Assessing the field relevance of testing protocols and injury risk functions employed in new car assessment programs

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Abstract - Over the past two decades the popularity of consumer crash test programs, commonly referred to as New Car Assessment Programs (NCAP), has grown across the world. They are popular among government regulators as they afford a means of promoting safety innovations and levels of vehicle performance beyond those dictated by national standards. They also fulfill the demand for information regarding the safety ranking of vehicles among consumers contemplating the purchase of a new vehicle.

There is no question that consumer crash test programs greatly influence vehicle design changes as well as accelerate the fitment of new safety features. The extent to which these changes can be expected to reduce serious and potentially fatal injuries will be influenced by how well the testing protocols and associated rating schemes correctly reflect the nature of the residual safety problem they seek to address.

Drawing on data contained primarily in the US National Automotive Sampling System (NASS), the field relevance of current and proposed testing and rating protocols addressing frontal crash test protection is examined. Emphasis is placed on examining how accurately injury rates computed from the dummy responses measured in consumer crash tests correspond to actual injury rates observed in the field. Additional data from Canadian field investigations and US databases such as the National Motor Vehicle Crash Causation Survey (NMVCCS) are examined to see how well frontal airbag firing times, crush pulse durations and other determinants of injury are replicated in consumer testing protocols. This portion of the analysis draws on data obtained from Event Data Recorders (EDR) in both field collisions and staged tests of the same vehicle model.

Vehicle rankings and overall frontal crash test ratings were found to be particularly sensitive to the choice of injury risk functions employed in the test. This was particularly true in the case of injury risk functions used to assess neck injury potential. Neck injury risk derived from Nij was found to show the least agreement with the field. Agreement between field chest injury rates and those derived from crash tests was improved considerably when chest injury risk functions for "older" occupants were employed. The paper concludes with a discussion of how different current testing protocols could be improved to enhance their field relevance.

INTRODUCTION

The past two decades have seen the number of consumer crash test programs steadily increase. There is also continuous interest in expanding the scope of existing programs to ensure that promising new vehicle safety technologies are addressed and promoted. Historically, these programs have focused on improving vehicle crashworthiness. In recent years, the scope of the programs has been expanded to include collision avoidance technologies.

Consumer crash test programs afford a means of not only accelerating the fitment of newly emerging safety technologies, but also of promoting the evolution of existing safety features to address the changing nature of the residual safety problem. Historically, younger males accounted for the majority of occupants killed or seriously injured in crashes. Today, at least in the case of belted occupants, the residual problem has shifted to females and the elderly. It has been argued that the 5th percentile female dummy represents not only the small size population but also much of the elderly population. The basis for this argument is that the use of a smaller, lighter dummy would encourage countermeasures which promote lower occupant restraint loading. Reductions in such loads would be particularly beneficial to the elderly due to their lower injury threshold.

This is a very important consideration since, in many countries, the driving population is aging. Over the next two decades, the number of individuals of 65 years of age or older is expected to double. There are also other competing trends, most noticeably in the number of individuals who are overweight or obese. The overweight population may not benefit from the safety systems optimized for the 5th percentile female, particularly in higher speed frontal crashes. The choices made in consumer crash test programs with respect to the testing protocols followed, the injury risk functions selected, and the priorities given to different body regions will all impact on how successful the program will be in promoting net societal benefit.

GLOBAL TRENDS IN NCAP

Australia, Europe, Japan and the US have had New Car Assessment Programs for several years with the one in the US starting in the late 70's. Whereas the original program included only frontal crash tests, with the advent of dynamic side impact standards, side crashes have entered NCAP's around the world. Pedestrian tests are also conducted in all regions except the US. While not including any pedestrian safety evaluation, the US NCAP contains Static Stability Factor (SSF) testing for rollover propensity.

Whereas, the Australian, European and Japanese NCAP's are conducted by single organizations in these regions, the US NCAP is conducted by the National Highway Traffic Safety Administration (NHTSA), but public domain testing is also conducted by the Insurance Institute for Highway Safety (IIHS) with different test modalities. NHTSA conducts full-frontal rigid barrier tests, movable deformable side impact tests, and tests for SSF. The IIHS conducts frontal offset-deformable barrier tests, side impacts with a moving deformable barrier representing the front-end of light trucks and vans (LTV's), and rear impact sled tests to rate the head restraints for whiplash protection. IIHS includes a Roof Strength-to-weight Ratio in their rating scheme based on static roof crush tests. Currently, the IIHS publishes their ratings separately for front, side, rear and rollover, and also have a combined rating for the vehicles tested. To get the highest ratings, the vehicles have to be fitted with Electronic Stability Control (ESC) which is being phased-in by a NHTSA regulation in the US.

Global comparisons: The suite of tests conducted in the Japanese NCAP come closest to those conducted by NHTSA and IIHS combined, except for side impact testing with a barrier that simulates the LTV population in the US. The Euro NCAP does not have a full-frontal rigid barrier test. All non-US NCAP's have gravitated towards the European regulatory test procedures and rating schemes for side and frontal-offset tests. Recently, China has also started NCAP testing of vehicles, following the European model, but the CNCAP has added the full frontal rigid barrier test. Noteworthy in China is that the test velocity for the frontal rigid barrier test is 48 km/h, that for the offset test is 56 km/h, and the rear seat is tested with an adult sized dummy. The Japanese NCAP is also introducing dummies in the rear seat in the offset deformable barrier frontal tests.

In general, the body areas being monitored and rated are the same in all the NCAP's. The NHTSA NCAP is not monitoring tibia loads, as has become the practice in all other parts of the world. The overall rating scheme in ANCAP, EuroNCAP, JNCAP and CNCAP are based on points gained in the various test configurations. The rating scheme in the US is somewhat different, based on the probability of injuries to the head, neck, chest and femurs, and a combined rating for all crash modes cannot be higher than 5-stars. The "Star Rating" has to be displayed on each new vehicle. The starting date for the new rating scheme has been postponed for a year. Based on past history, it is possible to have a 5-Star NHTSA NCAP car that may not achieve the highest rating from the IIHS and vice versa.

Industry Responses: Although the initial response from the automotive industry to both, the US NCAP in the late „70s and to the EuroNCAP, were not positive, lately industry has embraced the process and is advertising the ratings. They are motivated by the endorsement of their products' safety by an unbiased third party. The NCAP's have encouraged the introduction of several technologies like pre-tensioners, load limiters, side airbags, knee airbags and side curtains in vehicles and, lately, early introduction of ESC into the US fleet. Since, most NCAP test velocities are higher (generally by 8 km/h) than the regulatory test velocities, there is the danger that vehicles designed to achieve high ratings in these tests may be overly-optimized for the specific test condition. Since such crashes are substantially less frequent in the real world than are lower energy impacts, an optimization that produces even a slight increase in the injury risk at lower speeds can result in a substantial over-all increase in injuries in the real world. Additionally, the design emphasis could shift towards only those body areas being rated. For example, in the US, tibia injuries could be neglected in the full frontal rigid barrier tests, since the tibia loads are not monitored. Also, greater emphasis may be placed in reducing the most influential occupant responses even though the field data may not show the necessity for such a course of action.

Changes to US NCAP: After reviewing the information received in response to their January 2007 request for comments [1], NHTSA elected to introduce a wide variety of changes to the nature and structure of the NCAP rating program. The more significant changes, as they apply to the portion of the program involving frontal crash protection, included:

- substituting a Hybrid III 5th percentile female dummy in the front right seating position;
- expanding the body regions rated to include the neck and femurs;
- substituting chest deflection in place of chest acceleration to assess chest injury risk;
- substituting a 15 ms HIC in place of the 36 ms HIC;
- shifting emphasis from AIS 4+ to AIS 3+ injury risk in the case of the head, neck and chest;
- consideration of AIS 2+ injury risk in the case of the knee-thigh-hip complex; and
- use of a combined injury risk metric to calculate overall injury risk to the above-mentioned four body regions.

To support the above changes, a new set of injury risk functions was defined for use in translating the dummy responses measured in the test into injury risk. These injury risk functions can be expected to influence both restraint hardware and vehicle structure in the future. The success of this process hinges on the fidelity of the injury risk functions in predicting today's accident environment with the current demographics, and with the projected demographics for ten to twenty years in the future. If the injury risk functions utilized in the rating scheme end up prioritizing the wrong body areas for restraint optimization, the deployed designs may not be responsive to the real world needs of today, or for the future, even for the highest rated vehicles.

NATURE OF THE RESIDUAL FRONTAL CRASH PROBLEM AMONG BELTED OCCUPANTS IN THE US

Overview

The past two decades have seen a great number of regulatory interventions to improve frontal crash protection in the US. In 1984, NHTSA issued a final rule requiring that all passenger cars provide automatic crash protection, either airbags or automatic seat belts, in the driver and right-front passenger seating positions. This requirement was phased-in over a four year period starting with the 1987 model year (MY). In response to the Intermodal Surface Transportation Efficiency Act (ISTEA), passed by Congress in 1991, this automatic restraint requirement was altered to require all passenger cars and light trucks to be fitted with frontal airbags in both front outboard seating positions. This mandatory airbag requirement was phased-in starting with the 1994 MY fleet. All passenger cars had to have frontal airbags by the 1997 MY, and all light trucks had to have frontal airbags by the 1998 MY.

Compliance with these two revisions to Federal Motor Vehicle Safety Standard (FMVSS) 208 had to demonstrated in 48 km/h perpendicular, and angled frontal rigid-barrier tests using both belted and unbelted dummies. The protection requirements were initially defined in the context of the Hybrid IIII mid-size adult male dummy. In 2001, FMVSS 208 was amended to add testing with the Hybrid III small adult female dummy which was phased-in over a 4-year period starting with the 2004 MY[2]. FMVSS 208 was also amended to increase the rigid barrier test speed to 56 km/h for testing with the belted Hybrid III mid-size male dummy. This increased speed was phased-in over a 4-year period starting with the 2008 MY. In 2006, FMVSS 208 was amended again to increase the test speed to 56 km/h for the belted Hybrid III small female dummy. This speed increase will be phased-in over a 4-year period starting with the 2010 MY

In addition to the above-mentioned changes to the belted provisions of FMVSS 208, there have been other changes to the unbelted requirements of this standard which continue to be controversial. In 1997, in response to the rising number of children and occupants of short stature being seriously injured or killed by "first-generation" airbag systems, NHTSA issued an interim ruling allowing the use of a sled test with unbelted dummies as an option to the 48 km/h full frontal rigid barrier test. This was done to facilitate the depowering of airbags. The rigid barrier unbelted test was brought back as part of the 2000 "advanced" airbag ruling, but the speed of the test was reduced to 40 km/h[3]. Subsequent evaluations of the performance of sled-certified airbags in the field have generally concluded that depowered airbag systems have had either no impact, or have marginally improved the level of frontal protection afforded belted occupants [4,5,6,7]. However, concerns have been expressed that certified advanced airbags (CAC) offer a reduced level of protection to belted occupants.[8]

In view of the great influence of NCAP on vehicle design, there have been attempts by NHTSA to correlate the field performance of vehicles with their NCAP ratings. The last published evaluation was performed in 1994. In the 2008 NCAP notice [9], NHTSA argued that NCAP, in large part, was instrumental in the widespread fitment of safety devices, such as belt-pre-tensioners and load-limiting seat belts, which ultimately were shown to significantly improve belt performance [10]. The notice did not address how the positioning of the 5th percentile female or the selection of injury risk functions related to real world crash data. A more recent evaluation of the injury risk curves proposed in the new NCAP program by Laituri et al. observed that the proposed assessments show little agreement with field data [11]. The present study draws heavily on the approach employed by Laituri to assess the field relevance of the protocols advanced by NHTSA in the new NCAP program.

NASS/CDS

The 1988-2008 NASS data were searched for airbag equipped passenger vehicles that were involved in frontal collisions where at least one front outboard-seated adult occupant was restrained with a 3-point belt system. The study included impacts where the primary damage involved either the front of the vehicle, or the front left or right side of the vehicle forward of the passenger compartment, and the direction of force was between 10 o'clock and 2 o'clock. Secondary side impacts were permitted, but only if the damage extent in the Collision Deformation Classification (CDC) associated with the secondary impact was less than 3, indicating negligible interior compartment damage. All rollovers were excluded.

