Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems

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LIST OF SYMBOLS

Symbol	Units	Description
λ		Dimensionless scaling factors which are ratios between fundamental properties (length, mass, modulus, etc.) which characterize the two systems that are compared
p		Probability of injury
p-value		Statistical measure of the appropriateness of the model from regression analyses
AIS		Abbreviated Injury Scale
HIC_{36}		Head injury criteria (eqn 2.1) where the time interval is limited to 36 milliseconds
Fx	N	Shear load at the upper neck load cell
Fz	N	Axial load (negative for compression, positive for tension) at the upper neck load cell
My	N-m	Bending moment (negative for extension, positive for flexion) at the occipital condyles
Fint	N	Intercept value for compression or tension for calculating Nij (eqn 3.1)
Mint	N-m	Intercept value for extension or flexion at the occipital condyles for calculating Nij (eqn 3.1)
Nij		Normalized neck injury criteria (eqn 3.1)
dc		Normalized central chest deflections for the human surrogate measured using chestbands
dmax		Normalized maximum chest deflections from five locations for the human surrogate measured using chestbands
As	G	3 millisecond clip value for thoracic spinal acceleration measured in the dummy or human surrogate
Aint	G	Intercept for spinal acceleration used to calculate CTI (eqn 4.2)

Ac	G	Critical acceleration limit for thoracic injury criteria
D	mm	Chest deflection measured in the dummy
Dint	mm	Intercept for dummy chest deflection used to calculate CTI (eqn 4.2)
Dc	mm	Critical deflection limit for thoracic injury criteria
UR **UC** statistical **UL** **LR** **LL**		Five chestband measurement locations (upper right, upper center, upper left, lower right lower left) for deflection and velocity used in the analyses of thoracic injury
V	m/sec	Velocity of the chest measured either at the five location sites (UR, UC, UL, LR, LL) for the human surrogate by the chestband or at the sternum for the anthorpometric test devices
V*C **VC**	sec-1	Viscous criterion, which is the product of the chest velocity, V, and the normalized compression of the chest, D/Chest depth.
CTI		Combined Thoracic Index (eqn 4.2)

Restraint system (Table 4.1)

ABG	Air bag
DPL	Padded dash panel
KNEE	Knee bolster
LAP	Lap belt
2PT	2 point belt (shoulder belt without lap belt)
3PT	3 point belt

RIBFXR	Number of rib fractures (Table 4.1)

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EXECUTIVE SUMMARY

INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA) plans for upgrading the Federal Motor Vehicle Safety Standard (FMVSS) No. 208 frontal crash protection safety standard include improving protection requirements for the normally seated mid-sized adult male, as well as including additional requirements that will specify minimum requirements to minimize the risks from airbags to small-sized females and children in both normal and out-of-position seating locations. These new crash specifications will require the use of additional dummies of various sizes as well as additional performance criteria that appropriately represent injury thresholds of these additional population segments. The purpose of this report is to document the proposed injury criteria for specified body regions, including both the rationale and performance limits associated with them for all the various sized dummies to be used in the proposed upgrade of FMVSS No. 208 for frontal crash protection.

BACKGROUND

Injury criteria have been developed in terms that address the mechanical responses of crash test dummies in terms of risk to life or injury to a living human. They are based on an engineering principle that states that the internal responses of a mechanical structure, no matter how big or small, or from what material it is composed, are uniquely governed by the structure's geometric and material properties and the forces and motions applied to its surface. The criteria have been derived from experimental efforts using human surrogates where both measurable engineering parameters and injury consequences are observed and the most meaningful relationships between forces/motions and resulting injuries are determined using statistical techniques.

Development of human injury tolerance levels is difficult because of physical differences between humans. It is further complicated by the need to obtain injury tolerance information through indirect methods such as testing with human volunteers below the injury level, cadaver testing, animal testing, computer simulation, crash reconstructions, and utilization of crash test dummies. Each of these indirect methods has limitations, but each provides valuable information regarding human tolerance levels. Due to the prohibitive number (and cost) of tests required to obtain a statistically significant sample size, it ultimately becomes necessary to consolidate the available information each of these methods provides, and apply a judgement as to what best represents a reasonable tolerance level for a given risk of injury.

Human volunteer testing has the obvious shortcoming in that testing is done at sub-injurious exposure levels. It also poses problems in that instrumentation measurements must be obtained through non-invasive attachments, volunteers are most often military personnel who may not be representative of the average adult population, and the effects of muscle tension and involuntary reflexes are difficult to ascertain. While cadaver testing is essential to the development of human injury tolerances, it also has a number of inherent variables. Cardiopulmonary pressurization, post mortem tissue degradation, muscle tension, age, gender, anthropometry, and mass are all factors which produce considerable variability in test results. Animal testing also has this problem, along with the need to translate anatomy and injury to human scales, but has the advantage of providing tolerance information under physiologic conditions. Crash reconstructions provide injury data under normal human physiological conditions, however, the forces and accelerations associated with those injuries must be estimated. Computer simulation and testing with crash test dummies provide valuable information, but these methods are dependent upon response information obtained through the other methods.

Frequently criteria are developed, based on extensive analysis, for one size dummy (e.g., an adult) and these criteria are applied and translated to other size dummies (e.g., a child) through a process known as scaling. Scaling techniques overcome the influence of geometric and material differences between experimental subjects and the subjects of interest. This technique assumes that the experimental object and the object of interest are scale models of each other and that their mass and material differences vary by relatively simple mathematical relationships. If these assumptions are met, engineering experience shows that the scaled values are good approximations of the expected values. However, the more these assumptions are not valid, the more the translated physical measurements may be distorted from their true levels.

PROPOSED HEAD INJURY CRITERIA

Existing NHTSA regulations specify a Head Injury Criteria (HIC) for the 50th percentile male. The biomechanical basis for HIC for the 50th percentile adult male was reviewed and alternatives to this function were sought. While considerable progress has been made with the capabilities of analytical finite element head/brain models to simulate the major injury mechanisms prevalent in brain injury, it was felt that it would be premature for their results to be used in this current proposed rulemaking action. Therefore, the current HIC continues to be used as the regulatory injury function and that the level of 1000 continue to be the maximum allowable limit for the 50th percentile adult male.

Both geometric and material scaling, coupled with engineering judgement, were employed to translate the critical HIC value to other occupant sizes. The recommended critical HIC levels for the various occupant sizes are given in the table below.

Dummy Type	**Mid-Sized Male**	**Small Female**	**6 Year Old Child**	**3 Year Old Child**	**12 Month Old Infant**
Existing / Proposed HIC Limit	1000	1000	1000	900	660

PROPOSED NECK INJURY CRITERIA

Existing NHTSA regulations specify neck injury criteria for the 50th percentile male as part of the FMVSS No. 208 alternative test, S13.2. The primary sources of biomechanical data concerning airbag related neck injury conditions are a series of tests on pigs conducted by General Motors and Ford Motor Company in the 1980's. These tests simulated an airbag inflating in front of an out-of-position child in the passenger seating position. The age and type of pig was chosen so that the developmental stage was similar to that of the average three year old child. The tests were conducted in pairs, with one test involving the pig and the other using a 3 year old child dummy. While each paired test involved the same airbag design, a variety of designs were used during the test series. The injuries sustained by the pigs were determined post test by necropsy, and the mechanical conditions that caused these injuries were analyzed to be those obtained from measurements made on an instrumented child dummy exposed to the same event. Film analysis was used to verify that the kinematics of the pig and dummy were generally similar.

The biomechanical basis for neck injury criteria was reassessed. Statistical analysis of the GM portion of the data indicates that tension in the neck of the dummy (the force that stretches the neck) had the strongest statistical relationship with the observed pig injuries and that there was little improvement in injury predictive capability when bending moment was added. The Ford effort concluded, based on their data analysis, that a linear combination of tension and bending moment explained the experimental outcomes the best.

NHTSA used more appropriate statistical techniques to review the data. Neck tension continued to have the best relationship with injury. Adding neck extension (rearward) bending moment did not improve predictive capabilities. However, our engineering experience of how stresses are produced in structures leads us to agree with the Ford work that neck failure is most likely a function of both tension and bending moment. Consistent with this concept, the available data were re-analyzed to determine what combination of tension and extension moment best predicted the injury outcomes. The result of this analysis then became the basis of the proposed tension/extension requirement. Previous assessments for adult neck criteria provided the basis for establishing the ratio between critical flexion (forward) and extension (rearward) moments. Compressive limits were chosen to be the same as the tension limits based on data from recent tests on adult cadavers.

The resulting neck injury criteria, called "Nij", propose critical limits for all four possible modes of neck loading; tension or compression combined with either flexion (forward) or extension (rearward) bending moment. The Nij is defined as the sum of the normalized loads and moments, i.e.,

$$Nij = \frac{F_Z}{F_{\text{int}}} + \frac{M_Y}{M_{\text{int}}} \tag{3.1}$$

where F_Z is the axial load, F_{int} is the critical intercept value of load used for normalization, M_Y is the flexion/extension bending moment, and M_{int} is the critical interept value for moment used for normalization.

The critical intercept flexion and extension moments were scaled up and down to all other dummy sizes, while the critical intercept tension and compression values were only scaled from the three year-old for the child dummies. 50th male and 5th female tension and compression values were obtained from previously developed adult cadaveric test data rather than relying on values scaled from the three year-old. The scaled critical intercept values for the various sized dummies and loading modes are given below.

Dummy Type	Tension (N)	Compression (N)	Flexion (Nm)	Extension (Nm)
CRABI 12-month-old	2200	2200	85	25
Hybrid III 3-year-old	2500	2500	100	30
Hybrid III 6-year-old	2900	2900	125	40
Hybrid III small female	3200	3200	210	60
Hybrid III mid-sized male	3600	3600	410	125

In addition, analyses were conducted to compare the percentage of NCAP crashes predicted to have an AIS≥ 3 injury using Nij with the predicted percentage of neck injuries in NCAP-like crashes within the NASS data file. This comparison indicated that a normalized Nij limit of 1.0 should correspond to a 15 percent risk of serious injury, whereas a limit of 1.4 should correspond to a 30 percent injury risk. Our recommendation is to use an Nij allowable limit of 1.4, and comment is being requested on whether a critical value of 1.0 would be more appropriate.

PROPOSED THORACIC INJURY CRITERIA

NHTSA currently mandates regulatory limits of 60g for chest acceleration and 76 mm (3 inches) for chest deflection as measured on the Hybrid III 50th percentile male dummy. Considerable biomechanical information developed since the 1950's was used to assess potential loading threshold for chest injuries and it has been the basis for the existing criteria. Through the continued biomechanical research efforts of the NHTSA, a new series of 71 highly instrumented frontal impact tests using human surrogates were conducted over the last 5-6 years. This test series used five different restraint combinations (3-point belt, 2-point belt/knee bolster, driver airbag and lap belt, driver airbag and knee bolster, and driver airbag and 3-point belt) with a variety of crash pulses and velocity changes. The diverse capabilities of the instrumentation employed during this test series allowed the calculation and performance comparison of currently effective and potentially revised chest injury measures with the observed injury outcomes. It is the results from the analysis of this considerable data base that are the basis for the recommended thoracic performance criteria and tolerance limits.

The analyses performed looked at a variety of statistical measures (log likelihood, p-value, gamma function, and concordant/discordant percentages) to evaluate the ability of both individual and multiple response variables to explain the observed experimental injury results. Based on these statistical measures, the analysis demonstrated that while single variables, such as peak chest acceleration, peak chest deflection, or the Viscous Criterion (V*C) advanced by one or more non-NHTSA researchers, provided a measure of prediction of injury outcome, a formulation that included both peak chest acceleration and maximum chest deflection, called the Combined Thoracic Index (CTI) was found to provide superior predictive capability compared to all others examined. The formulation of the CTI is:

$$CTI = \frac{A_{\max}}{A_{\text{int}}} + \frac{D_{\max}}{D_{\text{int}}} \qquad (4.2)$$

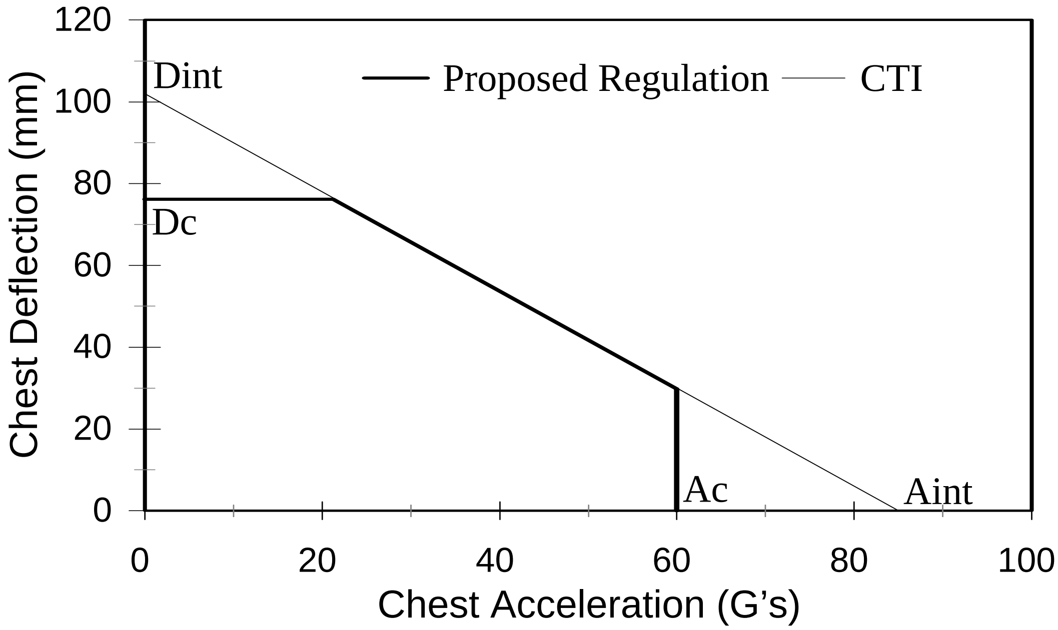
where A_{max} and D_{max} are the maximum observed acceleration and deflection,
and A_{int} and D_{int} are the corresponding maximum allowable intercept values.

The associated CTI injury risk curve (Figure 4-4) illustrates how the risk of serious injury increases with larger CTI values.

The basis for this deflection/acceleration criterion's good performance can be qualitatively explained by considering the differences in and consequences of the loading patterns that the various automotive restraint system apply to the human thoracic cage. All restraint systems are physically limited to applying forces over the areas with which they make contact with the body. Therefore, for the same total load applied to the body, a belt system applies greater loads along its smaller contact area than an airbag which applies loads over a larger contact area. Because the restraint loads are more concentrated under belt restrained conditions, the chest is more vulnerable to injury then if the same total load were applied over a larger area by an airbag. If a combination airbag/torso belt system is employed, depending on the characteristics of the individual systems, the predominant loading would range from line load with a stiff belt/soft bag system to a more distributed load area with a soft belt/stiff bag. A performance measure should, therefore, be sensitive to both belt and airbag loading conditions in order to evaluate overall safety benefit or injury threat.

The CTI encompasses the effects of both airbag and belt systems. First, the peak chest acceleration is a good indicator of the magnitude of the total forces being applied to the torso. Newton's second law (Force = Mass * Acceleration) supports this premise. Second, the chest deflection gives an indication of the portion that the torso belt is contributing to the overall restraint effort; i.e., the greater the deflection is per unit of acceleration, the more the belt system is contributing to the total restraint load. Therefore, because the CTI allows greater accelerations with lower deflections, it could be satisfied by restraint designs to have force limiting belt systems along with airbag systems that assume a greater portion of the restraint load. This is a demonstrated technique for improving the safety capabilities of belt/airbag systems.

The proposed thoracic injury criteria include the CTI formulation combined with two pragmatic restrictions; the total thoracic deflection shall not exceed 76 mm (3 inches) and the maximum chest acceleration shall not exceed 60 g for time periods longer than 3 milliseconds. The 76 mm (3 inch) maximum is a result of the fact that the Hybrid III 50th percentile dummy cannot sustain more than 79 mm (3.1 inches) of chest compression. Therefore, even if a greater deflection limit were allowed, the dummy could not provide an accurate assessment of the true deflection. Also, because there are few experimental data points at the high g (>60 g) and low deflection (<25 mm) regime to demonstrate that the CTI function is protective in those conditions, it is proposed that the maximum acceleration limit, regardless of the measured deflection, remain at 60 g. The combined effect of these considerations makes the proposed thoracic criteria for the 50th percentile male a combination of three requirements: (1) Limit the maximum chest acceleration to less than 60 g, (2) limit the maximum chest deflection to less than 76 mm (3 inches), and (3) limit the CTI to less than 1. These requirements are graphically illustrated in the following figure.



Critical intercept values that adjust the CTI for the various sized occupants are obtained via scaling techniques using geometric ratios, as discussed in Chapter 4. The following table provides the various scaled CTI intercept points for both acceleration and deflection for the various sized dummies.

Dummy Type	Mid-Sized Male	Small Female	6 Year Old Child	3 Year Old Child	12 Month Old Infant
Chest Deflection Intercept for CTI (Dint)	102 mm (4.0 in)	83 mm (3.27 in)	63 mm (2.47 in)	57 mm (2.2 in)	49 mm (2.0 in)

Chest Acceleration Intercept for CTI (Aint)	85	85	85	70	55

The additional limits on deflection and acceleration are similarly scaled for the other sized dummies, and are given in the table below.

Dummy Type	Mid-Sized Male	Small Female	6 Year Old Child	3 Year Old Child	12 Month Old Infant
Chest Deflection Limit for Thoracic Injury (Dc)	76 mm (3.0 in)	62 mm (2.5 in)	47 mm (1.9 in)	42 mm (1.7 in)	37 mm** (1.5 in)
Chest Acceleration Limit for Thoracic Injury Criteria (Ac)	60	60*	60	50	40

* Although geometric scaling alone would predict higher Ac values for females, it is believed that lower bone mineral density would offset this effect. Therefore, the acceleration tolerance values for small females are kept the same as for mid-sized males.

** The CRABI 12 month old dummy is currently not capable of measuring chest deflection.

PROPOSED LOWER EXTREMITY INJURY CRITERIA

While a great deal of research is currently underway both in experimental activities to determine biomechanical tolerance criteria and well as developing enhanced lower extremities for the dummies, both sets of activities are not ready for inclusion in these recommendations. Because femoral fractures in children are not a significant problem in automotive crashes, current recommendations are to continue using femur load only for the adult dummies. Therefore, NHTSA's current 10 kN limit for the axial femur load on the Hybrid III 50^{th} percentile male dummy is maintained. NHTSA is proposing a 6.8 kN limit, obtained by geometric scaling, for the 5^{th} percentile female dummy.

SUMMARY AND RECOMMENDATIONS

This report presents NHTSA's analysis of available biomechanical data to define mathematical relationships that can discriminate the mechanical impact conditions under which various portions of the human body will or will not be injured. In those cases where the data were sparse or not directly applicable, accepted engineering techniques, such as scaling and engineering judgement, were employed to both develop and extend existing knowledge to all of the various occupant sizes being considered for the proposed rulemaking action. The following table summarizes the proposals that are a result of this effort, and are believed to represent the best characterization of injury criteria available at this time.

Recommended Criteria	**Hybrid III Mid-Sized Male**	**Hybrid III Small Female**	**Hybrid III 6 Years**	**Hybrid III 3 Years**	**CRABI 12 Months**
Head Criteria					
HIC (36 msec)	1000	1000	1000	900	660
Neck Criteria					
Nij	1.4	1.4	1.4	1.4	1.4
Critical Intercept Values					
Tens./Comp. (N)	3600	3200	2900	2500	2200
Flexion (Nm)	410	210	125	100	85
Extension (Nm)	125	60	40	30	25
Thoracic Criteria					
1. Critical Spine Acceleration (g)	60	60	60	50	40
2. Critical Chest Deflection (mm)	76 (3.0 in)	62 (2.5 in)	47 (1.9 in)	42 (1.7 in)	37** (1.5 in)
3. Combined Thoracic Index (CTI)	1.0	1.0	1.0	1.0	1.0**
<u>CTI Intercept Values</u>					
Accel. (g's)	85	85	85	70	55
Deflection (mm)*	102 (4.0 in)	83 (3.3 in)	63 (2.5 in)	57 (2.2 in)	49 (2.0 in)
Lower Ext. Criteria					
Femur Load (kN)	10.0	6.8	NA	NA	NA

* Critical chest deflections are used to define the linear threshold for the Combined Thoracic Index given a theoretical condition of zero chest acceleration. The anthropomorphic dummies are not capable of measuring chest deflections to this extreme level.

** The CRABI 12 month old dummy is not currently capable of measuring chest deflection.

The following chapters delineate in much greater detail the available biomechanical data, its sources, and the procedures used to derive the proposed recommended performance levels for each major body area and occupant size. The appendices offer extensive examples of the application of the various proposed injury criteria to available test data as well as a computer program for calculating the Nij, given the recorded digital time histories of the neck loads.

Chapter 1
Introduction

Many researchers from around the world have contributed to the current base of knowledge of biomechanics. Over a century ago, researchers conducted tests to determine the strength of various biological tissues. [Duncan, 1874 and Messerer, 1880] Research into the safety of automotive occupants has been actively pursued for decades. Current issues and experimental results are presented every year at international conferences dedicated to biomechanics research. One of these annual meetings, the Stapp Car Crash Conference, has recently celebrated its 40^{th} anniversary. In developing the proposed injury criteria, the NHTSA's National Transportation Biomechanics Research Center (NTBRC) has drawn extensively from existing published research. Existing data from human cadavers, animal subjects, and to a limited degree live volunteers have been extensively analyzed during the process of developing the proposed injury criteria. Discussion of these previous experimental studies will be included in the sections for each individual body region.

In this introduction, two techniques - scaling and statistical analysis - that are used in developing the proposed injury criteria are summarized.

1.1 SCALING TECHNIQUES

Often, data can be collected for a specific type of vehicle occupant under a given loading condition, (e.g., an adult male), but data cannot be collected on other types of occupants. This is clearly evidenced by the paucity of biomechanical data available for children. Given these circumstances, biomechanics researchers must turn to scaling techniques and engineering judgement to develop injury criteria for other size occupants (e.g., children).

The type of scaling most commonly used in automotive applications is dimensional analysis. For mechanical systems in which thermal and electrical effects are absent, this technique allows the unknown physical responses of a given system to be estimated from the known responses of a similar system by establishing three fundamental scaling factors that are based on ratios between fundamental properties that characterize the two systems.(Newton, 1687, Langhaar, 1951 and Taylor, 1974) For structural analysis, the three fundamental ratios are length, mass density, and modulus of elasticity or stiffness. The scaling ratios for other variables of interest are based on the fundamental ratios.(Melvin, 1995) The three dimensionless fundamental ratios are defined as

Length Scale Ratio: $\lambda_L = L_1 / L_2$

Mass Density Ratio: $\lambda_\rho = \rho_1 / \rho_2$

Modulus of Elasticity Ratio: $\lambda_E = E_1 / E_2$

where the subscripts 1 and 2 refer to the subjects to be scaled to and from, respectively. Scale factors for all other physical quantities associated with the impact response of the system can be obtained from these three dimensionless ratios.

When scaling data between adult subjects it is generally assumed that the moduli of elasticity and mass densities are equal for both subjects, and that the scale factors for these quantities are equal to one. The effect of this assumption is that all the physical quantities can be scaled as functions of the basic length scale ratio, λ_L, assuming geometric similitude. When scaling data from adults to children, or between children of various ages, differences in the moduli of elasticity must be considered to account for the anatomic structural immaturity in children. Assuming mass density to be constant for all subjects ($\lambda_\rho = 1$), the following scale factors can be formed. (Melvin, 1995)

Length Scale Factor: $\lambda_L = L_1 / L_2$

Mass Scale Factor: $\lambda_m = (\lambda_L)^3$

Modulus of Elasticity Scale Factor: $\lambda_E = E_1 / E_2$

Time Scale Factor: $\lambda_T = \lambda_L / (\lambda_E)^{1/2}$

Acceleration Scale Factor: $\lambda_A = \lambda_E / \lambda_L$

Force Scale Factor: $\lambda_F = (\lambda_L)^2 \lambda_E$

Moment Scale Factor: $\lambda_M = (\lambda_L)^3 \lambda_E$

HIC Scale Factor: $\lambda_{HIC} = (\lambda_E)^2 / (\lambda_L)^{1.5}$

When applying the different scale factors to anthropomorphic dummies, it is necessary to determine whether or not the material scale factor has been incorporated into the design of the dummies. For example, the dummy chests were designed to provide proper structural stiffness. Thoracic injury criteria can thus be scaled using only geometric scale factors, assuming $\lambda_E = 1$. Head criteria are scaled using both geometric and material scaling, since the dummy heads are not necessarily designed with directly analogous mechanical properties.

1.2 STATISTICAL ANALYSIS TECHNIQUES

Because mechanical surrogates of humans (crash test dummies), rather than living humans, are used in crash tests to evaluate the safety attributes of vehicles, relationships between measurements of engineering variables made on the dummy and the probability of a human sustaining a certain type and severity of injuries are needed. The process to develop these relationships, commonly called injury criteria, is to conduct a series of experimental tests on highly instrumented biologically realistic human surrogates, such as cadavers, that expose them to crash conditions of interest. Measurements of engineering variables, such as forces, velocities, deflections, and accelerations, are made to mechanically characterize each impact event. Necropsy results are used to document the concomitant injuries. The data are entered into an appropriate database for analysis. The following procedures are considered by the NTBRC to provide the most meaningful relationships and thus were applied as indicated.

First, the level or severity of injury in each test was classified using the 1990 AIS manual. Each test in the data set was then assigned to one of two categories: (1) "no injury" representing the absence of injuries or minor injuries of AIS<3, or (2) "injury" representing serious injuries of AIS$\geq$3. Logistic regression was then used to develop injury criteria models where the mathematical relationship between the dichotomous dependent variable ("injury" or "no injury") and various independent measured or calculated variables such as spine acceleration were estimated. In logistic regression, a "null hypothesis" is initially made assuming that there is no relationship between the dependent injury variable and the candidate independent variable under study. The goodness of fit of the model is determined by examining the -2 log-Likelihood Ratio (-2log(LR)), which is a measure of the probability that the independent variable(s) explains the available outcomes. The -2log (LR) is used to test the null hypothesis and provide measures of rejection of the null hypothesis call "p-values". Higher values of -2log(LR) and lower p-values indicate that the model provides a better fit to the data.

Model building strategies and goodness of fit measures outlined by Hosmer and Lemeshow (1989) were used to develop the injury criteria models as well as for comparing their relative predictive ability. The Goodman-Kruskal Gamma of rank correlation was used for assessing the predictive ability of the model. Similar to R^2 in regression analysis, a Gamma value of 1 indicates perfect predictive ability while a value of 0 indicates no predictive ability of the model. The predictive ability of the model can also be assessed by the percentage of concordance and discordance. A greater percentage of concordance indicates better predictive ability of the model.

Much of the data used in this analysis have been previously analyzed using the Mertz/Weber method.(Mertz, 1996). This method uses only two data points from the available experimental data set to define the range of overlap region between "non-injury" and "injury", that is, the lowest value associated with "injury" and the highest value associated with "non-injury". Based on these two points, a modification of the "median rank" method is used to determine the mean and standard deviation of an assumed cumulative normal distribution function to explain the probability of an injurious event occurring. No statistical goodness of fit measures are used to guide the analysis or provide evaluations of the resulting predictive relationships.

Because of the considerable methodological differences between these two methods, significantly different functions can result from the data set depending on whether the Mertz/Weber method or logistic regression technique was employed. Therefore, because logistic regression technique uses the entire available experimental data set, uses the widely accepted statistical concept of "maximum likelihood" to obtain its results, and provides established statistical measures to evaluate absolute and relative predictive capabilities of the resulting relationships, logistic regression was used for all analyses performed in the development of cervical and thoracic injury criteria and tolerance limits discussed in this report.

Chapter 2
Head Injury Criteria

2.1 BACKGROUND

Motor vehicle crashes are the leading cause of severe head injuries in the United States. It has been estimated that automotive head injury accounts for nearly thirty percent of the total harm to car occupants.(Malliaris, 1982) While the introduction of airbag restraint systems has reduced the number and severity of automotive head injuries, they continue to be a leading source of injury. Over the past thirty years, a considerable effort has been devoted to determining head injury mechanisms and injury criteria. Although a great deal has been learned regarding head injuries, the only injury criteria in wide usage is the Head Injury Criterion (HIC), which was adopted over twenty-five years ago. HIC was first introduced as a curve fit to the Wayne State Tolerance Curve (WSTC).

The WSTC was first presented by Lissner (1960), and was generated by dropping embalmed cadaver heads onto unyielding, flat surfaces, striking the subject on the forehead. The WSTC (Figure 2-1) provides a relationship between peak acceleration, pulse duration, and concussion onset. In the original work, skull fracture was used as the criterion for determination of concussion and the onset of brain injury. The final form of the Wayne State Tolerance Curve was published by Gurdjian (Gurdjian 1963, Patrick 1963). In its final form, the WSTC was developed by combining results from a wide variety of pulse shapes, cadavers, animals, human volunteers, clinical research, and injury mechanisms. Skull fracture and/or concussion was used as the failure criterion, except for the long duration human volunteer tests in which there were no apparent injuries.

Gadd (1966) developed the Gadd Severity Index (GSI) to fit the WSTC curve, with a value greater than 1000 considered to be dangerous to life. It was based not only on the original Gurdjian data, but also upon additional long pulse duration data by means of the Eiband (1959) tolerance data and other primate sled tests. The GSI provided a good fit for both the short duration skull fracture data and the longer duration Eiband data out to 100 msec duration.

Versace (1971) noted that since the WSTC was developed for average accelerations, any comparison to it should be made using the average acceleration pulse of interest. He first proposed the HIC, which was then modified by NHTSA to provide a better comparison to the long duration human volunteer tests. In 1972, a proposal was issued to replace the GSI in FMVSS No. 208 with the following expression:

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \qquad (2.1)$$

where t_2 and t_1 are any two arbitrary times during the acceleration pulse. In 1986, the time interval over which HIC is calculated was limited to 36 msec. The current FMVSS No. 208 frontal protection standard sets the critical value of HIC at 1000 for the mid-sized male dummy using a 36 msec maximum time interval.

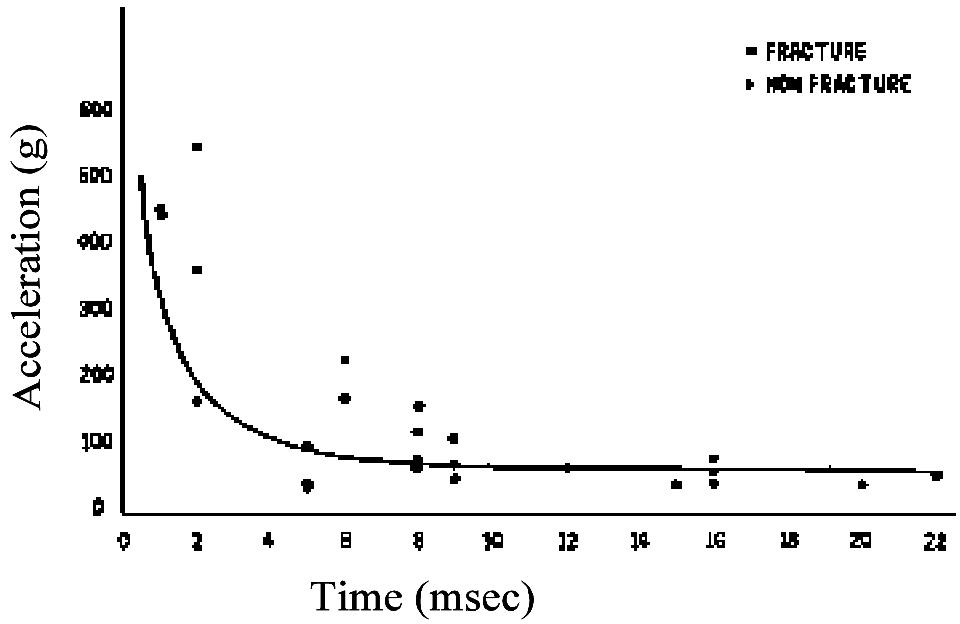


Figure 2-1. The Wayne State Tolerance Curve (WSTC).

2.2 SCALING HIC TO VARIOUS OCCUPANT SIZES

The scaling factor for HIC can be written as

$$\lambda_{HIC} = (\lambda_E)^2 / (\lambda_L)^{1.5}$$

where λ_E is the material scale factor and λ_L is the head length scale factor. It is important to consider the biofidelity of the human surrogate in establishing critical levels of the injury criteria. The skull structure for the various dummies is essentially a padded rigid aluminum shell, and does not account for changes in structural stiffness as does the human skull. Both geometric and material differences must be considered when scaling head injury criteria from one size occupant to another. Biomechanical data on the variation of skull stiffness with age is limited. However, as the occupant size gets smaller, geometric scaling would predict a higher tolerance but material scaling would predict a lower tolerance.

McPherson and Kriewall (1980) reported a study of the mechanical properties of fetal cranial bone. The study included tensile and bending tests on samples of skull bone from fetuses and one six year old child. Results indicated that the stiffness ratio with respect to the adult value was 0.243 for the newborn skull and 0.667 for the six year old.

Three different scaling methods were investigated for developing HIC values for various occupant sizes. Results from these scaling methods are shown in Table 2-1. Geometric scaling alone would predict a higher tolerance to head acceleration for a child than for an adult. For example, the HIC_{36} scale factor for a 12 month old dummy, assuming $\lambda_E = 1$, would be 1.34. Thus, the scaled HIC_{36} limit for a 12 month old is 1344.

Melvin (1995) uses the bone modulus as the material scale factor to compensate for differences in material response. This leads to relatively low values for children, such as 138 for a 12 month old. Scaled values in this paper are slightly different than those reported by Melvin because head length scale factors were taken from a different source (NHTSA, 1996).

A third method for scaling HIC assumes that pediatric skull deformation is controlled by the properties of the cranial sutures, rather than the skull bones. Using tendon strength as a surrogate for suture stiffness leads to a HIC_{36} limit for a 12 month old of 660, which falls in between the previous two methods. This method was used to scale the HIC_{36} limits proposed in the NPRM.

Table 2-1 shows the proposed HIC_{36} values for each dummy size. Although a scaled HIC_{36} value of 1081 was obtained for the six year old, a value of 1000 was maintained to avoid any reduction in the current level of safety for FMVSS No. 213. The proposed limit for the three year old was rounded up from 894 to 900. The limit for the 12 month old was rounded up from 659 to 660.

Table 2-1. Head Injury Scale Factors and Criteria.

	Mid-Sized Male	**Small Female**	**6 Year Old**	**3 Year Old**	**12 Month Old**
Head Length Scale Factor	1.000	0.931	0.899	0.868	0.821
Bone Modulus Scale Factor	1.000	*	0.667	0.474	0.320
Tendon Strength Scale Factor	1.000	*	0.960	0.850	0.700
Geometric Scaling Only	1000	1113	1173	1237	1344
Material Scaling with Bone Modulus	1000	1000*	522	278	138
Material Scaling with Tendon Strength	1000	1000*	1081	894	659
Proposed HIC_{36} Limit	1000	1000*	1000	900	660

* Data comparing the modulus and strength of female anatomic structures to male are not available at this time. Although geometric scaling alone would predict higher tolerance values for females, it is believed that lower bone mineral density would offset this effect. Therefore, the tolerance values for small females are kept the same as for mid-sized males.

2.3 HEAD INJURY RISK ANALYSIS

Prasad and Mertz (1985) analyzed available test data from human surrogates to determine the relationship between HIC and injuries to the skull and brain. Methodologies used to analyze the brain injury data had a number of limitations, and resulted in a risk curve nearly identical to the skull fracture injury risk. Skull fracture data consisted of head drop tests on both rigid and padded flat surfaces (Hodgson, 1977), sled tests against windshields (Hodgson, 1973), and helmeted drop tests (Got 1978, Tarriere 1982). The combined set of data consisted of 54 head impacts, with HIC values ranging from 175 to 3400. HIC durations ranged from 0.9 to 10.1 msec. The lowest HIC value associated with a skull fracture was 450, and the highest HIC value associated with a non-fracture was 2351.

These data were analyzed by Hertz (1993) fitting normal, log normal, and two-parameter Weibull cumulative distributions to the data set, using the Maximum Likelihood method to achieve the best fit for each function. The best fit of the data was achieved with the log normal curve, shown in Figure 2-2. The probability of skull fracture (MAIS ≥ 2) associated with a HIC_{36} value of 1000 for a mid-sized male is 47 percent. Based on scaling injury risk levels associated with the proposed HIC_{36} values for each dummy are assumed to be equivalent to the risk for a HIC_{36} value of 1000 for a mid-sized adult male.

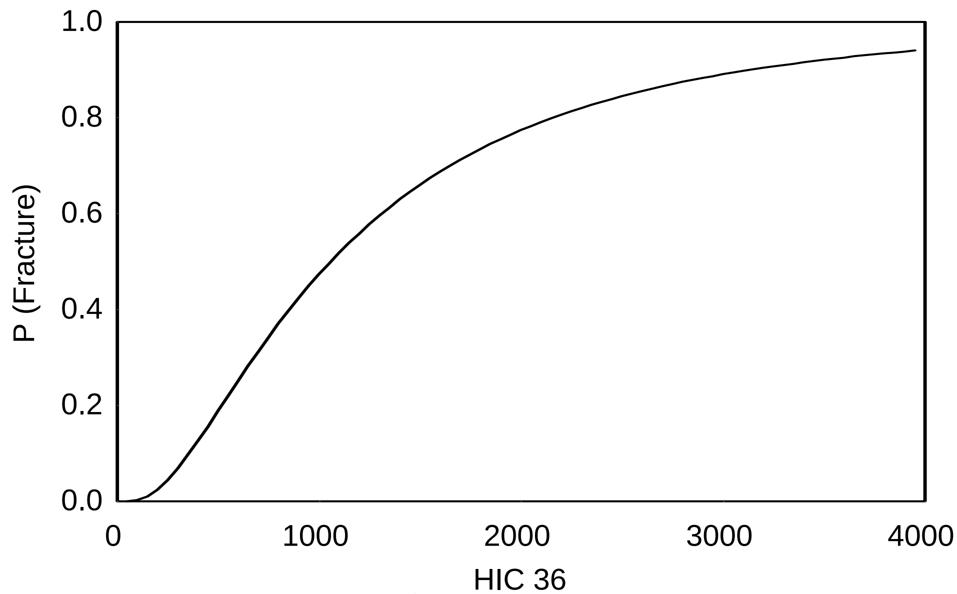


Figure 2-2. Injury risk curve for the Head Injury Criterion (HIC).

