.2	1.07	103.4	1	10.74	5.79	2
5	unpadded	6.7	67	M	44	1.19	68.9	0.5	10.79	4.38	0
7	unpadded	6.7	66	M	74.8	1.00	116.1	0.9	6.68	4.85	0
8	unpadded	6.6	64	F	73.9	1.00	36.8		6.2	3.95	0
10	thick pad	8.7	60	M	62.1	1.06	30	0.5	5.4	4.38	0
11	thick pad	8.9	54	F	55.3	1.11	36.9	0.6	5.77	4.54	0
12	thick pad	8.9	68	F	54.4	1.11	74.5	1	8.12	6.14	0
13	thick pad	8.3	62	M	66.7	1.04	52.9	1.4	4.74	3.39	0
14	thick pad	9.4	60	M	55.3	1.11	59.3	1.1	5.26	4.17	0
15	thick pad	8.9	43	F	68.9	1.03	53.2	1.2	4.31	3.4	0
17	thick pad	8.9	65	M	93	0.93	63.1	1.2	5.3	4.14	0
9	thin pad	9.2	61	F	54.9	1.11	58.2		7.93	5.28	3
16	thin pad	8.9	58	F	56.7	1.10	59.9	1.8	7.04	5.46	2

lamda: Basic scale factor given by $(\text{mass}/75)^{1/3}$, Fmax: Maximum normalized applied pelvic force, **average force:** obtained from force-time history as described in Zhu, et al. (1993)

APPENDIX H: SID-IISFRG SLED TEST DATA CONDUCTED AT MEDICAL COLLEGE OF WISCONSIN

																		THORAX			ABDOMEN		
tstref	tstcfn	thx_f	abd_f	pel_f	actb_f	iliac_f	pv_sum	TTI	ASA	SPU	SPL	RSPU	RSPL	PEL	RPEL	RLU	RLL	Dmax	Vmax	VCmax	Dmax	Vmax	VCmax
SD269	PHF	5374	2204	8356	228	1453	1943	212	48	44	59	45	61	68	69	149	300	54.41	6.58	0.65	57.00	7.44	0.74
SD265	PLF	3053	1345	4718	310	409	850	170	28	29	33	31	33	38	38	128	216	36.24	4.68	0.34	38.92	4.15	0.36
SD267	PLF	3172	1394	5007	266	480	866	153	29	29	34	30	34	35	35	119	206	37.21	4.40	0.32	40.12	4.10	0.38
average	PLF	3112	1370	4863	288	445	858	162	29	29	33	30	34	37	37	124	211	36.73	4.54	0.33	39.52	4.13	0.37
SD271	PLOP	2316	818	6039	336	1024	1590	158	30	28	34	29	35	38	39	111	235	22.66	4.49	0.31	23.15	3.33	0.21
SD272	PLOP	2315	886	6369	369	1304	1939	205	32	31	36	31	37	40	41	112	273	24.32	4.96	0.35	22.12	4.06	0.24
average	PLOP	2316	852	6204	353	1164	1765	182	31	30	35	30	36	39	40	111	254	23.49	4.73	0.33	22.64	3.70	0.23
SD270	RHF	13022	1870	19440	564	6103	6936	302	95	113	112	113	114	160	161	218	451	63.11	8.06	2.05	61.75	8.13	2.35
SD274	RHOP	9556	1926	26377	766	9593	10905	337	89	145	119	146	127	186	186	194	453	48.63	7.79	0.92	51.43	8.69	1.37
SD268	RLF	5450	891	10158	641	1632	2391	206	44	42	50	43	51	94	97	164	271	54.65	5.70	1.08	52.40	5.64	0.88
SD275	RLOA	2285	9056	2707	1653	388	2394	148	44	71	69	71	69	61	62	103	190	57.12	4.99	1.00	54.79	5.89	1.05
SD276	RLOA	2140	10267	2868	1227	406	1956	151	49	80	78	80	78	64	64	95	189	57.07	5.14	1.03	55.46	6.27	1.14
average	RLOA	2212	9661	2787	1440	397	2175	150	46	75	73	76	73	62	63	99	189	57.10	5.07	1.02	55.13	6.08	1.10
SD273	RLOP	3705	1151	14303	677	3979	5056	212	56	49	75	49	77	116	117	105	239	34.68	4.42	0.43	38.93	5.49	0.66
SD277	RLOT	19542	550	4181	809	409	1098	241	91	164	133	165	136	59	60	230	206	60.64	6.47	1.49	8.53	2.33	0.08