The occupant sample was restricted to belted drivers, and belted right front passengers, who were seated in a position equipped with an airbag. Occupants restrained by a conventional, manual 3-point belt were included in the sample. Automatic seat belt systems, including door-mounted 3-point belt systems were excluded. As a minimum, the gender, age, and NASS MAIS rating had to be known. For occupants with an MAIS rating between 0 and 2, the associated NASS collision weighting factor had to be less than 2,500. In the case of occupants with MAIS ≥ 3, the associated NASS collision weighting factor had to be less than 200. This was done to minimize distortions in the MAIS ≥ 3 injury frequencies which occur if filtering is confined only to collisions with very elevated NASS collision weights.

The above-mentioned selection criteria resulted in a frontal sample consisting of 19,907 front outboard occupants representing, when weighted, 6,109,236 occupants. The composition of the sample, in terms of vehicle damage assignments and ΔV reporting are given in Table 1. The sample was partitioned as a function of whether the damage could be described as “distributed” and whether or not the principal direction of force was from the 12 o’clock direction. These assignments are summarized in Table 2.

Table 1. Composition of Weighted and Unweighted NASS Belted Occupant Samples as a Function of Vehicle Damage and Reporting of Delta-V.

Primary Damage			**Total Frontal Sample**		**Frontals with Known ΔV**	
Damage Location GAD	**Damage Location SLH**	**Direction of Force**	**Weighted Sample**	**Unweighted Sample**	**Weighted Sample**	**Unweighted Sample**
F	**C, D, L, R, Y, Z**	**Any**	5,684,747	18,746	1,676,814	14,158
L	**F**	**10, 02**	166,601	447	20,936	377
		11, 12, 01	73,664	212	562,141	152
R	**F**	**10, 02**	119,640	311	48,384	257
		11, 12, 01	64,583	191	2,027,889	134
All	**All**	**All**	6,109,236	19,907	4,336,164	15,078

Table 2. Composition of Weighted NASS Belted Occupant Sample as a Function of FDEW Classification and Reporting of Delta-V.

****FDEW* ?**	**12FDEW* ?**	**Delta-V Not Known**	**(%)**	**Delta-V Known**	**(%)**	**All**	**(%)**
No	**No**	1,231,474	(72.6)	2,301,913	(52.2)	3,533,387	(57.8)
Yes	**No**	151,090	(8.9)	883,789	(20.0)	1,034,879	(16.9)
	Yes	313,183	(18.5)	1,227,787	(27.8)	1,540,970	(25.2)
All		**1,695,747**	**(100.0)**	**4,413,489**	**(100.0)**	**6,109,236**	**(100.0)**

The maximum AIS (MAIS) composition of the partitioned sample is depicted in Table 3.. Two trends are suggested by these data. The lowest rates of injury at the MAIS 3+ and MAIS 4+ severity intervals were observed in “distributed” impacts with an angular component of impact direction (i.e. non-12 o’clock). The 12FDEW* collision subset, which would be expected to most closely approximately a full frontal rigid barrier test, showed the highest rates of injury. One can also see large variations in the injury rates as a function of whether or not the ΔV was reported. In the case of ”non-distributed” (non-FDEW) and "barrier-like" (12FDEW*) collisions, the injury rates were substantially higher for the subset of cases where the ΔV was not reported.

Table3. Percentage Distribution of Weighted NASS Belted Occupant Sample as a Function of FDEW Classification and Reporting of Delta-V.

	Delta-V Reported ?					
	No			**Yes**		
	****FDEW* ?**			****FDEW* ?**		
	No	**Yes**			**Yes**	
		12FDEW* ?			**12FDEW* ?**	
		No	**Yes**		**No**	**Yes**
MAIS 0	59.052	46.369	53.585	47.003	35.988	49.696
MAIS 1	36.640	46.358	41.164	47.055	56.353	42.638
MAIS 2	3.089	6.312	3.506	4.942	6.632	6.351
MAIS 3	0.886	0.848	1.352	0.837	0.911	1.025
MAIS 4+	0.332	0.113	0.393	0.163	0.116	0.290
All	**100.000**	**100.000**	**100.000**	**100.000**	**100.000**	**100.000**
Injury Rates						
MAIS 2+	**4.31%**	**7.27%**	**5.25%**	**5.94%**	**7.66%**	**7.67%**
MAIS 3+	**1.22%**	**0.96%**	**1.75%**	**1.00%**	**1.03%**	**1.32%**
MAIS 4+	**0.33%**	**0.11%**	**0.39%**	**0.16%**	**0.12%**	**0.29%**

The composition and characteristics of the occupant sample, when weighted, as a function of gender and MAIS, are described in Table 4. In terms of occupant characteristics, there was a 49/51 percentage split between male and female occupants. The average ages of the male and female occupant groups were 36.7 and 37.1 years. The average weights of the male and female occupants were 84.7 and 67.7 kg. Their average heights were 177.9 and 164.3 cm, respectively. The average BMI values were 26.7 and 25.1. From the mean values, computed as a function of MAIS, we can see that among females, the mean age, weight, and BMI values all increase with increasing MAIS. The same trend can be seen among males in the case of mean age and mean BMI values. There was little variation in the mean occupant height values as a function of MAIS. This was true for both genders.

The composition of the weighted occupant sample as a function of the occupants' "NCAP classification" and MAIS is depicted in Table 5. For the purposes of classifying occupants in the present study, an occupant was taken to have sustained an "NCAP" injury if they sustained one of the following:

- a head or facial injury rated as AIS 3+
- a neck or spine (any) injury rated as AIS 3+
- a chest injury rated as AIS 3+ or
- a lower extremity injury to the knee-thigh-pelvis complex rated as AIS 2+.

Table 4. Composition and Characteristics of Weighted NASS Belted Occupant Sample as a Function of Gender and Maximum AIS Level.

MAIS Group	Weighted Counts		Mean Age		Mean Weight (kg)		Mean Height (cm)		Mean BMI	
	Males	**Females**	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**	**Males**	**Females**
MAIS 0	1,710,994	1,264,273	35.7	36.1	83.4	65.7	177.7	164.3	26.4	24.3
MAIS 1	1,148,529	1,606,358	37.7	37.2	86.0	68.7	178.2	164.4	27.0	25.5
MAIS 2	121,103	187,824	40.7	40.9	87.9	70.1	178.7	164.5	27.4	26.0
MAIS 3	23,465	32,863	42.2	46.1	86.8	72.3	177.6	164.2	27.7	27.2
MAIS 4+	7,846	5,980	47.1	47.9	89.2	78.6	177.5	166.0	28.3	28.4
All	**3,011,938**	**3,097,299**	**36.7**	**37.1**	**84.7**	**67.7**	**177.9**	**164.3**	**26.7**	**25.1**

Table 5 Composition of Weighted NASS Belted Occupant Sample as a Function of NCAP Classification and Maximum AIS Level.

MAIS Level	Total Frontal Occupant Sample			Occupant Sample with at Least One NCAP Related Injury			% of Occupants w/ NCAP-Related Injury
	DV Unknown	**DV Known**	**All**	**DV Unknown**	**DV Known**	**All**	**All**
MAIS 0	965,091	2,010,176	2,975,267	0	0	0	**0.0%**
MAIS 1	650,174	2,104,713	2,754,887	0	0	0	**0.0%**
MAIS 2	58,563	250,364	308,928	13,214	46,835	60,049	**19.4%**
MAIS 3	16,433	39,895	56,328	11,464	24,522	35,986	**63.9%**
MAIS 4+	5,485	8,341	13,826	5,442	8,045	13,487	**97.5%**
All	**1,695,747**	**4,413,489**	**6,109,236**	**30,121**	**79,402**	**109,523**	**1.793%**

Of the 6,109,236 individual occupants represented in the weighted frontal sample, 109,523 of the occupants sustained at least one of the above-mentioned injuries, yielding an overall occupant injury rate of 1.793% across all severities, independent of whether or not the ΔV for the occupied vehicle was reported. Among occupants in the frontal sample rated as MAIS 4+, the portion who sustained at least one NCAP injury was 97.5%. The only individuals excluded were essentially those who sustained isolated injuries to the abdomen at the AIS 4+ level. In the case of occupants in the frontal sample rated as MAIS 3+, the portion who sustained at least one NCAP injury was reduced to 63.9%. The excluded occupants took the form of individuals whose AIS 3+ injuries were confined to the abdomen, the upper extremities, and the lower extremities below the knee. The distribution of the individual injuries represented in frontal sample, as a function of body region injured and the associated AIS severity level, is provided in Table 6. The corresponding distribution of injuries for the "non-NCAP" occupants is provided in Table 7.

Table 6. Distribution of Individual Injuries Sustained by Occupants in the Frontal Sample as a Function of Body Region Injured and AIS Severity Level

Body Region	**AIS Level**					
	AIS 1	**AIS 2**	**AIS 3**	**AIS 4+**	**AIS 7**	**All**
Abdomen	387,625	21,797	4,556	2,414	4872	**421,263**
Back	344,745	27,757	2,151	420	0	**375,072**
Chest	1,029,519	42,232	18,645	11,373	2124	**1,103,893**
Face	1,187,872	15,364	1,741	3	51	**1,205,031**
Head	283,454	63,412	13,781	11,828	2888	**375,364**
L Ext	1,799,681	237,474	46,217	411	539	**2,084,322**
Neck	756,583	11,356	3,788	764	364	**772,855**
U Ext	2,342,524	132,633	25,060	0	640	**2,500,858**
Unknown	35414	0	0	41	87	**35542**
Whole Body	1291	0	0	0	0	**1291**
All	**8,168,708**	**552,026**	**115,939**	**27,254**	**11563**	**8,875,491**

Table 7. Distribution of Individual Injuries Sustained by "Non-NCAP" Occupants in the Frontal Sample as a Function of Body Region Injured and AIS Severity Level

Body Region	**AIS Level**					
	AIS 1	**AIS 2**	**AIS 3**	**AIS 4+**	**AIS 7**	**All**
Abdomen	363,525	10,368	1,765	339	4770	**380,766**
Back	335,257	16,786	0	0	0	**352,043**
Chest	980,543	31,597	0	0	1848	**1,013,988**
Face	1,123,992	10,309	0	0	51	**1,134,352**
Head	267,257	54,955	0	0	2800	**325,012**
L Ext	1,652,570	115,718	7,976	0	539	**1,776,803**
Neck	739,856	6,900	0	0	190	**746,946**
U Ext	2,238,491	107,195	15,452	0	640	**2,361,779**
Unknown	34540	0	0	0	87	**34627**
Whole Body	1223	0	0	0	0	**1223**
All	**7,737,254**	**353,829**	**25,193**	**339**	**10924**	**8,127,539**

Table 8. Distribution of Individual Injuries Sustained by "NCAP" Occupants in the Frontal Sample as a Function of Body Region Injured and AIS Severity Level

Body Region	**AIS Level**					
	AIS 1	**AIS 2**	**AIS 3**	**AIS 4+**	**AIS 7**	**All**
Abdomen	24,100	11,429	2,791	2,075	102	**40,497**
Back	9,488	10,971	2,151	420	0	**23,029**
Chest	48,976	10,635	18,645	11,373	276	**89,905**
Face	63,880	5,055	1,741	3	0	**70,679**
Head	16,197	8,457	13,781	11,828	88	**50,352**
L Ext	147,111	121,756	38,241	411	0	**307,519**
Neck	16,727	4,456	3,788	764	174	**25,909**
U Ext	104,033	25,438	9,608	0	0	**139,079**
Unknown	874	0	0	41	0	**915**
Whole Body	68	0	0	0	0	**68**
All	**431,454**	**198,197**	**90,746**	**26,915**	**639**	**747,952**

Table 9. Distribution of Individual "NCAP" Injuries Sustained by "NCAP" Occupants in the Frontal Sample as a Function of Body Region Injured and AIS Severity Level

Body Region	**AIS Level**					
	AIS 1	**AIS 2**	**AIS 3**	**AIS 4+**	**AIS 7**	**All**
Chest	0	0	18,645	11,373	0	30,018
Head-Face	0	0	15,522	11,832	0	27,354
KTP-Complex	0	78,602	29,517	411	0	108,530
Neck-Spine	0	0	5,938	1,184	0	7,122
All	**0**	**78,602**	**69,623**	**24,800**	**0**	**173,024**

The distribution of all of the individual injuries in the "NCAP" occupant subset of the frontal occupants, as a function of body region injured and associated AIS level, is summarized in Table 8. The subset of these injuries which are NCAP-related is described in Table 9. Collectively, we can see that the 109,523 individuals designated as NCAP occupants in the weighted frontal subset sustained a total of 747,952 individual injuries, 173,024 of these being NCAP-related injuries.