The probability of skull fracture (AIS ≥ 2) is given by the formula

$$p\ (fracture)\ =\ N\left(\frac{\ln(HIC)-\mu}{\sigma}\right),$$

where N( ) is the cumulative normal distribution, μ = 6.96352 and σ = 0.84664.

2.4 APPLICATION OF HIC TO AVAILABLE TEST DATA

Calculations of HIC were made for a wide variety of test data available in the NHTSA database (Tables C-1 to C-6 and C-11 to C-14). Analyses were conducted for data from 35 mph NCAP tests, 30 mph FMVSS No. 208 compliance tests, 48 kmph rigid barrier and 40 kmph offset tests with 5% adult female dummies, and out-of-position tests with the 3 year old, 6 year old and 5% adult female dummies.

Data from a total of 76 NCAP crash tests from 1997 and 1998 model year vehicles were analyzed for ATD's in both the driver and passenger position. For the 1998 model year vehicles, 98% of the drivers and 94% of the passengers had a value of $HIC_{36} \leq 1000$. For the 1997 model year vehicles, 97% of the drivers and 90% of the passengers had a value of $HIC_{36} \leq 1000$. However, when four vehicles (light trucks and vans) which were not equipped with an airbag on the passengers side were excluded from the analysis, 100% of the passengers in the 1997 model year vehicles had a value of $HIC_{36} \leq 1000$.

Data from a total of 34 FMVSS No. 208 compliance tests for 1996-1998 vehicles were analyzed for ATD's in both the driver and passenger positions. As required by FMVSS No. 208, all occupants had a value of $HIC_{36} \leq 1000$. Both passengers and drivers passed the requirement by a large margin, with an average value of HIC_{36} equal to 310 for the driver and 320 for the passenger.

Data from tests conducted at Transport Canada using the Hybrid III 5^{th} percentile adult female dummy in 1996-1998 model year vehicles were also analyzed. In these tests, the 5^{th} percentile female dummies were belted and seated in a fully forward position. For the twenty-three rigid barrier tests conducted at 48 kmph, all drivers and passengers had a value of $HIC_{36} \leq 1000$, with an average value of HIC_{36} equal to 320 and 310, respectively. For the eighteen 40% offset frontal tests conducted at 40 kmph, all drivers and all but one passenger had a value of $HIC_{36} \leq 1000$, with an average value of HIC_{36} equal to 263 and 511, respectively.

Out-of-position tests for different dummy sizes were also conducted and analyzed. The proposed tolerance values for the Hybrid III 3 and 6 year old dummies are 900 and 1000, respectively. A series of out-of-position tests were conducted in the child ISO-2 position, which is intended to maximize head and neck loading. This series used original equipment manufacturer (OEM) passenger airbag systems, which were termed "baseline", and prototype systems in which the OEM airbag was used in conjunction with inflators which were depowered by various degrees. Results for the 3 year-old dummy using baseline pre-1998 passenger airbags showed that one system, B-94, had values of HIC_{36} which exceeded 3500. The value of HIC_{36} for prototype system B-94 with 30% and 60% depowering was 1070 and 180, respectively. By contrast, two other baseline systems D-96 and I-96 had HIC_{36} values less than 900. Results for the 6 year-old dummy showed that the baseline systems B-94 and I-96 had values of HIC_{36} which exceeded 1000, while the other baseline system D-96 did not. The value of HIC_{36} for systems B-94 and I-96 were reduced to below 1000 with depowering by 30% and 27% respectively.

The final set of data analyzed for this report were from tests with the 5^{th} percentile adult female dummy in the driver ISO-1 position which is intended to maximize head and neck loading. In this series of tests using 1996 and 1998 model year vehicles, 8 out of 8 tests had a value of $HIC_{36} \leq 1000$, with an average value of HIC_{36} equal to 70.

In summary, almost all the NCAP tests, FMVSS No. 208 compliance tests, Transport Canada offset and rigid barrier tests using the 5% adult female, and out-of-position tests using the 5% adult female passed the proposed injury criteria of $HIC_{36} \leq 1000$. However, for out-of-position tests using the 3 year-old and 6 year-old, some baseline OEM airbag systems failed the proposed head injury criteria, but were able to pass when the inflator was depowered by various degrees.

Chapter 3
Neck Injury Criteria

3.1 BACKGROUND

The current FMVSS No. 208 alternative sled test includes injury criteria for the neck consisting of individual tolerance limits for compression (compression of the neck), tension (force stretching the neck), shear (force perpendicular to the neck column), flexion moment (forward bending of the neck), and extension moment (rearward bending of the neck). Tolerance values are based on a select number of volunteer, cadaver, and dummy tests. Limits are typically set at minimal threshold levels, but are based on small sample sizes.

The current tolerance level for axial compression was developed by Mertz et al (1978). They used a Hybrid III 50% male dummy to investigate the neck reaction loads when struck by a tackling block that had reportedly produced serious head and neck injuries in football players. The compression tolerance varied with the duration of the load application, with a peak value of 4000 Newtons.

Current tolerance levels for tension and shear loads were developed by Nyquist et al (1980). They used the Hybrid III 50% male dummy to reconstruct real-world collisions, and correlated field injuries with dummy responses for 3-point belted occupants in frontal collisions. Limits for tension and shear were set at 3300 N and 3000 N, respectively.

Tolerance levels for flexion and extension bending moments were based on sled tests conducted on volunteers and cadaver subjects.(Mertz, 1971) Volunteer tests provided data up to the pain threshold, and cadaver tests extended the limits for serious injuries. Ligamentous damage occurred in a small stature cadaver subject at an extension moment of 35 ft-lbs. This value was scaled up to an equivalent 50% male level of 42 ft-lbs (57 Nm). No injuries were produced during flexion testing, so the maximum measured value of 140 ft-lbs (190 Nm) was taken as the limit. It should be noted that these moment tolerance levels are based on human limits, rather than from dummy measurements. Tolerance limits are therefore dependent on the biofidelity of the dummy neck in bending.

Experimental tension tests on cadaveric specimens consist of a small number of studies. Yoganandan et al (1996) tested isolated and intact cadaveric specimens in axial tension under both quasistatic and dynamic conditions. Isolated specimens failed at a mean tension value of 1555 N. Intact specimens failed at a higher mean tension value of 3373 N. Shea et al (1992) investigated the tension tolerance of the neck with a fixed extension angle of 30 degrees. Under this combined loading condition, ligamentous cervical spine specimens failed at a mean tension value of 499 N. These results indicate that the presence of an extension moment would have a significant effect on the tensile tolerance of the cervical spine. One additional test conducted on a live baboon demonstrated that physiological failure of the spinal cord occurs at approximately half the distraction load which causes structural failure of the cervical column (Lenox, 1982).

3.1.1 Adult Versus Child Injury Tolerance

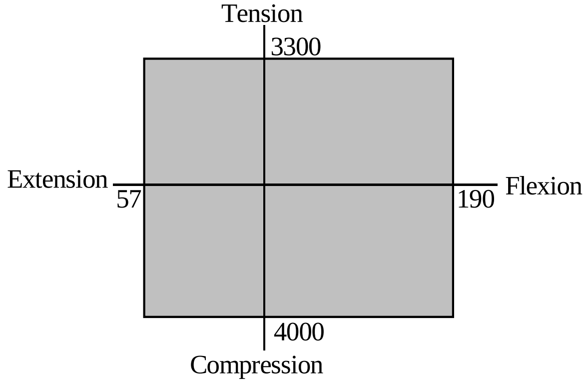
In scaling between people of different sizes and age groups, geometric differences do not fully account for the differences in tolerance to loading. Variations in material properties and the degree of skeletal maturity also have a strong effect on injury tolerance. Real world crash investigations, as documented through NHTSA's Special Crash Investigation Program, show the differences in injury patterns associated with age. For forward-facing children in close proximity to a deploying airbag, typical injuries include atlanto-occipital dislocations with associated contusions or lacerations of the brain stem or spinal cord. Closed head injuries are common, but skull fractures are typically not observed. For adults under the same airbag loading conditions, typical injuries include basilar skull fractures with associated contusions or lacerations of the brain stem or spinal cord. Atlanto-occipital dislocations are typically not observed.(Kleinberger, 1997)

One crude study on pediatric tolerance was conducted in 1874 by an obstetrician who pulled on the legs of stillborn children to determine how much force could be applied in a breech delivery before cervical injury occurred. One additional test was conducted on an infant that had died two weeks after birth. Although based on a single data point, the results indicate that the tolerance of the cervical spine significantly increases even within the first two weeks of life (Duncan, 1874).

Two additional studies were conducted using matched pairs of tests in which a juvenile porcine subject and a 3-year-old child dummy were subjected to out-of-position deployments from a number of different airbag systems (Mertz and Weber, 1982; Prasad and Daniel, 1984). The pig was judged by the authors to be the most appropriate animal surrogate based on a number of anatomical and developmental factors. Measured responses in the child dummy were correlated with injuries sustained by the surrogate. Prasad and Daniel concluded from their results that axial tension loads and extension (rearward) bending moments should be linearly combined to form a composite neck injury indicator. Critical values proposed for tension and extension for the 3-year-old dummy were 2000 N and 34 Nm, respectively.

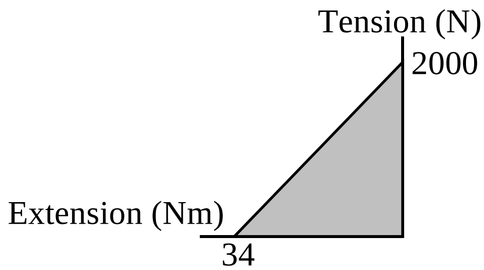
3.2 DEVELOPMENT OF Nij NECK INJURY CRITERIA

Current FMVSS No. 208 injury criteria for the neck using the alternative sled test include individual tolerance limits for axial loads, shear loads, and bending moments. If axial loads (tension and compression) and bending moments (flexion and extension) are plotted together on a graph, the requirement is that the dummy response must fall within the shaded box, as shown below.



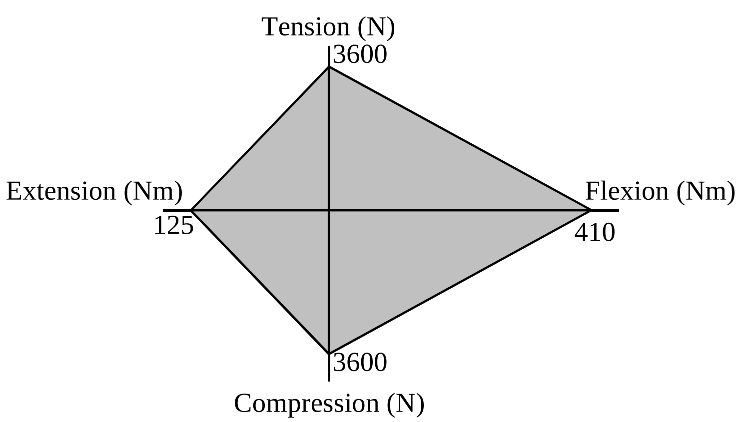
Using this formulation, if the mid-sized male dummy measures less than 3300 N of tension along with less than 57 Nm of extension moment, it would pass the current criteria. This formulation does not consider the combined effect of extension and tension.

The concept that a composite neck injury indicator should be based on a linear combination of axial tension loads and extension (rearward) bending moments was developed by Prasad and Daniel (1984) based on their results from experimental tests on porcine subjects. Based on their formulation for a 3 year old dummy, the allowable region in the tension/extension quadrant of the plot becomes the shaded area shown below. Any test falling above the diagonal line in this plot would exceed the tolerance levels.

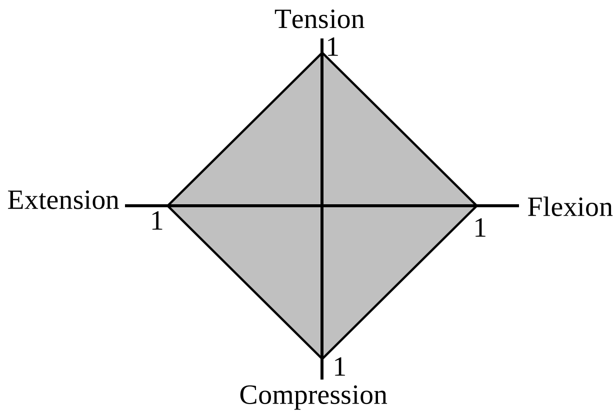


Next, the concept of neck criteria based on a linear combination of loads and moments, as suggested by Prasad and Daniel, was expanded to include the four major classifications of combined neck loading modes; namely tension-extension, tension-flexion, compression-extension, and compression-flexion. Proposed critical intercept values for tension load, compression load, extension moment, and flexion moment were established and are discussed later in section 3-3.

The resulting criteria are referred to as N_{ij}, where "ij" represents indices for the four injury mechanisms; namely N_{TE}, N_{TF}, N_{CE}, and N_{CF}. The first index represents the axial load (tension or compression) and the second index represents the sagittal plane bending moment (flexion or extension). This N_{ij} concept was first presented in NHTSA's report on child injury protection (Klinich, 1996). Graphically, the shaded region of the plot below shows the region for all four modes of loading which would pass the performance requirements for Nij. The intercept values shown are those proposed for the Hybrid III mid-sized male dummy.



Since each specific dummy has a unique set of critical intercept values, for subsequent scaling this plot has been normalized by dividing each semi-axis by its critical intercept value for a specific dummy. The resulting plot becomes symmetric about the origin and has maximum allowable values of unity. Graphically, the shaded box below designates the allowable values of loads and moments represented by this normalized calculation.



Real-world cervical injuries resulting from airbag interaction often are classified as tension-extension injuries. A tensile load applied to the neck results in stretching of both the anterior (front) and posterior (rear) soft tissues of the neck. If an extension (rearward) bending moment is superimposed upon the tensile load, the anterior soft tissues will be further stretched while the posterior tissues will become less stretched. Under this loading scenario, a tension-extension injury is more likely to occur than a tension-flexion, compression-extension, or compression-flexion injury. Accordingly, the value for N_{TE} would be expected to be the maximum of the four N_{ij} values.

3.2.1 Method of Calculation of Nij Criteria

In developing the Nij criteria, information produced in crash tests using dummies, and the significance of that information are considered. For any given loading of the dummy, the standard 6-axis upper neck load cell dynamically records the loads and moments in all three directions at the top of the neck. For a frontal collision, primary motion and measured neck reactions occur in the sagittal plane. Out of plane motion and reactions are typically of secondary importance. As a result, only the three measurements associated with sagittal plane motion are used in the current formulation of the N_{ij} neck injury criteria, namely axial load (F_Z), shear load (F_X), and flexion/extension bending moment (M_Y). Shear load is only used to calculate the effective moment at the occipital condyles. This is accomplished by multiplying the shear load by the height of the load cell above the condyles and subtracting this value from the Y-axis moment measured by the load cell.

Loads and moments are normalized with respect to critical intercept values defined for tension, compression, extension, and flexion. Normalized flexion and extension moments (M_{NY}) are added to the normalized axial load (F_{NZ}) to account for the superposition of load and moment.

The proposed neck injury criteria can thus be written as the sum of the normalized loads and moments.

$$Nij = \frac{F_Z}{F_{\text{int}}} + \frac{M_Y}{M_{\text{int}}} \quad (3.1)$$

where F_Z is the axial load, F_{int} is the critical intercept value of load used for normalization, M_Y is the flexion/extension bending moment, and M_{int} is the critical intercept value for moment used for normalization.

The values for calculating the N_{ij} are uniquely specified for each dummy, and are defined in Table 3-4 for the CRABI 12-month-old dummy and the Hybrid III 3-year-old, 6-year-old, small female, and mid-sized male dummies. Source code for a C++ program to calculate the Nij criteria using standard test data is included in Appendix D. This source code, as well as an executable version of the program, is also available from the NHTSA web site at http://www.nhtsa.dot.gov.

3.3 DEVELOPMENT AND SCALING OF Nij CRITERIA TO VARIOUS OCCUPANT SIZES

Initial critical intercept values for tension load and extension moment were calculated for the 3 year old dummy based on the Mertz/Prasad experimental test data. As noted at the beginning of section 3.2, previously published tolerance levels were based on individual tolerance limits. These independent limits, which do not account for the complex combined loading, were published in context of the short-term alternative sled test. Critical intercept values for axial load and sagittal plane bending were previously determined by assuming that each measurement was independently linked to the resulting injury. Tension limits were set assuming that no extension moment was applied. Similarly, bending limits were set assuming that no tension was present.

Since injuries were most likely associated with a combination of tension and extension, the data were re-analyzed using a multi-variate logistic regression to quantify the relationship. When the best correlation between the N_{ij} criteria and the documented injuries was determined, the critical intercept values for tension were found to be much higher than previously stated. For the 3 year old, the critical intercept tension and extension limits were 2500 N and 30 Nm, respectively.

Critical intercept tension and extension values for other dummy sizes were scaled from the 3 year old dummy using the scaling techniques presented in Chapter 1. Since material stiffness variations are incorporated into the dummy neck design, neck injury criteria were scaled using only geometric factors, assuming $\lambda_E = 1$. Forces were scaled according to cross-sectional area of the neck, represented by the circumference squared. Bending moments were scaled according to the third power of the neck length, represented by the circumference cubed. Circumference measurements are used to quantify neck length because it is a simple measurement to record. Circumference measurements and scale factors for each dummy size are shown in Table 3-1. Values included in this table were selected from several anthropometric studies conducted on adults and children (Snyder 1977, Schneider 1983, and Weber 1985).

Table 3-1. Scale Factors for Various Dummy Sizes.

Dummy	Neck Circ. (cm)	Neck Length Scale Factor λ_L	Axial Load Scale Factor λ_L^2	Bending Moment Scale Factor λ_L^3
CRABI 12-month-old	22.6	0.5901	0.3482	0.2055
Hybrid III 3-year-old	23.8	0.6214	0.3861	0.2399
Hybrid III 6-year-old	25.7	0.6710	0.4502	0.3021
Hybrid III small female	30.4	0.7937	0.6300	0.5000
Hybrid III mid-sized male	38.3	1.0000	1.0000	1.0000

Applying the scale factors from Table 3-1 to the critical intercept tension and extension limits for the 3 year old dummy yields the critical intercept values for all dummy sizes shown in Table 3-2. Values for critical intercept compression and flexion are established by setting fixed ratios between tension and compression loads, and between extension and flexion moments.

Table 3-2. Scaled Critical Intercept Values for Tension and Extension.

Dummy	Tension (N)	Extension (Nm)
CRABI 12-month-old	2200	25
Hybrid III 3-year-old	2500	30
Hybrid III 6-year-old	2900	40
Hybrid III small female	4000*	60
Hybrid III mid-sized male	6500*	125

* Proposed axial load limits for adult dummies are based on experimental data and are lower than the scaled values presented in this table.

To better understand the relationship between dummy and human responses to loading, a modeling study was conducted using Madymo to determine a scale factor between human and dummy neck loads and moments (Nightingale, 1998). In addition to the standard Madymo model of the Hybrid III dummy provided with the software, a second model was created to represent a human occupant. Axial stiffness of the neck and rotational stiffness of the occipital condyle joint were modified individually and in combination to determine their effect on measured loads. A generic airbag model was deployed into an out-of-position driver model initially placed in an ISO 1 position, which is intended to maximize loading on the head and neck. A summary of the results is presented in Table 3-3. These results indicate that the measured extension moments for the 50th percentile male dummy were approximately 2.4 times higher than for a human, whereas the tension and shear measurements did not change dramatically. This supports the recommended critical intercept extension moment value of 125 Nm suggested above for the mid-sized male dummy, although it is slightly more than double the previous human-based value of 57 Nm (Mertz, 1971).

Table 3-3. Neck Reactions from Simulations of OOP Airbag Deployments.

Model Configuration	Tension (N)	Shear (N)	Extension Moment (Nm)
Hybrid III Axial Stiffness Hybrid III Rotational Stiffness (Full Hybrid III Dummy Model)	4744	2787	-173*
Human Axial Stiffness Hybrid III Rotational Stiffness	3503	2653	-152
Hybrid III Axial Stiffness Human Rotational Stiffness	4599	4105	-123
Human Axial Stiffness Human Rotational Stiffness (Full Human Model)	3717	2769	-72*

* A ratio of approximately 2.4 exists between the Hybrid III and human extension moment responses.

Critical intercept values for flexion moment were set by maintaining the same ratio between flexion (190 Nm) and extension (57 Nm) established in previous injury assessment reference values (Mertz, 1971). Based on these previous limits, the critical intercept flexion values were set at 3.33 times the critical intercept extension values established above. Moment limits previously stated in the literature were based on human cadaveric tolerances, and did not represent dummy-based values (Mertz, 1971). Moment tolerances used in this report are based on dummy responses, and are significantly higher than the values in the regulations for the alternative sled test. Proposed critical intercept values for extension and flexion moment for all dummy sizes are shown in Table 3-4.

Table 3-4. Proposed Critical Intercept Values for Nij Neck Injury Calculation.

Dummy	Tension (N)	Compression (N)	Flexion (Nm)	Extension (Nm)
CRABI 12-month-old	2200	2200	85	25
Hybrid III 3-year-old	2500	2500	100	30
Hybrid III 6-year-old	2900	2900	125	40
Hybrid III small female	3200	3200	210	60
Hybrid III mid-sized male	3600	3600	410	125

Axial loading of the adult neck is a test condition for which there is significant experimental data. Proposed critical intercept values of tension and compression for adult dummies are therefore based on experimental data rather than on scaling. Nightingale (1997) conducted a series of compressive neck tests on 22 cadaveric head/neck specimens. Tests were conducted using a drop track system to produce impacts to the top of the head with impact velocities on the order of 3.2 m/s. Measured loads and accelerations on the specimens were correlated with documented injuries sustained by the specimens. Similar experimental data collected by Yoganandan and Pintar were included in their analyses, and a tolerance level for cadaveric specimens was established at 3.03 kN. After compensating for age, a compressive tolerance level of 3600 N was suggested. This value falls in between the previously published injury assessment reference values of 3300 N for tension (Nyquist 1980) and 4000 N for compression (Mertz 1978).

Based on the experimental data presented above, a critical intercept tension value for the mid-sized male dummy of 3600 N is proposed. The tension value proposed for the small female is 3200 N, which lies midway between the values for the mid-sized male and 6 year old dummies. Critical intercept values for children are all based on scaling from the 3 year old dummy as described above.

Compression tolerance levels were set equal to tension values based on preliminary NHTSA-sponsored tests on cadaveric head/neck specimens (Nightingale, unpublished). These tests indicate that the tolerance of the neck to compression is not significantly different from the tolerance for tension. Axial load limits for all dummy sizes are shown in Table 3-4.

3.4 NECK INJURY RISK ANALYSIS

Risk curves previously presented by Mertz (1997) were calculated based on the Mertz/Weber modified Median Rank method using experimental data from porcine subjects.(Mertz, 1982; Prasad, 1984) These data were re-analyzed using logistic regression, yielding the porcine risk curve shown in Figure 3-1. This curve represents the probability of injury to a porcine subject as a function of the measured loads and moments on a 3 year old child dummy placed in the same conditions, such as in close proximity to a deploying airbag. An Nij value of 1.0 on this curve is associated with approximately a 30% risk of an AIS$\geq$3 injury.

In order to establish the corresponding risk curve for a live human subject, a comparison was made between the injury rates predicted using Nij calculations from experimental dummy test data and real world injury rates estimated from the National Automotive Sampling System (NASS) database. Data from 1997 and 1998 New Car Assessment Program (NCAP) crash tests were analyzed and compared with NASS cases from similar crash conditions. NCAP tests involve a 56 km/h (35 mph) full rigid barrier impact with belted mid-sized male dummies in both the driver and passenger seating positions. It is important to note that NCAP tests use a 56 km/h (35 mph) impact velocity and belted dummies, whereas FMVSS No. 208 compliance tests at 48 km/h (30mph) use both belted and unbelted dummies. Therefore, it is not a requirement that NCAP tests meet FMVSS No. 208 injury criteria.

The probability of neck injury, given that a crash occurred, was examined for real world non-rollover frontal crashes in various delta-V ranges. Neck injuries included brain stem injuries and basilar skull fractures that occur as a result of loading to the neck. Although the biomechanics curves were based on AIS≥3 neck injuries, AIS≥2 NASS data was examined because there are a number of fatal injuries coded as AIS 2 "broken neck, only information available." Including these cases slightly overestimates real world neck injuries that are comparable to those estimated in the models. Generally, these injuries represent only about 1-3% of all AIS 2+ cases, and in the case of airbag vehicles there was only one AIS 2 case in the data between 25 and 30 mph delta V, which is not considered in the final analysis when only higher delta V crashes are considered.

Results from this risk comparison indicate that for New Car Assessment Program (NCAP) crash conditions, NASS data show about a 3 to 5 percent probability of neck injury for belted occupants of airbag equipped vehicles compared to about a 20 percent probability of neck injury predicted using the scaled porcine risk curve from Figure 3-1. For unbelted occupants with air bags, the probability of neck injury estimated from NASS is about 0.5 to 2 percent compared to about a 15 percent probability of neck injury from unbelted crash tests at 30 mph.

To take into account the differences between NASS-based injury risk estimates and experimental test data, the original porcine risk curve was shifted to the right so that an Nij value of 1.4 corresponded to a 30% risk of an AIS≥3 injury. This shifted risk curve shows a 15% injury risk for an Nij value of 1.0 and represents the best estimate of a human's probability of injury. Since the Nij criteria are defined as normalized injury measures, an Nij value of 1.0 represents a 15% risk of injury for all occupant sizes. The original porcine data from Mertz (1982) and Prasad (1984) were also used to calculate a risk curve for AIS≥5 injuries using logistic regression. Shifting this curve to the right the same amount as the AIS≥3 curve yields the risk curve shown in Figure 3-2.

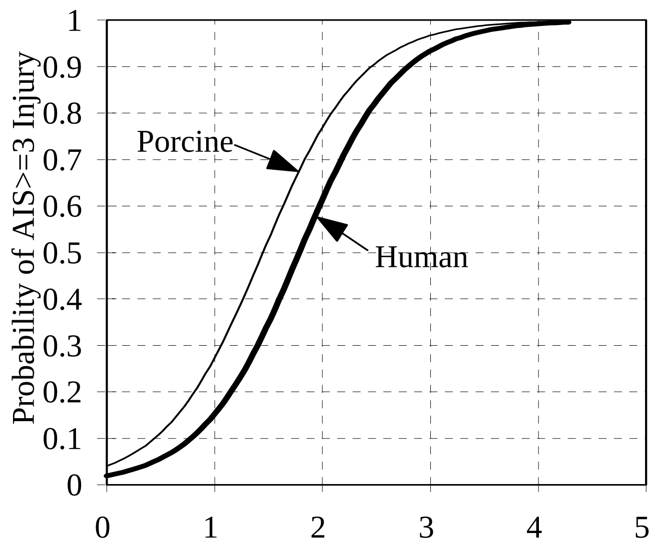
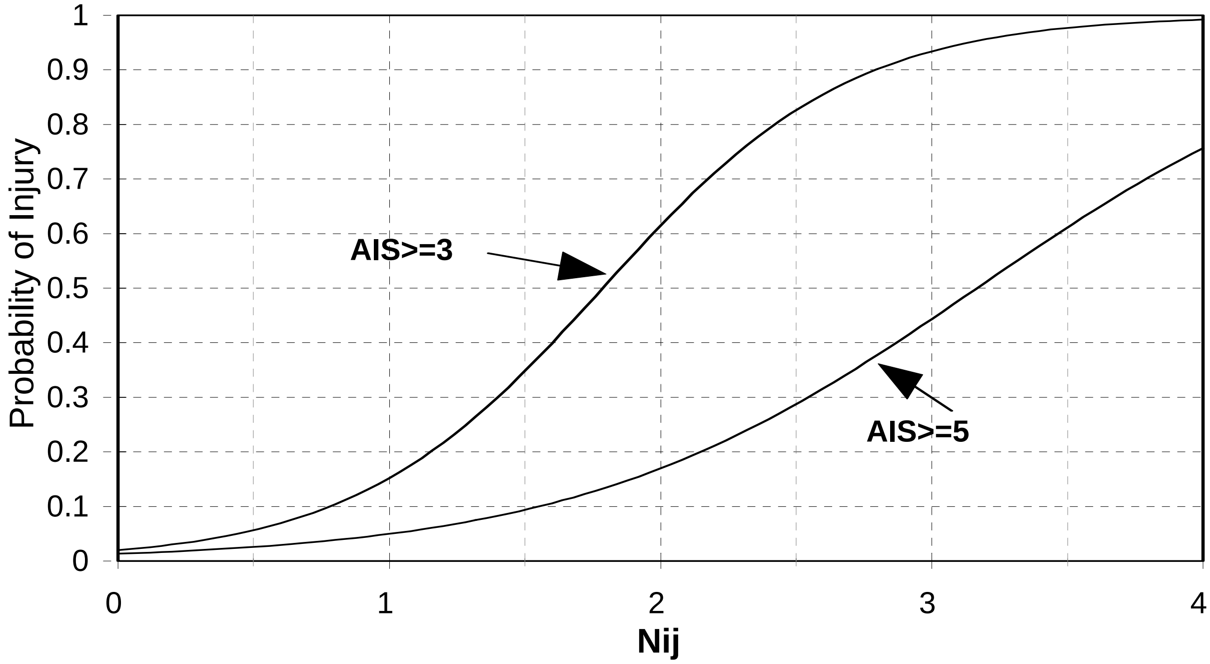


Figure 3-1. Injury Risk Curve for N_{ij} Neck Injury Criteria.



$$p(AIS \geq 3) = \frac{1}{1 + e^{3.906-2.185Nij}} \qquad p(AIS \geq 5) = \frac{1}{1 + e^{4.310-1.361Nij}}$$

Figure 3-2. N_{ij} Risk Curves for AIS 3+ and AIS 5+ Injuries.

3.5 APPLICATION OF PROPOSED Nij CRITERIA TO AVAILABLE TEST DATA

Calculations of Nij were made for a wide variety of test data available in the NHTSA database. Analyses were conducted for data from NCAP tests for both drivers and passengers, FMVSS 208 30 mph rigid barrier crash tests with 1998 vehicles, 25 mph offset tests with 5% female drivers and passengers, 30 mph rigid barrier tests with 5% female drivers, and out-of-position tests for 3 year old, 6 year old, and 5% female dummies. Results from these tests are presented graphically in Appendix A, and are included in tabular format in Appendix C.

Comparisons between the Nij combined neck injury criteria and current FMVSS 208 alternative sled test criteria are shown for the different types of data analyzed. Two points are plotted for each test, corresponding to each set of injury criteria. A typical plot is shown in Figure 3-3.

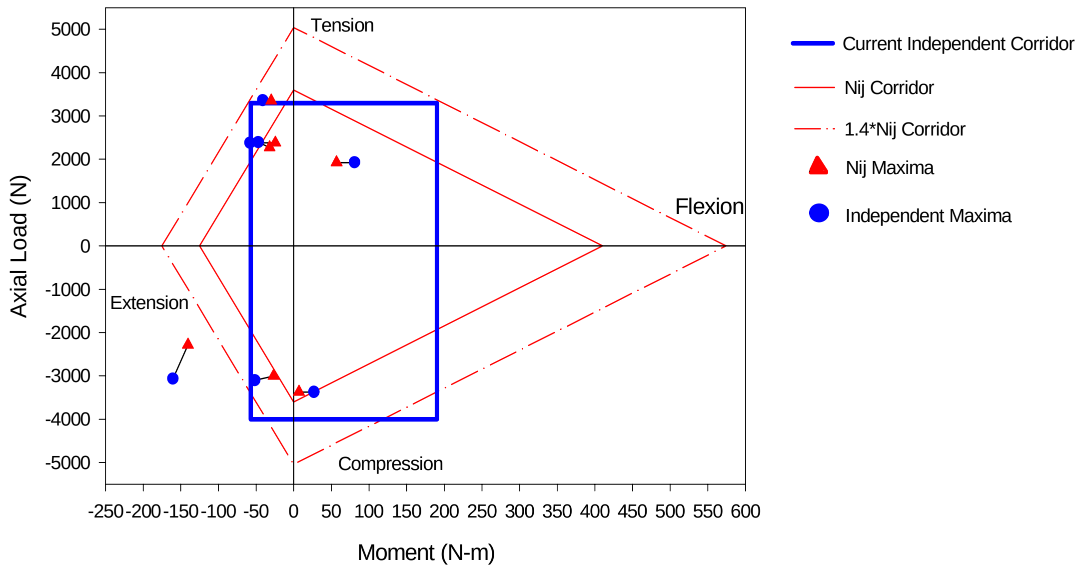


Figure 3-3. Typical Plot Comparing Nij with Current Injury Criteria.

The point corresponding to the Nij criteria, labeled with a ▲, is located at the values of axial load (F_Z) and flexion/extension bending moment (M_Y) which yield the maximum value for Nij. It is important to realize that these values for F_Z and M_Y are concurrent in time and are not necessarily equal to the maxima during the entire event. The point corresponding to the current FMVSS 208 criteria, labeled with a ●, is located at the overall maximum values of axial load and bending moment. The two values that determine this point are independent of time, and do not necessarily occur at the same time. It is also important to notice that shear load is not included on this plot.

Since the FMVSS 208 point always represents the overall maxima while the Nij point does not, it is impossible for the Nij point to be located further from the origin than the 208 point. To help identify the matched sets of points, they have been joined together by a line. If the line segment is short, and the points lie essentially on top of one another, it implies that the Nij maximum value occurs close to the same time as the independent maxima. If the line segment is long, this indicates that the Nij maximum occurs at a much different time than the independent maxima.

The thick solid rectangle in Figure 3-3 represents the current FMVSS 208 alternate sled test neck injury criteria for axial load and bending moment. The solid "kite" shape represents the Nij = 1.0 criteria, corresponding to a 15% risk of an AIS$\geq$3 injury. An Nij = 1.4 criteria is also shown in this plot, corresponding to a 30% risk of injury. The vertices for each region shown on the plot are scaled for each different dummy size. Data points lying within either the box or kite are considered to pass the corresponding criteria.

NCAP data from 1997 and 1998 were analyzed for both drivers and passengers. A total of 136 occupants from 72 tests conducted in 1997 and 1998 were analyzed. Results are summarized in Figures A-1 thru A-4 and in Tables C1 thru C4. In 1997 NCAP tests, 5 of 50 occupants had Nij values greater than 1.0, with a maximum recorded value of 1.339. For drivers, 4 of 25 exceeded an Nij value of 1.0 and for passengers, 1 of 25 exceeded 1.0. No occupants exceeded an Nij value of 1.4. In 1998 NCAP tests, only 9 of 86 occupants had Nij values greater than 1.0, with a maximum recorded value of 1.589. Five of 43 drivers exceeded a value of 1.0 and 4 of 43 passengers exceeded 1.0. Only one driver exceeded an Nij value of 1.4. Tables C-1 thru C-4 show a comparison between Nij and existing FMVSS 208 alternative sled test neck injury criteria. Using the existing sled test criteria, 20 of 136 exceeded the allowable tolerance levels. In 1998 NCAP tests, 4 of 43 drivers and 5 of 43 passengers exceeded the existing tolerance limits. In 1997 NCAP tests, 4 of 25 drivers and 7 of 25 passengers exceeded the existing tolerance limits.

Limited crash test data are available for the analysis of neck injury risk in unbelted frontal collisions because neck load cells were not required in compliance tests prior to the 1997 adoption of criteria in the sled test alternative under FMVSS 208. A series of six tests conducted under FMVSS 208 barrier crash conditions with 1998 vehicles was conducted at NHTSA's Vehicle Research and Test Center. Results from these tests are shown in Figures A-5 and A-6. All six tests, both drivers and passengers, easily fall within the allowable range for both the Nij criteria and existing FMVSS 208 sled test criteria.

Data from tests conducted at Transport Canada using belted Hybrid III 5^{th} percentile female dummy were also analyzed in two ways; using the Nij criteria and the scaled independent load and moment limits. In these tests, the 5% female dummies were belted with the seat positioned as far forward as possible and the seatback adjusted slightly more upright. Due to the far forward seating position and potential for late deployments for the offset tests, these conditions are quite severe and are somewhat similar to dynamic out-of-position tests.

Results from 30 mph rigid barrier tests and 25 mph offset frontal tests are presented in Figures A-7 thru A-14 and in Tables C-7 thru C-10. For the rigid barrier tests, a total of 16 of 31 drivers and 7 of 24 passengers exceeded an Nij = 1.0 limit. In 1998 vehicles, 3 of 9 drivers and 2 of 10 passengers exceeded this limit. In pre-1998 vehicles, 13 of 22 drivers and 5 of 14 passengers exceeded this limit. Using an allowable limit of Nij = 1.4, 2 of 9 drivers and 1 of 10 passengers exceeded the allowable limit in 1998 vehicles, and 7 of 22 drivers and 1 of 14 passengers exceeded the limit in pre-1998 vehicles.

For the 40 percent offset frontal tests, a total of 14 of 22 drivers and 5 of 18 passengers exceeded the Nij = 1.0 criteria. In 1998 vehicles, 6 of 10 drivers and 2 of 11 passengers exceeded this limit. In pre-1998 vehicles, 8 of 12 drivers and 3 of 7 passengers exceeded this limit. Using an alternative allowable limit of Nij = 1.4, 2 of 10 drivers and 1 of 11 passengers exceeded the allowable limit in 1998 vehicles, and 8 of 12 drivers and 2 of 7 passengers exceeded the limit in pre-1998 vehicles.

FMVSS 208 sled test neck injury criteria were scaled down to the 5^{th} percentile female dummy using scale factors published by Mertz.(Mertz, 1997) The resulting tolerance levels are 2080 N for tension, 2520 N for compression, 1950 N for shear, 95 Nm for flexion moment, and

28 Nm for extension moment. This set of criteria were used to compare Transport Canada test results with the Nij criteria. For the rigid barrier tests, a total of 18 of 31 drivers and 11 of 24 passengers exceeded the scaled FMVSS 208 criteria. In 1998 vehicles, 5 of 9 drivers and 4 of 10 passengers exceeded this limit. In pre-1998 vehicles, 13 of 22 drivers and 7 of 14 passengers exceeded this limit. For the 40 percent offset frontal tests, a total of 15 of 22 drivers and 6 of 18 passengers exceeded the scaled FMVSS 208 criteria. In 1998 vehicles, 7 of 10 drivers and 2 of 11 passengers exceeded this limit. In pre-1998 vehicles, 8 of 12 drivers and 4 of 7 passengers exceeded this limit. Figure 3-4 summarizes the results from the Transport Canada data, comparing the Nij and scaled FMVSS 208 criteria.