Tstcfn: test configuration:--R=rigid, P=padding, H=32km/h impact, L=24 km/h impact, F=flat wall, OP=pelvic offset, OT=thoracic offset, OA=abdominal offset; **thx_f:** maximum thoracic force, **abd_f:** max. abdominal force, **pel_f:** max. pelvic force, **actb_f:** max. acetabular force, **iliac_f:** max. iliac force, **pv_sum:** sum of acetabular and iliac force, **dmax:** max. upper, middle, and lower rib deflection, **Vmax:** Max. upper, middle, and lower rib velocity, **VCmax:** Max. upper, middle, and lower rib viscous criterion, **rlu, rll:** left upper and left lower rib acceleration (g's), **spu, spl, pel:** lateral upper spine, lower spine, and pelvic accelerations, **rspu, rspl, rpel:** resultant upper and lower spine and pelvic accelerations, **TTI:** computed as in Eppinger, (1984) without the age term, **ASA:** ASA20 computed as in Cavanaugh (1993).

APPENDIX I: COMBINED SIDE IMPACT TEST DATA FROM EPPINGER ET AL. (1984) AND CAVANAUGH ET AL. (1993).

TEST NO	MASS (kg)	AGE (years)	MAIS	TTI	T12 accel. (gs)
H82009	50.8	27	5	182	208
H82012	74.8	17	5	153	156
76T010	88.0	84	4	269	105
76T011	74.8	69	4	242	166
77T089	55.3	66	5	216	88
77T092	58.1	45	4	153	80
H80024	64.9	24	0	144	134
H81002	64.9	57	4	186	130
H81004	79.8	56	4	218	134
H82014	61.2	22	5		
H82016	49.9	21	2		
H82020	73.0	41	5	229	164
W SIC04	57.6	69	4	200	76
W SIC06	61.2	60	4	195	93
W SIC01	70.5	60	5		
W SIC02	49.5	64	5	181	116
W SIC03	70.0	37	5	188	128
H80011	88.9	27	2	163	90
H80017	69.9	38	2	129	74
H82018	84.8	28	3	128	71
H82019	66.7	47	3	167	85
W SIC05	44.0	67	4	150	92
W SIC07	74.8	66	4	172	42
W SIC08	73.9	64	5		51
W 487	54.0	54	2	125	58
H80018	61.2	21	1	85	64
H80020	66.7	26	1	92	74
H82008	98.9	61	5	189	79
H82021	98.9	48	4	193	75
H82022	77.1	50	4	180	109
H80021	63.0	29	0	113	55
H80023	82.1	41	3		86
H81011	59.0	43	2	127	95
H81012	45.8	33	2		116
H81015	73.0	44	1	109	43
H81021	57.2	48	0	126	66
W SIC10	62.1	60	2	164	97
W SIC11	55.3	54	2	129	55
W SIC13	66.7	62	4		
W SIC15	68.9	43	0	117	53
W SIC17	93.0	65	2	201	67
H83010	55.8	30	0	95	57
H83011	60.8	26	0		92
H83012	77.1	34	0	116	72
H83020	52.2	17	0	87	89
76T029	62.6	67	2	140	55
76T034	59.0	62	4	169	97
76T039	73.9	72	3	148	40
76T042	64.4	58	4	153	67
77T095	93.0	77	4	221	59
77T098	59.0	71	4	203	98
W SIC09	54.9	61	5	156	81
W SIC12	54.4	68	5	159	72
W SIC14	55.3	60	4	176	101
W SIC16	56.7	58	4	198	82
H83008	78.0	45	0	114	32
H83016	68.0	52	4	181	111
H83021	58.1	38	4	181	161
BMD001	68.9	40	4	209	139
BMD002	70.8	43	3	133	57
BMD003	73.5	55	4	167	49