Two approaches are used in the study to quantify occupant injury rates in field collisions at collision severities represented by the NCAP 56 km/h full frontal rigid barrier test. In the first approach, lower and upper bound injury rate estimates were computed from the NASS data. The ΔV interval 49-64 km/h was used to provide the lower bound estimate, and the ΔV interval 56-71 km/h was used to provide the upper bound estimate. The second approach was to compute a continuous 11-point moving average injury rate from the ΔV data.

Each approach has certain advantages. Computing fixed interval injury rates allows for simultaneous computation and comparison of the injury rate for cases where the ΔV data are missing with the overall injury rate for the sample. This provides a first order indication of whether the subset of cases with known ΔV is likely to overstate or understate the actual field rate. The advantage of the second approach is that the moving average estimates dampen injury rate fluctuations due to the NASS weighting factors.

The lower and upper bound estimates for the injury rate to any NCAP related body region/severity are presented in Figures 1 and 2, respectively. The lower bound estimate corresponds to 16.5%, while the upper bound estimate corresponds to 23.9%. Here we can see that the injury rate for any NCAP-related injury computed from the subset of cases with no reported ΔV corresponds to 1.776% which is in close agreement with the overall NCAP-related injury rate of 1.793% noted earlier for the overall frontal sample (see Table 5). The corresponding injury rates generated using the 11-point moving average method are depicted in Figure 3. For completeness, the injury rates for the four body region groupings considered in NCAP are also provided in Figure 3.

Since the crash pulse durations for the vast majority of field collisions are longer than those observed in rigid wall tests, the field ΔV that would most closely approximate the crash severity of a 56 km/h full frontal impact into a rigid wall is somewhat speculative. However, chest deflections measured in 48 km/h full frontal rigid wall tests have been found to correspond closely with those measured in offset frontal deformable barrier tests performed at 64 km/h [12]. If we define the rigid wall tests as "hard" crashes, and the offset tests as "soft", a 20%/80% field mix of hard and soft crashes would suggest that the two test environments would be represented by a 60 km/h field ΔV crash. This is also suggested by the chest injury rate data presented in Figure 3. The fact that the slope of the chest injury curve goes negative for a portion of the high speed ΔV interval (decreasing risk of chest injury with increasing collision severity) can be explained by the changing composition of the driving population. At collision severities beyond 60 km/h, the percentage of younger males (with a high tolerance to chest injury) represented increases dramatically with increasing crash severity [12].

From the plots presented in Figure 3, the highest rate of injury in one body region is to the knee-thigh-pelvis complex, while the lowest rate of injury is to the neck-spine complex. Indeed, in the case of the latter, the injury rate can be seen to only increase above 4% at longitudinal ΔVs in excess of 72 km/h. At this collision severity, the injury rates to all of the body regions can be seen to increase precipitously, an indication that the upper limits of passenger compartment integrity are likely being exceeded. This is also reflected in the interval plots used to define the upper bound injury rate for an NCAP collision. These plots are provided in Appendix A as a function of seating position.

For the subset of occupants who sustained at least one NCAP injury, fatality probabilities were computed as a function of the body regions involved. These results are presented in Table 10. As would be expected, the highest fatality probability (91.0%) was associated with individuals who sustained at least one NCAP-related injury in all four of the NCAP body regions. This was followed by individuals who sustained at least one NCAP-related injury to the head-face, the chest and the KTP-complex. The associated fatality probability for this injury combination was 54.4%.

Figure 1. Injury Rate : Any NCAP Injury / Lower Bound Estimate (49 – 64 km/h)

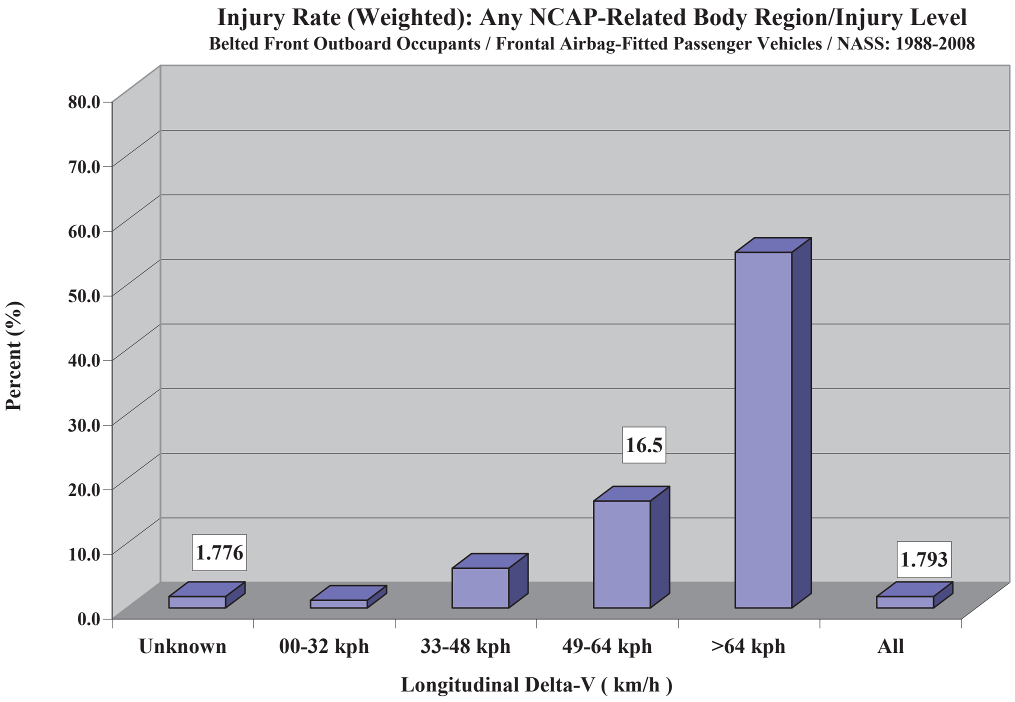


Figure 2. Injury Rate : Any NCAP Injury / Upper Bound Estimate (56-71 km/h)

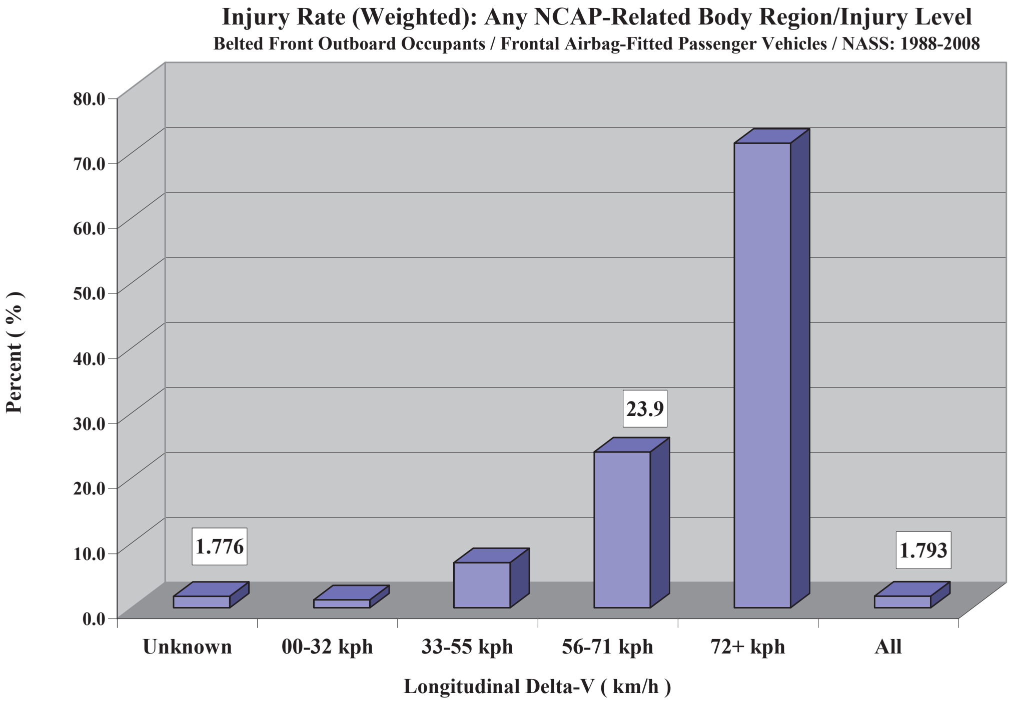
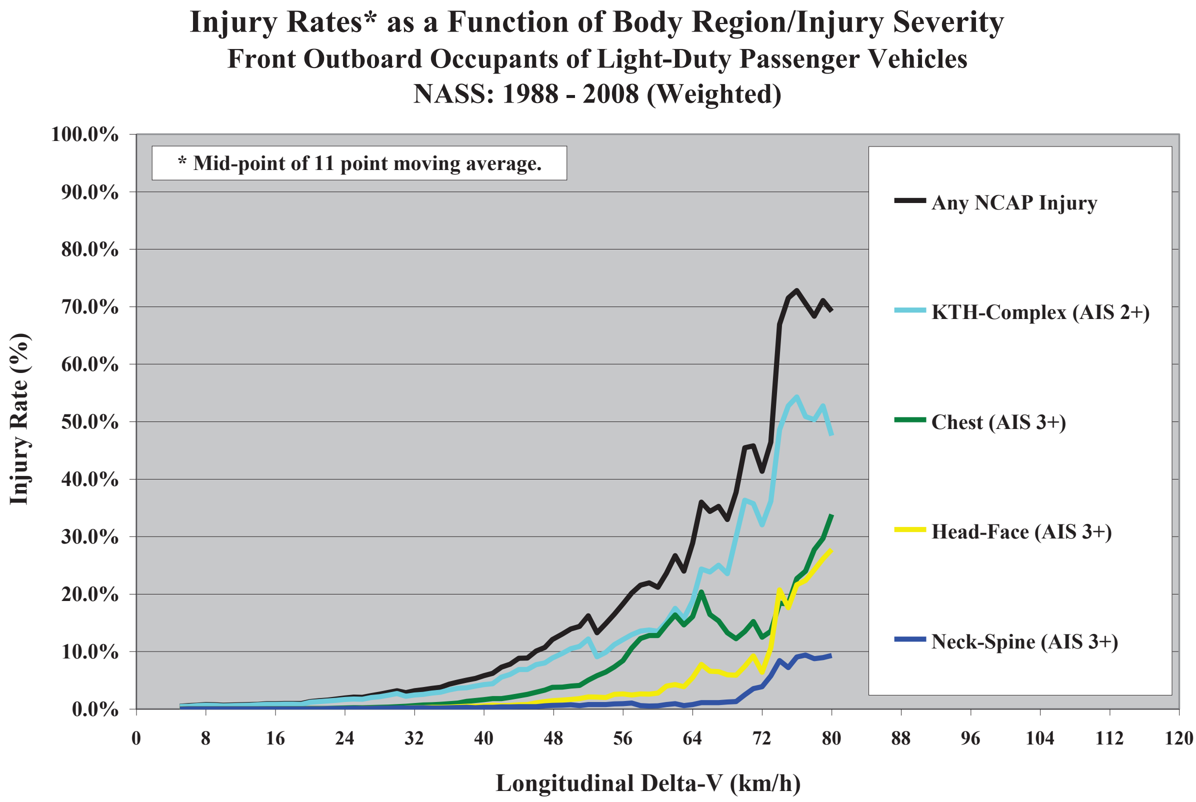


Figure 3. Mapping of Injury Rates



In the case of occupants whose injuries were confined to a single NCAP body region, the associated fatality probabilities, in decreasing order, were as follows:

Head-Face (AIS 3+)	23.2%
Chest (AIS 3+)	9.0%
Knee-Thigh-Pelvis (AIS 2+)	1.3%
Neck-Spine (AIS 3+)	0.6%

In the case of individuals whose NCAP injuries were confined to two body regions, the associated fatality probabilities for the most frequently occurring pairings, in decreasing order, were as follows:

Head-Face (AIS 3+) / Chest (AIS 3+)	41.7%
Head-Face (AIS 3+) / Neck-Spine (AIS 3+)	37.5%
Chest (AIS 3+) / Knee-Thigh-Pelvis (AIS 2+)	32.5%

The predominance of head and chest injuries is also reflected in the distribution of individual AIS 4+ injuries as a function of the body region in the frontal occupant sample. These results are presented in Table 11 as function of age group. Here we can also see that the relative ranking of the head and chest is determined by the age of the occupant. Among younger occupants, those in the 15-43 years bracket, AIS 4+ head injuries can be seen to clearly predominate while, in the case of older occupants, AIS 4+ chest injuries predominate. The percentage of AIS 4+ injuries involving the neck-spine region among all three age groups was low, of the order of 4%.