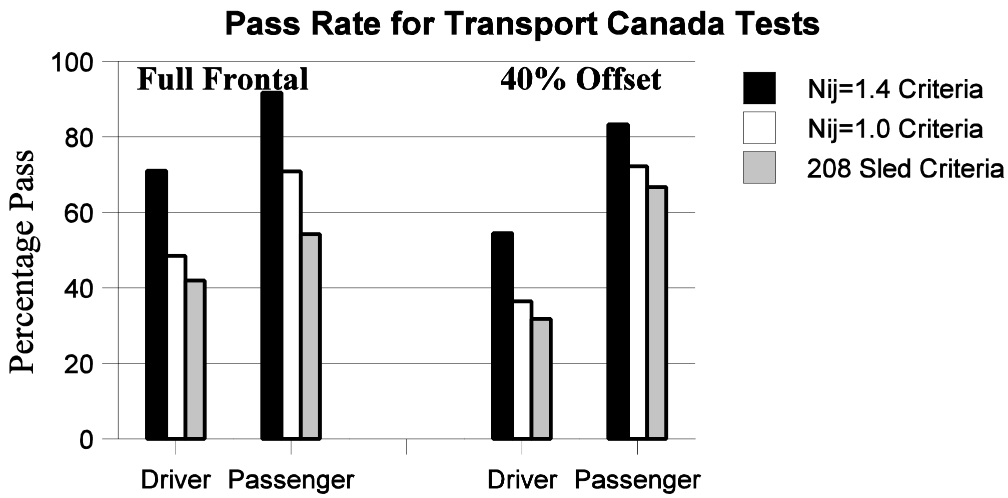


Figure 3-4. Comparison of Nij and Scaled 208 Criteria for Transport Canada Test Data.

This figure shows that under the conditions used for this testing, a larger percentage of the vehicles passed the Nij = 1.0 criteria than the scaled FMVSS 208 sled test criteria. However, it is important to note that since testing and criteria for a 5th percentile adult female dummy are not part of the current regulation, both sets of criteria represent an increase in the level of protection.

Out-of-position tests for different sized dummies were also conducted and analyzed by NHTSA. Results from out-of-position tests for the 3-year-old, 6-year-old, and 5% female dummies in ISO 1 and ISO 2 positions are shown in Figures A-15 thru A-27 and Tables C-11 thru C-14. The ISO 1 position for adult dummies places the chin just above the airbag module; the ISO 2 position centers the sternum on the module. ISO 1 tests for adults are intended to maximize loading to the head and neck, resulting in higher risk of neck injuries. For children, the ISO 2 position places the chin above the airbag module. Thus, ISO 2 tests for children are intended to maximize loading to the head and neck, resulting in higher risk of neck injuries. Since these tests represent the worst case scenarios involving airbag deployments, dummy measurements are expected to be relatively high.

Results from the 5th percentile female tests are shown in Figures A-15 and A-16, and in Tables C-11 and C-12. For the 5th percentile female dummy, 8 of 9 tests in the ISO 1 position and 5 of 9 tests in the ISO 2 position exceeded the Nij ≤ 1.0 criteria. Using an allowable value of Nij = 1.4, 5 of 9 tests in the ISO 1 position and 2 of 9 tests in the ISO 2 position exceeded this limit. Using the existing FMVSS 208 criteria scaled to the 5th percentile female, 8 of 9 tests in the ISO 1 position and 7 of 9 tests in the ISO 2 position exceeded the tolerance limits.

Out-of-position data for children comes from a series of tests conducted with the Hybrid III 3- and 6-year-old dummies using prototype airbag systems to investigate the effect of depowering. Three baseline airbag systems and a number of different levels of depowering for each system were tested. Results from these tests are shown in Figures A-17 thru A-27, and in Tables C-13 and C-14. These results clearly show the effect of depowering on the neck reactions measured in the dummies. For example, the baseline B94 airbag system with the child dummies in the ISO 2 position yielded a maximum Nij value of 4.94 for the 3-year-old and 4.05 for the 6-year-old. With 30 percent depowering of this airbag system, the Nij values for the 3- and 6-year-old dummies were 2.80 and 1.61, respectively. Depowering this system by 60 percent yields maximum Nij values of 1.34 and 0.69, respectively.

The final set of test data analyzed for this report was from a series of crash reconstructions conducted with a Hybrid III 6-year-old dummy. Three cases involving serious and fatal injuries to a child of approximately 6 years of age were selected from reports prepared by NHTSA’s Special Crash Investigation Team. An additional two cases involving only minor injuries were selected from NASS. Figure A-28 shows the results from these reconstructions. The three cases involving serious and fatal injuries fall well outside of the allowable regions of the plot. The two cases involving only minor injuries fall inside the Nij = 1.0 criteria limit, but just outside of the tolerance limits established by scaling the existing FMVSS 208 neck injury criteria. Scaled tolerance levels used for the 6 year old dummy are 1490 N for tension, 1800 N for compression, 1400 N for shear, 57 Nm for flexion moment, and 17 Nm for extension moment. A complete set of tolerance levels scaled from existing FMVSS 208 alternative sled test neck criteria to all dummy sizes is shown in Table 3-5.

Table 3-5. Tolerance Limits Scaled from FMVSS 208 Sled Test Criteria to Various Dummy Sizes.

	Hybrid III 50% Male	Hybrid III 5% Female	Hybrid III 6 Year Old	Hybrid III 3 Year Old	12 Month Old CRABI
Tension (N)	3300	2080	1490	1270	1150
Compression (N)	4000	2520	1800	1540	1390
Shear (N)	3100	1950	1400	1200	1080
Flexion (Nm)	190	95	57	46	39
Extension (Nm)	57	28	17	14	12

Taking into consideration all of the experimental data for the various crash test conditions presented in this section, and comparing the results with real world injury statistics, the recommended neck injury criteria reasonably predict the occurrence of injuries in these types of crashes. Furthermore, the percentage of vehicles which pass the recommended Nij criteria is generally slightly higher than with the force and moment limits currently used in the FMVSS 208 alternative sled test. In general, based upon the foregoing analysis, the Nij criteria have been demonstrated to be reasonable injury criteria for use with the proposed upgrade to the FMVSS 208 frontal impact protection standard.

Chapter 4
Thoracic Injury Criteria

4.1 BACKGROUND

Classic work by Stapp (1970) and Mertz and Gadd (1968) led to the development of the injury threshold for chest acceleration of 60G's. The first injury assessment recommendation for the rib cage and underlying organs using chest deflection was developed by Neathery et al. (1975) for blunt frontal loading. Neathery et al. recommended a chest injury assessment value of three inches maximum sternal compression for a 50^{th} percentile male in blunt frontal impact. This recommendation represented a 50% risk of an AIS $\geq$3 thoracic injury for a 45 year old human.

Viano and Lau (1988) re-analyzed the data Neathery used and provided a recommendation of 35% external chest compression to avoid rib cage collapse due to multiple rib fractures and crush to internal organs. Assuming a chest depth of 229 mm for the 50^{th} percentile male, this corresponds to a chest deflection of 65 mm. Based on this study, Mertz (1984) revised his original maximum chest deflection requirement from 75 mm to 65 mm for blunt impact.

Mertz et al. (1991) developed thoracic injury risk curves based on Hybrid III chest compression response with shoulder belt loading by comparing the chest compression response of the Hybrid III dummy with injuries to car occupants in similar exposures. According to Mertz's injury risk curve for belt restrained occupants, 2 inches of chest compression in the Hybrid III dummy is associated with a 40% risk of injury while 3 inches is associated with a 95% risk of injury.

Horsch (1991) demonstrated that the location of the belt on the shoulder and pelvis of the dummy influenced the measured chest deflection. As a result, the actual chest deflection of a car occupant under similar conditions was underestimated using the Hybrid III dummy in many instances. Horsch et al. (1991) analyzed field data and equivalent tests with Hybrid III dummy and determined that 40 mm of Hybrid III chest deflection for belt restrained occupants was associated with a 25% risk of an AIS$\geq$3 thoracic injury.

Horsch and Schneider (1988) reported that the Hybrid III dummy demonstrates biofidelity at and above 4.6 m/s impact velocity but it may be stiffer than the human chest at lower impact velocities. Sled tests at 30 mph using the Hybrid III dummy with belt restraints or airbag restraints suggested that the chest compression velocity was approximately 2 to 3.5 m/sec and so the dummy chest would behave stiffer than a human chest under belt or airbag restraint environments. Therefore, injury assessment based on chest deflection measured in the Hybrid III chest under belt or airbag restraints in a 30 mph crash would under predict the actual injury outcome. Hence, this suggests that even the recommended injury criteria of 65 mm maximum chest deflection may be high.

4.2 ANALYSIS OF HUMAN SURROGATE TEST DATA

Data available in NHTSA's Biomechanics database from sled tests using human surrogates were analyzed to establish a thoracic injury criterion with improved injury predictive capabilities over other existing criteria. A total of seventy one frontal impact sled tests from three different impact trauma laboratories were examined and analyzed using logistic regression as discussed in Chapter 1. Data from fifty-four of these sled tests have previously been published. (Morgan, 1994). In each test, the human surrogate was restrained by one of five possible system configurations at the driver's position: (1) 3-point belt, (2) 2-point belt/knee bolster, (3) driver airbag and lap belt, (4) driver airbag and knee bolster, and (5) combined driver airbag and 3-point belt. The change in velocity (ΔV) of these tests ranged from 23 to 56 km/h. Following the tests, the surrogates were radiographed and necropsied to delineate any trauma that occurred during the impact event. The level or severity of injury was coded using the 1990 AIS manual. All AIS$\geq$3 injury in these tests involved rib fractures or associated soft tissue lacerations. The mean age of the human surrogates was 60 years and the mean mass was about 70 kg. Details of these 71 sled tests are presented in Table 4-1.

Human surrogates were fitted with tri-axial accelerometers at the first thoracic vertebrae. Chestbands (Eppinger, 1989) were wrapped around the chest at the location of the fourth and the eighth rib to obtain continuous measurements of chest deformations during impact. Chest deflections at five different locations UL, UC, UR, LL, and LR on the chest (Figure 4-1) were obtained by tracking the distance between pairs of points on the periphery. Chest deflections were then normalized by the chest depth of the specimen. Chest deflection was differentiated to obtain rate of deflection, from which velocity V and V*C were computed. The chest deflection and rate of deflection obtained from chestband data are external measurements which include the deflection and rate of deflection of the skin and flesh as well as those of the ribs.

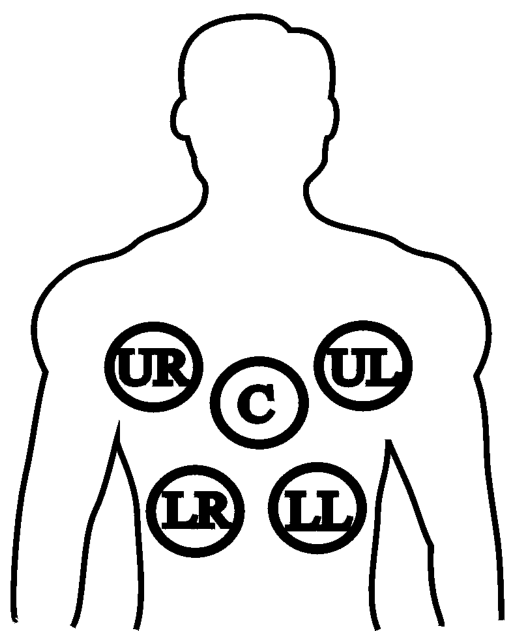


Figure 4-1. Location of five chest deflection measurement sites.

Table 4.1
Details of The 71 Tests Using Human Surrogates

TESTID	VELOCITY	RESTRAINT	AGE	SEX	MASS	AIS	RIBFXR	A_S	MAX. NORMALIZED DEFLECTION (in)					MAX. INSTANT. EXTERNAL VELOCITY (m/sec)					MAX. V*C
	(kph)	TYPE			(kg)			g's	UL	UC	UR	BL	BR	UL	UC	UR	BL	BR	(m/sec)
ASTS47	33.50	3PT	65	M	66	1	1		0.15	0.21	0.26	0.00	0.15	1.66	1.53	1.73	0.74	1.58	0.29
ASTS53	34.90	2PT/KNE	61	F	61	3	21	38.07	0.25	0.31	0.39	0.00	0.06	3.98	2.77	2.64	1.11	1.72	0.64
ASTS61	46.70	3PT/DPL	62	M	66	4	23	42.58	0.23	0.30	0.26	0.29	0.39	2.69	3.78	3.12	4.86	2.86	0.97
ASTS66	48.30	3PT/DPL	57	M	51	3	20		0.28	0.28	0.26	0.11	0.22	3.71	1.97	2.32	1.45	2.59	0.50
ASTS79	48.00	3PT/DPL	68	M	66	4	19	42.36	0.36	0.35	0.22	0.04	0.36	2.79	2.74	2.34	0.95	2.45	0.71
ASTS93	48.80	ABG/KNE	66	M	89	4	25	66.99	0.26	0.32	0.38	0.27	0.33	5.91	7.33	9.02	4.96	5.55	2.28
ASTS94	49.60	ABG/KNE	66	F	62	5	18	88.17	0.25	0.26	0.26	0.23	0.36	2.71	2.46	2.00	3.58	5.41	1.41
ASTS96	34.00	ABG/KNE	58	F	97	4	14	111.54	0.05	0.05	0.05	0.05	0.08	2.02	1.73	2.15	1.30	1.37	0.06
ASTS97	33.50	ABG/KNE	67	M	74	5	14	70.42	0.11	0.13	0.14	0.13	0.14	1.38	1.51	1.55	3.01	1.78	0.26
ASTS102	33.20	2PT/KNE	60	M	95	5	19	25.27	0.22	0.30	0.32	0.06	0.19	4.00	4.98	4.49	1.33	2.23	1.30
ASTS103	32.50	2PT/KNE	57	M	102	5	13		0.11	0.12	0.16	0.06	0.08	3.56	5.19	5.91	2.03	2.28	0.38
ASTS104	32.30	2PT/KNE	66	F	104	5	11	28.22	0.40	0.52	0.43	0.00	0.35	2.30	3.23	3.34	0.62	2.42	1.03
ASTS113	47.30	2PT/KNE	24	F	57	5	12	43.37	0.33	0.40	0.29	0.12	0.21	1.65	1.96	1.42	1.89	1.65	0.53
ASTS174	25.90	3PT/KNE	57	F	61	3	12	29.74	0.24	0.33	0.33	0.01	0.03	2.51	3.21	2.94	0.66	1.00	0.97
ASTS175	25.70	3PT/KNE	58	M	116	2	3	28.33	0.25	0.32	0.25	0.06	0.19	2.68	2.99	2.25	0.67	1.75	0.64
ASTS223	54.90	2PT/KNE	59	M	61	4	13	47.30	0.40	0.45	0.30	0.00	0.19	2.60	3.10	2.15	0.56	1.57	0.77
ASTS224	54.30	2PT/KNE	58	M	65	4	16	42.30	0.22	0.34	0.44	0.08	0.17	2.23	2.92	3.18	3.98	1.56	0.90
ASTS225	53.90	2PT/KNE	36	M	72	4	16	43.10	0.32	0.22	0.13	0.02	0.34	4.13	3.59	2.44	0.87	4.77	1.04
ASTS227	53.50	2PT/KNE	53	M	70	3	10	50.73	0.36	0.39	0.37	0.01	0.20	8.51	8.00	5.75	1.10	1.91	2.21
ASTS228	54.70	2PT/KNE	47	M	84	4	16	43.28	0.22	0.34	0.42	0.04	0.21	6.24	7.89	9.94	2.30	2.87	2.95
ASTS229	54.00	2PT/KNE	37	M	60	4	17	46.94	0.27	0.19	0.13	0.06	0.40	3.56	2.88	2.06	1.12	3.55	1.00
ASTS250	54.90	2PT/KNE	39	M	50	4	12	54.04	0.17	0.13	0.10	0.04	0.10	2.68	2.64	2.41	0.66	0.65	0.34
ASTS258	55.40	2PT/KNE	69	M	64	4	14	54.31	0.20	0.27	0.31	0.05	0.20	2.85	3.67	4.55	1.31	2.71	0.82
ASTS259	56.40	2PT/KNE	67	F	77	3	15	80.83	0.09	0.13	0.17	0.00	0.07	1.38	1.96	2.60	0.46	0.77	0.23
ASTS294	56.80	3PT/KNE	68	M	55	4	10	62.00	0.22	0.31	0.38	0.26	0.26	2.92	2.66	3.08	5.36	2.72	0.94
ASTS296	59.80	3PT/KNE	59	M	73	4	26	61.60	0.29	0.41	0.36	0.04	0.25	2.95	3.52	3.27	0.87	2.67	1.13
ASTS303	57.50	3PT/ABG	64	M	50	3	4	51.94	0.16	0.12	0.08	0.00	0.10	2.61	1.70	1.43	0.44	1.56	0.13
ASTS304	59.40	3PT/ABG	65	M	57	4	15	67.62	0.30	0.34	0.25	0.01	0.17	3.11	3.75	3.19	0.99	3.24	0.85
ASTS305	59.40	3PT/ABG	66	F	58	4	12	67.64	0.40	0.37	0.29	0.02	0.21	3.30	3.03	2.60	0.90	2.22	0.77
UVA333	58.20	3PT/ABG	66	M	58	3	12	78.70	0.18	0.19	0.14	0.00	0.08	1.72	1.82	1.44	0.54	0.94	0.28
UVA334	58.20	3PT/ABG	66	M	58	3	12	72.89	0.23	0.23	0.24	0.01	0.14	1.38	1.36	1.44	1.14	1.70	0.30
UVA335	58.60	3PT/ABG	66	M	58	2	12	52.13	0.15	0.12	0.08	0.02	0.10	1.89	2.61	2.52	0.62	0.82	0.11
UVA356	57.20	ABG/KNE	64	M	74	4	30	60.07	0.20	0.23	0.25	0.32	0.30	4.63	4.37	4.22	6.16	3.73	1.04
UVA357	57.20	ABG/KNE	48	M	80	5	19	75.95	0.21	0.23	0.23	0.31	0.31	3.63	4.05	3.74	4.48	4.23	0.64
UVA358	59.00	ABG/KNE	40	M	81	4	17	56.60	0.13	0.15	0.15	0.20	0.30	1.29	1.57	1.51	2.78	3.35	0.48

TESTID	VELOCITY	RESTRAINT	AGE	SEX	MASS	AIS	RIBFXR	A_S	MAX. NORMALIZED DEFLECTION (in)					MAX. INSTANT. EXTERNAL VELOCITY (m/sec)					MAX. V*C
	(kph)	TYPE			(kg)			g's	UL	UC	UR	BL	BR	UL	UC	UR	BL	BR	(m/sec)
H9013	48.00	3PT/KNE	34	M	71	0	0	27.23	0.40	0.44	0.32	0.09	0.09	4.08	4.15	3.07	6.51	1.83	1.33
H9207	48.60	ABG/KNE	25	M	74	0	0	48.54	0.08	0.11	0.12	0.11	0.16	1.15	1.49	1.29	2.05	1.59	0.19
H9212	48.00	ABG/KNE	38	M	79	0	0	45.65	0.14	0.16	0.14	0.13	0.07	2.05	2.24	2.11	2.41	2.02	0.23
H9216	48.00	3PT/KNE	20	M	86	2	0	33.68	0.25	0.18	0.10	0.01	0.06	2.30	2.64	2.17	1.04	1.00	0.47
H9310	48.00	3PT/KNE	52	F	68	2	1	28.78	0.30	0.27	0.19	0.02	0.15	2.34	2.01	1.53	0.78	1.38	0.40
H9311	48.00	ABG/3PT	47	F	76	2	0	31.28	0.17	0.24	0.19	0.04	0.21	1.83	2.56	2.15	1.01	1.37	0.39
H9312	48.00	ABG/3PT	32	M	85	2	3	31.54	0.14	0.16	0.14	0.01	0.21	2.06	2.14	1.68	1.36	1.63	0.20
RC101	49.90	3PT	58	M	85	4	10	39.92	0.10	0.12	0.11	0.11	0.35	2.97	3.45	4.03	2.53	4.05	1.23
RC102	48.30	3PT	58	M	73	4	12	89.53	0.17	0.22	0.16	0.14	0.41	3.53	3.87	3.30	1.41	3.19	1.17
RC103	48.30	3PT	66	M	76	3	8		0.42	0.51	0.43	0.09	0.12				2.22	2.61	0.18
RC104	48.30	3PT	58	M	70	3	13	40.47	0.04	0.13	0.17	0.03	0.17	1.85	1.77	2.28	1.21	3.38	0.41
RC105	48.30	3PT	67	M	73	3	19	72.89	0.40	0.43	0.40	0.09	0.29	10.51	9.28	5.11	1.39	3.77	3.14
RC106	48.30	3PT	44	M	90	4	9	53.00	0.32	0.34	0.31	0.00	0.08	11.98	12.46	9.61	1.97	2.42	2.28
RC107	48.30	3PT	63	F	77	4	22	46.58	0.39	0.37	0.26	0.17	0.32	2.79	2.69	2.51	2.23	3.70	0.91
RC108	48.30	3PT	57	M	73	4	8	54.87	0.35	0.22	0.12	0.08	0.04	7.90	6.09	4.22	1.47	1.32	2.19
RC109	48.30	3PT	59	M	91	3	12	32.33	0.27	0.36	0.46	0.14	0.24	4.96	5.40	5.15	6.62	3.41	2.05
RC110	48.30	3PT	63	F	61	4	24	56.40	0.11	0.24	0.34	0.05	0.37	8.06	7.06	7.91	1.05	4.66	1.73
RC112	48.30	ABG/LAP	67	F	50	2	3	43.96	0.12	0.16	0.18	0.01	0.00	2.13	2.70	2.99	1.01	0.83	0.37
RC113	48.30	ABG/LAP	64	M	70	2	3	43.27	0.36	0.33	0.30	0.04	0.08	3.53	3.75	3.50	2.48	2.77	0.78
RC114	48.30	ABG/LAP	58	M	73	0	0	59.66	0.24	0.23	0.20	0.21	0.16	4.91	5.07	4.37	3.28	2.45	0.58
RC115	48.30	ABG/3PT	67	F	57	3	13		0.23	0.29	0.33	0.17	0.33	3.85	5.62	3.49	3.57	3.61	0.76
RC116	48.30	ABG/3PT	68	M	59	4	10	28.80	0.31	0.26	0.22	0.10	0.12	3.05	2.53	2.44	2.46	2.31	0.64
RC117	23.20	3PT	76	M	58	3	9	23.51	0.19	0.25	0.26	0.01	0.18	3.14	4.06	3.59	0.41	1.81	0.83
RC118	46.50	ABG/KNE	29	F	41	0	0	44.04	0.19	0.21	0.19	0.15	0.26	1.41	2.25	2.33	1.25	3.29	0.35
RC119	45.40	ABG/KNE	71	M	81	4	11	53.71	0.20	0.24	0.28	0.35	0.47	7.66	9.54	11.06	11.87	9.48	3.05
RC120	23.50	3PT	51	M	66	3	8	21.73	0.40	0.36	0.28	0.26	0.26	2.51	2.53	2.32	2.24	2.34	0.85
RC121	24.50	3PT	67	M	66	0	0	16.21	0.26	0.23	0.18	0.03	0.09	2.06	1.87	1.70	0.57	1.14	0.40
RC122	23.70	3PT	81	F	60	2	4	15.17	0.21	0.24	0.20	0.04	0.14	1.28	1.49	1.28	0.73	1.24	0.19
RC123	23.70	3PT	67	F	68	2	1	15.84	0.26	0.22	0.15	0.01	0.16	1.75	1.63	1.18	0.44	1.47	0.27
RC124	31.60	ABG/KNE	76	M	80	0	0	18.40	0.16	0.19	0.19	0.24	0.21	6.16	5.31	3.16	3.71	2.67	0.44
RC125	43.80	ABG/KNE	75	F	85	3	10	45.55	0.23	0.26	0.27	0.32	0.36	1.64	3.00	3.48	3.69	3.51	1.01
RC126	34.70	ABG/KNE	64	F	54	3	6	26.85	0.18	0.18	0.15	0.27	0.39	1.16	1.37	1.35	4.91	5.11	1.08
RC127	34.40	ABG/KNE	81	M	62	2	3	20.61	0.12	0.11	0.11	0.14	0.20	2.05	1.35	1.29	1.51	2.51	0.33
RC128	29.90	ABG/3PT	67	F	46	2	3	23.10	0.34	0.34	0.26	0.05	0.22	2.32	2.37	2.01	0.54	2.09	0.48
RC129	32.80	ABG/LAP	59	M	78	3	8		0.15	0.17	0.17	0.19	0.11	1.99	2.27	2.16	4.69	3.42	0.63
RC130	32.70	ABG/3PT	56	M	63	2	4		0.17	0.19	0.13	0.04	0.13	1.46	1.72	1.46	0.68	1.49	0.25

Statistical analyses were conducted using the 3 millisecond clip value of thoracic spine resultant acceleration (A_s), maximum normalized central chest deflection (dc) corresponding to the location of chest deflection measurement on the Hybrid III dummy, maximum normalized chest deflection at any one of the five locations on the chest (dmax), maximum chest velocity (V), and the maximum Viscous Criterion (VC) at any one of the five locations on the chest. The statistical analyses were also repeated using the 3 millisecond clip value of thoracic spine resultant acceleration which was normalized by length based on the cube root of the cadaver mass. Since the difference between the results using the unscaled and scaled spinal accelerations was not significant and the unscaled accelerations produced a slightly better fit to the data, the analyses presented use the unscaled spinal accelerations.

Thoracic injury outcomes classified using the AIS scale were reclassified into two categories: all tests with thoracic AIS<3 were classified as "no injury," and all tests with AIS$\geq$3 were classified as "injury." Logistic regression was used to develop the various injury criteria models. Model building strategies and goodness of fit measures outlined by Hosmer and Lemeshow (1989) were used to develop the models as well as for comparing their relative predictive ability. The goodness of fit of the model was determined by examining the -2log-likelihood ratio (-2log(LR)) which is a measure of the probability that the independent variables explain the available outcome. The -2 log(LR) is used to test the null hypothesis that the coefficient associated with the independent variable is zero. Under the null hypothesis, -2log(LR) has a chi-square distribution and SAS tests this null hypothesis and provides p-values. Higher values of -2log(LR) and lower p-values indicate that the model provides a better fit to the data. Assuming the null hypothesis is true, the difference in the -2log LR value between one model and another where an extra independent variable is added is a chi-square distribution with one degree of freedom. The null hypothesis that the coefficient associated with the additional variable was tested using this chi-square distribution.

The Goodman-Kruskal Gamma of rank correlation was used for assessing the predictive ability of the model. Similar to R^2 in regression analysis, a Gamma value of 1 indicates perfect predictive ability while a value of 0 indicates no predictive ability of the model. Predictive ability of the model can also be assessed by the percentage of concordance and discordance. The greater the percentage of concordance, the better the predictive ability of the model.

The probability of injury from a logistic regression model is given by $p=(1+e^{-(\alpha+\beta*x)})^{-1}$, where x is the value of the risk factor in the model and α and β are regression coefficients. The first logistic regression analyses were univariate using the single independent variables, A_s, dmax, dc, V, and VC. The p-value and goodness of fit measures for these analyses suggest that A_s and VC are better predictors of injury than dmax or dc (Table 4.2). The results also suggest that dmax is a better predictor of injury than dc.

Next, models using linear combination of measured parameters were developed. Model VI is a linear combination of dc and A_s while model VII is a linear combination of dmax and A_s (Table 4-2). The null hypotheses that the coefficients associated with dc and dmax are zero in Models VI and VII are rejected suggesting that the linear combination models are better than the models using single independent variables (Models I-V). Also, the higher -2Log (LR) value of Model VII over Model VI suggests that model VII is a better fit of the data. The improved predictive ability of Model VII, over Model VI, is reflected by its higher gamma values and greater concordance.

Table 4-2. Details of Logistic Regression Models

Model (α+β*risk factor)	-2Log(LR)	p-value	concord	discord	Gamma
I. $-1.5+0.054A_s$	16.06	0.0001	75.2%	24.8%	0.505
II. -0.031+3.53dc	2.62	0.1053	60.6%	39.4%	0.215
III. -1.38+7.65dmax	10.82	0.0010	69.6%	30.4%	0.394
IV. -0.14+1.38VC	13.15	0.0003	73.7%	26.3%	0.476
V. -0.48+0.35V	10.55	0.0012	71.8%	28. 2%	0.446
VI. $-3.74+0.063A_s+7.41dc$	23.5	0.0001	78.5%	21.5%	0.575
VII. $-6.43+0.076A_s+13.68dmax$	37.1	0.0001	84.8%	15.2%	0.700

Figures 4-2 to 4-4 present the logistic regression injury risk curves (AIS≥3) for models I, III, and VII. These models represent respectively the resultant spinal acceleration, maximum chest deflection at any one of five measured points, and a combination of spinal acceleration and chest deflection from the five measured points. The linear combination of spinal acceleration and chest deflection (Model VII) separated the injured data (AIS≥3) from the non injured data (AIS<3) better than any of the other models. Models I and III both yield risk curves which predict approximately a 20% injury risk at zero loading, further indicating their reduced predictive capabilities.

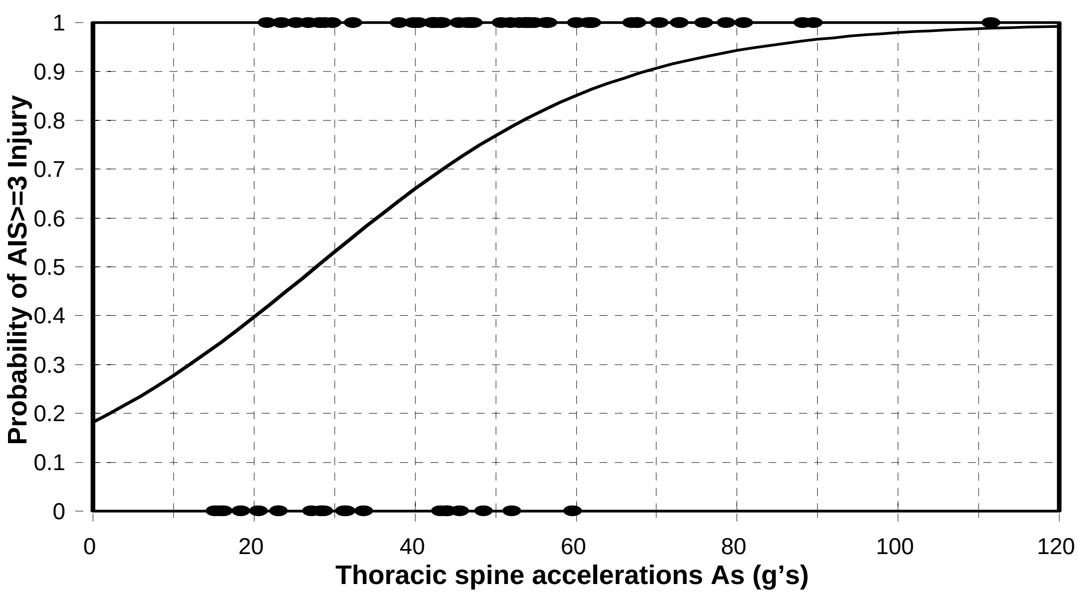


Figure 4-2. Probability of injury using spinal acceleration as risk factor (model I). Filled in circles represent 71 sled test data categorized as AIS≥3 injury (=1) and AIS<3 injury (=0).

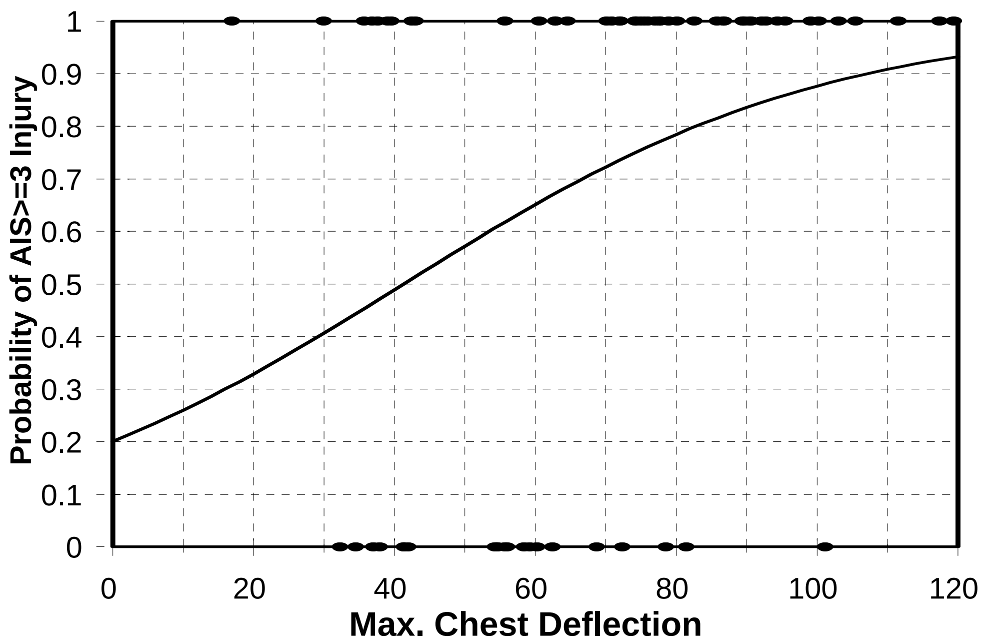


Figure 4-3. Probability of injury using maximum chest deflection (dmax) as risk factor (model III).

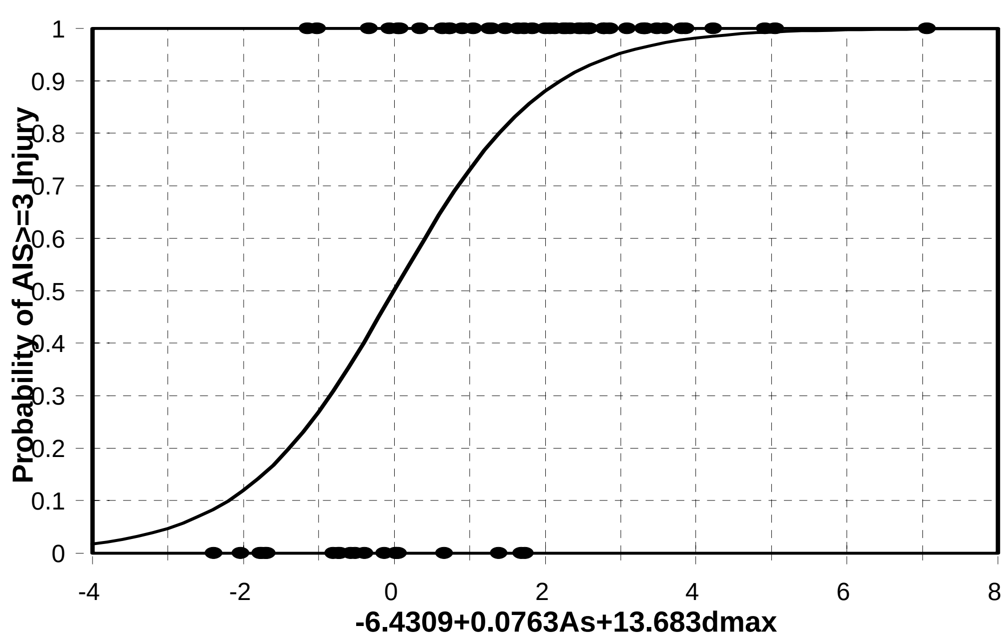


Figure 4-4. Probability of injury using linear combination of dmax and A_s as risk factor (model VII).

The improved predictive abilities of models using dmax over models using dc can be explained by the distribution of the location of maximum deflections. Table 4-3 presents the location of maximum deflection among the five locations on the chest. Maximum chest deflection occurs at the upper central chest location in only 25% of the sled tests. The central chest deflection (dc) versus maximum chest deflection (dmax) for the seventy-one cadaver sled tests, sorted by the restraint system, is shown in Figure 4-5. The difference between dc and dmax is quite high in some 2 and 3 point belt restrained tests. In these tests, dmax was at the lower chest location of LR while dc is computed at location UC (Figure 4-1). The difference between dc and dmax is also quite high in some airbag restraint tests where the steering wheel rim penetrated into the lower chest resulting in maximum chest deflection at the lower chest location (LL or LR).

Table 4-3 Location of Maximum Deflection in Belt and Airbag Sled Tests

Restraint Type	UL	UC	UR	LL	LR
Belt	15	17	13	0	8
Airbag	1	1	2	5	9
Total	16	18	15	5	17

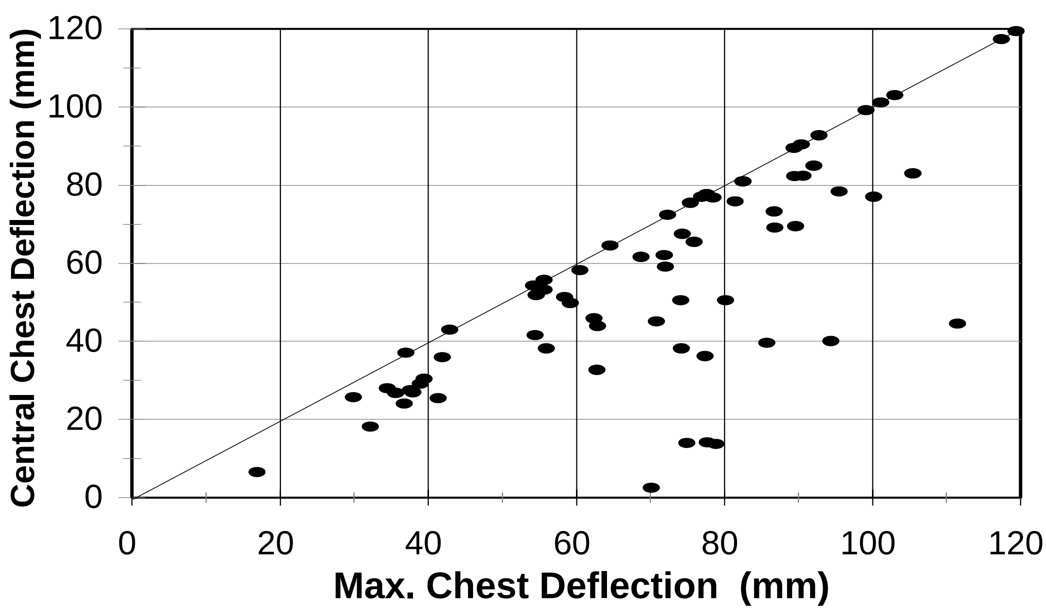


Figure 4-5. Plot of dmax versus dc. Maximum chest deflection occurs at the central chest location in only 25% of the tests.