Table 10 . Fatality Outcome as a Function of NCAP Body Region/Severity Grouping Involved

Head-Face AIS 3+	Neck-Spine AIS 3+	Chest AIS 3+	KTP Complex AIS 2+	Fatality	Total	(%)	Rank
No	No	No	Yes	980	77,144	1.3%	**12**
		Yes	No	1,004	11,198	9.0%	**10**
			Yes	1,889	5,816	32.5%	**6**
	Yes	No	No	19	3,323	0.6%	**13**
			Yes	0	720	0.0%	**14**
		Yes	No	19	354	5.4%	**11**
			Yes	15	108	13.9%	**9**
Yes	No	No	No	1,101	4,749	23.2%	**8**
			Yes	391	1,393	28.1%	**7**
		Yes	No	741	1,775	41.7%	**4**
			Yes	983	1,806	54.4%	**2**
	Yes	No	No	100	267	37.5%	**5**
			Yes	0	67	0.0%	**14**
		Yes	No	75	150	50.0%	**3**
			Yes	595	654	**91.0%**	**1**
All				**7,912**	**109,523**	**7.2%**	

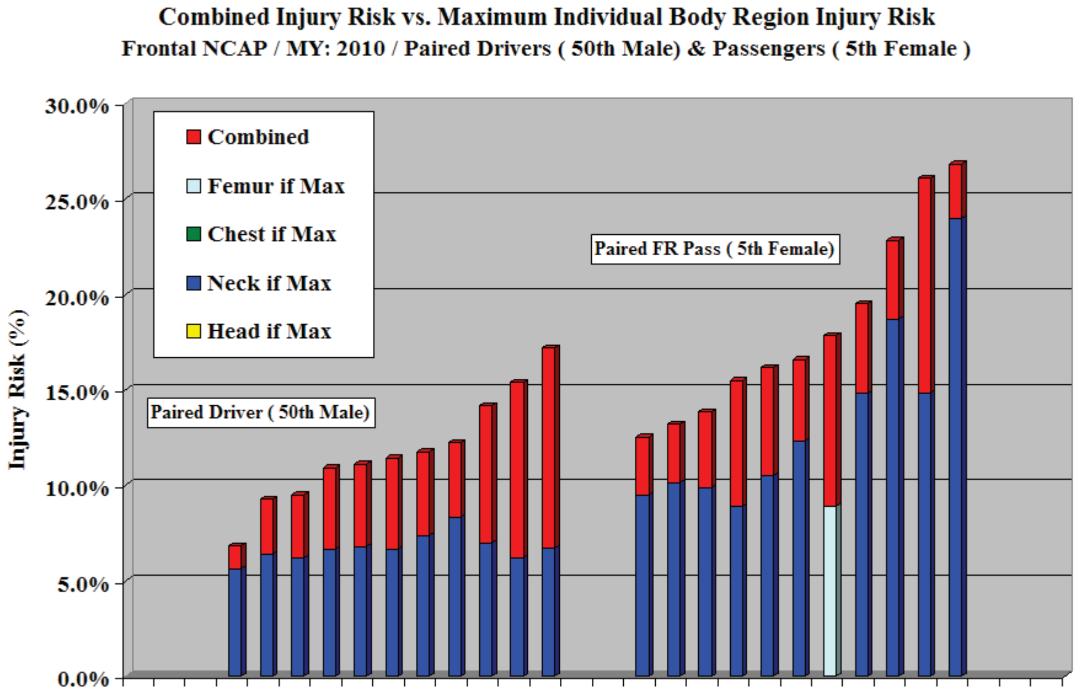
Table 11. Distribution of Individual AIS 4+ Injuries in Frontal Sample as a Function of NCAP Body Region and Age of Occupant

Age of Occupant	Chest AIS 4+	Head-Face AIS 4+	KTP-Complex AIS 4+	Neck-Spine AIS 4+	Other AIS 4+
15-43 Yrs	29.8%	**55.8%**	1.9%	4.2%	8.3%
44-64 Yrs	**51.5%**	31.9%	1.4%	4.6%	10.7%
65-97 Yrs	**51.2%**	37.1%	0.7%	4.1%	7.0%
All	41.7%	43.4%	1.5%	4.3%	9.0%

INVESTIGATION OF FIELD RELEVANCE OF PROPOSED NCAP CHANGES

NHTSA recently completed a series of 11 full frontal rigid wall tests of 2010 model year passenger vehicles following the testing protocols announced for the revised NCAP program, including the substitution of the Hybrid III 5th female for the 50th male in the right front passenger seating position. The dummy responses obtained in this series of 11 tests were processed to allow calculation of the combined probability of injury (CPI) for each dummy using the injury risk functions defined in the new NCAP frontal rating scheme. The body region which had the highest probability of injury was also identified. The results are summarized in Figure 4.

Figure 4



What is most striking regarding these results is that, except for one front right passenger, the neck is shown to have the highest risk of injury. This is completely at odds with all of the NASS field findings, which consistently show the neck-spine to have the lowest rate of injury of the four NCAP body regions. The lower bound NASS estimates, previously discussed are summarized in Figures A.1 and A.2, respectively for drivers and front right passengers. The corresponding upper bound NASS estimates are presented in Figures A.3 and A.4.

To further explore how body region injury rankings generated by the new injury risk functions referenced in NCAP correlate with field data, a retrospective review of NCAP tests previously performed by NHTSA was undertaken. Data for a total of 456 NCAP tests were secured and processed using the injury risk functions which will be used in the new NCAP program. This total included 302 tests of 1988 to 2006 model year passenger vehicles. This subset of tests was judged to most closely represent the vehicle population in the NASS database.

A comparison of the injury probabilities for the driver derived from this series of 302 tests with the injury rates for the driver derived from the NASS analyses is presented in Table 12. Here we can see there is very close agreement between the NCAP tests and the NASS field data with respect to the combined probability of injury value, as well as for the risk of AIS 3+ injury to the head-face body region. However, as in the case of the 2010 MY tests noted above, we again see that the risk of neck injury calculated from the NCAP test data is grossly overstated, while risks to the chest, and the knee-thigh-pelvis, appear to be understated.

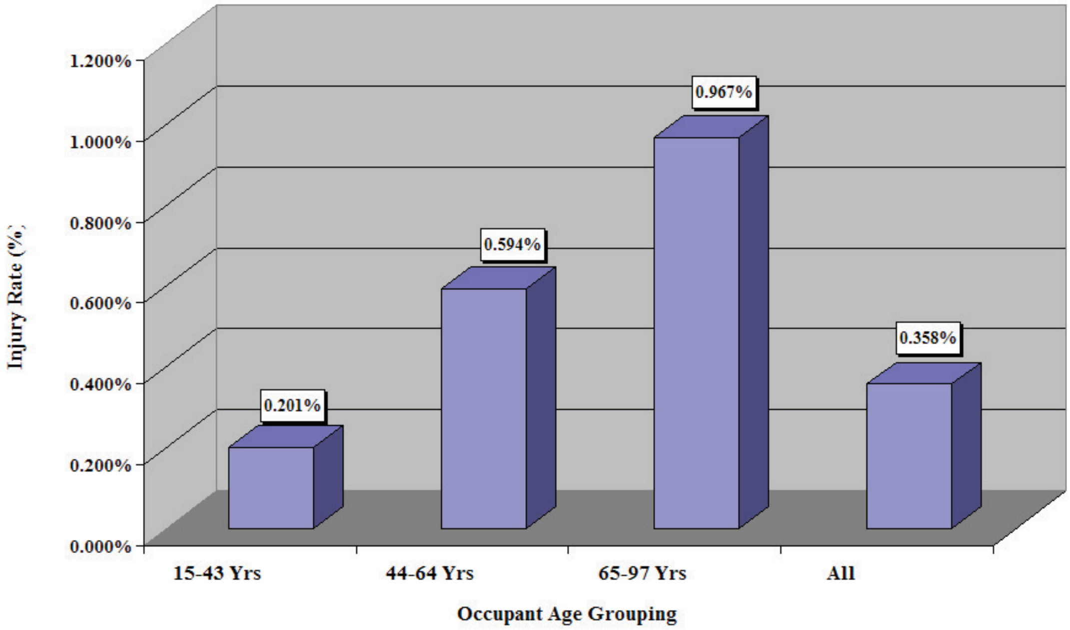
Table 12. Comparison of Injury Risks Derived from NASS Field Data with Those Derived from NCAP tests (Driver Only)

Body Region	Injury Rates - Field Data (NASS)			Injury Rates - NCAP
	49 - 64 km/h Lower Bound	56 - 71 km/h Upper Bound	Mid-Point Estimate	Model Years 1988-2006
Neck-Spine >= 3	0.7%	0.7%	0.7%	7.9%
Head-Face >= 3	2.4%	4.0%	3.2%	2.3%
Chest >= 3	7.7%	13.6%	10.6%	6.8%
KNP >= 2	11.3%	16.7%	14.0%	4.9%
NCAP (Any)	16.7%	25.1%	20.9%	20.1%

In the case of the neck, the lack of correlation can, in large part, be directly attributable to the shape of the Nij injury risk function NHTSA is proposing to employ in the new NCAP program. The proposed Nij injury risk curve is depicted in Figure B.1 of Appendix B. The risk function has a non-zero risk intercept (4% risk for Nij = 0), and has a shallow rising slope. Consequently, it can be expected to overstate neck injury risk for all Nij values below 1. Eliminating Nij, and employing only the neck axial force to compute neck injury risk, reduces the 1998-2006 NCAP driver risk from 7.9% to 0.5%. The revised risk value compares favorably with the 0.7% rate for the neck-spine (all) calculated from the NASS field data.

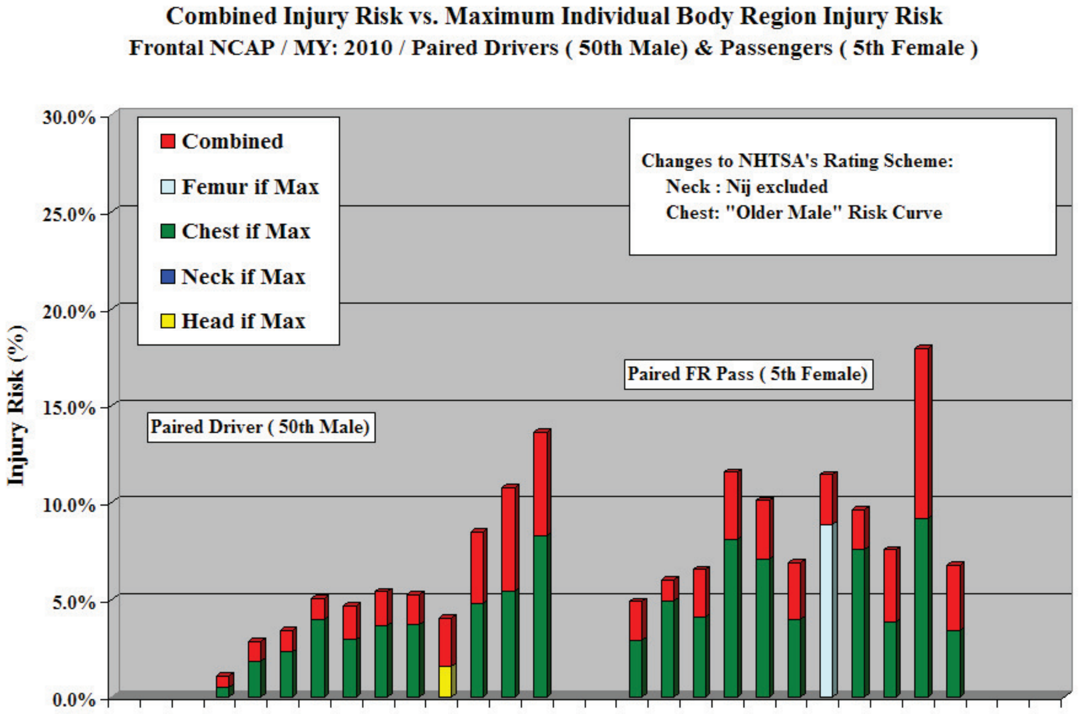
Figure 5

AIS >= 3 Chest Injury Rate



In the case of the chest, NHTSA elected to employ an injury risk curve normalized to a 35 year-old occupant on the basis that this corresponds to the mean age of the US driving population. While this is true, it is important to recognize that the risk of chest injury varies greatly as a function of age. As reflected in the NASS chest injury rates depicted in Figure 5, the injury rate of belted occupants between 44 and 64 years of age is close to 3 times greater than that of occupants between 15 and 43 years of age. This differential is even greater for the oldest segment of the population (65+). This group, which is expected to double over the next decade, shows a chest injury rate close to 5 times that of younger occupants. Since the mean age of the belted population who sustain AIS>=3 chest injury in the US is currently 50 years, a more representative chest injury risk function is desirable. Of the chest injury risk curves already defined in the published literature, the closest representative chest injury risk function would be the “older male” [13]. This would change the 1998-2006 NCAP driver risk from to 6.8% to 12.4%. The revised rate compares favorably with the chest injury rate interval of 7.7% - 13.6% derived from the NASS field data.

Figure 6



The impact of the two changes, when applied to the 11 vehicles previously tested by NHTSA in their validation program is depicted in Figure 6. The overall risk ratings, and the relative ranking of the vehicles, have changed significantly. Rather than the neck, the chest is now judged to be at highest risk of injury, particularly among passengers. This again is in complete agreement with the nature of the residual belted occupant safety problem, as determined by the earlier NASS analyses.

INVESTIGATION OF CRASH PULSES

With the advent of airbags, many vehicles now possess on-board recording systems that, in the event of a frontal collision, capture information related to the crash. Typically, event data recorders (EDR) capture details of the collision itself, such as the crash pulse, the seat belt pre-tensioner and air bag firing times, as well as some pre-crash data elements, such as vehicle speed, throttle and brake application, and seat belt use status. The crash pulse information captured by EDR's has been shown to be reasonably accurate through comparisons of the processed EDR data with equivalent data captured by laboratory instrumentation during staged collisions [14,15,16].

In both Canada and the US, government research programs have integrated the use EDR data into their in-depth collision investigation programs. As a result, there are growing databases of real-world collisions that include detailed crash pulses and other data elements from the crash phase. These data provide valuable insight into the performance of vehicle structures and safety systems in crashes. They also afford a means of evaluating the field relevance of crash tests employed in regulations and consumer safety programs.

The use of a full-width rigid wall test has long been popular in regulatory environments in North America as this test provides a stable and repeatable environment for assessing restraint system performance with belted as well as unbelted dummies. The crash pulses generated in these test are comparatively short and, for a given vehicle model, the pulse duration is largely insensitive to the test speed. This can be observed from the velocity-times histories obtained in a series of tests of the same vehicle model conducted by Transport Canada [14].

From the data presented in Figure C.2, it can also be observed that air bag decision to fire times can vary greatly as a function of collision environment [14]. The shortest times are typically associated with rigid wall tests of vehicles with single stage airbags (6.7 ms average) while the longest time (85 ms) was associated with a low-speed offset frontal deformable barrier test conducted at 40 km/h. Subsequent rigid wall tests of vehicles fitted with dual-stage airbags showed an increase in the average air bag decision to fire time to 13 ms (range of 8 to 16 ms).

The range of airbag decision to fire times typically observed in the field are depicted in Figures C.3 and C.4. The data presented in Figure C.3 are drawn from in-depth collision investigation performed in Canada, while those in Figure C.4 are drawn from NHTSA's National Motor Vehicle Crash Causation Survey database [17]. Here we can see that there very close agreement between the two datasets in the range of airbag decision to fire times. In both samples, the fire times ranged from just below 10 ms to over 140 ms The average fire times were nearly identical in the Canadian and US samples (33 ms vs. 34 ms).

The velocity-time histories obtained in full frontal rigid wall tests over the speed range from 40 km/h to 56 km/h are compared with those obtained in 64 km/h offset frontal deformable barrier tests in Figure C.5. For comparative purposes, the velocity-time histories observed in the Canadian field sample, for the subset of cases where the maximum recorded ΔV exceeded 40 km/h, are depicted in Figure C.6. The corresponding velocity-time histories observed in the Canadian field sample, for the subset of cases where the maximum recorded ΔV exceeded 32 km/h, are depicted in Figures C.7 and C.8 as a function of whether not the airbag fire time exceeded 18 ms. As can be seen from the collective findings, there is very minimal overlap of the velocity-time histories produced in staged full width rigid barrier tests with those produced in offset deformable barrier tests. To encompass the full range of velocity-time histories and airbag fire times observed in the field both types of tests are required.

SUMMARY AND DISCUSSION

Two agencies conduct vehicle crashworthiness rating tests in the US - NHTSA and IIHS. Between the two rating programs, full rigid barrier tests, offset deformable barrier tests form the basis for the frontal ratings. For side impacts, crabbed and perpendicular moving deformable barriers representing the LTV fleet in the US and pole tests are the basis. IIHS conducts sled tests of seats in rear impact to rate their occupant protection. For rollover ratings, roof crush resistance is tested, and a vehicle's static stability factor is determined. This suite of tests makes the US public domain testing program one of the most comprehensive in the world.

New Car Assessment Programs continue to evolve as more safety technologies and regulations are introduced. A review of the major programs in the US, Europe, Japan and China shows that there are many similarities in the test protocols, and some differences, the prime one being the lack of full-frontal barrier crash tests in EuroNCAP. Worldwide, the rating schemes adopted are generally similar and are based, in large part, on crash test dummy responses of the important body regions – the head, neck, chest, femurs and lower extremities. The ratings generally relate to known injury assessment reference values that have entered into regulations in the various regions, although minor variations exist. All global rating schemes, except for the newly revised NHTSA NCAP rating scheme, utilize the regulatory limits for dummy responses as the upper boundary for gaining points, and lower values are set for gaining maximum points. In general, the points are cumulated for the different crash modes and a Star Rating is given. The latest rating scheme proposed by the NHTSA is similar, but will be based on the combined probability of injury to different parts of the body, i.e. head, neck, chest and femur/thigh/hip complex.

A rating system based on combined probability of injury has merit in that it promotes the development of technologies that would have the biggest effect in minimizing real world injuries. However, it is important that the injury risk curves used in the scheme are relevant, and predict real world accident data. Vehicle rankings and overall frontal crash test ratings were found to be particularly sensitive to the choice of injury risk functions employed in the test. This was particularly true in the case of injury risk functions used to assess neck injury potential. Neck injury risk derived from Nij was found to show the least agreement with the field.

The analysis of data presented in this paper also suggests the need to consider the age, gender and weight of the injured population when developing NCAP rating systems for frontal crashes. Ideally, the rating scheme should consider the changing trends in occupant demographics. This is particularly critical in the selection of the chest injury risk function. Chest injury risk increases substantially with increasing age. In most countries, the mean age of the driving population is expected to increase over the next decade. Consequently, the choice of chest injury risk function can be expected to influence how successful the NCAP rating scheme will be in improving frontal crash protection as the population ages.