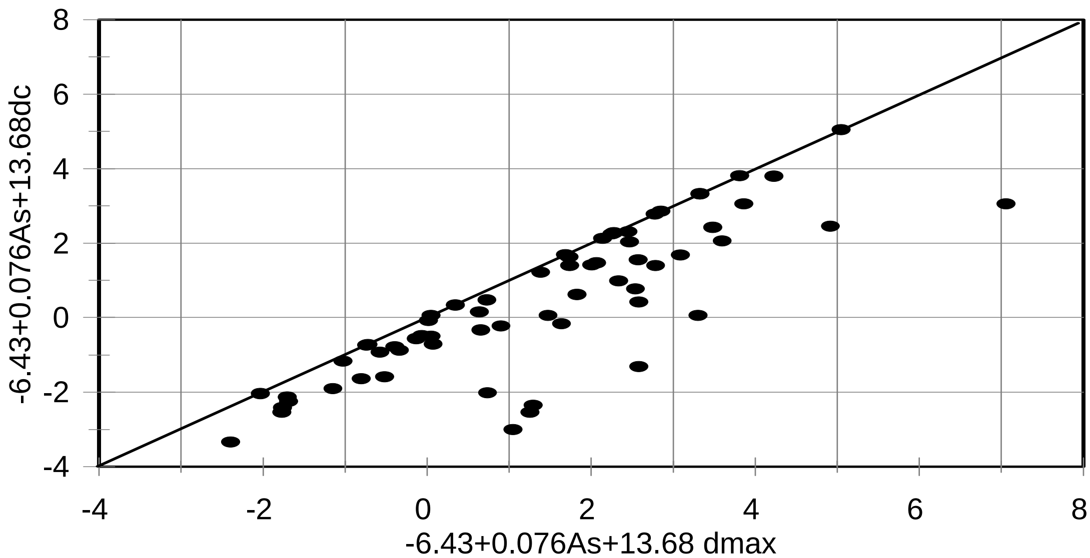


Figure 4-6. Model VII using dmax versus Model VII using dc as an estimator of dmax. The large differences in dmax and dc noted in Figure 4-5 is diminished due to the effect of spinal acceleration.

For the 71 human surrogate tests used in the analyses, a 3-msec clip value of spinal acceleration (A_s) has been shown to correlate well with injury since it represents the overall severity of the loading on the subject. For example, in some cadaver sled tests used in the analysis, there was significant steering wheel rim penetration into the lower thorax which resulted in significant injury but presented low chest deflection at the upper thorax. The spinal acceleration in these test were reasonably high and therefore the linear combination of A_s and dmax proved to be a good predictor of injury. An injury criteria using chest deflection alone may not have predicted the correct injury level under such circumstances as well as the linear combination of deflection and acceleration. The Hybrid III dummy has only one chest deflection gage and it has been noted by various researchers (Backaitis et al., 1986), (Cesari, et al., 1990) that the maximum deflection may be missed in some instances. For these reasons, it is believed that the linear combination model using dmax and A_s is the most appropriate injury criteria for assessing thoracic trauma. However, since only one deflection measurement is available on most dummies, the central chest deflection will be used with this formulation. This will result in slightly lower calculated values for Model VII since dc equals dmax in roughly 20 percent of the tests as described above and shown in Figure 4-6. It is intended that the maximum deflection from multiple points on the chest will be incorporated into the standard when all of the dummies have multiple measurement capabilities.

4.3 DEVELOPMENT OF COMBINED THORACIC INDEX (CTI) FOR THE 50% ADULT MALE

Using the probability of injury curve in Figure 4-4, lines of equal probability of injury for the linear combination of deflection and spinal acceleration (Model VII) were generated (Figure 4-7). Since the analyses were conducted using normalized deflections, the chest deflections in Model VII, dmax, were multiplied by 230 mm which represents the chest depth of a 50% adult male. Model VII used the normalized external chest deflections, the sum of the deflection of the ribs and skin, measured on cadavers using chest bands. However, the chest deflections measured on the dummy represent only the internal chest deflections of the ribs. To account for the difference between cadaver and dummy deflection measurements, 6 mm was subtracted from the external chest deflection to represent internal rib deflection. Therefore, the probability of injury function for Model VII can be re-written using internal chest deflections measured on the dummy, D, with the following equation,

$$p = \frac{1}{1+e^{-(-6.43+0.076\,As+0.063\,D)}} \qquad (4.1)$$

The 50% probability of injury line for the population of human surrogates studied was chosen to be the most appropriate thoracic injury criteria. The 50% probability of injury for the human surrogate would correspond to about a 25% probability of injury for the live human subjects, as will be discussed in detail in Section 4.5. The equation of the 50% probability of injury line using the deflections adjusted for the dummy given by equation (4.1) is mathematically equivalent to a line which has intercepts on the vertical and horizontal axes of D_{int}= 102 mm and A_{int} = 85g, respectively. Thus, the combined thoracic injury criteria, CTI, is defined with the following equation,

$$CTI = \frac{A_{max}}{A_{int}} + \frac{D_{max}}{D_{int}} \qquad (4.2)$$

where Amax is the maximum value of 3 ms clip spinal acceleration (As), Dmax is the maximum value of the dummy deflection (D), and A_{int} and D_{int} are the respective intercepts as defined above.

The current FMVSS No. 208 stipulates that during the specified crash test, the chest deflection of the 50th percentile Hybrid III male dummy cannot exceed 3 inches (76 mm) and its chest acceleration cannot exceed 60 G. In contrast, the CTI formulation , at its extremes, would allow 85 G's of chest acceleration with zero deflection and 102 mm of deflection with zero chest acceleration. Since neither of these extremes is physically realizable in a crash, it was deemed that a combination of both the current 208 and new CTI criteria would be the most practical set of requirements. Because the physical design of the 50% male Hybrid III dummy currently limits its maximum deflection to a value of only slightly greater that 76 mm, it is proposed that the 76 mm maximum deflection limit be retained for all acceleration conditions. Likewise, because the database from which the CTI was developed does not contain any specific examples of low injury (<AIS=3) under conditions of high acceleration (>60 G.) and low chest deflection (<30.5 mm), it is recommended that the current FMVSS No. 208 limit of 60 G also be retained. The 76 mm deflection limit and the 60 G acceleration limit are shown in Figure 4-8.

To complete the performance specification, a third requirement, based on the CTI formulation, would be that for any intermediate response condition falling below the prescribed maximum acceleration and deflection limits, that the quantity $A_{max}/A_{int} + D_{max}/D_{int}$, be less than or equal to 1. A test must satisfy all three of the above criteria to pass as shown in Figure 4-8 for the 50th percentile male dummy Exceeding any of the three criteria would constitute a failure of the thoracic injury criteria.

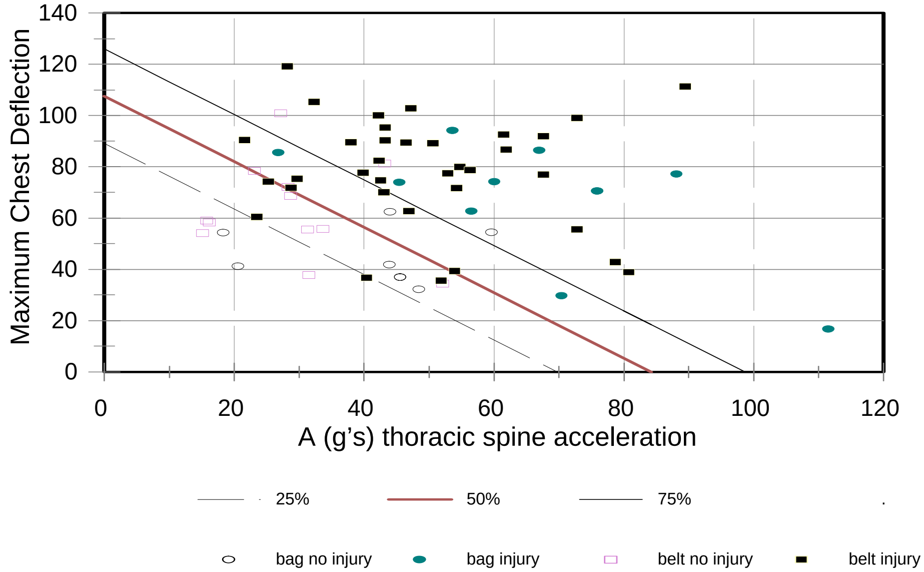


Figure 4-7. Lines of equal probability of AIS≥3 injury using the linear combination of maximum deflection and spinal acceleration (Model VII). A 0 represents tests with AIS <3 and a 1 represents tests with AIS≥1.

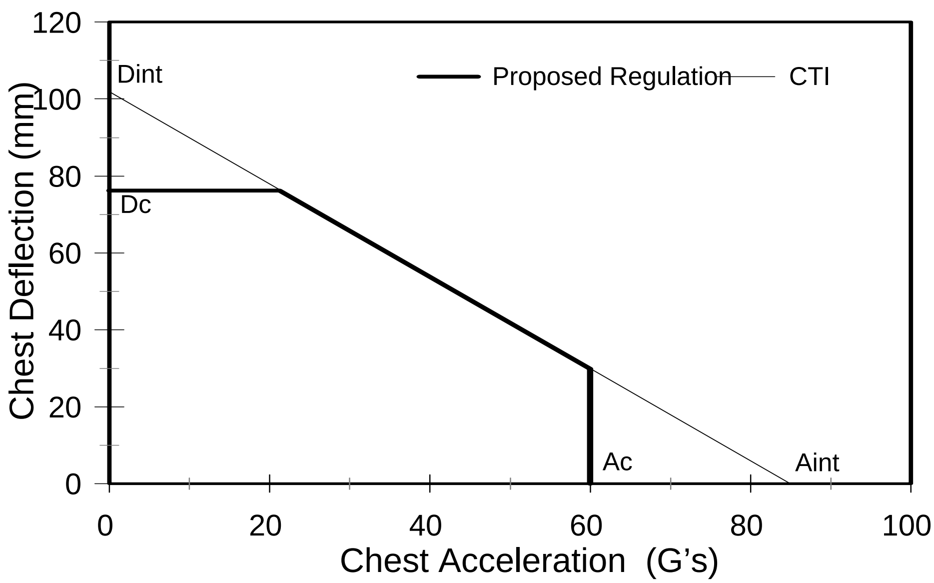


Figure 4-8. Injury criteria requirements for mid-sized adult male Hybrid III dummy.

4.4 SCALING OF THORACIC INJURY CRITERIA TO VARIOUS OCCUPANT SIZES

As discussed in Chapter 1, scaling techniques are necessary to obtain injury assessment reference values for the various dummy sizes. Thoracic injury threshold lines have been scaled using techniques similar to those used by Melvin for the CRABI 6-month infant dummy (Melvin, 1995). Geometric scale factors were taken from Mertz's paper on Injury Assessment Reference Values (Mertz, 1997). In his paper, Melvin discusses the importance of scaling, not only by geometric size, but also by the material stiffness of the biological structures. Dummy chests were designed with varying stiffness to account for changes in material bending properties for different aged occupants. Deflection criteria can thus be scaled using only geometric factors, assuming $\lambda_E = 1$, while acceleration criteria use both geometric and material scaling factors. The relevant scale factors presented in the paper are given in Table 4-4 for reference. Thus, deflections for various dummy sizes, D, or accelerations, A, can be found by scaling as follows:

$$\begin{aligned} D &= \lambda_{L,\,\mathrm{Depth}}\; D_{50\%\,male} \\ A &= \frac{\lambda_E}{\lambda_{L,\,\mathrm{Mass}}}\; A_{50\%\,male} \end{aligned} \qquad (4.3)$$

where the threshold values for the 50% male dummy are $D_{50\%male}$ and $A_{50\%male}$.

Table 4-4. Thoracic Scaling Factors for Various Occupant Sizes

Scale Factor	Mid-Sized Male	Small Female	6 Year Old	3 Year Old	12 Month Old
Length Based on Chest Depth ($\lambda_{L,\,Depth}$)	1.000	0.817	0.617	0.557	0.485
Length Based on Mass ($\lambda_{L,\,Mass}$)	1.000	0.862	0.650	0.578	0.504
Bone Modulus Scale Factor (λ_E)	1.000	*	0.667	0.474	0.320

* Data comparing the modulus and strength of female anatomic structures to male are not available at this time.

Thus, the deflection and acceleration intercepts for the Combined Thoracic Index for the 50% adult male and the current deflection and acceleration limits established for the 50% male Hybrid III in FMVSS No. 208 were all scaled according to equation 4.3, and are presented in Table 4-5.

Table 4-5. Scaled Deflection and Acceleration Values for Various Occupant Sizes

Value	Mid-Sized Male	Small Female	6 Year Old	3 Year Old	12 Month Old
Chest Deflection Intercept for CTI (Dint)	102 mm (4.0 in)	83 mm (3.3 in)	63 mm (2.47 in)	57 mm (2.2 in)	49 mm (2.0 in)
Chest Acceleration Intercept for CTI (Aint)	85	85	85	70	55
Chest Deflection Limit for Thoracic Injury (Dc)	76 mm (3.0 in)	62 mm (2.5 in)	47 mm (1.9 in)	42 mm (1.7 in)	37 mm** (1.5 in)
Chest Acceleration Limit for Thoracic Injury Criteria (Ac)	60	60*	60	50	40

* Although geometric scaling alone would predict higher A_c values for females, it is believed that lower bone mineral density would offset this effect. Therefore, the acceleration tolerance values for small females are kept the same as for mid-sized males.

** The CRABI 12 month old dummy is currently not capable of measuring chest deflection.

A normalized set of threshold limits is shown in Figure 4-9. Using the appropriate scaled critical limits from Table 4-5, this plot is applicable to all dummy sizes.

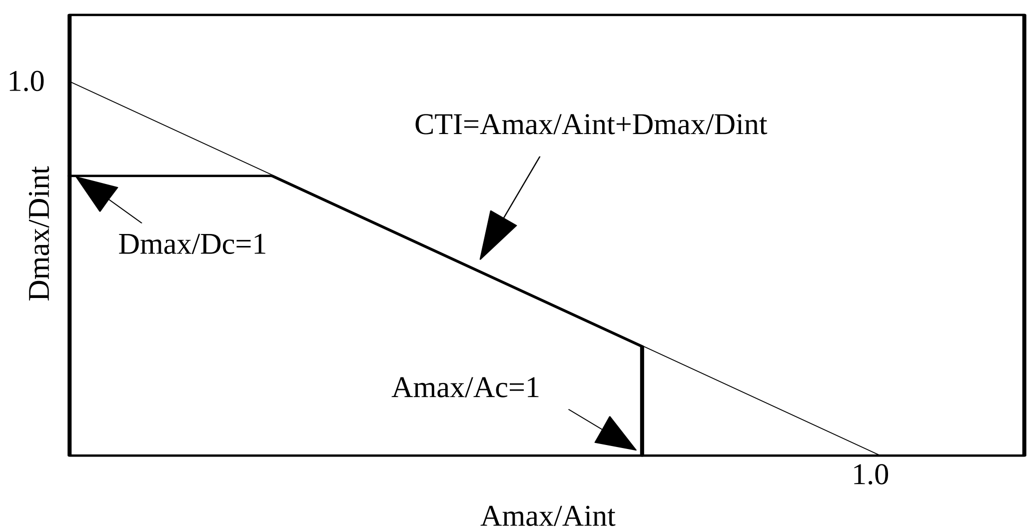


Figure 4-9. Normalized proposed injury criteria requirements for all dummy sizes.

4.5 DEVELOPMENT OF PROBABILITY OF INJURY RISK CURVES FOR THE THORAX

4.5.1 Adjustment of Risk Curves for Live Human Subjects

Viano et al. (1977) observed statistically significant differences in biomechanical responses and injuries between live and postmortem animals. On an average, the live animals demonstrated 26% lower rib fractures than the postmortem animals for the same level of chest deflection. Horsch et al. (1991) noted that human surrogates are more easily injured than car occupants for similar exposures. This apparent difference in tolerance between car occupants and human surrogate data was also noted by Foret Bruno et al. (1978). Yoganandan et al. (1991) noted that in human surrogate sled tests, there was consistently higher reporting of rib fractures from detailed autopsy than from radiography alone. They noted that for the same crash severity, greater severity injury was reported in human surrogate sled tests than in field data. They attributed these differences to the method of identifying rib fractures and the differences in the dynamic response characteristics of the living human and the surrogate.

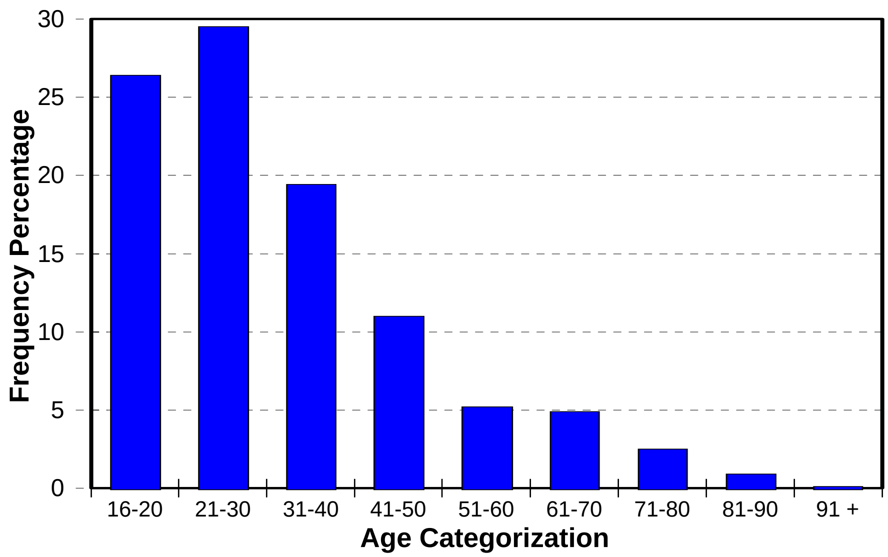


Figure 4-10. Age distribution of the USA driving population exposed to frontal collisions.

The 50% probability of injury line used in the development of the Combined Thoracic Index (Figure 4-7) would represent a significantly lower probability of injury for a car occupant. Figure 4-10 presents the age distribution of the USA population exposed to frontal collisions based on NASS files. The weighted average age of the driving population is approximately 30 years. The average age of the 71 surrogates used in the sled tests is 58 years. Thus, there was a nearly thirty year difference in average age of the surrogate data as compared to that of the average driving population. This thirty year age difference, the increased fragility of cadavers, and the over reporting of injury in experimental tests suggested an adjustment in the probability of injury to represent the probability of AIS$\geq$3 thoracic injury for the average live human driving population.

Based on all these factors, the 50% probability of injury line in Figure 4-7 was adjusted to represent a 25% probability of injury level for the live human driving population. The adjusted probability of injury curve written in terms of CTI (defined in Equation 4.2) and the original unadjusted curve are shown in Figure 4-11.

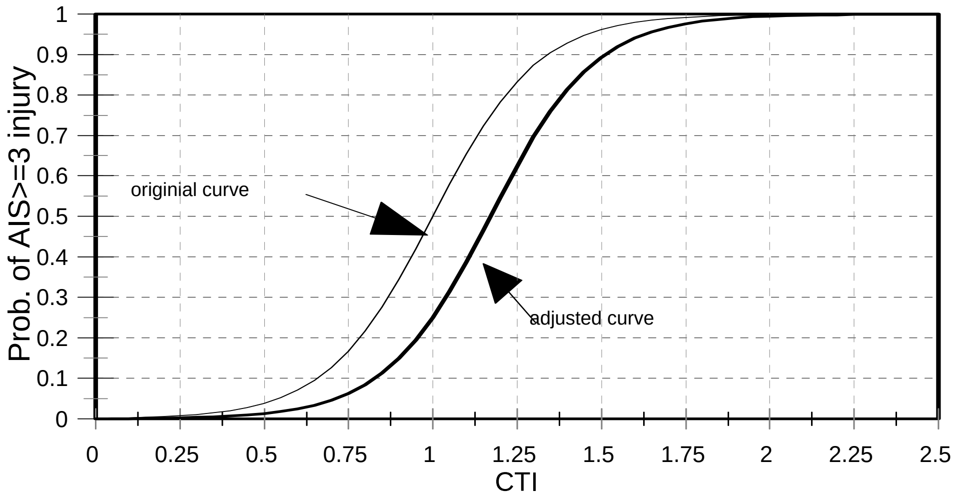
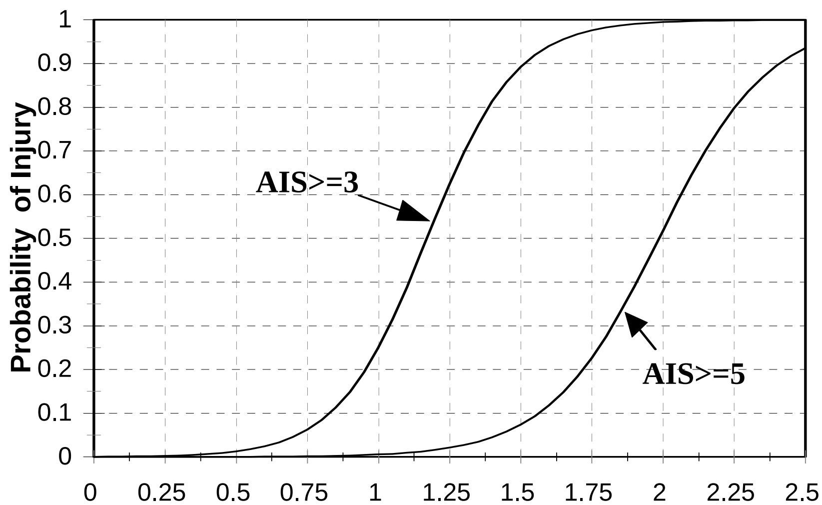


Figure 4-11. Reduced probability of injury using Model VII as the risk factor to relate sled test data to real world crashes. A value of one corresponds to 25% probability of injury.



$$p(AIS \geq 3) = \frac{1}{1+e^{(7.529-6.431CTI)}} \qquad p(AIS \geq 5) = \frac{1}{1+e^{(10.328-5.201CTI)}}$$

Figure 4-12. CTI Risk Curves for AIS 3+ and AIS 5+ Thoracic Injuries.

Data from the 71 human surrogate tests were also analyzed using logistic regression to determine the probability of AIS$\geq$5 thoracic injury. The resulting AIS$\geq$5 curve was shifted the same amount as the AIS$\geq$3 curve to account for differences between the surrogate test subjects and the average driving population. Both the adjusted AIS$\geq$3 and AIS$\geq$5 injury risk curves are shown in Figure 4-12.

To verify that the thoracic injury risk curve was reasonable, comparisons were made between the injury rates predicted using CTI calculations from experimental test data and real world injury rates estimated from the NASS database. NASS data for front seat outboard occupants involved in frontal, non-rollover crashes from 1988 to 1996 were analyzed to determine whether injury probabilities estimated from NASS were reasonably close to those predicted by CTI calculations using vehicle crash test data gathered from FMVSS No. 208 compliance testing and NCAP testing.

For unbelted occupants in high speed crashes (delta-V $\geq$ 35), the probability of AIS 3+ chest injury was 27 percent for airbag equipped vehicles and 34 percent for all vehicles. This is roughly twice the injury rate for belted occupants. Applying biomechanical data to comparable results from unbelted compliance testing from 1996-97 indicates about a 24 percent probability of AIS 3+ injury for drivers and 9 percent for right front passengers. Since drivers represent about 75 percent of all front seat occupants, this implies a predicted average injury probability for front seat occupants of about 20 percent. Thus, for unbelted front seat occupants in high speed crashes, CTI somewhat underestimates the risk of injury based on NASS data.

For crashes comparable to NCAP test conditions, NASS data indicate a 7 to 14 percent probability of having an AIS 3+ chest injury. Applying biomechanical data to NCAP belted tests indicates that lap/shoulder belted airbag vehicle occupants have about a 19 to 24 percent probability of receiving an AIS 3+ chest injury. Thus for belted front seat occupants in NCAP type crashes, CTI appears to somewhat overestimate the risk of injury based on NASS data. Looking at both belted and unbelted vehicle occupants, the adjusted probability of injury curve developed for the Combined Thoracic Index seems to reasonably represent the injury frequency in real world crashes.

4.6 APPLICATION OF PROPOSED THORACIC INJURY CRITERIA TO AVAILABLE TEST DATA

The proposed thoracic injury criteria requires each test to satisfy three performance requirements. These are (1) the 3 ms clip acceleration is less than or equal to Ac, (2) the maximum chest deflection is less than or equal to Dc, and (3) the Combined Thoracic Index (CTI) is less than 1.0. The thoracic injury criteria were calculated for a wide variety of tests available in the NHTSA database. Analyses were conducted for data from 30 mph FMVSS No. 208 compliance tests, 35 mph NCAP tests, 48 kmph rigid barrier and 40 kmph offset tests with 5th percentile female dummies, and out-of-position test with the 3 year-old, 6 year-old, and 5th percentile female dummies. The accompanying graphs and data for all the tests presented here are provided in detail in Appendices B and C.

4.6.1 Application of Proposed Thoracic Injury Criteria to FMVSS No. 208 Barrier and NCAP Tests

Data from 1996 to 1998 FMVSS No. 208 full barrier crash tests and 1997-1998 NCAP tests were analyzed to determine how various production vehicles performed using the proposed thoracic injury criteria. Figures B.1 - B.4 present the 3 msec clip value of chest acceleration and maximum chest deflection of drivers for the various FMVSS No. 208 and NCAP tests along with the thoracic threshold lines for the 50th percentile male.

For the FMVSS No. 208 barrier tests, 20 out of 29 dummies in the driver position in 1996-1997 vehicles passed. Since many manufacturers have opted to use the alternative sled test for compliance testing for the 1998 model year vehicles, data from frontal barrier tests is limited to 5 vehicles for the 1998 model year vehicles. In those tests, 4 out of 5 drivers in 1998 production vehicles passed the thoracic criteria. 25 out of 27 passengers in 1996-1997 production vehicles passed the thoracic injury criteria and 4 out of 5 passengers in 1998 production vehicles passed. Thus, the average passing rate 1996- 1998 vehicles in FMVSS No. 208 tests is 71% for dummies in the driver position and 94% for dummies in the passenger position.

For the NCAP tests with 1998 model year vehicles, 36 out of 49 dummies in the driver position passed all three performance specifications for the proposed thoracic injury criteria, compared to 23 out of 29 dummies in the driver position in 1997 vehicles. All 49 passengers in 1998 vehicles and 22 out of 29 passengers in 1997 vehicles passed the thoracic criteria. Thus, the average passing rate for 1997 and 1998 vehicles in NCAP tests was 76% for drivers and 80% for passengers.

4.6.2 Application of the Proposed Thoracic Injury Criteria to Vehicle Crash Tests with the 5th Percentile Female Dummy

Data from tests conducted at Transport Canada using the Hybrid III 5th percentile female dummy in model year 1996-1998 vehicles were also analyzed. In these tests, the dummy in the driver and passenger position were belt restrained and the seat was adjusted to the full forward position. Figures B.5 - B.8 present the 3 msec clip value of chest acceleration and maximum chest deflection for the various Transport Canada tests along with the thoracic threshold lines for the 5th percentile female dummy.

Vehicle crash tests into the European deformable barrier at 40 kmph (25 mph) closing speed and a 40% offset were conducted with belted 5th percentile female dummies in model year 1996-1998 vehicles. Such a vehicle crash involves a soft crash pulse which may result in late deployment of the airbag in some vehicles. All dummies in the driver and passenger position passed the thoracic injury criteria due to the soft crash pulse.

A second series of 48 kmph (30 mph) vehicle crashes of model year 1996-1998 vehicles into a rigid barrier were conducted using the belted 5th percentile adult female dummies in the driver and passenger position seated in the full frontal seat track position. 17 out of 23 drivers in the pre-1998 vehicles and 6 out of 9 drivers in the 1998 vehicles passed the thoracic injury criteria. 9

out of 14 passengers in the pre-1998 production vehicles and 8 out of 10 passengers in the 1998 production vehicles passed. Thus, the average passing rate for the 5th percentile female dummy was 72% for the driver position and 71% for the passenger position.

4.6.3 Application of Proposed Thoracic Injury Criteria to Out-of-Position Test Conditions Using the 5th Percentile Adult Female Dummy

Out-of-position tests were conducted to investigate the trauma induced when the vehicle occupant is in close proximity to the deploying airbag. Since fatalities due to airbag interaction have been noted in real world crashes to mainly involve children and small female occupants, out-of-position tests were conducted using the 5th percentile female dummy, Hybrid III 6-year old dummy, and the Hybrid III 3-year old dummy. Figures B.9 - B.10 present the 3 msec clip value of chest acceleration and maximum chest deflection of drivers for the various out-of-position tests along with the thoracic threshold lines for the 5th percentile female dummy.

Out-of-Position Component Tests with the 5th Percentile Adult Female Dummy

Crandall et al. (1997) conducted driver ISO-2 out-of-position tests with small female postmortem human subjects using “more aggressive” and “less aggressive” airbags, the details of which are presented in Table 4-6. The chest deflection measurements in these tests were external chest deflections obtained from chest band data. Hence, 6mm was subtracted to reflect internal rib deflection. Airbags P-MA and D-PS-0 were considered to be more aggressive than the P-LA, D-P and D-PS-20 airbags. All the subjects in these out-of-position tests sustained AIS$\geq$3 chest injuries and all the tests failed the thoracic injury criteria (Figure 4-13).

Table 4-6. Out-of-Position Tests using Small Female Surrogates

Airbag Type	AIS	Chest Defl (mm)	Chest Accel. (G)	CTI
P-LA	3	56	41.5	1.04
P-MA	4	150	78.2	2.49
P-LA	3	73.6	58	1.40
D-PS-0	5	83.1	64.9	1.58
D-P	4	81	29.3	1.23
D-PS-20	4	81.9	51.0	1.44
P-MA	5	103	138.2	2.49

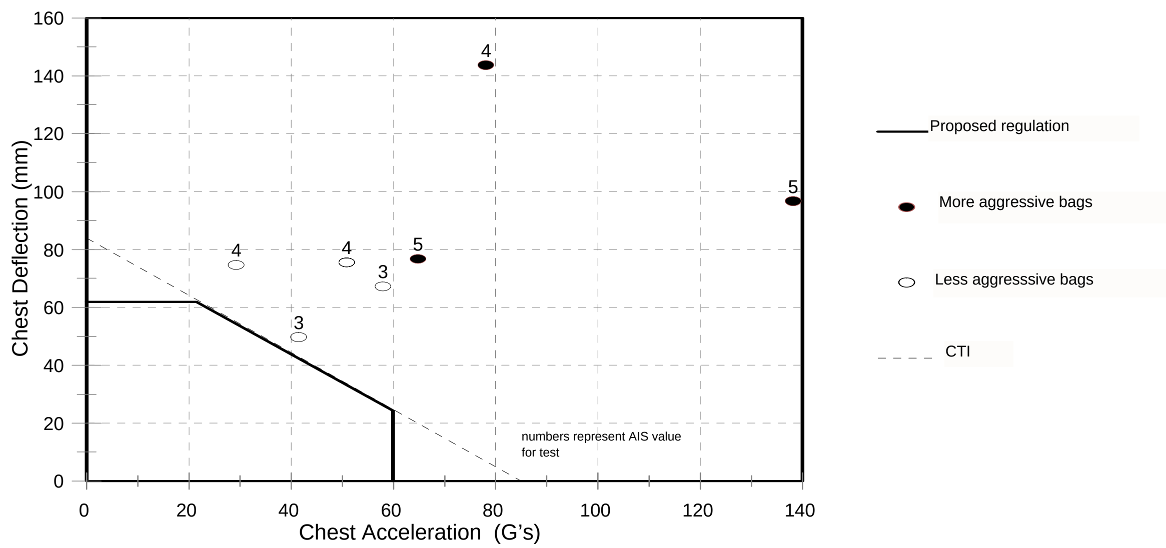


Figure 4-13. Proposed thoracic injury criteria for small female dummy and human surrogate ISO-2 OOP test data. Injury outcome in all the tests were AIS≥3 and all failed the proposed criteria.

Table 4-7. Out-of-Position Tests using 5th Percentile Female Hybrid III Dummy

Airbag Type	Deflection Dmax (mm)	3 ms Clip Acceleration Amax (g)	Velocity (m/s)	VC (m/s)	CTI
A-96	43.5	20.8	8.5	0.98	0.76
A-96	54.9	38.2	9.95	1.85	1.1
A-94	73.6	63.0	11.5	3.2	1.62
E-96	43.4	35.8	6.7	0.93	0.94
E-94	64.0	31.8	10.2	2.48	1.14
E-94	68.5	36.0	11.7	2.47	1.24
F-96	32.7	22.5	7.1	0.67	0.65
F-94	43.2	34.5	10.9	1.29	0.92

Data from eight 5th percentile female Hybrid III dummy ISO-2 out-of-position tests using air bags from equivalent 1994 and 1996 model year cars are shown in Table 4-7. The airbags coded as A-96, E-96, and F-96 are from 1996 cars which were considered to be less aggressive than their counterparts from 1994 cars, coded as A-94, E-94, and F-94. It was noted from earlier studies that the A series air bags were significantly more aggressive than the F series air bags. This is consistent with the chest deflection and chest acceleration measurements in these tests.

The less aggressive airbags consistently have lower CTI values than the corresponding more aggressive airbags. The measurements from these dummy out-of-position tests are plotted against the injury threshold lines for the small female dummy and are shown in Figure 4-14. All the airbags of lower aggressivity except A-96 pass the CTI criteria. These observations suggests that CTI is a good discriminator between more aggressive and less aggressive air bags.

Out-of-Position Vehicle Tests with 5th Percentile Adult Female Dummy

The driver ISO-1 out of position test condition is intended to maximize head and neck loading from airbag deployment. Tests were conducted using pairs of 1998 and pre-1998 vehicle airbag systems to investigate their relative aggressivity for the same vehicle model. Only one pre-1998 airbag failed the thoracic criteria. Also, all the 1998 air bags appeared less aggressive to the chest than the corresponding pre-1998 air bags.

The driver ISO-2 out-of-position test condition is intended to maximize chest loading due to airbag deployment. Tests were also conducted using pairs of 1998 and pre-1998 vehicle airbag systems. One pre-1998 airbag and one 1998 airbag failed the criteria. Although the same pairs of production vehicle airbags were used in the ISO-2 tests as in the ISO-1 tests, the 1998 airbags in the ISO-2 tests do not appear less aggressive to the chest than the corresponding pre-1998 airbags for all the production vehicles.

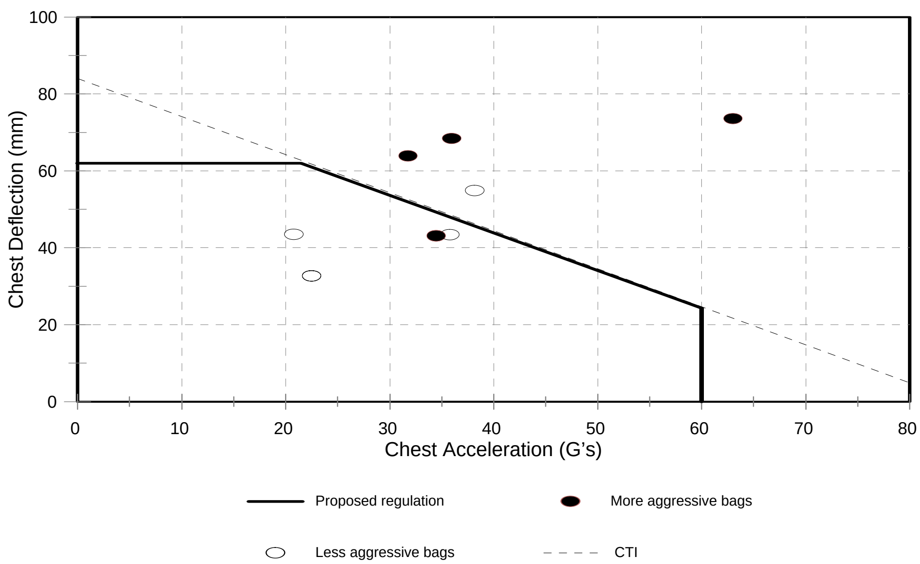


Figure 4-14. Proposed thoracic injury criteria for small female and ISO-2 OOP dummy tests. Most less aggressive airbags pass criteria while aggressive air bags fail the criteria.

4.6.4 Application of Proposed Thoracic Injury Criteria to Out-of-Position Test Conditions Using 6-Year Old and 3 -Year Old Dummies

Out-of-position tests were conducted to investigate the trauma induced when the child dummy is in close proximity to the deploying airbag. Figures B.11-B.14 present the 3 msec clip value of chest acceleration and maximum chest deflection of drivers for the various out-of-position tests along with the thoracic threshold lines for the 6 year-old and 3 year-old dummies.

Two out-of-position test conditions were considered for the 6 year-old and 3 year-old Hybrid III dummies. The child ISO-1 position is designed primarily to evaluate contact forces of the deploying airbag on the chest. This position is intended to represent a standardized worst case condition in which the child has been thrown against the frontal structure of the vehicle's interior due to pre-impact braking and/or vehicle impact. The child ISO-2 position is designed to primarily address the contact forces and loading forces of the deploying airbag on the head and neck. This position is intended to represent a worst case scenario in which the child slides forward or is sitting forward on the seat while the upper torso jack-knifes forward toward the instrument panel.

In each of the out-of-position tests conditions with the child dummies, both baseline and depowered airbag systems were tested. Baseline tests (D1 in Figures B-11 through B-14) were conducted with the original airbag inflator, while corresponding depowered tests were conducted using the same airbag module, but with some percentage of propellent removed from the inflator (D2). Corresponding baseline and depowered tests are connected by lines. As more propellent is removed from the inflator, the aggressivity of the airbag reduces. This decrease in aggressivity is correlated with a decrease in the proposed thoracic injury criteria, suggesting that these criteria predict thoracic injury risk for children reasonably well.

Chapter 5
Lower Extremity Criteria

A vast amount of research is currently being conducted to better understand the complex mechanisms of foot and ankle injuries. New dummy legs and associated injury criteria are under development, but are not yet available for use with this standard. Current recommendations are to continue using femur load for the adult dummies, but not for the child dummies. The suggested tolerance for femur load is 10 kN for the 50% male, and 6.8 kN for the 5% female. Cross-sectional area of the femur was used to obtain the tolerance value for the small female. Anthropometric data was taken from the literature (Mertz, 1989).

Figure 5-1 shows the injury risk curve associated with femur loads. A femur load of 10 kN for the mid-sized male dummy represents a 35 percent risk of sustaining an AIS$\geq$2 injury. Injury risk values for the small female are assumed to be equivalent to the male risk after application of the scale factor.