Acknowledgements

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Figure A.1

Frontal Crash Injury Rate as a Function of Body Region and AIS Severity

Belted Occupants / Frontal Airbag-Fitted Passenger Vehicles / NASS: 1988-2008

Drivers / Delta-V Interval: 49-64 kph

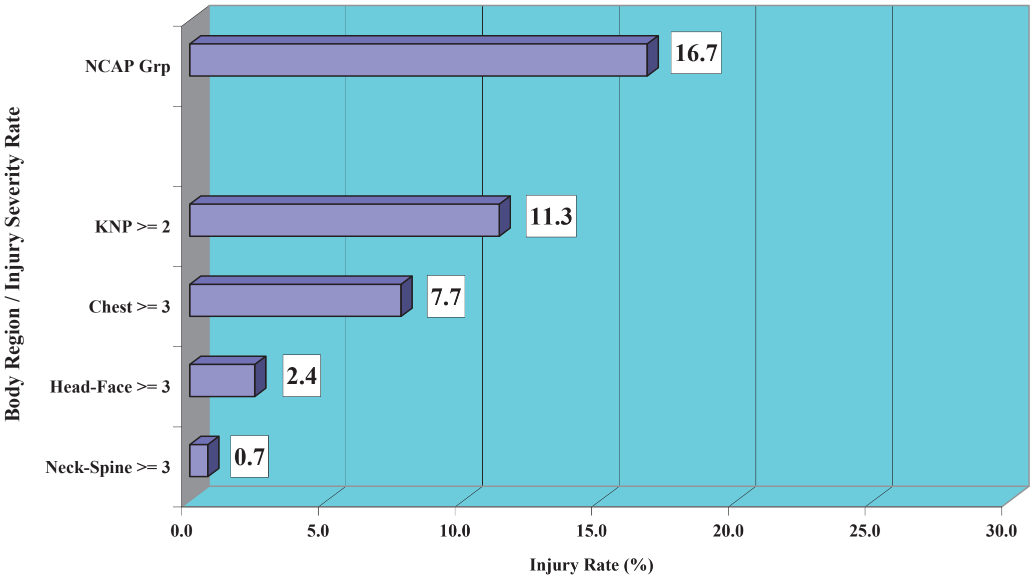


Figure A.2

Frontal Crash Injury Rate as a Function of Body Region and AIS Severity

Belted Occupants / Frontal Airbag-Fitted Passenger Vehicles / NASS: 1988-2008

Front Right Passengers / Delta-V Interval: 49-64 kph

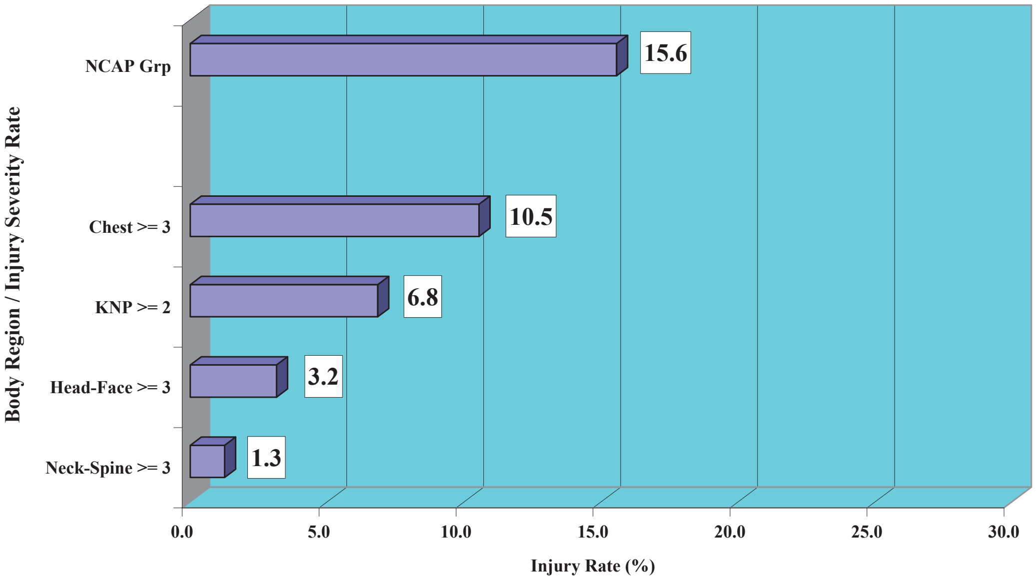


Figure A.3

Frontal Crash Injury Rate as a Function of Body Region and AIS Severity

Belted Occupants / Frontal Airbag-Fitted Passenger Vehicles / NASS: 1988-2008

Drivers / Delta-V Interval: 56-71 kph

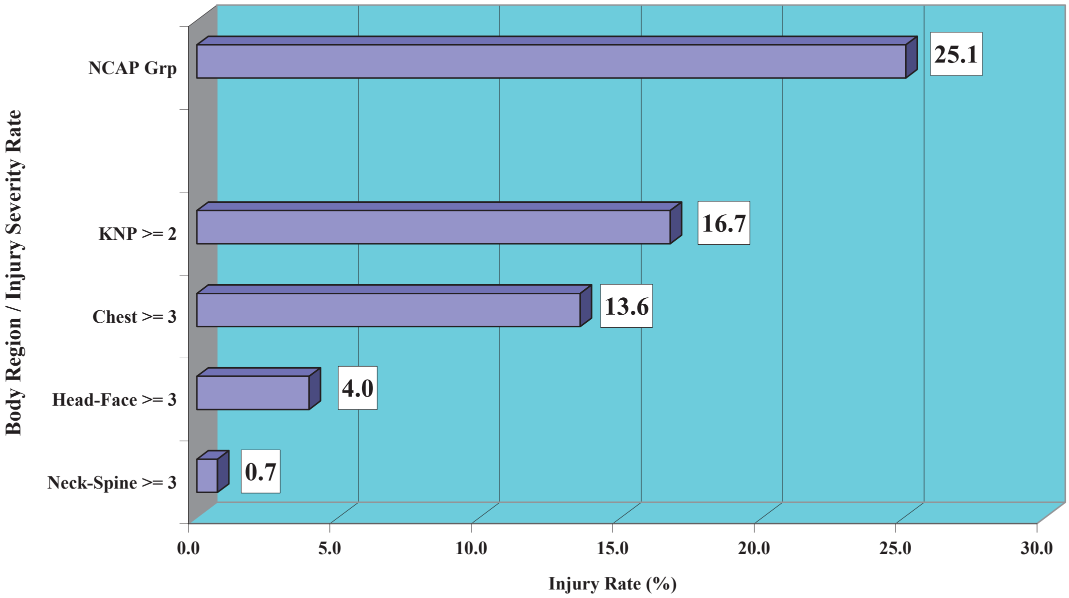


Figure A.4

Frontal Crash Injury Rate as a Function of Body Region and AIS Severity

Belted Occupants / Frontal Airbag-Fitted Passenger Vehicles / NASS: 1988-2008

Front Right Passengers / Delta-V Interval: 56-71 kph

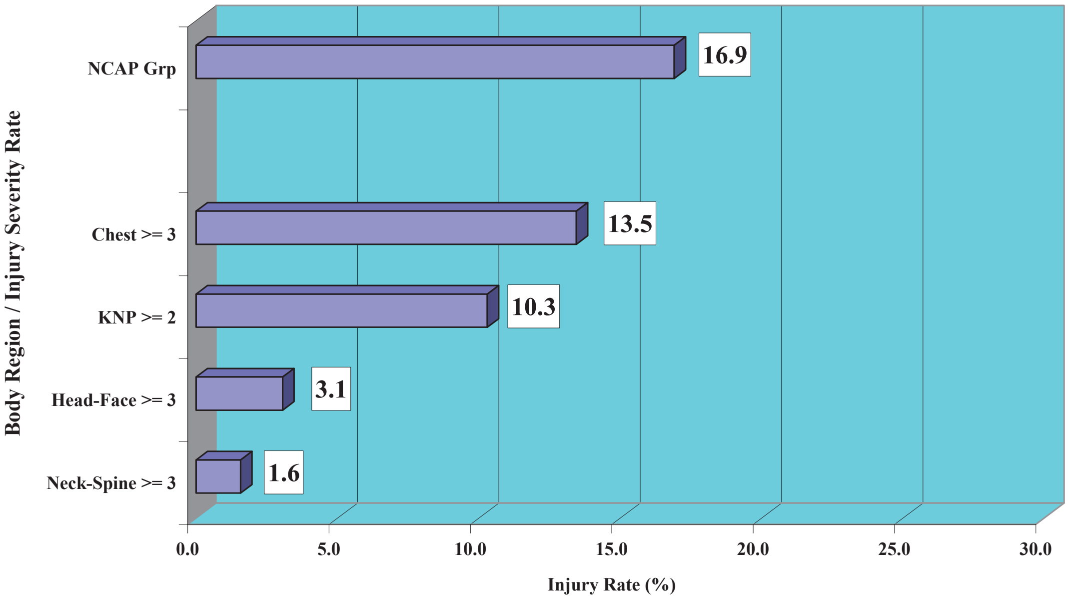


Figure B.1

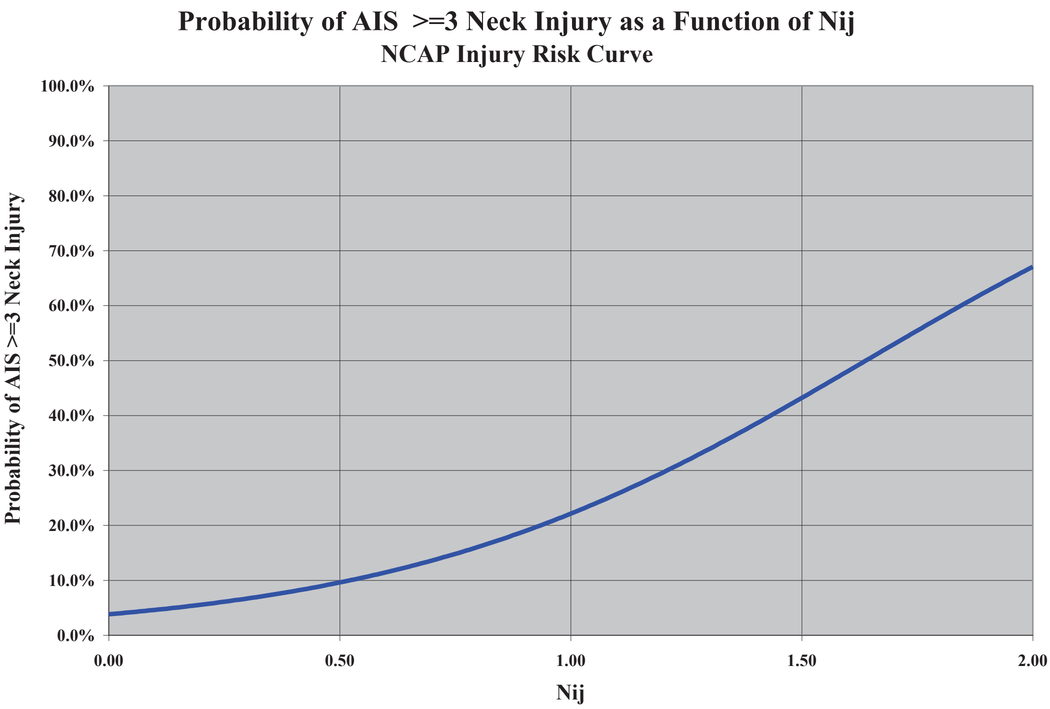


Figure B.2

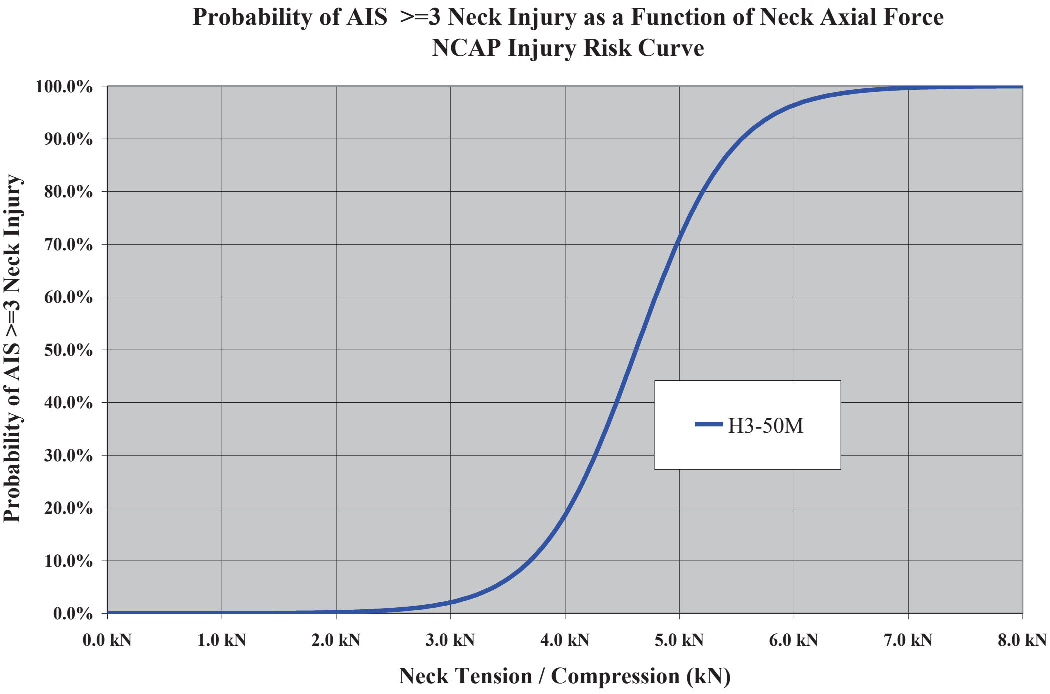
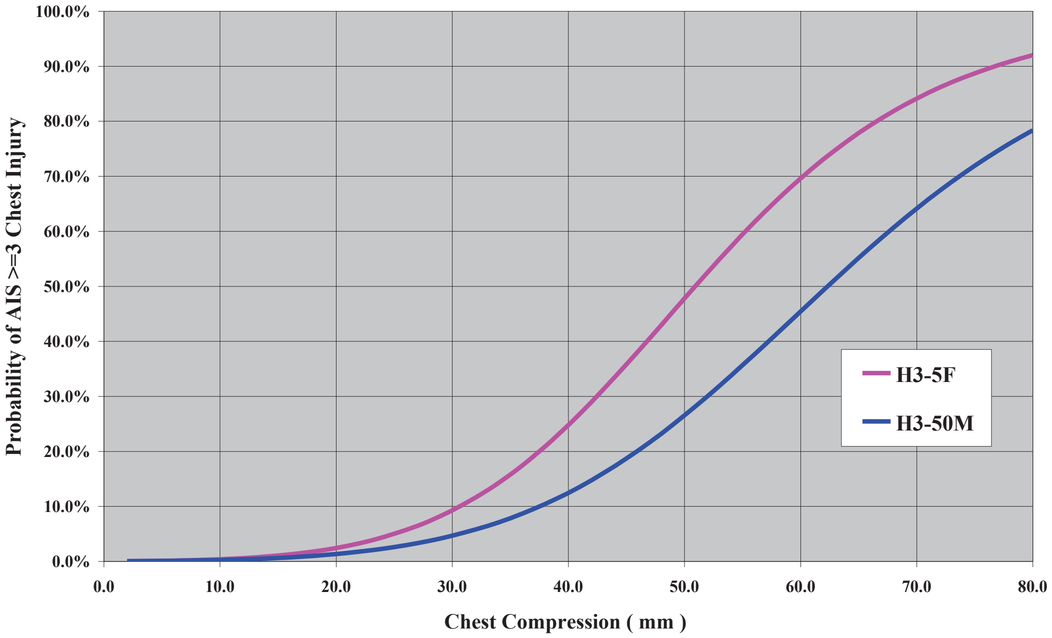
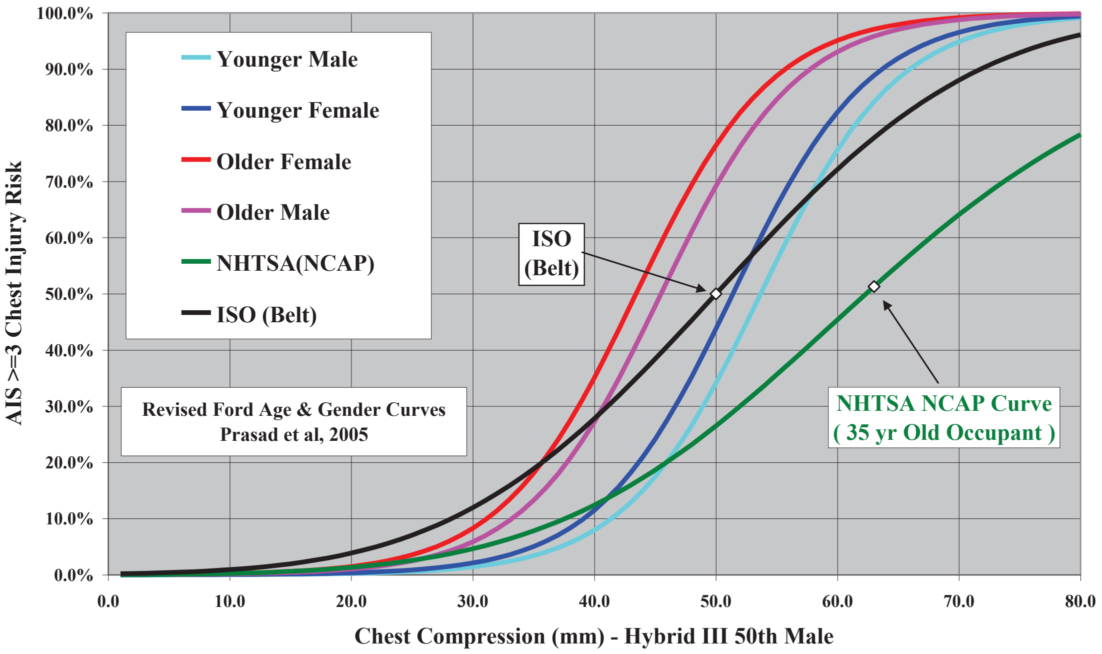


Figure B.3



Probability of AIS >=3 Chest Injury as a Function of Chest Compression
NCAP Injury Risk Curves

Figure B.4



Risk of AIS>=3 Chest Injury
(Based on Deflections Measured with a Hybrid III 50th Male ATD)

Figure C.1

Rigid Wall Delta-V Profiles (Same Vehicle)

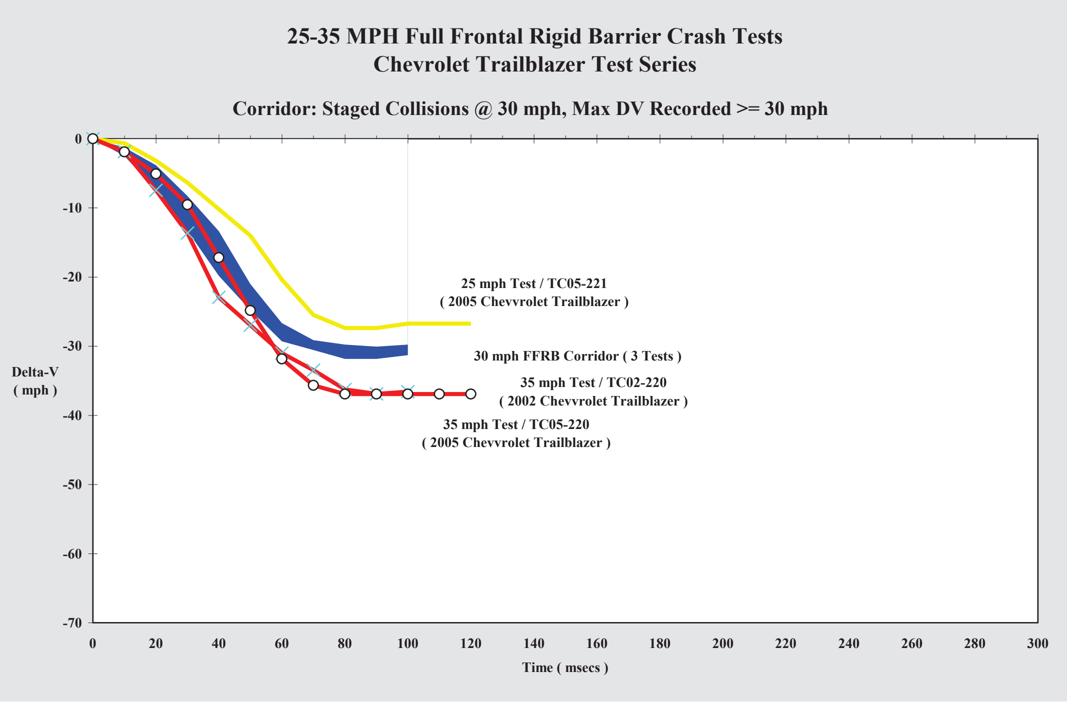


Figure C.2

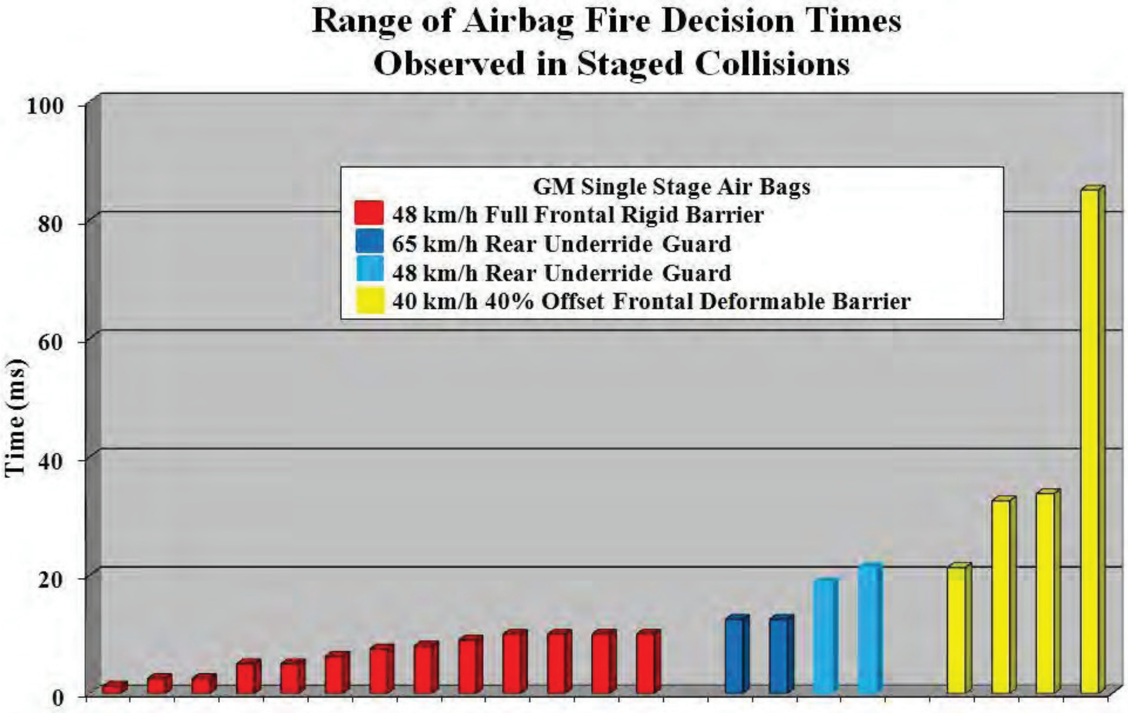


Figure C.3

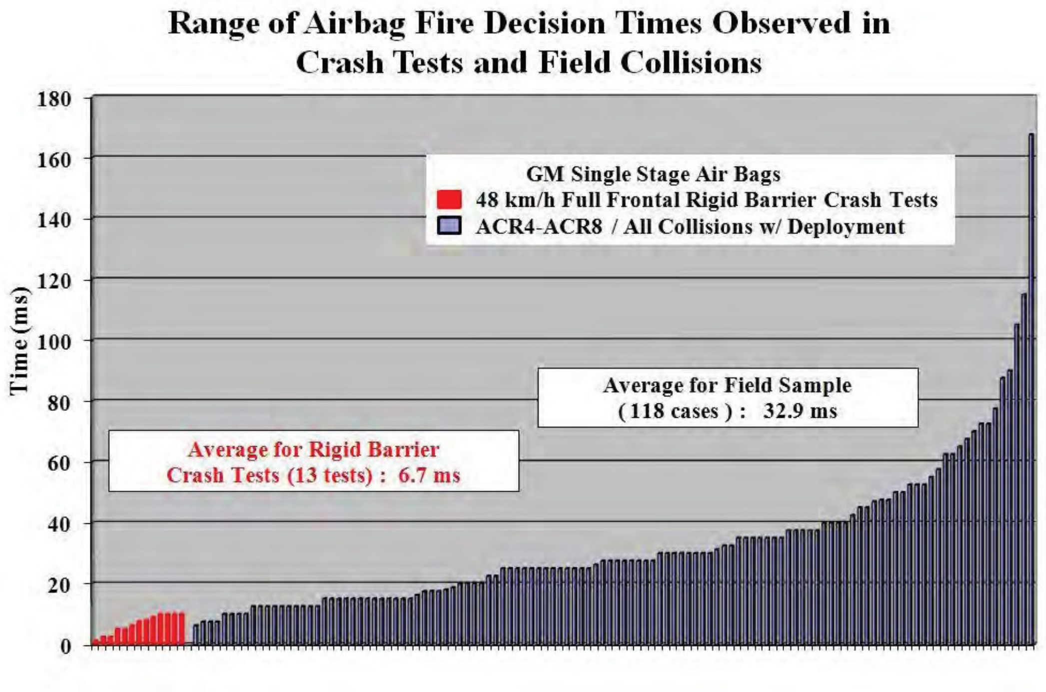


Figure C.4