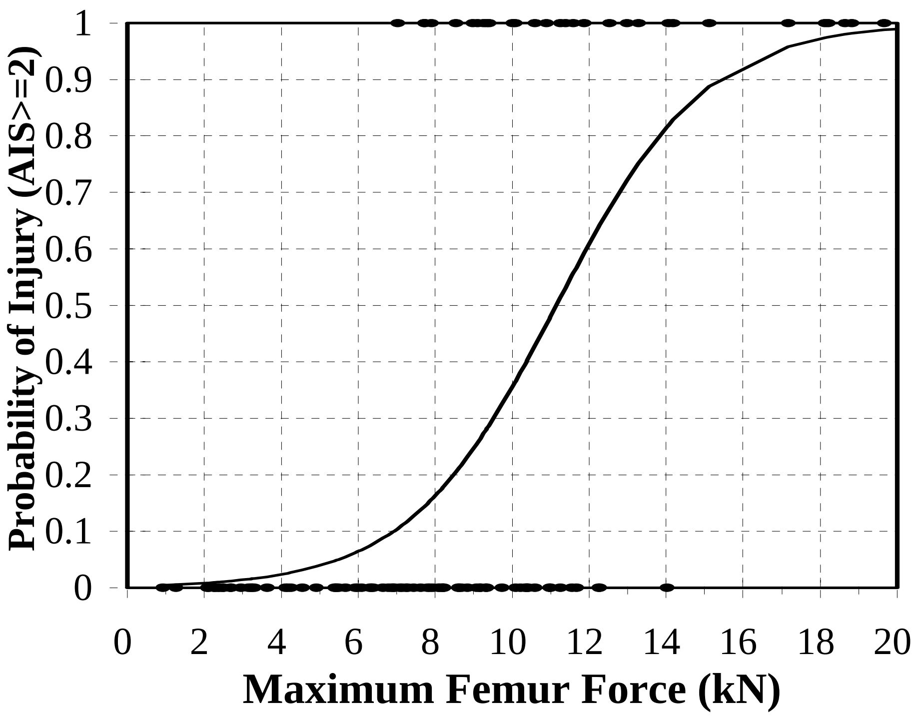


Figure 5-1. Injury risk curve for femur loads.

Chapter 6
Recommendations

Summarizing all of the discussion presented in this paper, Table 6-1 shows the injury criteria and critical values recommended for each body region. HIC is currently being recommended for head protection, scaled appropriately for all dummy sizes. A neck criteria of Nij$\leq$1.4 is being recommended, with critical values defined for all dummies. For the chest, the Combined Thoracic Index (CTI) is recommended, along with individual limits on chest deflection and spinal acceleration. Femur load is recommended only for the adult dummies.

Table 6-1. Recommended Injury Criteria for FMVSS No. 208 Upgrade

Recommended Criteria	**Hybrid III Mid-Sized Male**	**Hybrid III Small Female**	**Hybrid III 6 YO**	**Hybrid III 3 YO**	**CRABI 12 MO**
Head Criteria (HIC_{36})	1000	1000	1000	900	660
Neck Criteria					
Nij	1.4	1.4	1.4	1.4	1.4
Nij Intercept Values					
Tens./Comp. (N)	3600	3200	2900	2500	2200
Flexion (Nm)	410	210	125	100	85
Extension (Nm)	125	60	40	30	25
Thoracic Criteria					
1. Critical Spine Acceleration (g)	60	60	60	50	40
2. Critical Chest Deflection (mm)	76 (3.0 in)	62 (2.5 in)	47 (1.9 in)	42 (1.7 in)	37** (1.5 in)
3. Combined Thoracic Index (CTI)	1.0	1.0	1.0	1.0	1.0**
CTI Intercept Values					
Accel. (g's)	85	85	85	70	55
Deflection (mm)*	102 (4.0 in)	83 (3.3 in)	63 (2.5 in)	57 (2.2 in)	49 (2.0 in)
Lower Ext. Criteria					
Femur Load (kN)	10.0	6.8	NA	NA	NA

* Critical chest deflections are used to define the linear threshold for the Combined Thoracic Index given a theoretical condition of zero chest acceleration. The anthropomorphic dummies are not capable of measuring chest deflections to this extreme level.

** The CRABI 12 month old dummy is not currently capable of measuring chest deflection.

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We would also like to acknowledge the efforts of NHTSA's National Center for Statistics and Analysis, who maintain the National Automotive Sampling System, Fatality Analysis Reporting System, and Special Crash Investigations Program. These databases provided critical information by which to assess the real world occurrence of injuries and fatalities. Injury risk curves presented in the report were verified using these data.

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Appendix A

Application of Proposed Nij Neck Injury Criteria to Available NHTSA Test Data

Calculations of Nij were made for a wide variety of test data available in the NHTSA database. Analyses were conducted for data from NCAP tests for both drivers and passengers, FMVSS 208 30 mph rigid barrier crash tests with 1998 vehicles, 25 mph offset tests with 5th percentile female drivers and passengers, 30 mph rigid barrier tests with 5% female drivers, and out-of-position tests for 3 year old, 6 year old, and 5th percentile female dummies. Results from these tests are presented in tabular format in Appendix C.

The following graphs compare the Nij combined neck injury criteria and current FMVSS 208 alternative sled test criteria for the different types of data analyzed. Two points are plotted for each test, corresponding to each set of injury criteria. The point corresponding to the Nij criteria, labeled with a ▲, is located at the values of axial load (F_Z) and flexion/extension bending moment (M_Y) which yield the maximum value for Nij. It is important to realize that these values for F_Z and M_Y are concurrent in time and are not necessarily equal to the maxima during the entire event. The point corresponding to the current FMVSS 208 criteria, labeled with a ●, is located at the overall maximum values of axial load and bending moment. The two values that determine this point are independent of time, and do not necessarily occur at the same time. It is also important to notice that shear load is not included on this plot.

Since the FMVSS 208 point always represents the overall maxima while the Nij point does not, it is impossible for the Nij point to be located further from the origin than the 208 point. To help identify the matched sets of points, they have been joined together by a line. If the line segment is short, and the points lie essentially on top of one another, it implies that the Nij maximum value occurs close to the same time as the independent maxima. If the line segment is long, this indicates that the Nij maximum occurs at a much different time than the independent maxima.

The thick solid rectangle in Figure 3-2 represents the current FMVSS No. 208 alternate sled test neck injury criteria for axial load and bending moment. The figure legend indicates this criteria as the "Current Independent Corridor" for the 50th percentile male and as "Scaled Independent Corridor" for the other sized dummies. The solid "kite" shape represents the Nij = 1.0 criteria, corresponding to a 15% risk of an AIS$\geq$3 injury. An Nij = 1.4 criteria is also shown in this plot, corresponding to a 30% risk of injury. The vertices for each region shown on the plot are scaled for each different dummy size. Data points lying within either the box or kite are considered to pass the corresponding criteria.

Results from out-of-position tests with the child dummies are presented for an air bag system in which propellant was removed from the inflator for three systems, coded B, D and I (Figures A-17 through A-28). Baseline tests were conducted with the original airbag inflator, while corresponding depowered tests were conducted using the same airbag module, but with some percentage of propellent removed from the inflator.

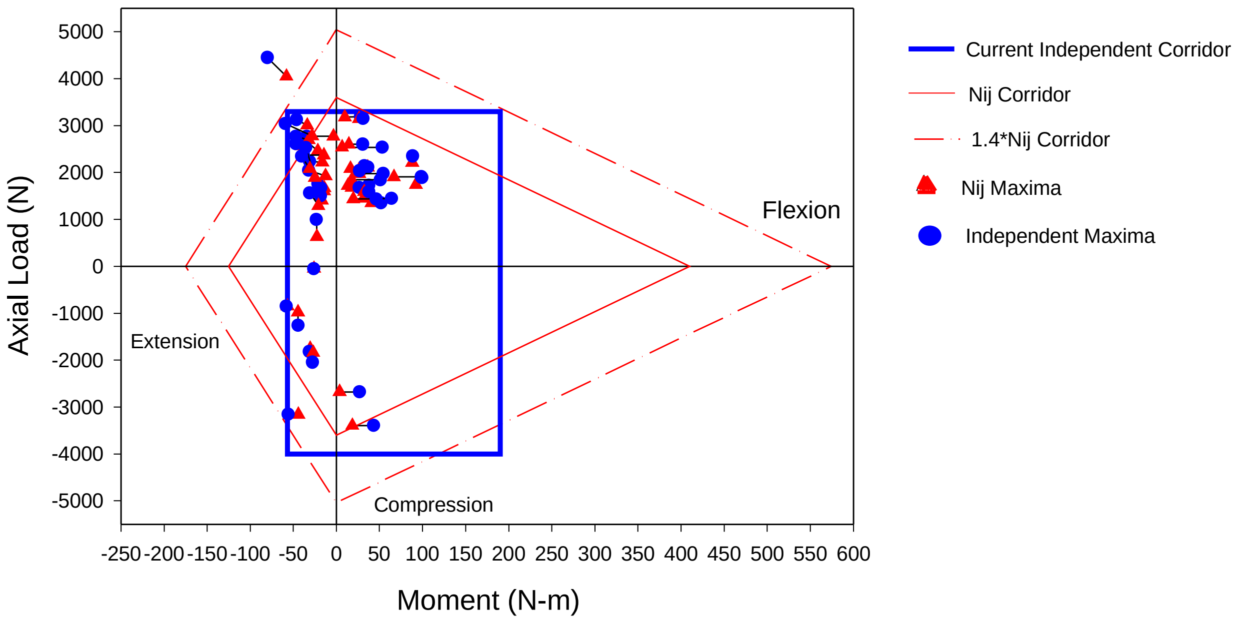

Figure A-1. Comparison of Neck Injury Criteria for 1998 NCAP Tests with ATD in Driver Position.

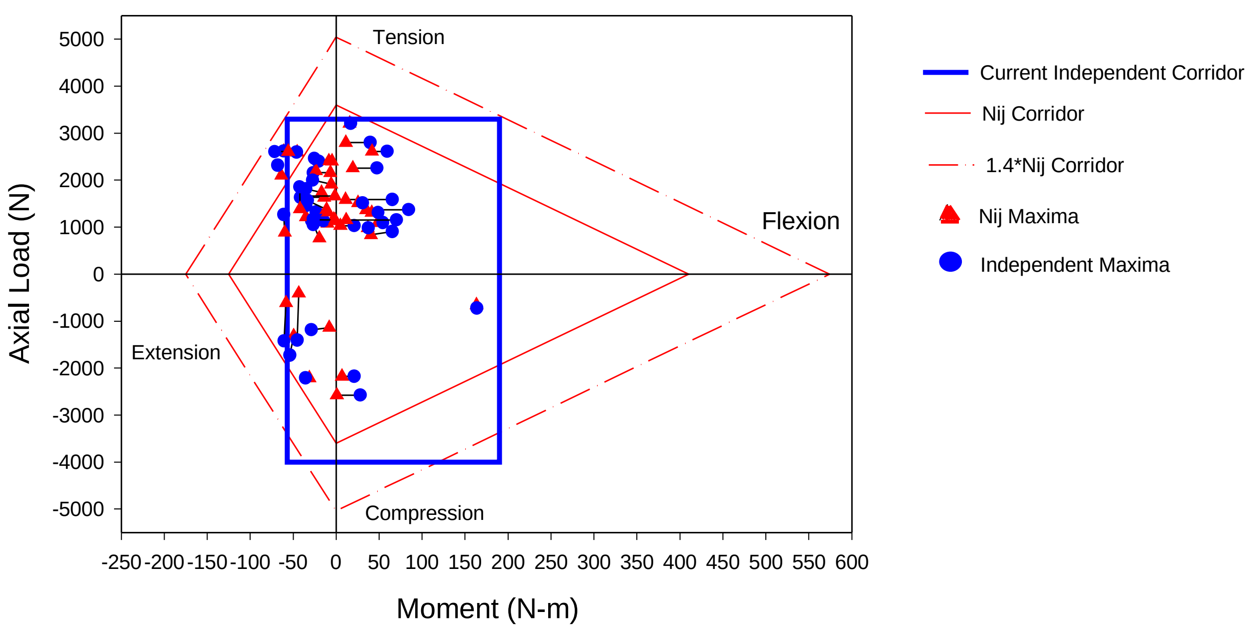

Figure A-2. Comparison of Neck Injury Criteria for 1998 NCAP Tests with ATD in the Passenger Position.

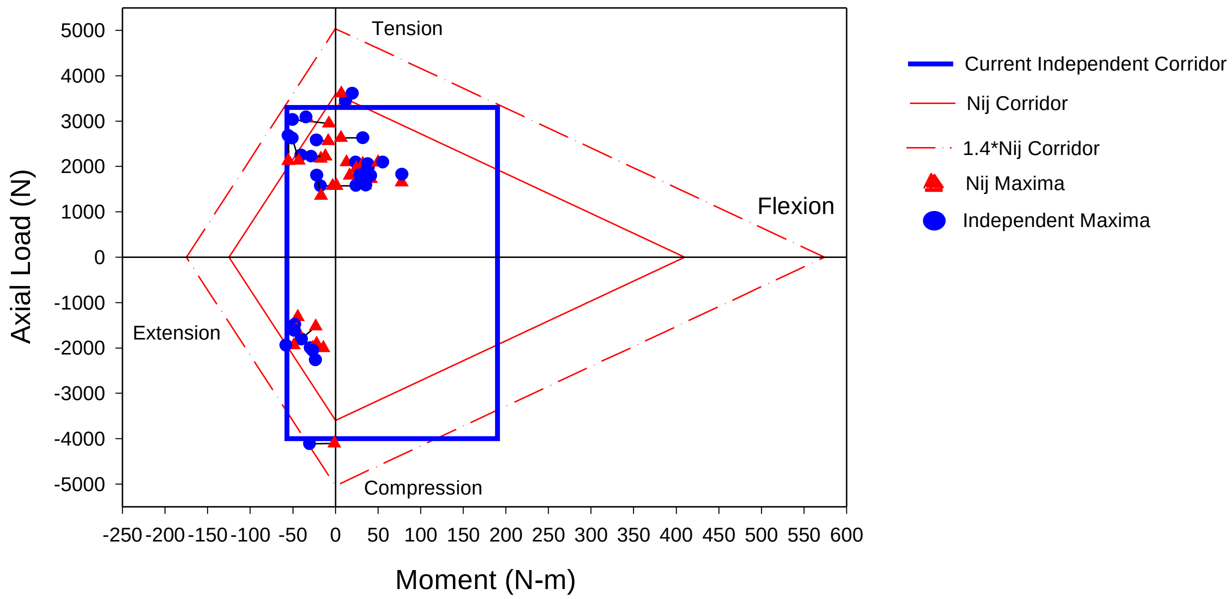

Figure A-3. Comparison of Neck Injury Criteria for 1997 NCAP Tests with ATD in the Driver Position.

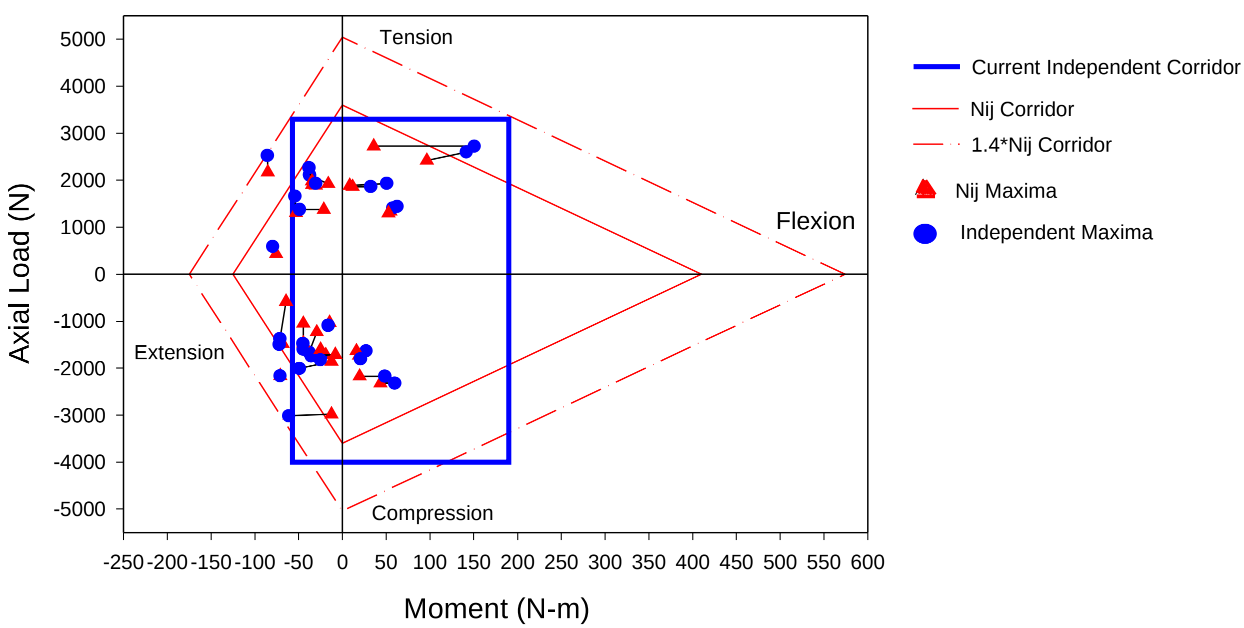

Figure A-4. Comparison of Neck Injury Criteria for 1997 NCAP Tests with ATD in Passenger Position.

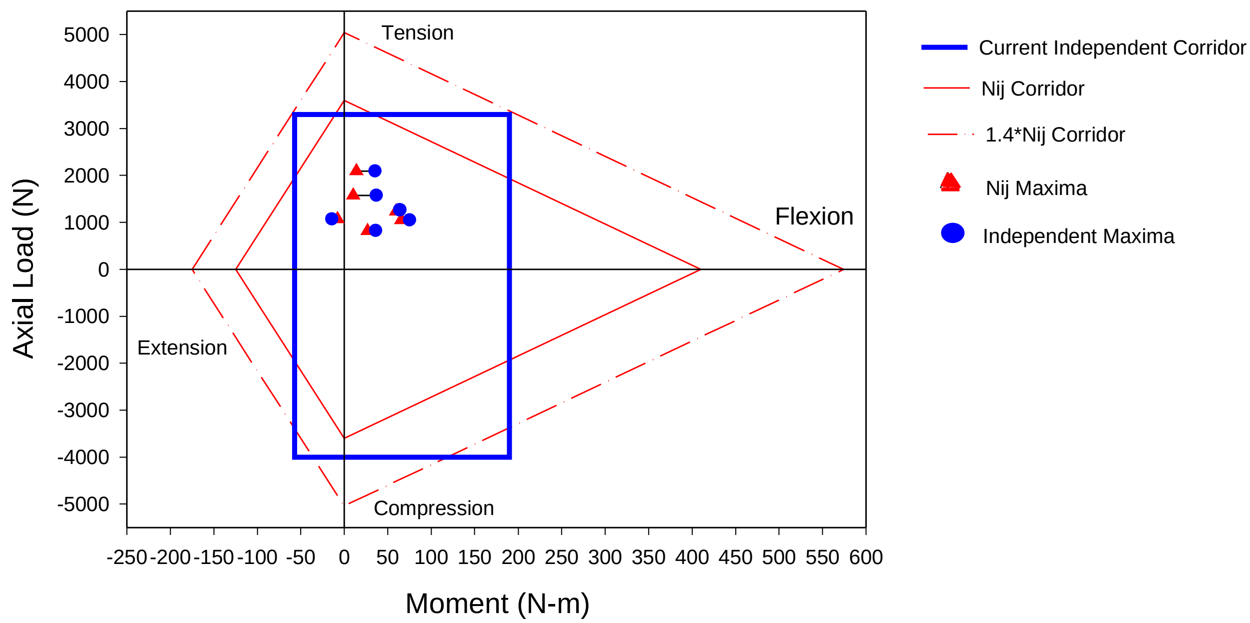

Figure A-5. Comparison of Neck Injury Criteria for 30 mph Unbelted Barrier Crash Tests for Vehicles using ATD in the Driver Position.

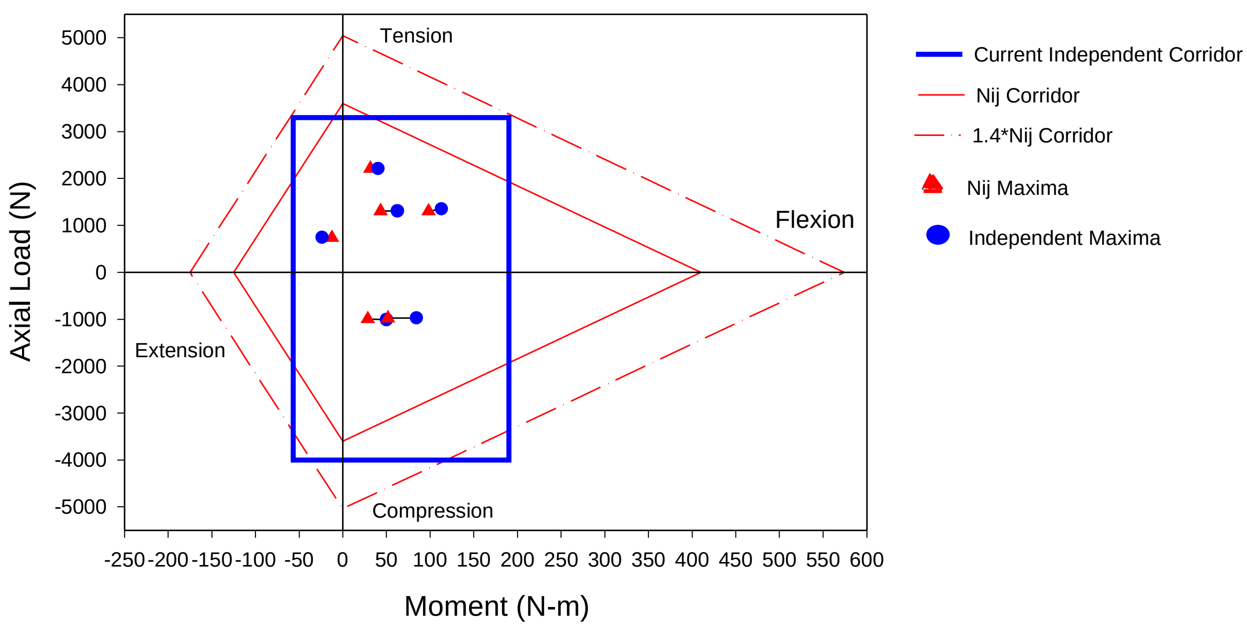

Figure A-6. Comparison of Neck Injury Criteria for 30 mph Unbelted Barrier Crash Tests for Vehicles using ATD in the Passenger Position.

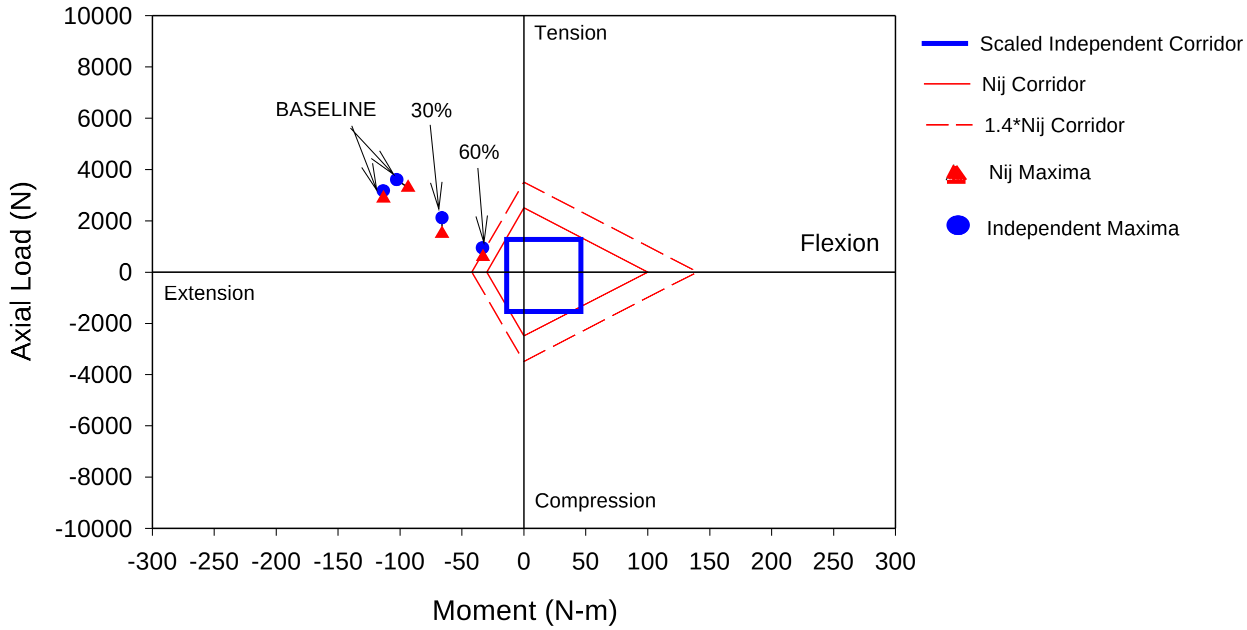

Figure A-23. Comparison of Neck Injury Criteria for Out-of-Position Tests with Hybrid III 3YO Dummy in ISO 2 Position using air bag system B, model year 1994. The labels indicate tests performed with the unmodified baseline system or with the inflator with 30 or 60 percent propellant removed.

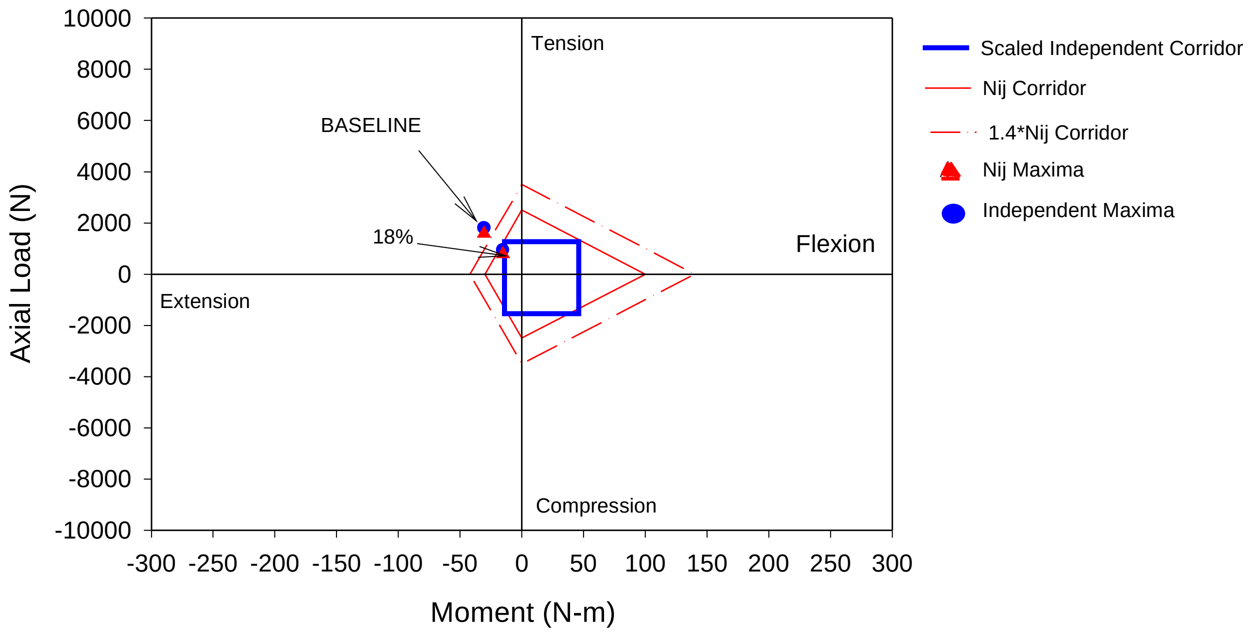

Figure A-24. Comparison of Neck Injury Criteria for Out-of-Position Tests with Hybrid III 3YO Dummy in ISO 1 Position using air bag system D, model year 1996. The labels indicate tests performed with the unmodified baseline system or with the inflator with 18 percent propellant removed.

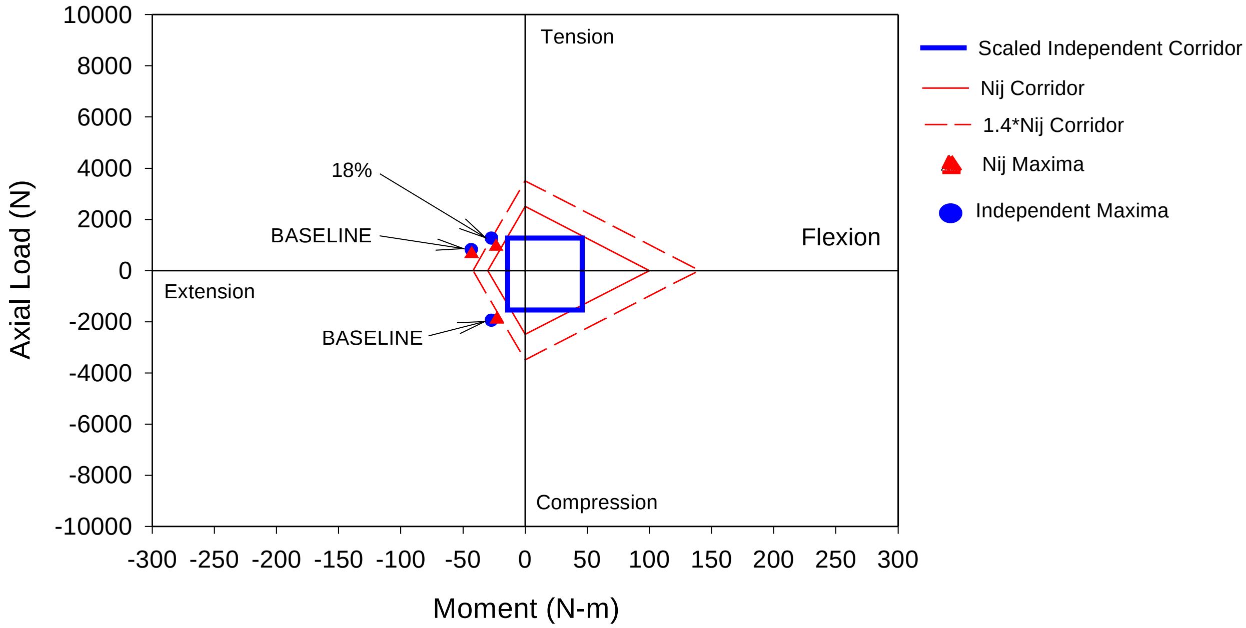

Figure A-25. Comparison of Neck Injury Criteria for Out-of-Position Tests with Hybrid III 3YO Dummy in ISO 2 Position using air bag system D, model year 1996. The labels indicate tests performed with the unmodified baseline system or with the inflator with 18 percent propellant removed.

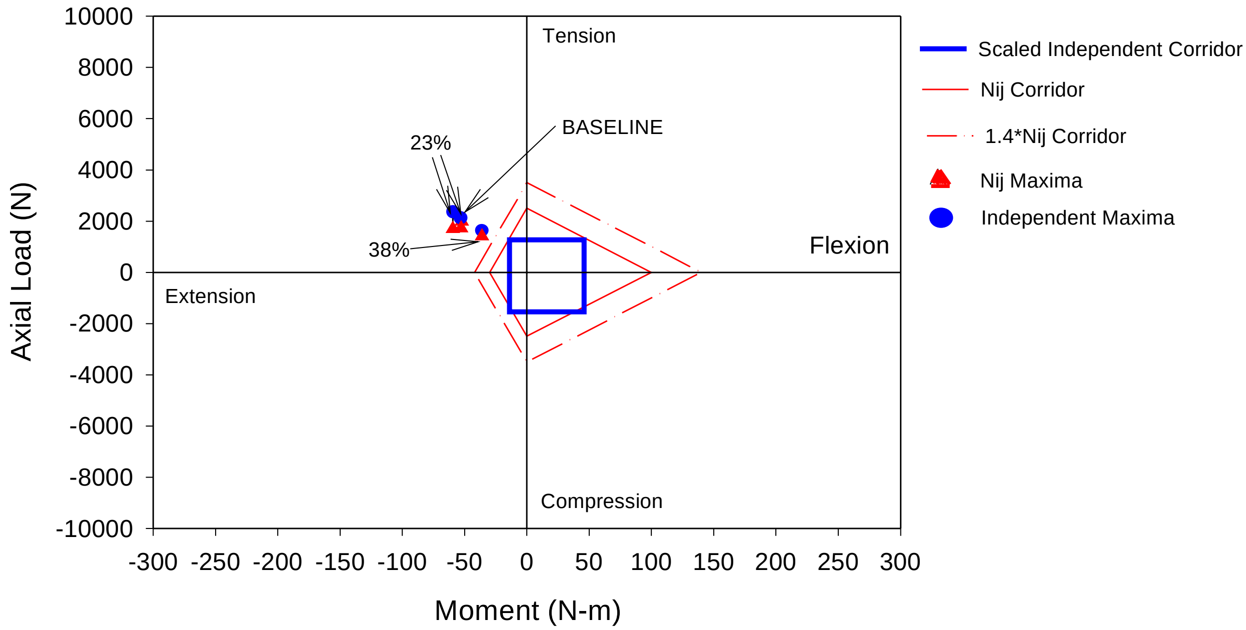

Figure A-26. Comparison of Neck Injury Criteria for Out-of-Position Tests with Hybrid III 3YO Dummy in ISO 1 Position using air bag system I, model year 1996. The labels indicate tests performed with the unmodified baseline system or with the inflator with 23 percent propellant removed.

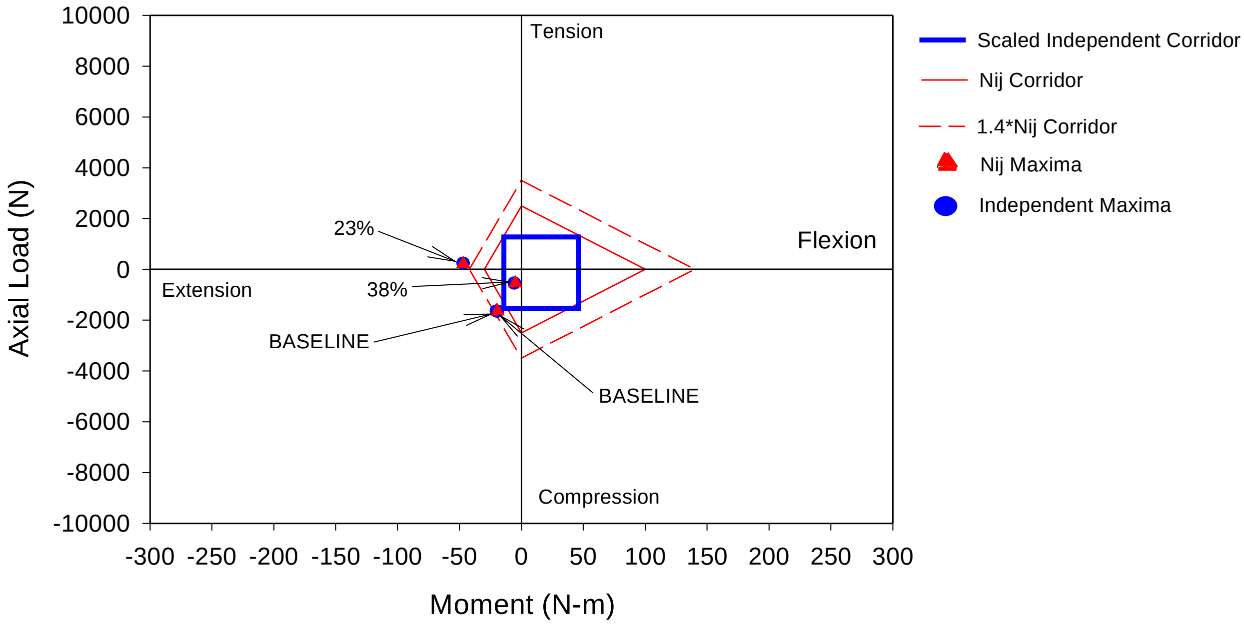

Figure A-27. Comparison of Neck Injury Criteria for Out-of-Position Tests with Hybrid III 3YO Dummy in ISO 2 Position using air bag system I, model year 1996. The labels indicate tests performed with the unmodified baseline system or with the inflator with 23 and 38 percent propellant removed.

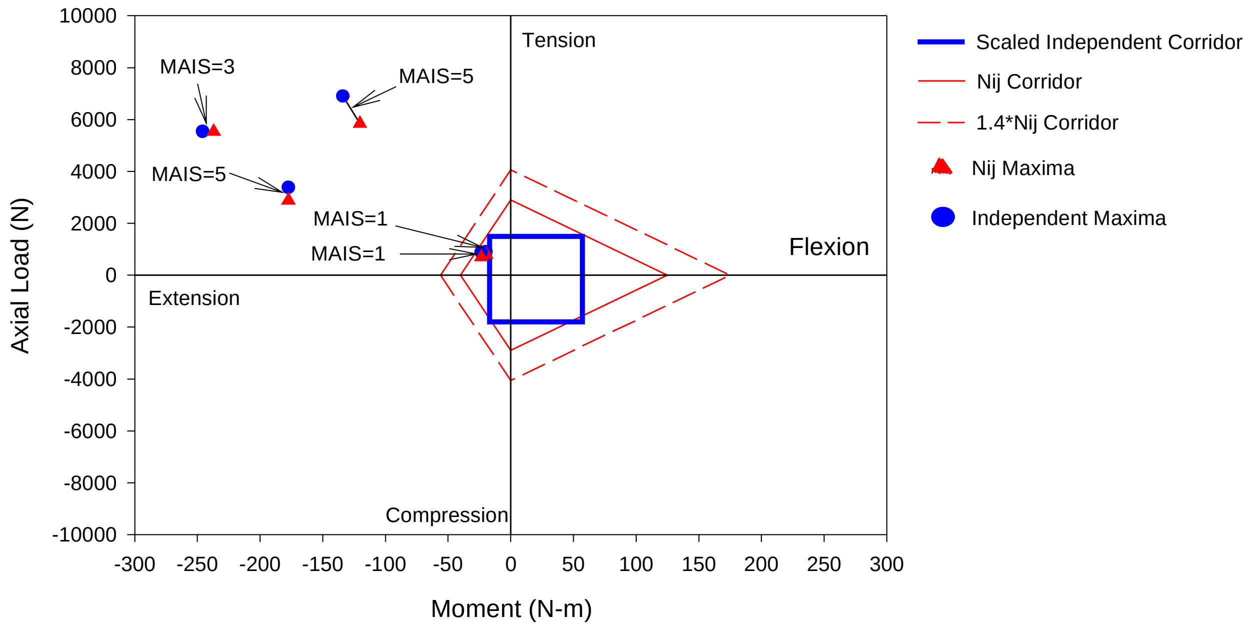

Figure A-28. Comparison of Neck Injury Criteria for Hybrid III 6YO Dummy Data from NASS and SCI Case Reconstructions.