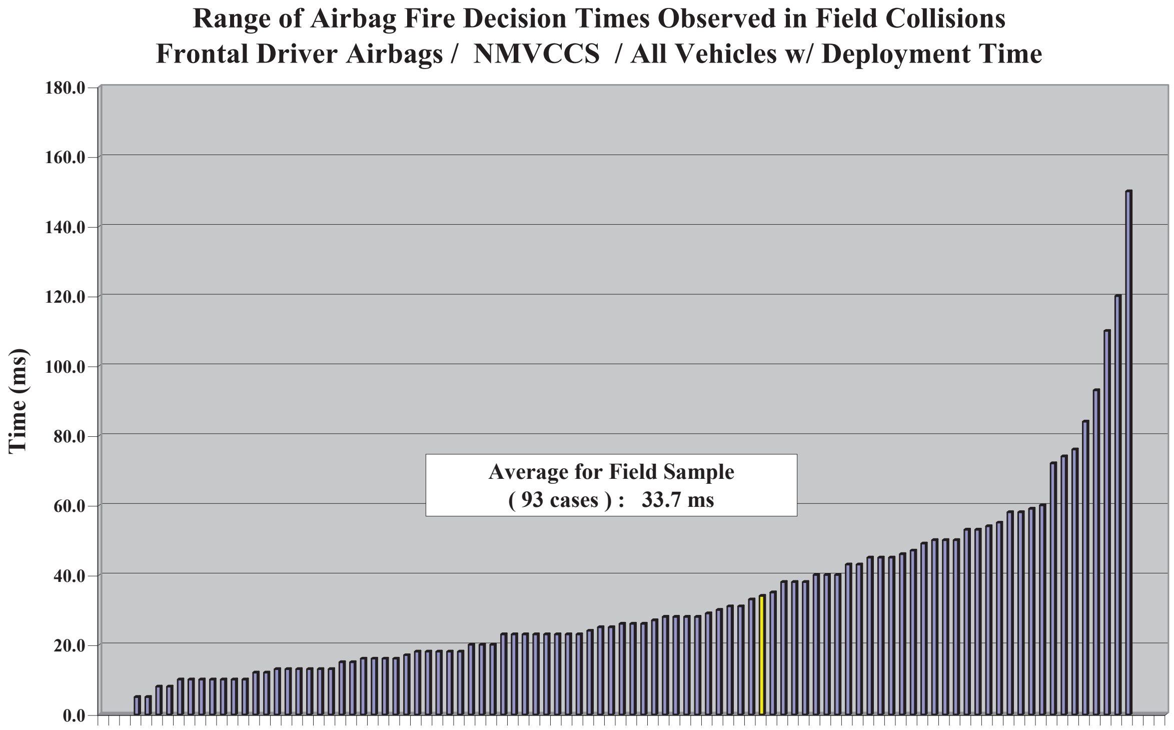


Figure C.5

FFRB vs. OFDB Velocity Time Histories

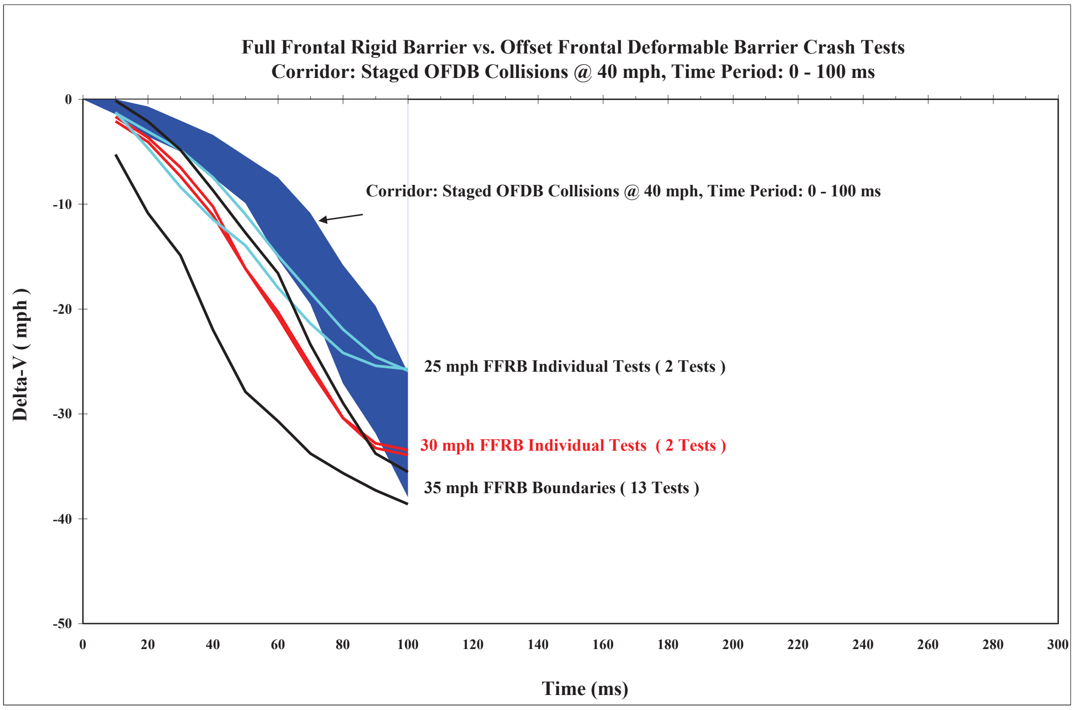


Figure C.6

Delta-V Time Histories Observed in Field Collisions

GM Single Stage Airbags / Maximum Recorded Delta-V >= 25 mph

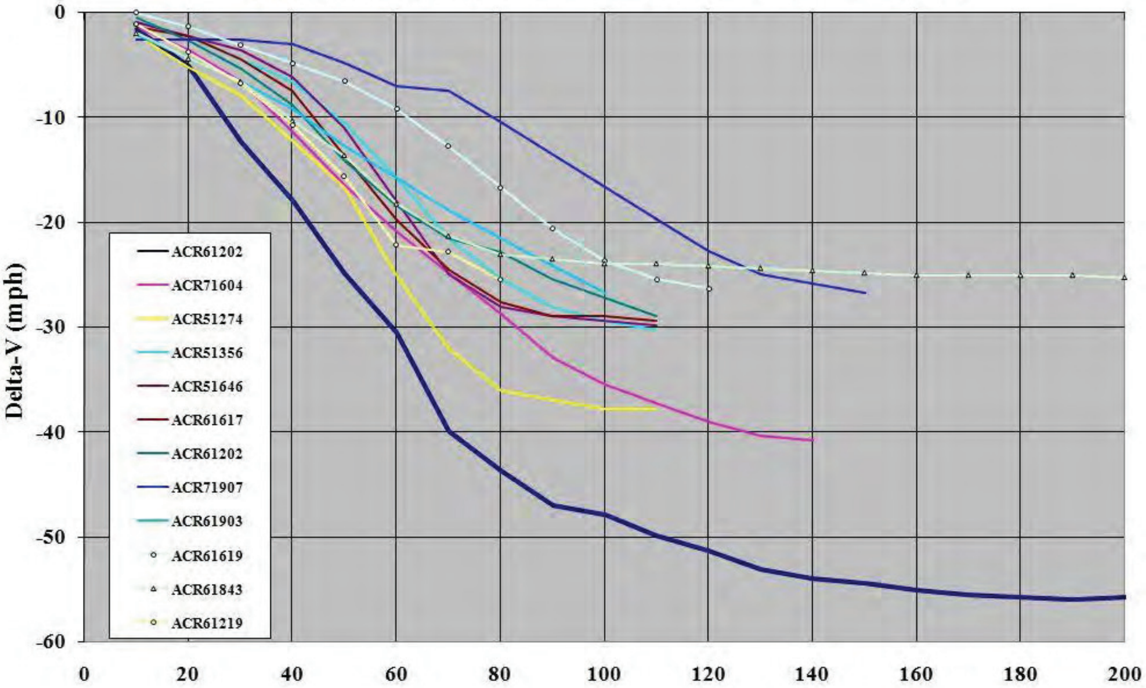


Figure C.7

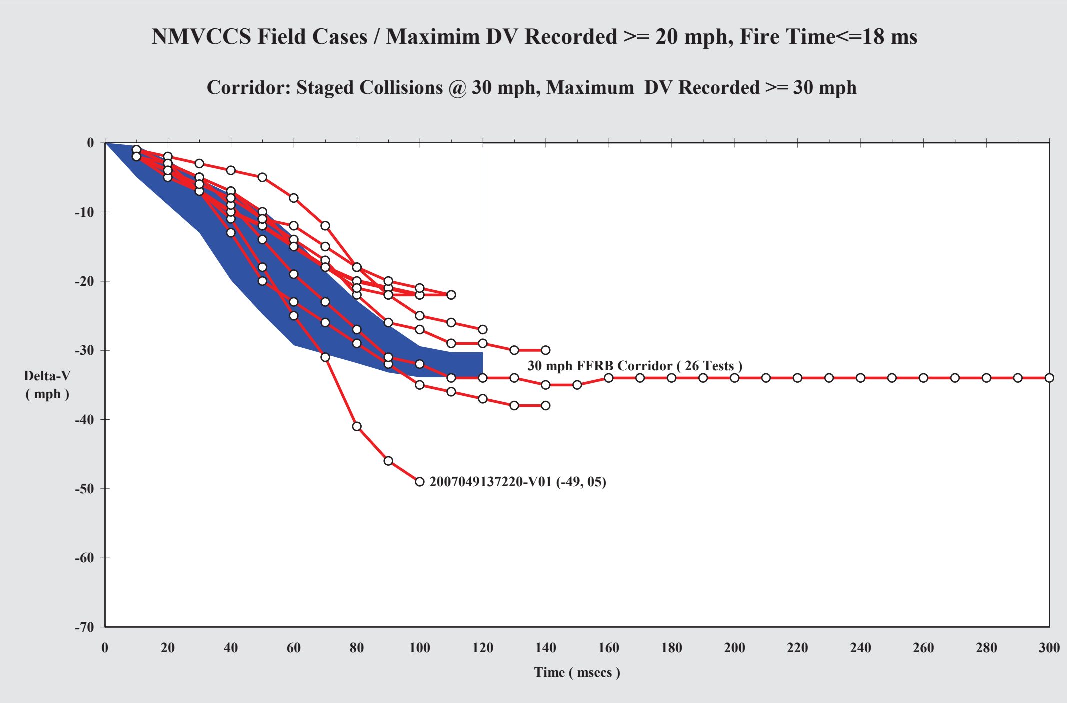
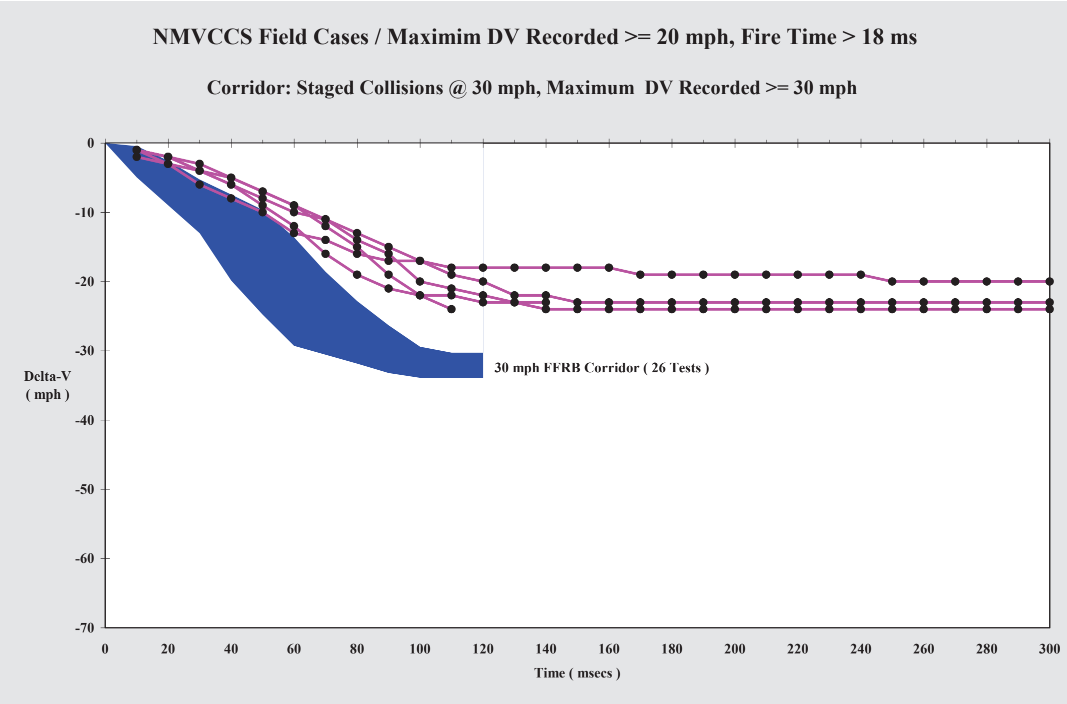


Figure C.8



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