Appendix B

Application of Proposed Thoracic Injury Criteria to Available NHTSA Test Data

The thoracic injury criteria were calculated for a wide variety of tests available in the NHTSA database. Analyses were conducted for data from 30 mph FMVSS No. 208 compliance tests, 35 mph NCAP tests, 48 kmph rigid barrier and 40 kmph offset tests with 5^{th} percentile female dummies, and out-of-position test with the 3 year-old, 6 year-old, and 5^{th} percentile female dummies. The results are presented in a tablular for in Appendix C.

In the following figures, the 3 msec clip thoracic spine acceleration and the maximum sternal chest deflection measured by the dummy are plotted on the x and y axes, respectively. A solid line represents the combination of the three proposed thoracic injury critieria. These are (1) the 3 ms clip acceleration is less than or equal to Ac, (2) the maximum chest deflection is less than or equal to Dc, and (3) the Combined Thoracic Index (CTI) is less than 1.0. A test must be below the solid line to pass the proposed thoracic injury criteria.

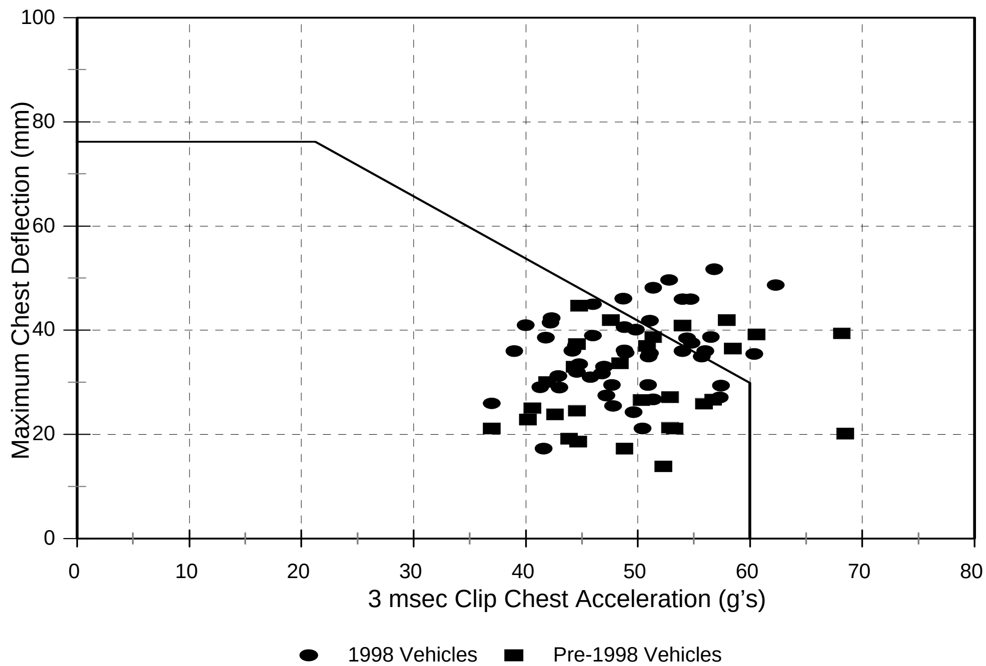

Figure B-1. 1997 and 1998 NCAP Crash Tests with the ATD in the Driver Position and Thoracic Injury Threshold Line for 50th Percentile Male Dummy. The passing rate for the dummy in the driver position is 76%.

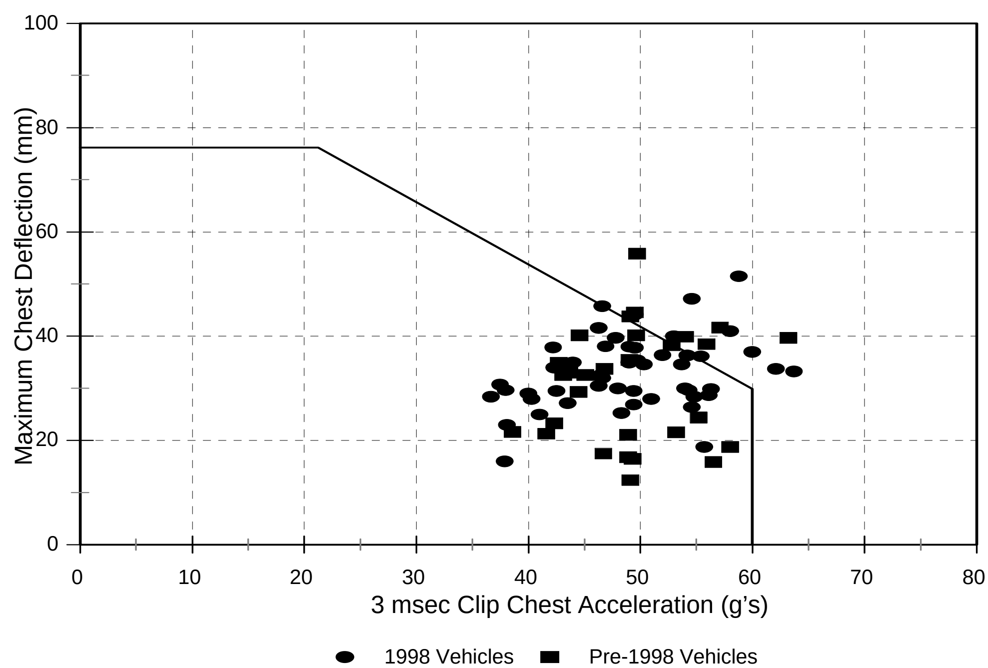

Figure B-2. 1997 and 1998 NCAP Crash Tests with the ATD in the Passenger Position and Thoracic Injury Threshold Line for 50th Percentile Male Dummy. The passing rate for the dummy in the passenger position is 80%.

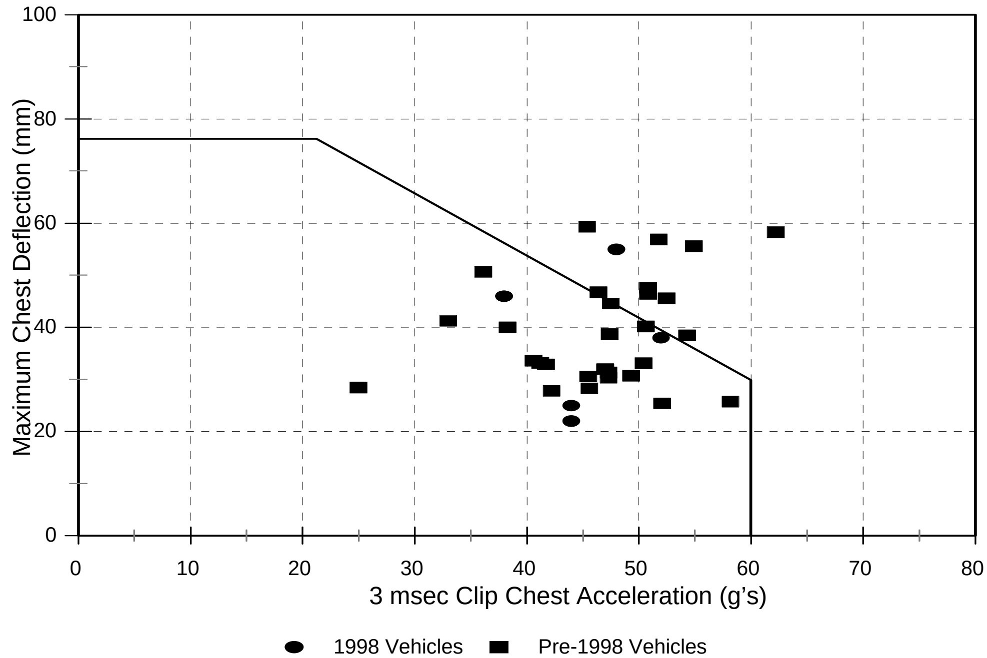

Figure B-3. 1996 - 1998 FMVSS 208 Crash Tests with the ATD in the Driver Position and Thoracic Injury Threshold Line for 50th Percentile Male Dummy. The passing rate for the dummy in the driver position is 71%.

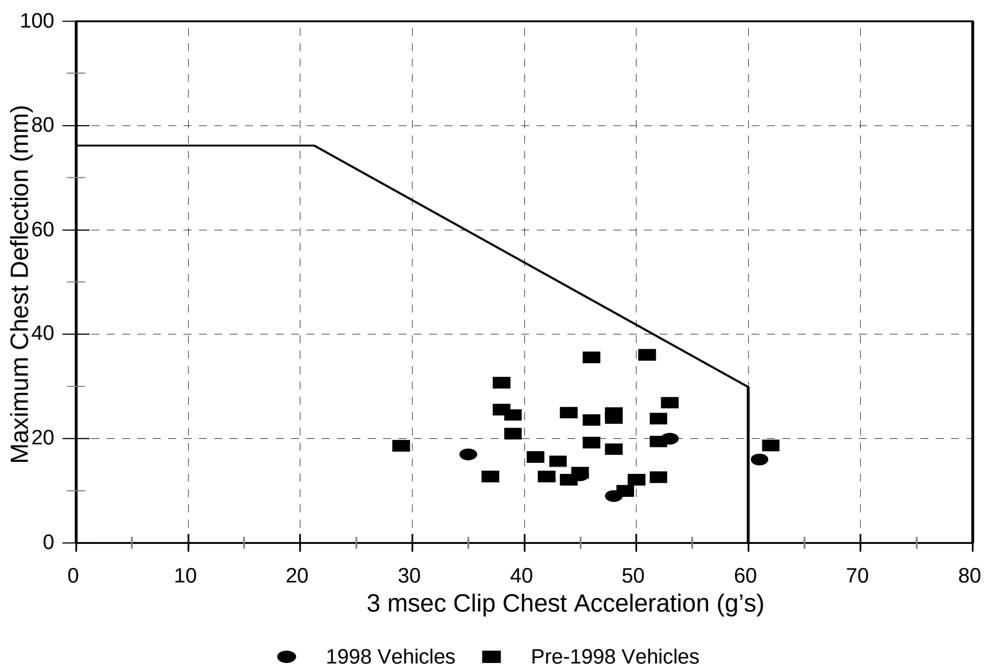

Figure B-4. 1996 -1998 FMVSS 208 Crash Tests with the ATD in the Passenger Position and Thoracic Injury Threshold Line for 50th Percentile Male Dummy. The passing rate for the dummy in the passenger position is 94%.

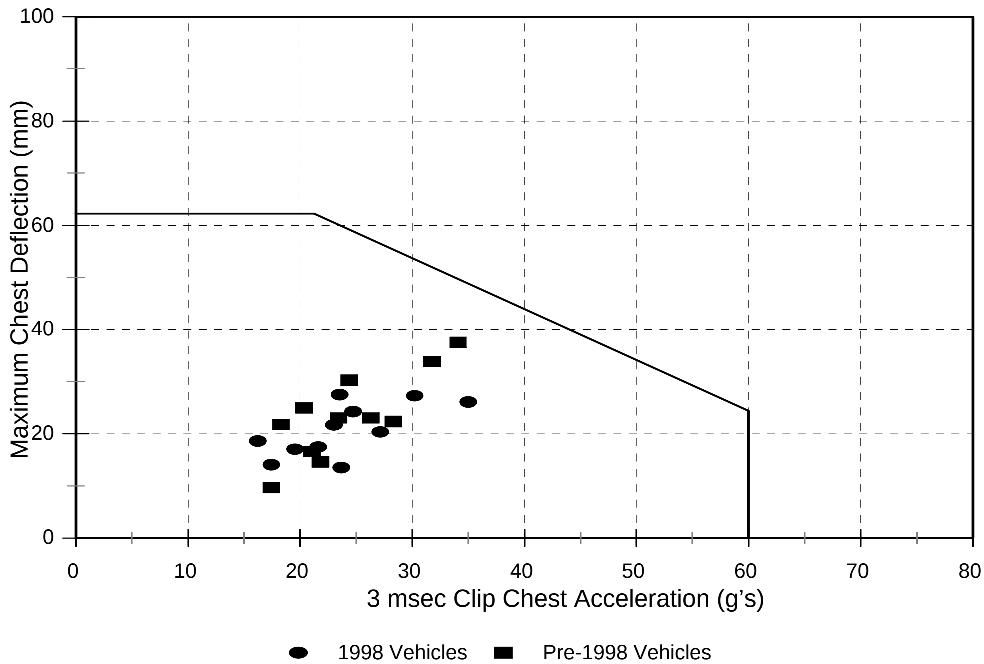

Figure B-5. 1998 and pre-1998 Vehicle Offset Crash Tests with the 5th Percentile Female Hybrid III in the Driver Position and Thoracic Injury Threshold Line for 5th Percentile Female Dummy. The passing rate for the dummy in the driver position is 100%.

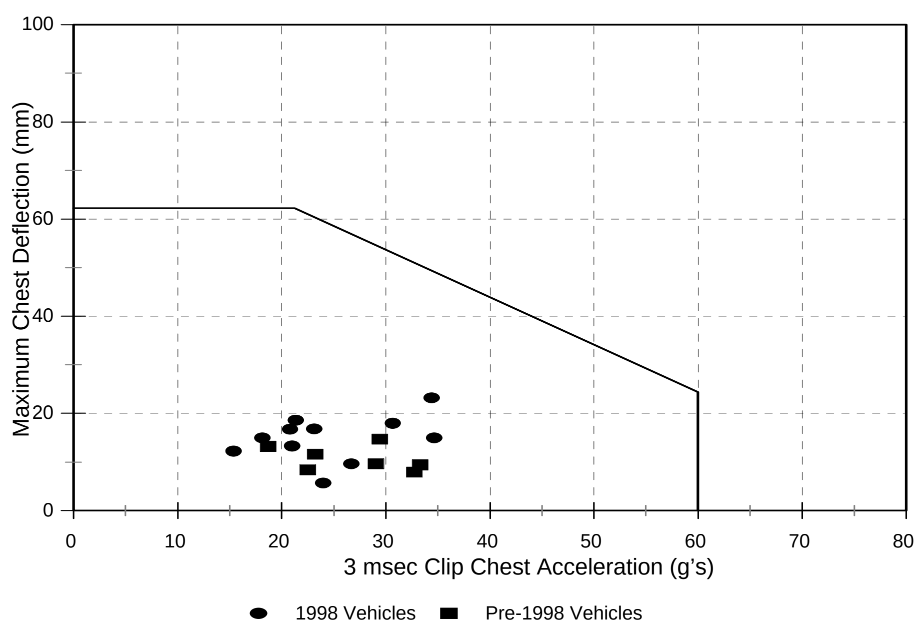

Figure B-6. 1998 and pre-1998 Vehicle Offset Crash Tests with the 5th Percentile Female Hybrid III in the Passenger Position and Thoracic Injury Threshold Line for 5th Percentile Female Dummy. The passing rate for the dummy in the driver position is 100%.

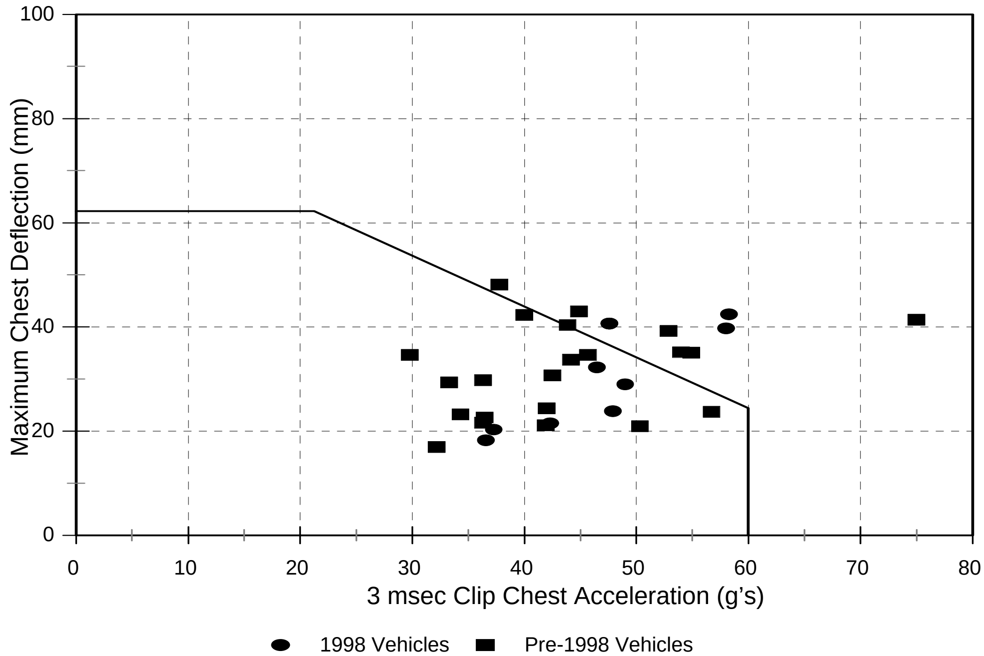

Figure B-7. 1998 and pre-1998 FMVSS208 Type Tests with the 5th Percentile Female Hybrid III Belted Driver and Thoracic Injury Threshold Line for 5th Percentile Female Dummy. The passing rate for the dummy in the driver position in these tests is 72%.

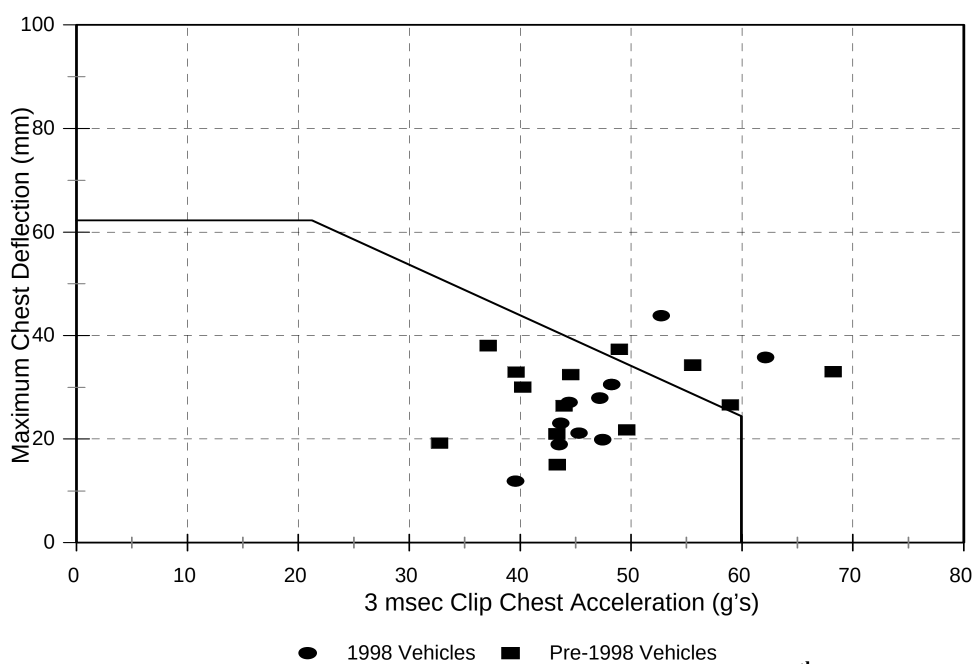

Figure B-8. 1998 and pre-1998 FMVSS208 Type Tests with the 5th Percentile Female Hybrid III Belted Passenger and Thoracic Injury Threshold Line for 5th Percentile Female Dummy. The passing rate for the dummy in the passenger position in these tests is 71%.

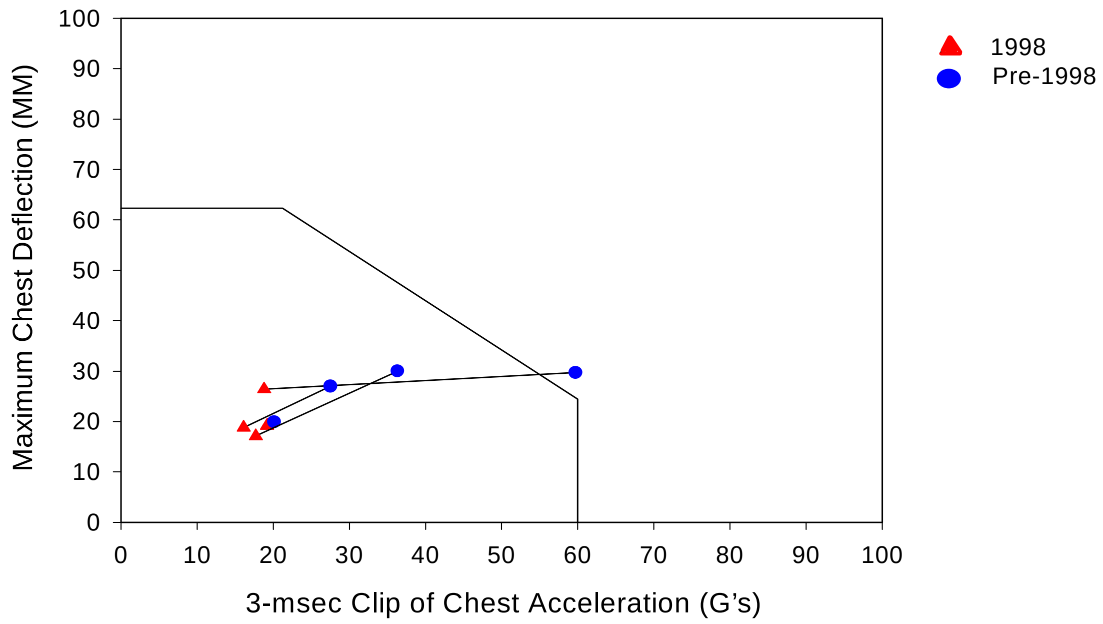

Figure B-9. 1998 and pre-1998 air bag systems with the 5th percentile female dummy in the ISO-1 position and the corresponding thoracic injury threshold lines. Tests using the same air bag module are connected by lines. Only one pre-1998 vehicle air bag fails the thoracic injury criteria.

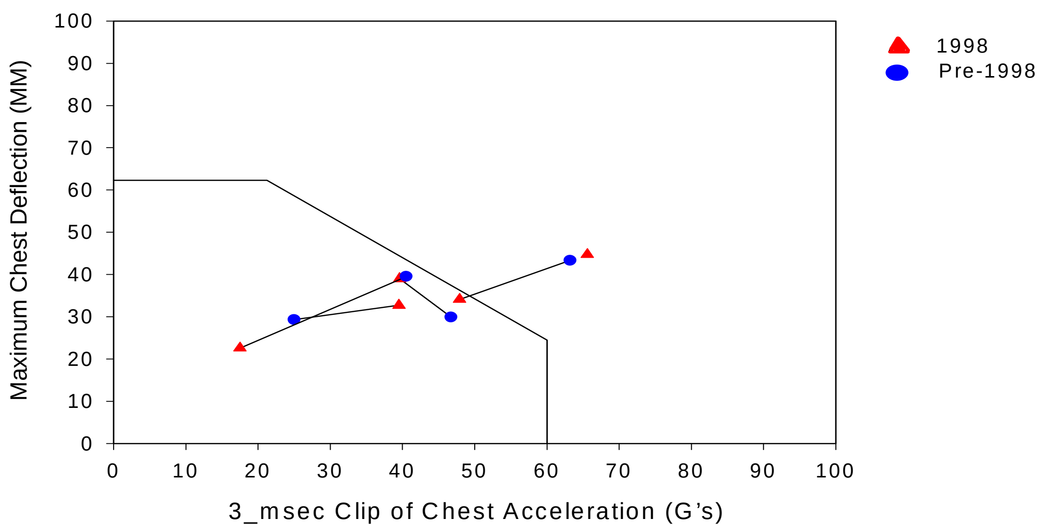

Figure B-10. 1998 and pre-1998 air bag systems with the 5th percentile female dummy in the ISO-2 position and the corresponding thoracic injury threshold lines. Tests using the same air bag module are connected by lines. Not all 1998 vehicle air bags are less aggressive than their corresponding pre-1998 vehicle air bags in the ISO-2 condition.

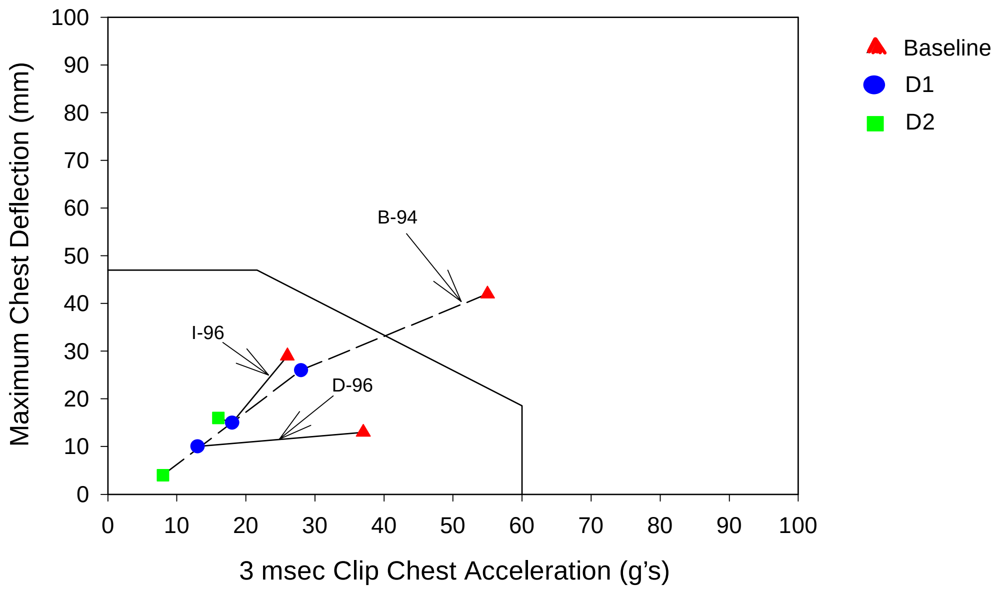

Figure B-11. ISO-1 out-of-position tests for 6 year-old dummy with baseline and propellent removed air bags (D1 and D2) and thoracic injury threshold lines for the 6 year-old dummy. Tests using the same air bag module are connected by lines. D2 has a greater percentage of propellent removed than in D1. As the propellent was removed, the aggressivity of the bag was reduced and produced lower thoracic injury values.

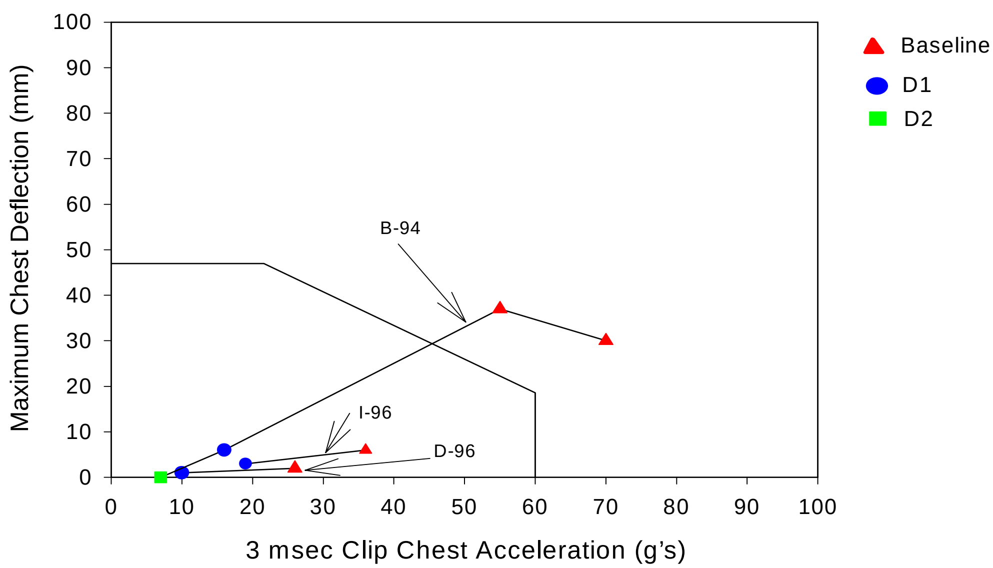

Figure B.12- ISO-2 out-of-position test data for 6-year old dummy with baseline and propellent removed air bags (D1 and D2). Tests using the same air bag module are connected by lines. The percentage of propellent removed in D2 is greater than in D1. As the propellent was removed, the aggressivity of the bag was reduced which produced lower thoracic injury values.

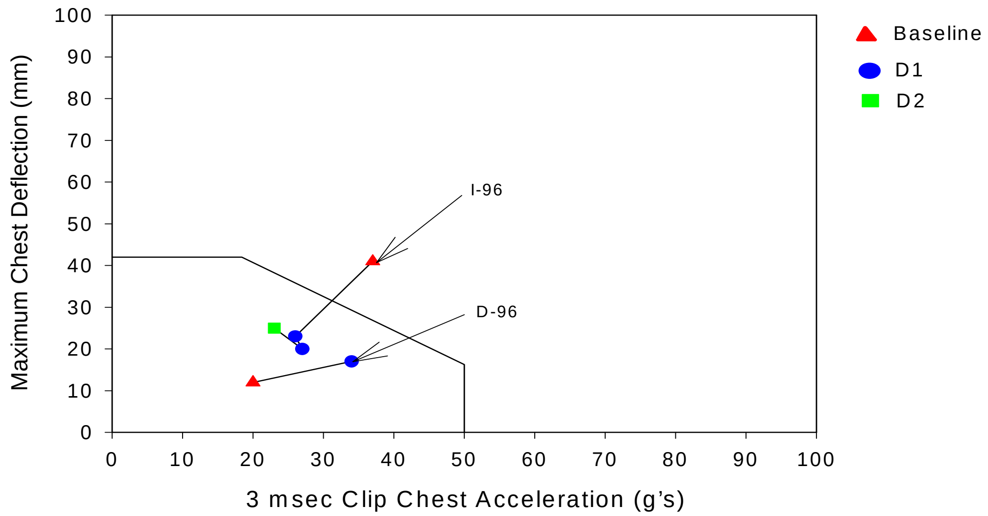

Figure B.13- ISO-1 out-of-position test data for 3-year old dummy with baseline and propellent removed air bags (D1 and D2). Tests using the same air bag module are connected by lines. The thoracic injury threshold line is for a 3 year old. The percentage of propellent removed in D2 is greater than in D1. As the propellent was removed, the aggressivity of the bag was reduced which produced lower thoracic injury values.

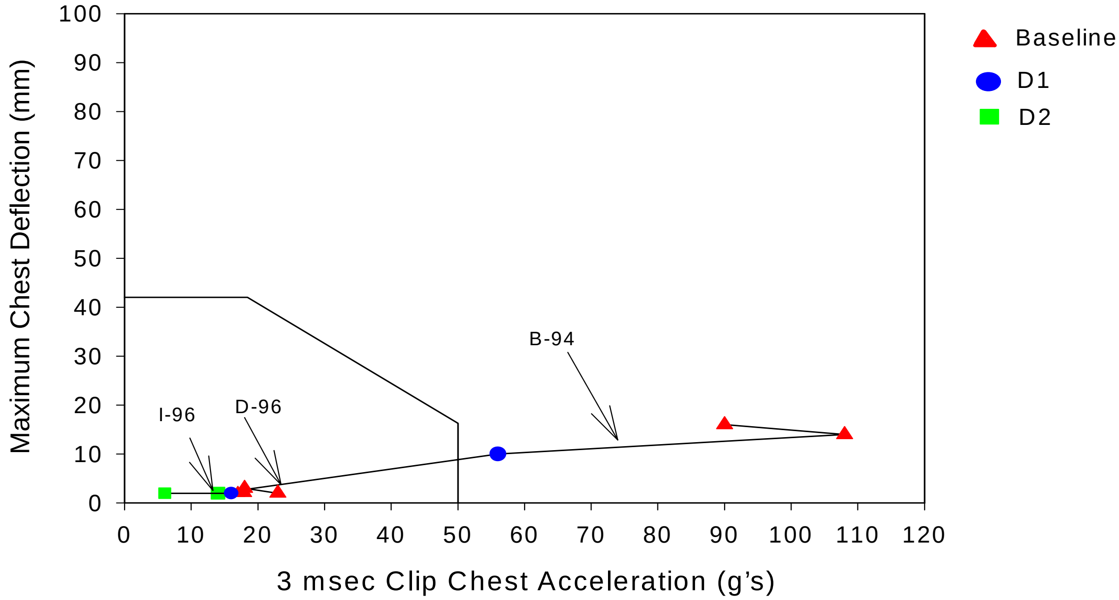

Figure B.14- ISO-2 out-of-position test data for 3-year old dummy with baseline and propellent removed air bags (D1 and D2). Tests using the same air bag module are connected by lines. CTI threshold line is for a 3 year old. The percentage of propellent removed in D2 is greater than in D1. As the propellent was removed, the aggressivity of the bag was reduced which produced lower thoracic injury values.

Appendix C

Tabulated Results from Analyses of Available NHTSA Test Data

Table C.1 **1998 NCAP TESTS - ATD IN DRIVER POSITION, 49 VEHICLE MODEL**

				DRIVER											
MAKE	MODEL	SALES VOLUME	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. S	Max Pos. S	Max Ext.	Max Flex.	Max. Com	Max Ten.	Nij
			(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			1000	60	76			1							
FORD	WINDSTAR	222,000	363	41.6	17.3	0.81	0.057	0.660	435.8	201.9	4.4	51.7	42.1	1352.1	0.48
DODGE	CARAVAN	188,000	870	52.8	49.7	2.15	0.491	1.110	351.9	225.0	47.2	3.6	535.5	2610.6	1.04
JEEP	G CHEROKEE	274,000	948	56.0	36.0	2.99	0.435	1.013	455.9	344.8	7.9	43.2	3394.1	643.1	0.99
FORD	CROWN VICTORIA	184,000	602	39.0	36.0	1.51	0.117	0.813	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SATURN	SL2	216,480	435	40.0	41.0	1.42	0.238	0.874	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SUBARU	LEGACY	85,000	525	51.0	35.0	2.12	0.295	0.944	105.1	672.5	21.6	43.3	206.8	1761.3	0.56
NISSAN	FRONTIER	53,500	1000	46.0	45.0	2.33	0.371	0.984	558.9	350.4	45.4	28.0	691.5	3192.8	0.91
DODGE	STRATUS	200,000	872	54.4	38.5	2.25	0.302	1.019	392.4	1114.0	22.0	99.5	1378.4	1889.7	0.71
DODGE	G. CARAVAN	337,000	1026	54.0	46.0	3.33	0.348	1.088	245.4	416.4	33.7	27.1	2675.6	210.9	0.75
FORD	RANGER	483,000	441	51.1	41.8	1.61	0.312	1.013	337.9	278.0	32.3	29.6	654.3	2045.4	0.64
CHEVROLET	CAVALIER (2DR	335,000	643	57.3	27.1	1.81	0.210	0.941	221.4	1052.9	18.1	64.1	84.7	1671.1	0.58
CHEVROLET	CAVALIER (4DR	175,000	514	54.0	36.0	1.97	0.352	0.990	405.9	839.7	37.5	36.3	406.5	2111.7	0.68
FORD	WINDSTAR	222,000	353	37.0	26.0	1.56	0.128	0.691	397.2	619.3	23.1	54.4	241.2	993.3	0.36
FORD	CONTOUR	206,000	514	42.2	41.5	2.79	0.431	0.905	338.8	316.1	11.1	54.5	178.9	1974.3	0.61
DODGE	NEON	207,000	655	56.5	38.7	2.18	0.221	1.046	252.9	978.6	19.2	98.4	404.7	1904.9	0.69
TOYOTA	CAMRY	350,000	525	45.8	31.0	1.44	0.174	0.844	271.9	606.3	44.6	14.3	1258.7	76.6	0.63
HONDA	ACCORD	512,000	631	48.9	35.7	1.56	0.217	0.927	357.6	444.0	31.6	10.6	1820.3	107.3	0.73
CHEVROLET	MALIBU	253,000	691	41.8	38.6	2.33	0.337	0.872	1013.2	333.5	58.3	43.8	848.8	1350.0	0.69
TOYOTA	COROLLA	268,400	722	44.5	37.1	1.67	0.185	0.889	393.5	863.1	35.1	88.4	958.6	2349.5	0.83
HONDA	CIVIC	146,000	620	49.8	40.1	1.90	0.217	0.981	334.8	353.8	23.0	32.4	1157.4	2140.7	0.62
TOYOTA	AVALON	66,600	513	50.4	21.2	0.84	0.072	0.802	649.9	222.3	12.3	27.0	291.7	2034.7	0.63
CHEVROLET	LUMINA	217,000	679	47.8	25.5	1.07	0.128	0.813	127.1	439.9	26.1	14.0	175.7	2362.2	0.87
TOYOTA	4RUNNER	130,500	760	56.8	51.7	2.21	0.398	1.177	751.4	158.2	56.1	62.7	3156.2	3749.5	1.23
FORD	F150 PICKUP	480,000	497	42.3	42.3	1.81	0.254	0.914	345.3	438.3	34.4	39.5	1113.0	2770.5	0.80
FORD	TAURUS	425,000	577	48.8	36.2	1.88	0.272	0.930	533.4	415.8	28.2	31.0	370.1	3148.4	0.94
FORD	EXPLORER	419,000	567	55.7	35.0	2.09	0.261	1.000	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CHEVROLET	VENTURE	151,564	538	43.0	29.0	1.48	0.166	0.791	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CHEVROLET	S-10	113,289	634	54.7	46.0	2.21	0.381	1.096	720.6	774.5	36.1	57.6	714.4	2686.7	0.86
TOYOTA	SIENNA	65,850	468	42.9	31.2	1.45	0.138	0.812	537.2	568.0	27.0	63.9	222.1	1446.8	0.48
BUICK	CENTURY	204,509	887	46.8	31.7	1.80	0.20	0.863	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FORD	ESCORT	337,000	681	54.8	37.6	1.73	0.14	1.015	788.9	113.2	31.2	38.6	85.2	2238.2	0.75
NISSAN	ALTIMA	187,000	887	51.1	35.6	1.84	0.15	0.952	378.4	632.7	27.8	19.4	2048.1	199.9	0.73
CHEVROLET	S10 BLAZER	264,294	675	51.4	26.8	1.90	0.23	0.868	810.8	282.8	47.0	50.8	235.8	2769.5	1.01
ISUZU	RODEO	100,000	676	60.4	35.5	2.61	0.34	1.060	609.3	516.4	31.6	53.1	964.2	2536.3	0.72
TOYOTA	TACOMA	61,000	731	51.4	48.2	2.53	0.32	1.079	912.5	152.6	46.4	30.6	1268.5	3124.5	1.11
CHEVROLET	SUBURBAN	115,339	595	44.2	36.1	1.70	0.20	0.875	347.0	220.9	31.5	30.4	499.5	2601.1	0.76
NISSAN	SENTRA	138,000	898	48.8	40.6	1.87	0.20	0.974	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DODGE	DURANGO	118,000	997	62.3	48.7	2.94	0.69	1.212	848.4	567.3	80.0	13.6	763.2	4448.1	1.59
LEXUS	ES300	42,800	512	49.6	24.3	1.22	0.13	0.823	697.1	313.8	9.0	46.1	129.4	1435.2	0.45
NISSAN	MAXIMA	132,000	570	47.7	29.5	1.78	0.15	0.852	248.8	338.5	18.4	29.8	156.5	1502.3	0.53
CHEVROLET	CAMARO	93,080	469	44.6	32.0	1.70	0.14	0.840	132.4	758.6	38.3	26.4	347.3	2372.2	0.78
DODGE	RAM1500	269,280	691	47.2	27.5	2.05	0.15	0.826	415.8	515.8	35.4	3.3	755.9	2528.1	0.73
DODGE	DAKOTA	158,000	550	50.9	29.5	1.73	0.24	0.889	352.7	549.9	59.2	36.9	963.3	3040.4	1.00
HONDA	CRV	72,200	453	57.4	29.4	1.16	0.14	0.965	183.6	679.8	40.5	67.1	375.5	2341.7	0.82
TOYOTA	RAV4	55,500	434	48.7	46.1	2.35	0.46	1.027	518.1	485.9	30.9	48.6	270.9	1564.3	0.53
FORD	MUSTANG	11,800	435	41.3	29.1	1.24	0.13	0.772	227.9	389.0	15.0	37.8	513.3	1728.5	0.51
FORD	EXPEDITION	289,000	544	44.8	33.5	1.86	0.25	0.857	559.4	248.6	24.2	51.0	392.1	1843.2	0.56
VOLVO	S70	30,746	259	46.0	39.0	2.22	0.314	0.925	530.1	265.5	10.6	26.6	86.8	1679.1	0.51
OLDS	INTRIGUE	114,119	589	47.0	33.0	1.68	0.180	0.878	287.4	212.2	7.9	37.6	236.4	1588.3	0.52

Table C.2 **ATD IN DRIVER POSITION, 29 VEHICLE MODELS**

				DRIVER											
MAKE	**MODEL**	**LES VOLU**	**HIC_36**	**ACCEL.**	**CHEST DEFL.**	**VEL.**	**V*C**	**CTI**	**Max Neg. S**	**Max Pos. S**	**Max Ext.**	**Max Flex.**	**Max. Com**	**Max Ten.**	**Nij**
			(g's)	**(g's)**	**(mm)**	**(m/s)**	**(m/s)**		**(N)**	**(N)**	**(NM)**	**(NM)**	**(N)**	**(N)**	
Standard/Proposed Standard			**1000**	**60**	**76**			**1**							
FORD	F150 PICKUP	296,000	548	53.3	21.2	0.99	0.055	0.836	138.1	332.9	44.9	23.8	959.2	2095.8	0.61
PONTIAC	GRAND PRIX	144,000	719	52.9	21.3	1.07	0.087	0.832	366.1	369.3	16.9	38.0	227.7	2058.0	0.65
JEEP	WRANGLER	117,498	566	42.6	23.9	1.56	0.171	0.736	409.8	256.4	55.4	11.9	130.8	2680.6	1.03
PONTIAC	GRAND AM	102,500	626	44.7	18.6	1.27	0.081	0.709	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MITSUBISHI	GALANT	63,200	526	54.0	40.9	1.95	0.283	1.038	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FORD	ESCORT	465,000	959	57.9	42.0	2.30	0.266	1.095	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CADILLAC	DE VILLE	104,000	656	44.6	37.4	1.65	0.222	0.893	134.9	534.8	23.5	23.1	2263.5	507.1	0.71
CHEVROLET	S-10	117,120	955	52.9	27.2	1.57	0.157	0.890	864.4	575.3	30.5	46.7	4114.0	1270.4	1.15
HONDA	ACCORD	355,450	447	50.8	37.0	1.70	0.150	0.962	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FORD	CLUBWAGON	117,000	932	47.6	42.0	2.11	0.324	0.973	602.4	336.0	41.5	41.4	703.1	1794.9	0.58
CHEVROLET	BLAZER	364224	595	56.7	26.7	1.48	0.183	0.930	644.6	1029.2	79.6	37.4	1189.0	3185.9	1.34
VOLVO	960	9,182	511	44.6	24.6	1.26	0.096	0.767	517.0	305.5	27.4	35.7	789.5	1582.4	0.52
FORD	EXPEDITION	171,000	369	41.9	30.1	1.40	0.140	0.789	341.1	740.0	29.5	29.2	1998.9	685.5	0.67
PONTIAC	GRAND AM	212,500	517	40.6	25.1	1.07	0.090	0.725	348.9	746.9	17.5	27.1	174.8	1573.3	0.46
TOYOTA	RAV4	473,000	919	51.4	38.7	3.58	0.507	0.986	474.2	165.1	22.4	27.4	784.6	2579.7	0.78
HYUNDAI	ACCENT	277,000	918	58.5	36.5	2.02	0.260	1.047	506.7	344.9	39.9	20.4	1808.2	259.9	0.61
CHEVROLET	CAVALIER	469,000	646	50.3	26.6	1.47	0.140	0.854	257.2	1225.3	47.7	31.8	1485.6	425.3	0.72
CHEVROLET	MALIBU	253,000	810	44.4	33.0	2.21	0.211	0.847	423.6	1234.6	58.1	55.2	1942.2	1016.5	0.93
DODGE	PICKUP	44,000	793	48.4	33.7	1.26	0.130	0.901	318.8	665.9	26.8	37.3	2058.2	842.8	0.77
TOYOTA	CAMRY	385,300	625	68.5	20.2	1.14	0.070	1.005	643.0	335.7	10.0	78.1	91.0	1826.7	0.65
CHEVROLET	TAHOE	142,770	833	44.8	44.7	2.58	0.373	0.967	293.1	289.7	40.4	23.4	1002.2	2244.7	0.74
TOYOTA	TACOMA	42,300	1411	68.2	39.4	2.51	0.334	1.190	231.5	354.9	40.3	11.9	886.4	3453.4	0.99
CHEVROLET	K1500 PICKUP	176,649	314	37.0	21.2	1.10	0.075	0.644	581.0	469.7	9.1	38.7	212.3	1977.7	0.60
CHEVROLET	PICKUP	394,134	467	40.2	22.9	2.23	0.264	0.698	914.4	414.5	48.1	35.7	1618.2	1426.1	0.81
DODGE	DAKOTA	95,999	668	52.3	13.9	0.92	0.035	0.752	586.9	406.2	32.6	32.2	654.1	2630.1	0.75
BUICK	LESABRE	223,000	565	43.9	19.2	0.91	0.041	0.705	572.1	242.7	30.2	28.6	408.5	1812.7	0.54
CHEVROLET	VENTURE	123,000	692	48.8	17.3	0.94	0.063	0.744	330.6	339.1	50.3	13.7	710.5	3033.3	0.88
JEEP	CHEROKEE	81,649	692	60.6	39.2	3.28	0.562	1.099	124.0	714.4	34.5	18.9	389.8	3089.9	1.12
MITSUBISHI	MONTERO	8,700	641	55.9	25.9	1.29	0.088	0.913	104.2	531.6	50.6	46.1	1243.5	2623.8	0.94

Table C.3 **1998 NCAP TESTS - ATD IN PASSENGER POSITION, 49 VEHICLE MODELS**

			PASSENGER													
MAKE	MODEL	SALES VOLUME	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. S	Max Pos. S	Max Ext.	Max Flex.	Max. Com	Max Ten.	Nij
			(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			1000	60	76			1							
FORD	WINDSTAR	222,000	294	37.9	16.0	0.09	0.033	0.603	668.3	368.1	45.3	20.9	2176.6	48.8	0.62
DODGE	CARAVAN	188,000	788	53.0	40.0	1.52	0.309	1.017	288.4	672.3	18.3	65.5	821.5	1584.5	0.47
JEEP	G CHEROKEE	274,000	546	58.0	41.0	5.18	0.257	1.086	187.5	775.2	53.9	11.8	1726.6	701.3	0.76
FORD	CROWN VICTORIA	184,000	335	40.0	29.0	2.16	0.102	0.756	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SATURN	SL2	216,480	585	44.0	35.0	1.47	0.215	0.862	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SUBARU	LEGACY	85,000	623	49.0	38.0	2.28	0.299	0.950	196.5	503.5	41.6	31.3	1332.6	1632.4	0.57
NISSAN	FRONTIER	53,500	521	54.0	30.0	2.14	0.245	0.931	585.0	1456.5	28.0	163.7	723.6	1188.4	0.58
DODGE	STRATUS	200,000	641	53.7	34.6	1.71	0.191	0.972	570.6	286.5	20.5	19.4	1181.9	2401.3	0.71
DODGE	G. CARAVAN	337,000	994	60.0	37.0	1.82	0.169	1.070	341.1	541.8	35.7	17.8	2209.6	536.8	0.86
FORD	RANGER	483,000	545	42.5	29.5	1.33	0.144	0.790	611.0	617.3	31.1	54.4	778.7	1095.7	0.42
CHEVROLET	CAVALIER 2DR	335,000	620	46.5	32.6	1.35	0.141	0.868	414.4	402.1	28.3	26.9	181.1	1137.4	0.38
CHEVROLET	CAVALIER 4DR	175,000	751	47.8	39.7	2.12	0.281	0.953	438.8	692.8	26.5	35.9	443.2	1054.3	0.37
FORD	WINDSTAR	222,000	470	38.0	29.7	2.28	0.254	0.739	451.4	27.0	35.2	26.3	82.2	1453.8	0.62
FORD	CONTOUR	206,000	617	49.4	29.5	2.00	0.193	0.872	325.6	666.5	10.7	84.5	64.9	1367.5	0.47
DODGE	NEON	207,000	533	50.3	34.6	2.48	0.309	0.932	534.6	305.5	21.7	25.8	140.3	2405.6	0.74
TOYOTA	CAMRY	350,000	488	37.5	30.7	1.10	0.142	0.743	324.3	217.2	28.9	15.9	1182.4	256.2	0.38
HONDA	ACCORD	512,000	596	52.0	36.4	1.57	0.196	0.970	553.5	81.7	45.3	30.0	1406.8	243.2	0.46
CHEVROLET	MALIBU	253,000	473	49.7	35.4	2.09	0.280	0.933	549.1	447.9	21.9	30.8	214.4	1516.7	0.48
TOYOTA	COROLLA	268,400	566	46.6	32.0	1.40	0.198	0.863	315.0	433.1	26.6	40.3	478.1	1167.9	0.35
HONDA	CIVIC	146,000	531	54.8	28.4	1.35	0.131	0.924	1138.3	172.0	21.4	65.3	524.3	902.3	0.33
TOYOTA	AVALON	66,600	577	36.7	28.4	1.04	0.115	0.711	174.0	427.2	14.7	25.5	242.6	1133.3	0.35
CHEVROLET	LUMINA	217,000	495	40.3	28.0	1.41	0.119	0.750	671.0	324.4	9.7	37.5	221.8	982.6	0.36
TOYOTA	4RUNNER	130,500	743	58.8	51.5	2.55	0.439	1.199	543.6	324.1	25.8	39.7	407.8	2797.9	0.80
FORD	F150 PICKUP	480,000	615	46.3	41.6	1.71	0.239	0.954	480.3	425.9	26.6	26.9	1047.6	2156.3	0.65
FORD	TAURUS	425,000	486	51.0	28.0	1.54	0.178	0.876	873.0	465.5	19.3	48.8	1049.0	1307.9	0.46
FORD	EXPLORER	419,000	558	54.6	26.4	1.41	0.102	0.902	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CHEVROLET	VENTURE	151,564	962	48.0	30.0	2.44	0.264	0.860	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CHEVROLET	S-10	113,289	450	56.1	28.7	2.48	0.269	0.942	999.4	413.5	68.1	45.0	500.5	2315.5	1.10
TOYOTA	SIENNA	65,850	395	42.3	34.0	1.62	0.152	0.832	769.8	103.1	61.0	36.2	89.4	1266.2	0.73
BUICK	CENTURY	204,509	1325	56.3	29.9	1.57	0.17	0.957	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FORD	ESCORT	337,000	532	63.7	33.3	1.46	0.17	1.077	321.1	670.7	9.7	17.0	1331.2	3206.2	0.93
NISSAN	ALTIMA	187,000	1119	55.4	36.2	2.04	0.13	1.008	646.7	207.3	10.1	28.1	2575.3	447.5	0.72
CHEVROLET	S10 BLAZER	264,294	503	55.7	18.8	1.50	0.10	0.840	786.7	478.9	28.8	47.6	442.6	2256.9	0.67
ISUZU	RODEO	100,000	631	54.2	36.3	3.16	0.41	0.995	315.1	590.4	60.8	50.1	1425.3	1597.8	0.64
TOYOTA	TACOMA	61,000	683	54.6	47.2	2.25	0.29	1.107	446.8	308.8	33.2	59.3	774.7	2610.5	0.83
CHEVROLET	SUBURBAN	115,339	589	46.6	45.8	1.99	0.31	0.999	983.8	33.6	61.0	56.9	388.5	2620.3	1.21
NISSAN	SENTRA	138,000	797	49.5	44.2	1.90	0.24	1.017	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DODGE	DURANGO	118,000	627	62.1	33.8	1.81	0.21	1.063	1001.6	232.7	45.9	57.5	631.8	2594.7	1.08
LEXUS	ES300	42,800	479	48.3	25.3	1.40	0.16	0.817	528.7	121.4	15.3	21.1	420.2	1028.6	0.30
NISSAN	MAXIMA	132,000	647	54.3	29.7	1.76	0.17	0.931	236.4	682.2	25.4	13.3	459.5	2459.5	0.80
CHEVROLET	CAMARO	93,080	328	38.1	23.0	1.13	0.07	0.675	214.2	772.7	27.4	65.3	436.5	1999.7	0.58
DODGE	RAM1500	269,280	330	49.4	26.9	1.57	0.10	0.846	188.3	1508.0	71.5	43.7	525.2	2608.3	1.17
DODGE	DAKOTA	158,000	563	49.5	37.8	2.73	0.27	0.954	132.7	944.0	35.0	60.2	194.7	1814.3	0.62
HONDA	CRV	72,200	438	43.5	27.2	1.69	0.15	0.779	209.0	838.9	23.3	72.4	610.7	1321.1	0.46
TOYOTA	RAV4	55,500	355	46.3	30.5	1.46	0.20	0.845	214.1	704.4	38.5	56.3	361.6	1660.8	0.47
FORD	MUSTANG	11,800	364	46.9	38.1	2.33	0.28	0.927	75.7	776.4	42.6	40.1	392.9	1855.2	0.72
FORD	EXPEDITION	289,000	569	42.2	37.9	1.92	0.25	0.870	138.2	318.3	33.3	29.8	430.9	1569.7	0.47
VOLVO	S70	30,746	294	41.0	25.0	1.76	0.116	0.728	394.6	391.6	26.5	39.6	304.8	1161.4	0.33
OLDS	INTRIGUE	114,119	1139	49.0	35.0	1.28	0.159	0.921	847.2	148.4	18.7	70.1	189.0	1153.4	0.35

Table C.4 **1997 NCAP TESTS - ATD PASSENGER POSITION, 29 VEHCILE MODELS**

			PASSENGER												
MAKE	**MODEL**	**SALES VOLUME**	**HIC_36**	**ACCEL.**	**CHEST DEFL.**	**VEL.**	**V*C**	**CTI**	**Neg. Shear**	**Max Pos. Shear**	**Max Ext.**	**Max Flex.**	**Max. Compr.**	**Max Ten.**	**Nij**
			(g's)	**(g's)**	**(mm)**	**(m/s)**	**(m/s)**		**(N)**	**(N)**	**(NM)**	**(NM)**	**(N)**	**(N)**	
Standard/Proposed Standard			**1000**	**60**	**76**			**1**							
FORD	F150 PICKUP	296,000	474	41.6	21.3	0.97	0.062	0.699	199.1	930.3	37.3	41.4	516.0	2101.2	0.66
PONTIAC	GRAND PRIX	144,000	529	49.1	12.4	0.71	0.028	0.700	N/A	N/A	N/A	N/A	N/A	N/A	N/A
JEEP	WRANGLER	117,498	487	56.5	15.9	1.34	0.062	0.821	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PONTIAC	GRAND AM	102,500	372	42.3	23.3	2.98	0.162	0.727	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MITSUBISHI	GALANT	63,200	487	49.6	40.2	2.42	0.357	0.979	643.4	887.7	72.1	15.2	1498.9	340.1	0.96
FORD	ESCORT	465,000	436	55.9	38.5	2.35	0.217	1.037	934.5	113.2	48.2	59.8	2319.6	400.2	0.75
CADILLAC	DE VILLE	104,000	552	52.8	38.3	2.21	0.158	0.998	553.3	425.7	49.1	17.0	2006.8	262.6	0.62
CHEVROLET *	S-10	117,120	1205	43.1	32.6	1.52	0.250	0.828	620.9	445.1	44.8	37.2	1602.3	1238.0	0.65
HONDA	ACCORD	355,450	713	46.8	33.8	1.50	0.230	0.883	616.3	164.4	25.0	26.2	1767.0	430.3	0.63
FORD	CLUBWAGON MP	117,000	565	49.5	44.6	2.82	0.337	1.021	153.6	859.4	37.7	42.4	230.9	2109.8	0.80
CHEVROLET *	BLAZER	364,224	1525	49.1	43.8	2.07	0.271	1.009	832.8	1604.5	43.8	98.3	2701.9	3011.4	0.97
VOLVO	960	9,182	698	53.2	21.6	1.00	0.065	0.838	292.4	253.7	29.5	27.0	1637.4	1005.8	0.49
FORD	EXPEDITION	171,000	393	42.7	34.9	2.20	0.230	0.846	617.8	67.3	48.6	20.7	1803.7	203.1	0.53
PONTIAC	GRAND AM	212,500	617	45.1	32.6	1.07	0.085	0.851	337.0	525.5	54.3	12.5	1059.5	1657.2	0.79
TOYOTA	RAV4	473,000	743	57.1	41.7	3.59	0.438	1.082	911.7	326.3	28.7	57.7	468.1	1402.1	0.51
HYUNDAI	ACCENT	277,000	252	49.0	35.5	2.80	0.310	0.926	864.0	363.0	71.5	29.9	1378.6	316.2	0.68
CHEVROLET	CAVALIER	469,000	885	44.5	29.3	1.80	0.200	0.812	473.1	922.5	38.1	26.3	1664.3	567.1	0.58
CHEVROLET	MALIBU	253,000	546	43.7	33.0	1.75	0.257	0.839	454.7	417.2	35.5	20.6	1739.1	407.4	0.54
DODGE *	PICKUP	44,000	1004	54.0	39.9	1.50	0.230	1.028	361.2	986.8	16.2	11.8	1092.5	125.3	0.40
TOYOTA	CAMRY	385,300	501	48.9	16.8	1.14	0.054	0.741	356.5	472.8	25.1	24.5	1822.9	367.1	0.65
CHEVROLET	TAHOE	142,770	545	44.6	40.2	1.88	0.233	0.920	97.4	914.7	38.1	73.0	659.9	2265.9	0.83
TOYOTA *	TACOMA	42,300	962	49.7	55.8	2.26	0.382	1.134	205.9	1742.4	66.5	150.6	1078.2	2722.9	0.84
CHEVROLET	K1500 PICKUP	176,649	381	48.9	21.1	1.60	0.164	0.783	830.4	368.1	72.6	48.4	2173.9	1104.9	0.65
CHEVROLET	PICKUP	394,134	688	38.6	21.7	0.90	0.053	0.668	753.6	581.3	49.0	39.9	1666.2	1375.7	0.55
DODGE	DAKOTA	95,999	602	58.0	18.8	1.59	0.056	0.867	1148.6	586.3	79.7	34.8	1750.8	584.7	0.73
BUICK	LESABRE	223,000	686	46.7	17.5	0.81	0.046	0.722	283.3	611.9	45.0	32.1	1477.2	398.5	0.77
CHEVROLET	VENTURE	123,000	704	49.3	16.5	2.79	0.078	0.742	415.8	851.4	71.2	30.7	2162.5	408.7	1.17
JEEP	CHEROKEE	81,649	512	63.2	39.7	2.36	0.323	1.134	382.2	500.6	30.5	39.2	530.8	1927.2	0.77
MITSUBISHI	MONTERO	8,700	679	55.2	24.4	6.90	0.705	0.890	598.9	270.7	61.4	45.9	3015.6	2112.9	0.93

* no air bag for Passenger

Table C.5 **1996-1998 FMVSS 208 TESTS - ATD IN DRIVER POSITION**

			DRIVER					
MAKE	MODEL	YEAR	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI
			(g's)	(g's)	(mm)	(m/s)	(m/s)	
Standard/Proposed Standard			**1000**	**60**	**76**			**1**
DODGE	CARAVAN	1996	447	47.5	44.6	3.4	0.570	0.998
MITSUBISHI	MIRAGE	1996	215	54.9	55.6	6.5	1.500	1.193
PONTIAC	BONNEVILLE	1996	209	41.7	32.9	1.8	0.240	0.814
LINCOLN	TOWN CAR	1996	153	41.2	33.2	1.9	0.190	0.811
HONDA	CIVIC	1996	149	50.8	47.6	2.8	0.470	1.066
HYUNDAI	ACCENT	1996	346	50.6	40.2	3.0	0.480	0.991
HYUNDAI	SONATA	1996	292	62.2	58.3	3.1	0.680	1.306
TOYOTA	4RUNNER	1996	806	58.2	25.8	1.0	0.100	0.939
TOYOTA	CELICA	1996	502	45.5	30.6	1.2	0.170	0.836
ISUZU	RODEO	1996	122	36.1	50.7	2.8	0.510	0.924
NISSAN	PICKUP	1996	469	52.5	45.6	3.9	0.590	1.066
DODGE	NEON	1996	238	47.3	30.4	3.7	0.260	0.856
JEEP	CHEROKEE	1996	385	47.4	38.7	2.3	0.310	0.938
DODGE	INTREPID	1996	382	40.6	33.6	3.3	0.280	0.808
TOYOTA	TACOMA	1996	438	46.4	46.8	4.5	0.760	1.007
NISSAN	PATHFINDER	1996	423	50.8	46.4	4.0	0.740	1.054
ISUZU	TROOPER II	1996	149	45.4	59.4	3.5	0.700	1.119
FORD	TAURUS	1996	491	50.4	33.1	2.9	0.410	0.919
FORD	F150 PICKUP	1997	340	49.3	30.7	2.6	0.300	0.882
CHRYSLER	SEBRING CONVERTI	1997	445	52.1	25.4	1.4	0.150	0.863
LINCOLN	MARK	1997	75	25.0	28.5	2.4	0.200	0.575
SATURN	SL1	1997	NA	33.0	41.3	2.0	0.180	0.795
MITSUBISHI	GALANT	1997	135	51.8	56.9	4.3	0.890	1.169
PONTIAC	GRAND AM	1997	340	54.3	38.5	1.8	0.300	1.018
CADILLAC	ELDORADO	1997	188	45.6	28.3	0.8	1.170	0.815
FORD	E150 VAN	1997	263	47.3	31.4	1.7	0.140	0.866
FORD	EXPEDITION	1997	330	42.2	27.8	1.3	0.170	0.770
CHEVROLET	S-10	1997	486	38.3	40.0	1.8	0.250	0.844
FORD	TAURUS *	1997	290	47.0	32.0	2.4	0.328	0.868
FORD	EXPLORER *	1998	306	44.0	22.0	1.5	0.151	0.734
DODGE	NEON *	1998	339	44.0	25.0	1.4	0.137	0.764
TOYOTA	CAMRY *	1998	264	52.0	38.0	2.1	0.271	0.986
DODGE	CARAVAN *	1998	507	48.0	55.0	3.3	0.504	1.106
HONDA	ACCORD *	1998	108	38.0	46.0	2.8	0.445	0.900

** These tests have an upper Neck load cell (See Table C.15)*

TABLE C.6 **1996-1998 FMVSS 208 TESTS - ATD IN PASSENGER POSITION**

			PASSENGER					
MAKE	MODEL	YEAR	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI
			(g's)	(g's)	(mm)	(m/s)	(m/s)	
Standard/Proposed Standard			1000	60	76			1
DODGE	CARAVAN	1996	130	39.0	24.6	2.8	0.330	0.701
MITSUBISHI	MIRAGE	1996	567	62.0	18.7	2.3	0.160	0.913
PONTIAC	BONNEVILLE	1996	453	50.0	12.1	2.5	0.050	0.707
LINCOLN	TOWN CAR	1996	133	37.0	12.8	1.0	0.040	0.561
HONDA	CIVIC	1996	305	43.0	15.7	0.9	0.040	0.660
HYUNDAI	ACCENT	1996	182	41.0	16.5	2.0	0.080	0.645
HYUNDAI	SONATA	1996	249	39.0	21.0	2.3	0.150	0.666
TOYOTA	4RUNNER	1996	286	46.0	19.3	2.2	0.110	0.731
TOYOTA	CELICA	1996	265	44.0	25.0	2.4	0.160	0.764
ISUZU	RODEO	1996	334	51.0	36.1	3.2	0.430	0.955
NISSAN	PICKUP	1996	443	62.0	N/A	N/A	N/A	N/A
DODGE	NEON	1996	171	46.0	23.6	2.6	0.180	0.773
JEEP	CHEROKEE	1996	299	48.0	24.9	1.9	0.120	0.810
DODGE	INTREPID	1996	344	52.0	19.5	1.2	0.090	0.804
TOYOTA	TACOMA	1996	397	46.0	35.6	2.1	0.310	0.892
NISSAN	PATHFINDER	1996	809	53.0	26.9	3.3	0.320	0.888
ISUZU	TROOPER II	1996	116	48.0	24.0	4.2	0.260	0.801
FORD	TAURUS	1996	167	46.0	N/A	N/A	N/A	N/A
FORD	F150 PICKUP	1997	231	45.0	13.5	1.0	0.040	0.662
CHRYSLER	SEBRING CONVERTI	1997	483	52.0	23.9	2.1	0.150	0.847
LINCOLN	MARK	1997	78	29.0	18.6	1.8	0.100	0.524
SATURN	SL1	1997	236	42.0	12.8	1.3	0.050	0.620
MITSUBISHI	GALANT	1997	234	38.0	25.6	2.0	0.220	0.699
PONTIAC	GRAND AM	1997	147	52.0	12.6	1.8	0.070	0.736
CADILLAC	ELDORADO	1997	350	48.0	18.0	2.1	0.150	0.742
FORD	E150 VAN	1997	147	45.0	13.5	3.8	0.160	0.662
FORD	EXPEDITION	1997	516	44.0	12.1	1.0	0.030	0.637
CHEVROLET	S-10	1997	769	38.0	30.7	2.5	0.270	0.749
FORD	TAURUS *	1997	299	49.0	10.0	1.0	0.025	0.675
FORD	EXPLORER *	1998	312	48.0	9.0	1.0	0.028	0.653
DODGE	NEON *	1998	419	61.0	16.0	1.6	0.068	0.875
TOYOTA	CAMRY *	1998	432	35.0	17.0	1.1	0.077	0.579
DODGE	CARAVAN *	1998	379	53.0	20.0	1.6	0.102	0.820
HONDA	ACCORD *	1998	237	45.0	13.0	1.0	0.044	0.657

** These tests have an upper Neck load cell (See Table C.15)*

Table C.7 **TRANSPORT CANADA, 40 KMPH / 40% OFFSET Belted 5th Female ATD in Driver Position**

				DRIVER											
MAKE	**MODEL**	**Year**	**HIC_36**	**ACCEL.**	**CHEST DEFL.**	**VEL.**	**V*C**	**CTI**	**Max Neg. Shear**	**Max Pos. Shear**	**Max Ext.**	**Max Flex.**	**Max. Compr.**	**Max Ten.**	**Nij**
			(g's)	**(g's)**	**(mm)**	**(m/s)**	**(m/s)**		**(N)**	**(N)**	**(NM)**	**(NM)**	**(N)**	**(N)**	
Standard/Proposed Standard			1000	**60**	**76.2**			**1**							
98 VEHICLE MODELS															
Nissan	Altima	1998	117	16.2	18.6	1.01	0.106	0.413	1207.0	113.1	56.9	15.7	67.9	1499.0	1.34
Honda	Accord	1998	647	23.6	27.6	1.59	0.490	0.606	2315.6	179.3	76.6	2.1	602.6	3495.3	2.10
Dodge	Neon	1998	612	35.0	26.1	1.21	0.220	0.724	3493.8	102.5	127.2	0.2	117.4	2829.2	2.79
Toyota	Corolla	1998	183	23.7	13.6	0.29	0.057	0.440	395.8	188.2	23.9	20.9	69.8	1370.2	0.64
Toyota	Tacoma	1998	356	27.1	20.4	0.37	0.127	0.562	366.1	117.1	20.8	15.3	412.3	1535.1	0.63
Ford	Explorer	1998	223	24.7	24.3	0.68	0.188	0.581	1196.2	10.3	29.8	1.2	57.1	2573.5	1.02
Nissan	Sentra	1998	380	21.6	17.5	1.72	0.181	0.464	858.6	481.9	45.7	39.4	589.3	2246.3	1.25
Ford	Escort	1998	88	17.4	14.1	0.65	0.062	0.373	1129.8	33.1	56.4	35.2	6.3	1478.1	1.31
Ford	F150	1998	45	19.6	17.1	0.90	0.076	0.434	214.8	106.2	8.6	15.0	39.3	645.8	0.31
Pontiac	Grand Prix	1998	194	30.2	27.3	2.27	0.383	0.682	413.3	116.1	11.8	22.3	22.2	2090.2	0.71
PRE-98 VEHCILE MODELS															
Dodge	Caravan	1998	94	23.1	21.8	0.67	0.118	0.531	1591.5	25.6	69.2	1.2	36.8	1184.3	1.47
Pontiac	Grand Prix	1997	75	17.5	9.7	0.86	0.028	0.321	572.4	185.8	22.5	10.5	115.5	693.4	0.59
Toyota	Camry	1997	318	24.4	30.3	1.19	0.227	0.648	2210.0	11.6	54.3	1.8	3.8	1762.9	1.43
VW	Jetta	1997	32	21.8	14.7	1.34	0.057	0.432	510.6	273.2	26.9	22.0	230.3	832.3	0.66
Ford	Escort	1997	146	21.1	16.6	1.17	0.103	0.446	2193.6	86.1	133.2	15.7	25.4	754.9	1.81
Suzuki	Esteem	1996	90	26.3	23.1	2.38	0.301	0.585	292.2	205.1	16.8	17.7	228.5	1225.1	0.53
Toyota	Tacoma	1996	681	23.4	23.1	3.10	0.223	0.551	979.3	435.8	52.4	19.0	704.6	3043.7	1.45
Chevrolet	Lumina	1996	321	31.8	33.9	6.61	1.033	0.778	1604.7	152.1	66.9	5.1	307.9	2675.5	1.65
Chevrolet	Cavalier	1996	115	18.3	21.9	2.54	0.200	0.476	401.6	215.3	23.3	22.4	269.8	1329.8	0.71
Dodge	Avenger	1996	457	34.1	37.6	3.37	0.381	0.850	3479.5	217.0	134.2	9.9	644.3	4583.0	3.41
Ford	Contour	1995	367	28.3	22.4	2.13	0.264	0.600	2977.1	223.9	123.5	16.2	504.6	2751.7	2.90
Dodge	Caravan	1994	246	20.4	25.0	0.67	0.175	0.538	1566.0	60.8	67.0	19.1	32.4	1008.6	1.43

Table C.8 **TRANSPORT CANADA, 40 KMPH / 40% OFFSET Belted 5th Female ATD in Passenger Position**

				PASSENGER											
MAKE	MODEL	Year	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
			(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			1000	60	76.2			1							
	98-VEHICLE MODELS														
Nissan	Altima	1998	194	24.0	5.7	0.53	0.016	0.350	276.8	514.4	4.3	90.5	1948.4	34.9	1.03
Honda	Accord	1998	517	21.0	13.4	0.37	0.034	0.407	350.7	560.2	33.3	41.5	1310.5	545.8	0.61
Dodge	Neon	1998	323	34.7	15.0	0.69	0.057	0.587	107.7	753.6	10.6	29.7	82.5	1142.4	0.47
Toyota	Corolla	1998	629	30.7	18.0	0.62	0.046	0.576	1705.4	133.3	8.7	66.3	1872.2	1900.8	0.79
Toyota	Tacoma	1998	188	34.4	23.3	0.51	0.256	0.682	615.2	37.6	24.6	4.0	107.9	1650.1	0.78
Ford	Explorer	1998	172	26.7	9.6	0.35	0.049	0.429	134.9	872.6	11.6	67.0	1300.4	1027.7	0.71
Nissan	Sentra	1998	186	18.2	15.0	0.40	0.034	0.393	283.3	359.2	9.6	23.6	8.3	791.4	0.27
Ford	Escort	1998	25	15.4	12.3	0.19	0.018	0.327	283.7	543.4	2.4	40.8	564.8	276.1	0.37
Ford	F150	1998	37	23.1	16.9	0.22	0.065	0.474	160.6	275.1	4.6	13.5	82.5	631.5	0.22
Pontiac	Grand Prix	1998	557	20.8	16.8	0.65	0.031	0.445	989.8	423.5	57.6	35.9	17.8	2314.5	1.52
Dodge	Caravan	1998	175	21.4	18.6	0.34	0.075	0.474	151.4	250.2	5.9	19.5	41.3	961.5	0.39
	PRE-98 VECHILE MODELS														
Pontiac	Grand Prix	1997	133	32.7	8.0	0.21	0.024	0.480	359.5	609.4	22.2	41.5	207.5	1125.2	0.64
Toyota	Camry	1997	2320	33.3	9.4	0.35	0.061	0.504	512.7	1252.6	64.2	57.9	4049.7	2950.5	1.58
VW	Jetta	1997	54	23.2	11.7	0.37	0.028	0.412	608.3	42.7	33.4	14.3	104.7	1104.3	0.82
Ford	Escort	1997	61	22.6	8.5	0.42	0.026	0.366	852.7	20.5	39.6	19.1	28.6	1231.2	1.01
Chevrolet	Lumina	1996	759	29.4	14.7	1.28	0.096	0.522	1223.6	309.3	60.3	23.4	288.8	3507.1	1.91
Chevrolet	Cavalier	1996	39	18.7	13.3	1.57	0.201	0.379	309.3	669.9	3.6	48.9	234.9	434.8	0.32
Dodge	Caravan	1994	211	29.1	9.6	0.28	0.033	0.457	133.0	1058.1	4.4	84.5	527.4	481.7	0.52

Table C.9 — **TRANSPORT CANADA, 48 KMPH Rigid Barrier, Belted 5th Female ATD in Driver Position**

				DRIVER											
MAKE	MODEL	Year	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
			(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			1000	**60**	**76.2**			**1**							
		98 VEHCILE MODELS													
Nissan	Altima	1998	282	42.3	21.5	0.730	0.139	0.754	296.1	207.7	15.8	12.5	168.7	1480.6	0.57
Honda	Accord	1998	321	46.5	32.3	1.730	0.305	0.932	1050.2	112.7	48.8	2.2	328.6	1647.4	1.28
Dodge	Neon	1998	437	49.0	29.0	0.890	0.294	0.922	150.3	247.6	12.9	8.4	338.8	1995.7	0.64
Toyota	Corolla	1998	415	36.6	18.3	0.620	0.110	0.649	374.0	114.4	27.6	4.7	355.2	1957.0	0.73
Toyota	Tacoma	1998	688	58.3	42.5	1.060	0.487	1.193	498.6	58.1	20.2	4.9	435.8	2729.6	0.98
Ford	Explorer	1998	229	58.0	39.8	1.370	0.727	1.157	1669.8	19.5	64.6	12.7	275.9	2179.0	1.76
Nissan	Sentra	1998	342	37.3	20.3	1.410	0.117	0.681	206.7	56.6	14.8	4.3	7.0	1363.2	0.64
Mazda	626	1998	259	47.9	23.9	1.390	0.131	0.849	1874.6	197.5	83.7	3.0	662.9	2150.5	1.99
Nissan	Frontier	1998	636	47.6	40.7	0.850	0.412	1.046	563.1	117.0	33.7	11.5	435.2	1626.5	0.96
		PRE-98 VEHICLE MODELS													
Dodge	Caravan	1998	399	44.9	43.0	1.210	0.510	1.041	232.1	155.5	8.0	12.5	367.9	1566.9	0.54
Toyota	Tacoma	1996	872	75.0	41.4	1.190	0.520	1.376	584.5	270.0	46.7	8.3	1767.8	2802.5	1.31
Dodge	Avenger	1996	353	36.3	29.8	0.880	0.293	0.783	2469.5	155.5	99.9	6.0	453.9	2710.5	2.38
Mazda	MPV	1996	290	36.5	22.7	0.930	0.167	0.700	2274.7	158.9	97.9	10.1	326.9	2612.1	2.27
Mercury	Mystique	1996	307	42.0	24.4	1.100	0.241	0.785	1608.2	153.8	74.5	10.7	387.2	2593.0	1.93
Chevrolet	Cavalier	1996	195	41.9	21.2	0.890	0.109	0.746	193.1	529.8	16.7	12.2	603.0	1856.7	0.63
Suzuki	Esteem	1996	497	45.8	30.6	1.210	0.293	0.904	521.2	205.1	23.7	9.8	1006.1	1980.5	0.72
Mazda	Miata	1996	65	40.0	42.3	1.560	0.425	0.975	1080.1	223.9	48.5	32.3	549.1	1793.2	1.25
Toyota	Corolla	1996	259	36.3	21.7	1.600	0.123	0.686	358.9	294.0	29.3	9.2	431.6	1637.7	0.89
GM	Venture	1997	443	45.7	34.7	2.060	0.468	0.952	N/A	N/A	N/A	N/A	276.1	2120.1	N/A
Jeep	TJ	1997	296	37.8	48.2	3.100	0.680	1.020	370.9	56.4	25.0	15.5	333.3	1669.4	0.71
Hyundai	Tiburon	1997	115	44.2	33.8	3.140	0.396	0.923	3363.3	147.0	105.2	40.2	520.5	1844.0	2.29
Ford	F150 PU	1997	515	54.9	35.1	2.480	0.401	1.065	439.2	164.1	27.6	26.3	803.0	1812.3	1.01
Saturn	SL	1997	255	29.8	34.7	2.810	0.577	0.765	155.5	179.4	11.9	16.8	403.1	1593.3	0.58
Suzuki	X90	1997	404	54.0	35.2	2.240	0.424	1.055	982.7	213.6	66.3	10.8	1050.5	2513.7	1.54
Dodge	Dakota	1997	197	43.9	40.4	3.360	0.666	0.998	731.5	205.1	40.3	7.4	720.5	1736.1	1.01
Chevrolet	Cavalier	1997	170	33.3	29.4	2.78	0.481	0.743	300.8	276.9	24.0	19.1	520.5	1469.5	0.65
Toyota	Rav4	1997	541	52.9	39.3	3	0.468	1.091	1162.1	126.5	57.7	30.0	799.8	2491.5	1.73
Chevrolet	Malibu	1997	212	34.3	23.2	2.84	0.27	0.680	965.6	237.6	49.3	5.6	736.3	2047.1	1.39
Pontiac	Grand Prix	1997	221	32.2	17.0	0.78	0.054	0.582	220.6	47.5	22.9	10.6	85.6	1262.4	0.59
Toyota	Camry	1997	277	42.5	30.7	0.63	0.333	0.866	2838.1	15.4	112.5	10.2	232.8	1895.5	2.42
VW	Jetta	1997	188	50.3	21.0	0.77	0.182	0.842	691.3	164.3	22.5	27.6	34.9	1249.7	0.73
Ford	Escort	1997	286	56.7	23.7	1.05	0.132	0.950	1019.1	84.0	54.5	1.8	255.0	1901.8	1.37

Table C.10 **TRANSPORT CANADA, 48 KMPH Rigid Barrier, Belted 5th Female ATD in Passenger Position**

				PASSENGER											
MAKE	MODEL	Year	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
			(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			1000	**60**	**76.2**			**1**							
98 VEHCILE MODELS															
Nissan	Altima	1998	476	39.6	11.9	0.280	0.047	0.608	195.8	627.8	10.7	74.0	1342.3	196.7	0.770
Honda	Accord	1998	351	43.7	23.1	0.790	0.174	0.789	94.3	397.8	21.9	14.5	241.2	1056.7	0.530
Dodge	Neon	1998	416	47.4	19.9	0.950	0.087	0.796	121.3	719.4	7.0	47.0	728.6	518.5	0.300
Toyota	Corolla	1998	973	43.5	19.0	0.410	0.050	0.738	1985.3	166.1	4.8	29.3	1903.9	577.5	0.650
Toyota	Tacoma	1998	464	62.2	35.8	1.060	0.343	1.159	627.1	500.7	39.9	37.1	374.4	1447.0	1.100
Ford	Explorer	1998	283	45.3	21.2	0.660	0.113	0.786	214.0	379.0	13.5	21.9	585.1	1249.0	0.530
Nissan	Sentra	1998	372	44.5	27.1	0.760	0.208	0.846	249.5	374.2	20.4	29.4	291.9	1066.2	0.490
Mazda	626	1998	297	47.2	27.9	1.410	0.207	0.888	2301.1	122.0	96.4	18.2	222.1	2782.9	2.350
Nissan	Frontier	1998	568	52.8	43.9	1.120	0.602	1.144	324.0	286.1	29.5	45.4	2126.1	1050.3	0.860
Dodge	Caravan	1998	403	48.3	30.6	0.790	0.270	0.933	305.9	584.4	19.5	37.4	458.9	1476.8	0.780
PRE-98 VEHICLE MODELS															
GM	Venture	1997	129	44.0	26.5	1.720	0.526	0.833	516.1	488.8	24.6	34.2	393.6	2002.7	0.860
Jeep	TJ	1997	280	37.1	38.1	1.580	0.731	0.891	367.4	335.0	28.5	12.5	273.0	1552.0	0.830
Hyundai	Tiburon	1997	385	59.0	26.6	1.460	0.272	1.011	225.6	536.6	9.7	24.9	495.1	990.2	0.420
Ford	F150 PU	1997	310	55.6	34.4	1.560	0.489	1.064	478.5	430.7	3.4	30.4	406.3	1123.5	0.400
Saturn	SL	1997	314	40.2	30.1	1.520	0.273	0.832	358.9	241.0	11.2	24.4	396.7	1815.4	0.630
Suzuki	X90	1997	218	53.1	36.4	2.020	0.332	1.059	572.5	374.3	34.3	42.9	361.8	2018.6	1.000
Dodge	Dakota	1997	148	39.7	33.0	2.100	0.606	0.860	815.2	145.3	47.7	32.4	431.6	1596.4	1.270
Chevrolet	Cavalier	1997	455	49.62	21.8	1.34	0.308	0.844	218.8	528.1	13.8	26.0	707.8	1263.2	0.480
Toyota	Rav4	1997	827	68.22	33.1	12.7	1.171	1.197	492.2	188.0	31.0	3.4	1536.1	2961.2	1.170
Chevrolet	Malibu	1997	319	43.39	15.1	11.88	1.142	0.690	76.9	651.1	21.4	56.4	1190.2	587.2	0.530
Pontiac	Grand Prix	1997	273	43.33	21.0	0.4	0.125	0.761	1027.0	302.5	45.2	8.2	88.2	1638.0	1.240
Toyota	Camry	1997	173	32.77	19.3	0.4	0.072	0.615	222.2	791.2	7.3	78.5	1694.5	272.9	0.820
VW	Jetta	1997	198	48.95	37.4	0.7	0.381	1.022	755.0	196.9	39.7	16.7	292.6	1849.4	1.210
Ford	Escort	1997	257	44.57	32.5	0.83	0.209	0.912	1249.2	1.7	57.5	30.9	82.5	2015.0	1.590

Table C.11 ISO-1 OOP TESTS WITH FIFTH PERCENTILE FEMALE HYBRID III DUMMY IN DRIVER POSITION

Make and Model	YEAR	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
		(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			**60**	**76**			**1**							
Honda Accord	1998	110	20.0	18.7	2.77	0.455	0.458	1259.0	82.2	54.2	0.2	15.0	1666.0	1.33
Toyota Camry	1998	35	19.2	19.2	3.03	0.130	0.455	1352.0	165.0	55.6	5.2	4.5	1538.0	1.36
Toyota Camry	1996	81	20.1	19.9	2.94	0.190	0.474	603.0	130.0	20.8	5.5	34.3	1587.0	0.79
Dodge Neon	1998	57	28.8	26.4	1.86	0.230	0.654	1743.0	361.0	85.7	15.3	256.0	1760.0	1.83
Dodge Neon	1996	105	59.7	29.7	4.16	0.310	1.057	2217.0	365.0	103.6	6.0	111.0	2359.0	2.20
Ford Taurus	1998	41	17.7	17.1	3.90	0.100	0.412	275.0	1002.0	80.6	20.0	5.5	1447.0	1.70
Ford Taurus	1996	167	36.3	30.0	N/A	0.390	0.785	314.0	1242.0	90.0	23.0	86.0	2430.0	1.47
Ford Explorer	1998	23	16.1	18.8	3.30	0.150	0.413	89.6	743.0	58.5	1.3	88.8	1338.0	1.28
Ford Explorer	1996	103	27.5	27.0	5.71	0.270	0.645	250	1801	144.6	9.2	225	2365	2.89

Table C.12 ISO-2 OOP TESTS WITH FIFTH PERCENTILE FEMALE HYBRID III DUMMY IN DRIVER POSTIO

				DRIVER										
Make and Model	**YEAR**	**HIC_36**	**ACCEL.**	**CHEST DEFL.**	**VEL.**	**V*C**	**CTI**	**Max Neg. Shear**	**Max Pos. Shear**	**Max Ext.**	**Max Flex.**	**Max. Compr.**	**Max Ten.**	**Nij**
		(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard			**60**	**76**			**1**							
Honda Accord	1998	237	65.0	44.7	1.02	0.044	1.298	613.0	89.0	26.3	47.2	13.8	1627.0	0.70
Toyota Camry	1998	41	39.5	32.7	6.97	0.920	0.855	978.0	34.6	36.3	6.6	57.9	1389.0	0.84
Toyota Camry	1996	35	25.0	29.3	4.88	0.410	0.644	940.0	88.0	29.1	3.8	70.2	1115.0	0.74
Dodge Neon	1998	34	47.9	34.1	4.36	0.380	0.970	578.0	NA	27.6	34.7	NA	775.0	0.58
Dodge Neon	1996	176	63.2	43.3	6.49	0.630	1.260	2560.0	207.0	104.7	14.0	33.7	3498.0	2.39
Ford Taurus	1998	17	39.6	39.0	8.80	1.170	0.931	243.0	629.0	48.4	12.4	10.8	1141.0	1.04
Ford Taurus	1996	45	46.7	29.9		1.210	0.906	175.0	774.0	52.0	15.0	85.0	1110.0	0.73
Ford Explorer	1998	10	17.5	22.6	3.20	0.250	0.476	77.3	801.0	54.5	7.3	74.9	815.0	1.12
Ford Explorer	1996	33	40.5	39.5	7.70	1.300	0.948	43.3	1551.0	124.1	3.2	16.3	1443.0	2.30

Table C.13

Child ISO Testing Baseline vs. Prototype 1998 Air Bag
Three years

Tstno	Airbag	Dummy	ISO Position	Depower Level	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
					(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard					1000	**60**	**76.2**			**1**							
3391	B-94	3 yo	2	baseline	3878	90	16.0	5.79	0.493	1.564	123.6	414.0	113.5	23.8	387.7	3160.5	4.94
3390	B-94	3 yo	2	baseline	3770	108	14.0	4.17	0.246	1.783	1714.3	513.1	10.6	102.6	158.3	3588.9	2.36
3393	B-94	3 yo	2	30%	1071	56	10.0	3.25	0.115	0.980	893.3	224.5	66.1	5.4	110.3	2108.4	2.8
3392	B-94	3 yo	2	60%	179	14	2.0	0.00	0.014	0.232	235.7	269.0	33.3	1.0	34.8	926.8	1.34
3447	D-96	3 yo	1	baseline	386	34	17.0	6.46	0.389	0.782	733.7	733.7	30.7	30.0	19.4	1804.7	1.65
3451	D-96	3 yo	1	18%	143	20	12.0	2.59	0.172	0.498	286.6	599.9	15.4	15.6	1.1	948.5	0.82
3453	D-96	3 yo	2	baseline	709	18	3.0	2.73	0.002	0.317	4.5	613.2	43.1	9.6	1031.7	815.8	1.69
3394	D-96	3 yo	2	baseline	91	23	2.0	1.02	0.005	0.369	524.3	168.9	26.9	1.9	1951.0	111.8	1.53
3452	D-96	3 yo	2	18%	295	17	N/A	N/A	N/A	N/A	377.9	204.6	27.1	6.2	366.8	1261.4	1.15
3462	I-96	3 yo	1	baseline	289	37	41.0	8.50	2.378	1.247	1353.0	280.0	53.3	1.1	13.5	2119.7	2.54
3476	I-96	3 yo	1	23%	260	26	23.0	4.68	0.472	0.770	1280.8	251.2	53.0	1.2	2.0	2115.3	2.45
3463	I-96	3 yo	1	23%	250	27	20.0	5.79	0.323	0.740	1630.5	115.6	59.4	0.6	3.4	2362.7	2.66
3464	I-96	3 yo	1	38%	112	23	25.0	5.23	0.658	0.761	887.1	126.6	36.2	0.9	3.4	1625.0	1.77
3465	I-96	3 yo	2	baseline	78	17	2.0	1.59	0.015	0.275	37.5	61.5	19.3	2.0	1659.7	31.8	1.31
3475	I-96	3 yo	2	baseline	98	18	2.0	1.87	0.019	0.296	346.5	384.4	20.2	2.3	1646.4	29.4	1.33
3466	I-96	3 yo	2	23%	272	16	2.0	1.96	0.012	0.266	128.4	940.5	47.0	8.8	666.1	231.0	1.65
3467	I-96	3 yo	2	38%	13	6	2.0	1.12	0.010	0.116	62.2	66.8	5.6	2.3	546.3	20.8	0.37

Table C.14

Child ISO Testing Baseline vs. Prototype 1998 Air Bag
Six Years

Tstno	Airbag	Dummy	ISO Position	Depower Level	HIC_36	ACCEL.	CHEST DEFL.	VEL.	V*C	CTI	Max Neg. Shear	Max Pos. Shear	Max Ext.	Max Flex.	Max. Compr.	Max Ten.	Nij
					(g's)	(g's)	(mm)	(m/s)	(m/s)		(N)	(N)	(NM)	(NM)	(N)	(N)	
Standard/Proposed Standard					1000	**60**	**76.2**			**1**							
3364	B-94	6 yo	1	baseline	1017	55	42.0	20.86	0.842	1.313	4854.2	134.0	174.8	0.0	5.1	6410.9	5.45
3380	B-94	6 yo	1	30%	245	28	26.0	5.10	0.321	0.746	2059.6	66.2	83.1	0.5	6.7	2549.0	2.58
3384	B-94	6 yo	1	60%	24	8	4.0	2.12	0.031	0.154	576.6	52.8	30.7	0.3	0.0	1402.6	0.77
3363	B-94	6 yo	2	baseline	1432	66	29.0	3.82	0.223	1.237	2860.7	1087.0	106.3	24.7	0.0	5728.6	3.83
3365	B-94	6 yo	2	baseline	1956	55	37.0	14.85	0.357	1.236	2978.6	1308.5	92.1	37.6	14.0	9183.6	4.15
3361	B-94	6 yo	2	baseline	2405	70	30.0	9.07	0.386	1.297	2844.2	2322.6	84.1	45.2	3.2	7259.4	3.69
3383	B-94	6 yo	2	30%	301	16	6.0	1.86	0.028	0.279	1051.7	828.2	51.1	20.9	19.7	2226.6	1.62
3385	B-94	6 yo	2	60%	65	7	0.0	0.00	0.000	0.076	295.2	457.6	20.6	10.0	19.7	843.2	0.51
3362	B-94	6 yo	3	baseline	1369	18	2.0	1.29	0.005	0.246	232.2	2545.0	40.9	9.8	2208.1	611.7	1.39
3381	B-94	6 yo	3	30%	67	9	N/A	N/A	N/A	N/A	26.4	686.8	38.4	3.1	1236.9	350.5	0.98
3386	B-94	6 yo	3	60%	3	1	0.0	0.00	0.000	0.015	22.0	52.8	-5.2	1.7	151.2	125.6	0.15
3448	D-96	6 yo	1	baseline	878	37	13.0	3.49	0.183	0.638	625.1	867.3	28.6	27.4	154.6	2040.9	1.31
3449	D-96	6 yo	1	18%	60	13	10.0	1.73	0.049	0.315	417.8	176.6	21.9	4.2	2.0	736.8	0.77
3395	D-96	6 yo	2	baseline	371	26	2.0	1.18	0.006	0.339	273.0	585.6	8.6	16.0	2782.3	6.6	1.07
3450	D-96	6 yo	2	18%	153	10	1.0	1.82	0.022	0.136	145.2	594.2	15.6	38.2	1173.3	817.2	0.63
3468	I-96	6 yo	1	baseline	679	26	29.0	3.48	0.650	0.772	2505.6	185.4	86.4	3.4	5.5	3577.6	2.98
3469	I-96	6 yo	1	23%	74	18	15.0	2.59	0.144	0.447	1175.8	30.8	58.8	0.3	7.8	1714.4	1.82
3474	I-96	6 yo	1	38%	71	16	16.0	2.27	0.215	0.442	894.5	78.8	47.8	0.9	24.1	1598.8	1.52
3470	I-96	6 yo	2	baseline	1999	36	6.0	2.02	0.460	0.517	462.5	942.5	81.3	4.0	390.9	3051.0	1.28
3471	I-96	6 yo	2	23%	627	19	3.0	1.62	0.016	0.266	79.2	559.4	28.9	4.2	211.5	1529.4	0.85
3472	I-96	6 yo	3	baseline	1673	31	9.0	1.89	0.078	0.505	885.5	898.0	50.0	5.8	52.7	2929.4	2.06
3473	I-96	6 yo	3	23%	316	11	1.0	0.92	0.003	0.148	62.1	444.1	49.3	2.2	109.2	669.3	1.38

Table C.15

FMVSS BARRIER 208 TESTS WITH UPPER NECK LOAD CELL ATD IN DRIVER AND PASSENGER POSITIONS

Make and Model	YEAR	Max Neg. Shear (N)	Max Pos. Shear (N)	Max Ext. (NM)	Max Flex. (NM)	Max Compr. (N)	Max Ten. (N)	Nij
		Driver						
Dodge Caravan	1998	180.3	601.9	15.6	14.3	205.8	2096.3	0.59
Ford Taurus	1997	994.5	321.8	14.0	36.9	124.6	1576.9	0.46
Ford Explorer	1998	1149.1	424.4	14.2	42.8	767.8	1070.9	0.36
Dodge Neon	1998	951.2	43.7	8.1	63.9	293.3	1264.8	0.49
Toyota Camry	1998	1223.2	167.1	7.9	75.2	303.5	1052.5	0.45
Honda Accord	1998	560.2	261.3	5.9	36.2	258.5	823.8	0.29
		Passenger						
Dodge Caravan	1998	355.7	1221.9	14.3	69.8	673.8	1353.8	0.50
Ford Taurus	1997	1418.5	350.7	21.3	62.5	990.0	1305.1	0.47
Ford Explorer	1998	1580.8	326.4	18.7	50.1	1009.3	594.4	0.35
Dodge Neon	1998	1184.3	219.7	23.0	40.4	873.5	2210.6	0.69
Toyota Camry	1998	1187.3	199.4	23.8	47.7	770.7	742.0	0.31
Honda Accord	1998	2004.4	215.6	21.3	84.2	975.7	412.9	0.40

Table C.16 **1994-1996 NCAP**

NOTE: ATD IN DRIVER POSITION HAS AN AIR BAG WHILE PASSENGER POSITION DOES NOT

				DRIVER											
MAKE	**MODEL**	**Year**	**HIC_36**	**ACCEL.**	**CHEST DEFL.**	**VEL.**	**V*C**	**CTI**	**Max Neg. Shear**	**Max Pos. Shear**	**Max Ext.**	**Max Flex.**	**Max. Compr.**	**Max Ten.**	**Nij**
			(g's)	**(g's)**	**(mm)**	**(m/s)**	**(m/s)**		**(N)**	**(N)**	**(NM)**	**(NM)**	**(N)**	**(N)**	
Standard/Proposed Standard			1000	**60**	**76**			**1**							
BUICK	CENTURY	1993	542	46.6	39.0	1.72	0.251	0.932	512.3	62.2	19.8	12.5	111.0	1735.7	0.50
DODGE	SPIRIT	1994	778	43.9	42.0	2.21	0.343	0.930	544.4	845.1	82.9	3.2	1160.3	3154.2	1.19
CHEVROLET	CORSICA	1994	586	59.4	29.0	3.26	0.170	0.984	263.7	428.6	0.0	0.0	3181.4	519.1	0.97
OLDSMOBILE	ACHIEVA	1994	844	46.2	33.0	8.73	0.693	0.868	1251.5	238.0	104.3	27.5	1983.3	411.8	1.20
BUICK	REGAL	1994	503	44.2	45.0	2.26	0.434	0.963	481.5	269.7	39.7	11.0	1972.2	360.1	0.79
HYUNDAI	ELANTRA	1994	575	54.4	48.0	5.29	0.470	1.112	352.1	762.3	21.2	57.0	164.7	1663.6	0.52
CHEVROLET	CAVALIER	1995	814	52.3	32.0	1.46	0.134	0.930	518.1	438.9	24.5	65.6	97.7	1566.1	0.59

				PASSENGER											
MAKE	**MODEL**	**Year**	**HIC_36**	**ACCEL.**	**CHEST DEI**	**VEL.**	**V*C**	**CTI**	**Max Neg. S**	**Max Pos. S**	**Max Ext.**	**Max Flex.**	**Max. Com**	**Max Ten.**	**Nij**
			(g's)	**(g's)**	**(mm)**	**(m/s)**	**(m/s)**		**(N)**	**(N)**	**(NM)**	**(NM)**	**(N)**	**(N)**	
Standard/Proposed Standard			1000	**60**	**76**			**1**							
BUICK	CENTURY	1993	931	39.2	43.0	1.31	0.196	0.884	111.6	1665.5	26.6	76.2	172.8	2380.6	0.69
DODGE	SPIRIT	1994	807	51.0	52.0	2.46	0.406	1.112	168.5	1658.9	341.7	2392.8	46.7	73.6	0.75
CHEVROLET	CORSICA	1994	1296	45.5	36.0	2.97	0.302	0.890	180.0	1499.6	0.0	0.0	3100.3	128.6	0.97
OLDSMOBILE	ACHIEVA	1994	1104	48.8	17.0	3.30	0.116	0.741	949.4	2198.6	94.3	52.4	3061.9	626.2	1.27
BUICK	REGAL	1994	2045	49.0	52.0	2.32	0.398	1.088	140.3	1597.9	34.5	61.9	3369.2	529.1	1.08
HYUNDAI	ELANTRA	1994	1602	56.4	68.0	3.34	0.574	1.333	142.2	1373.1	23.2	25.7	287.9	3360.5	0.96
CHEVROLET	CAVALIER	1995	788	51.9	34.0	3.60	0.269	0.945	961.4	251.4	42.8	26.3	509.3	1924.0	0.60

Appendix D

Software Program to Calculate Nij Neck Injury

```
//-----------------------------------------------------------
//        Nij Version 6 Reference Implementation
//
//    This code is a reference implementation of the Nij Version 6 injury criteria
//        this was written for purposes of clarity and no consideration has been made for speed. style,
//        or efficiency.  The Standard C++ library was used to avoid any confusion due to c-style
//        memory allocation.
//
//    Program Input:
//        This program requires input of three ascii x-y files, where each line of the input
//        file contains two floating point values, one for the time and one for the y value
//
//        *** All three files must have the same number of points and the same time data ***
//
//        *** All input data must be unfiltered and will be filtered within this program
//
//        Additionally, the program queries for the dummy size and whether the condyle correction factor
//        is to be applied
//
//    Program Output:
//        The Nij injury criteria, the time of Peak injury
//-----------------------------------------------------------
#include <iostream>
#include <fstream>
#include <vector>
#include <ctype.h>

using namespace std;
typedef vector <double> DBLVECTOR;

#include "bwfilt.h"                        // bwfilt implementation

// declarations
bool ReadAsciiFile ( char *filename, DBLVECTOR &x, DBLVECTOR &y);
void VectorMax( float &Max, float &MaxTime, DBLVECTOR &time, DBLVECTOR &fVector);
void VectorMin( float &Min, float &MinTime, DBLVECTOR &time, DBLVECTOR &fVector);
double FindTimeStep( DBLVECTOR &time );


int main( int argv, char *argc[])
{
    DBLVECTOR tx, ty, tz, xForce, yMoment, zForce;
    char szbuf[255];

    // read in the filename for the x axis
    cout << "Enter file Name for X axis Force Data: "<< endl;
    cin >> szbuf;
    if ( !ReadAsciiFile(szbuf, tx, xForce) )
    {
        cout << "Error X axis data File" << endl;
        exit (0);
    }

    // read in the filename for the y axis
    cout << "Enter file Name for Y axis Moment Data: "<< endl;
```

```
cin >> szbuf;
if ( !ReadAsciiFile(szbuf, ty, yMoment) )
{
      cout << "Error Y axis data File" << endl;
      exit (0);
}

// read in the filename for the x axis
cout << "Enter file Name for Z axis Force Data: "<< endl;
cin >> szbuf;
if ( !ReadAsciiFile(szbuf, tz, zForce) )
{
      cout << "Error Z axis data File" << endl;
      exit (0);
}

// make sure all three files have identical X axis data
if ( (tx.size() != ty.size()) || (tx.size() != tz.size()) )
{
      cout << "Time data does not match between Axes" << endl;
      exit (0);
}
int i;
for (i=0; i<tx.size(); i++)
{
      if ( (tx[i]!=ty[i]) || (tx[i]!=tz[i]) )
      {
            cout << "Time data does not match between Axes" << endl;
            exit (0);
      }
}

// clear two of the time arrays - not needed any longer
ty.erase(ty.begin(), ty.end() );
tz.erase( tz.begin(), tz.end() );

// find the time step, and make sure that it is constant (within 1%)
double del = FindTimeStep( tx );
if (del<=0.0)
{
      cout << "Could not find a constant time step for the data" << endl;
      exit(0);
}

// Filter the data
bwfilt( xForce, del, 600);
bwfilt( zForce, del, 1000);
bwfilt( yMoment, del, 600);

// Select the dummy type
int nDummyType=0;
cout << "1 - CRABI 12 month old Dummy" << endl;
cout << "2 - Hybrid III - 3 Year old Dummy" << endl;
cout << "3 - Hybrid III - 6 Year old Dummy" << endl;
cout << "4 - Hybrid III - 5th % female Dummy" << endl;
```

```
cout << "5 - Hybrid III - 50th % male Dummy" << endl;
cout << "6 - Hybrid III - 95th % male Dummy" << endl;
cout << endl << "Enter Dummy Type :";
cin >> nDummyType;
if ( (nDummyType <=0) || (nDummyType > 6) )
{
    exit( 0 );
}

// set the critical values based on the dummy type
double CVt, CVc, CVs, mCVf, mCVe, fCondyle;
switch (nDummyType)
{
case 1:                     // CRABI 12 month old Dummy
    CVt = 2200.0;
    CVc = 2200.0;
    CVs = 0.0;
    mCVf =  85.0;
    mCVe =  25.0;
    fCondyle = 0.0058;
    break;
case 2:                     // Hybrid III - 3 Year old Dummy
    CVt = 2500.0;
    CVc = 2500.0;
    CVs = 0.0;
    mCVf = 100.0;
    mCVe =  30.0;
    fCondyle = 0.0;
    break;
case 3:                     // Hybrid III - 6 Year old Dummy
    CVt = 2900.0;
    CVc = 2900.0;
    CVs = 0.0;
    mCVf = 125.0;
    mCVe =  40.0;
    fCondyle = 0.01778;
    break;
case 4:                     // Hybrid III - 5th % female Dummy
    CVt = 3200.0;
    CVc = 3200.0;
    CVs = 0.0;
    mCVf = 210.0;
    mCVe =  60.0;
    fCondyle = 0.01778;
    break;
case 5:                     // Hybrid III - 50th % male Dummy
    CVt = 3600.0;
    CVc = 3600.0;
    CVs = 0.0;
    mCVf = 410.0;
    mCVe = 125.0;
    fCondyle = 0.01778;
    break;
case 6:                     // Hybrid III - 95th % male Dummy
    CVt = 4000.0;
```

```
    CVc = 4000.0;
    CVs = 0.0;
    mCVf = 550.0;
    mCVe = 165.0;
    fCondyle = 0.01778;
    break;
}

// prompt for Condyle Correction
cout << "Correct for Occipital Condyle Offset (" << fCondyle << ") Y / N ?" << endl;
char yesNo;
cin >> yesNo;
yesNo = toupper( yesNo );

// compute the normalized data
DBLVECTOR Tension, Compression, Shear, Flexion, Extension;
for (i=0; i<tx.size(); i++)
{
    Shear.push_back( xForce[i] / CVs );                // Shear
    if (zForce[i] > 0 )
    {
        Tension.push_back( zForce[i] / CVt );          // Tension
        Compression.push_back( 0.0f );
    }
    else
    {
        Compression.push_back( -zForce[i] / CVc );     // Compression
        Tension.push_back( 0.0f );
    }

    // Condyle Correction
    if (yesNo == 'Y')
    {
        yMoment[i] -= xForce[i] * fCondyle;
    }

    if (yMoment[i] > 0 )
    {
        Flexion.push_back( yMoment[i] / mCVf );            // Flexion
        Extension.push_back( 0.0f );
    }
    else
    {
        Extension.push_back( -yMoment[i] / mCVe ); // Extension
        Flexion.push_back( 0.0f );
    }
}

// find the maximums and the time of the maximum
float maxTension, maxCompression, maxShear, minShear;
float maxFlexion, maxExtension;
float tTension, tCompression, tShearmax, tShearmin;
float tFlexion, tExtension;
VectorMax( maxTension, tTension, tx, Tension);
VectorMax( maxCompression, tCompression, tx, Compression);
```

```
    VectorMax( maxShear, tShearmax, tx, Shear);
    VectorMin( minShear, tShearmin, tx, Shear);
    VectorMax( maxFlexion, tFlexion, tx, Flexion);
    VectorMax( maxExtension, tExtension, tx, Extension);

    // Output the Maximums
    cout << "Maximum Shear      \t" << maxShear*CVs << "\tat " << tShearmax << " ms" << endl;
    cout << "Minimum Shear      \t" << minShear*CVs << "\tat " << tShearmin << " ms" << endl;
    cout << "Maximum Tension    \t" << maxTension*CVt << "\tat " << tTension << " ms" << endl;
    cout << "Maximum Compression\t" << maxCompression*CVc << "\tat " << tCompression << " ms"
<< endl;
    cout << "Maximum Flexion    \t" << maxFlexion*mCVf << "\tat " << tFlexion << " ms" << endl;
    cout << "Maximum Extension  \t" << maxExtension*mCVe<< "\tat " << tExtension << " ms" << endl;
    cout << endl;

    // Compute the Nij Values
    DBLVECTOR Ntf, Nte, Ncf, Nce;
    for (i=0; i<tx.size(); i++)
    {
        Ntf.push_back( Tension[i] + Flexion[i] );
        Nte.push_back( Tension[i] + Extension[i] );
        Ncf.push_back( Compression[i] + Flexion[i] );
        Nce.push_back( Compression[i] + Extension[i] );
    }

    // save the Max Value and the Time of the Max Value
    float maxNtf, maxNte, maxNcf, maxNce;
    float tNtf, tNte, tNcf, tNce;
    VectorMax( maxNtf, tNtf, tx, Ntf );
    VectorMax( maxNte, tNte, tx, Nte );
    VectorMax( maxNcf, tNcf, tx, Ncf );
    VectorMax( maxNce, tNce, tx, Nce );

    // Output the results
    cout << "Maximum Ntf\t" << maxNtf << "\tat " << tNtf << " ms" << endl;
    cout << "Maximum Nte\t" << maxNte << "\tat " << tNte << " ms" << endl;
    cout << "Maximum Ncf\t" << maxNcf << "\tat " << tNcf << " ms" << endl;
    cout << "Maximum Nce\t" << maxNce << "\tat " << tNce << " ms" << endl;
    cout << endl;

    return 0;
}

bool ReadAsciiFile ( char *szFilename, DBLVECTOR &x, DBLVECTOR &y)
{
    ifstream inFile;

    inFile.open( szFilename );
    if (inFile.fail() )
    {
        return false;
    }

    double xTemp, yTemp;
    while ( !inFile.eof() )
```

```
    {
        inFile >> xTemp >> yTemp;
        // check for errors
        if (inFile.fail() )
        {
            // input failed - save the data we already have and return;
            if (x.size() > 0)
                break;
            // no data was read - return an error
            return false;
        }
        x.push_back( xTemp );
        y.push_back( yTemp );
    }
    // close the file
    inFile.close();
    return true;
}

void VectorMax( float &Max, float &timeMax, DBLVECTOR &time, DBLVECTOR &fVector)
{
    Max = timeMax = 0.0f;
    for (int i=0; i<fVector.size(); i++)
    {
        if (fVector[i] > Max)
        {
            Max = fVector[i];
            timeMax = time[i];
        }
    }
}

void VectorMin( float &Min, float &timeMin, DBLVECTOR &time, DBLVECTOR &fVector)
{
    Min = timeMin = 0.0f;
    for (int i=0; i<fVector.size(); i++)
    {
        if (fVector[i] < Min)
        {
            Min = fVector[i];
            timeMin = time[i];
        }
    }
}

double FindTimeStep( DBLVECTOR &time )
{
    // make sure there is data
    if ( time.size()<=2)
        return 0.0;

    double del = time[1]-time[0];
    double test;
    double tError = 0.01*del;            // allow a 1% deviation in time step
    for (int i=2; i<time.size(); ++i)
```

```
    {
        test = time[i] - time[i-1];
        if ( test<=0)
            // check for errors - time must be monotonically increasing
            return 0.0;
        else if ( abs(test-del) > tError)
            return 0.0;
    }
    return del;
}
```

```
#include <math.h>
#include <vector>
#include <iostream>
typedef std::vector <double> DBLVECTOR;

template< class T >
inline
T const &
min( T const & x, T const & y ) { return ( ( x < y ) ? x : y ); }

//=============================================================================
//    In-Place Second-Order Butterworth Filter of Time Series
//
//    Function:
//          Filters data forward and backward with a second order
//          Butterworth algorithm, giving zero phase shift and according to the
//          SAE J211.  This algorthim operates on the -3db cutoff frequency, which is
//          indicated as Fn in the J211 s[ecification.  There is an overloaded entry
//          point which allows specifying one of the J211 Channel Frequency Classes.
//          This routine implements  the algorithm outlined in J211 and uses a reversed
//     mirror pre-start treatment for both the forward and reverse passes.
//
//    Authors: Stuart G. Mentzer, Stephen Summers
//
//    Fortran version - 5/95, C version 9/96, C++ standard library version 3/98
//
//    input:
//          y - pointer to data array (float)
//          del - time increment between points in y (float)
//          fCut - Cutoff Frequency, -3db, indicated as Fn in SAE J211
//    return:
//          0 on success
//          1 on failure
//=============================================================================

int bwfilt( DBLVECTOR &y, float del, float fCut)
{
  int nTailPoints, nHalfTailPoints, i;
  double f6db, wd, wa, a0, a1, a2;
  double b1, b2, x0, x1, x2, y0, y1, y2, ynfp2;

  int nPoints = y.size();
  // Check for a positive number of points
  if (nPoints <= 0 )
  {
       std::cout << " BWFILT Error - Nonpositive number of Data Points";
       return(0);
  }
  // Check positive time step
  if (del <= 0 )
  {
       std::cout << " BWFILT Error - Nonpositive time step";
    return(0);
  }
  // Check positive cutoff frequency
```

```
if (fCut <= 0 )
{
      std::cout << " BWFILT Error - Nonpositive Cutoff Frequency";
   return(0);
}

// Set 6dB attenuation frequency
f6db = fCut * 1.2465;

// Compute filter coefficients per J211
wd = 6.2831853L * f6db;
wa = sin(wd * del * 0.5) / cos(wd * del * 0.5);
a0 = wa*wa / (1. + sqrt(2.0)*wa + wa*wa);
a1 = 2 * a0;
a2 = a0;
b1 = -2.0*(wa*wa - 1.0) / (1.0 + sqrt(2.0)*wa + wa*wa);
b2 = (-1.0 + sqrt(2.0)*wa - wa*wa) / (1.0 + sqrt(2.0)*wa + wa*wa);

// Set the number of tail points to use
nTailPoints = (int)(0.01 / ( min(fCut*0.01, 1.0) * del) + 0.5);

//SAE J211 reccomends at least 10 ms, increase if necessary
i = (int) (0.01 / del + 0.5);
if (nTailPoints < i)
      nTailPoints = i;

// regardless of time step and Frequency spec, use at least one point
if (nTailPoints < 1)
  nTailPoints = 1;

// Make sure that enough data points exist for the tail, else cut back tail
if (nTailPoints > nPoints)
{
      //cout << "BWFILT tail length < 10 ms, does not satisfy SAE J211 reccomendation";
      nTailPoints = nPoints;
}

// Set up pre-start array - Inverted mirror
ynfp2 = 2 * y[0];
x1 = ynfp2 - y[nTailPoints];
x0 = ynfp2 - y[nTailPoints-1];
y1 = 0.0;
nHalfTailPoints = ( nTailPoints / 2 ) + 1;
for (i=nHalfTailPoints; i<=nTailPoints; i++)
{
   y1 = y1 + y[i];
}
y1 = ynfp2 - ( y1 / ( nTailPoints - nHalfTailPoints + 1 ) );
y0 = y1;
for (i=-nTailPoints+2; i<=-1; i++)
{
   x2 = x1;
   x1 = x0;
   x0 = ynfp2 - y[-i];
   y2 = y1;
```

```
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
  }

  // Filter forward
  for (i=0; i<nPoints; i++)
  {
    x2 = x1;
    x1 = x0;
    x0 = y[i];
    y2 = y1;
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
    y[i] = (float) y0;
  }

  // setup the pre-start array for the backward filter
  ynfp2 = 2 * y[nPoints-1];
  x1 = ynfp2 - y[nPoints -1 -nTailPoints];
  x0 = ynfp2 - y[nPoints -2 -nTailPoints];
  y1 = 0.0;
  for (i=nHalfTailPoints; i<=nTailPoints; i++)
  {
    y1 = y1 + y[nPoints -1 -i];
  }
  y1 = ynfp2 - ( y1 / ( nTailPoints - nHalfTailPoints + 1 ) );
  y0 = y1;
  for (i=nPoints-nTailPoints+3; i<=nPoints-2; i++)
  {
    x2 = x1;
    x1 = x0;
    x0 = ynfp2 - y[i];
    y2 = y1;
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
  }
  // Filter backwards
  for (i=nPoints-1; i>=0; i--)
  {
    x2 = x1;
    x1 = x0;
    x0 = y[i];
    y2 = y1;
    y1 = y0;
    y0 = a0*x0 + a1*x1 + a2*x2 + b1*y1 + b2*y2;
    y[i] = (float) y0;
  }
  return(1);
}
//
//    optional entry routine to BWFILT using a channel frequency class.
//    This routines translates the J211 Channel Frequency Class into
//    specified cutoff frequency (Fn).
//
int bwfilt( DBLVECTOR &y, float del, int nClass)
```

```
{
    if ( (nClass!= 60) && (nClass!=180) && (nClass!=600) && (nClass!=1000) )
        std::cout << "Frequency Channel Class is not specified in SAE J211";

    return(bwfilt( y, del, (float)(nClass*1.666667) ));
}
//
//  overloaded function definition to allow calling with separate array
//  pointers so that the original displacement data is not overwritten
//
int bwfilt( DBLVECTOR &y, DBLVECTOR &yf, float del, float fCut)
{
    for (int i=0; i<y.size(); i++)
        yf[i] = y[i];

    return(bwfilt( yf, del, fCut ));
}
```