ANALYSIS OF INJURY TRENDS IN FRONTAL UNIVERSITY OF MICHIGAN CIREN CASES IN THE CONTEXT OF CRASH TESTS

Bridget O'Brien-Mitchell
Kacy Bailey
Daniel Faust
Jack Jensen
Julie Kleinert
Christine Wodzinski
Carla Kohoyda-Inglis
Stewart Wang
University of Michigan Program for Injury Research and Education
United States
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ABSTRACT

Four-hundred forty two U-M CIREN (University of Michigan Crash Injury Research and Engineering Network) cases have previously been compared to crash tests used in the automotive industry. The comparison demonstrated that the majority of cases were similar in crash configuration and extent to industry crash tests, while smaller proportions either had a greater extent of crash deformation or had different crash configurations than those commonly produced in crash tests.

Of the 442 cases, 290 frontal cases were analyzed in greater detail to understand trends in injury causation while considering physical characteristics of occupants (gender, age, body mass index.) Those trends were then evaluated in the context of biomechanics of crash test tools such as Anthropomorphic Test Devices [ATDs] and injury risk curves. Several trends were identified and presented.

INTRODUCTION

Studies have demonstrated that fatality rates from motor vehicle crashes in the United States have been reduced over the last several decades. As an example the fatality rate per 100 million miles driven was 5.5 in 1966 and steadily declined to 1.41 in 2006. In addition, injuries have been reduced from 169 injuries per 100 million miles driven in 1988 to 85 in 2006. Despite the significant improvements in automotive safety, there continue to be about 38,500 annual fatalities due to motor vehicle crashes [1]. Therefore there is benefit to investigating the remaining fatalities and injuries due to motor vehicle crashes.

The goal of this project was to analyze the injuries sustained by occupants in frontal crash U-M CIREN cases and identify trends within crash configurations and Collision Deformation Classification (CDC) extent groups [2].

Of the 290 frontal case occupants, 73% were drivers and 19% were right front passengers. There were slightly more females, 51%, than males, 49%. The average age of the case occupants was 41 years old. 66% of the women and 50% of men were using 3-point seat belts. The average Body Mass Index (BMI) was 27.3 which is categorized as overweight [3].

BACKGROUND

Comparison of Frontal Crash U-M CIREN Cases to Existing Types of Crash Tests

Auto manufacturers routinely conduct crash tests to verify compliance to crash test regulations for any country in which a vehicle may be marketed, for evaluations of consumer metric tests, and for internal review of vehicle performance. Four-hundred forty two U-M CIREN (University of Michigan Crash Injury Research and Engineering Network) cases have previously been compared to crash tests used in the automotive industry. Table 1 lists the frontal crash test types that were developed for comparison to the U-M CIREN cases in the previous study [2].

Table 1.
Included Industry Crash Tests

0 Degree Frontal (FMVSS 208 or Frontal NCAP)
Left Angle or Offset (FMVSS 208 angle or IIHS offset)
Right Angle or Offset (FMVSS 208 angle)
Frontal Center Pole
Frontal Offset Pole
Bumper Underride

The cases were additionally divided by those with CDC extents above and below the extents assigned to these crash tests. Finally, the remaining frontal cases were grouped in new crash configuration categories as shown in Table 2.

Table 2.
Frontal Crash Types without a Corresponding Crash Test

Left small overlap
Right small overlap
Underride
High undercarriage
Sideswipe
Corner underride
Offset underride

It is important to acknowledge that this study is based solely on cases documented in the U-M CIREN database. As such, the uninjured population is not included for comparison. By the definition of the CIREN selection criteria, all of the case occupants are severely injured patients. Those crashes in which there are no injuries or only minor injuries are not included in the CIREN database or the U-M CIREN database, and are not referenced in this study. Thus it is not appropriate to use the CIREN database or the U-M CIREN database in isolation to estimate risk to the driving public.

The distribution of U-M CIREN frontal cases is shown in Figure 1. 53.8% of the 290 frontal cases studied matched an existing crash test configuration with an extent less than or equal to the test. 32.1% of the frontal cases matched an existing crash test configuration but with greater extent, and 14.1% did not match an existing crash test configuration.

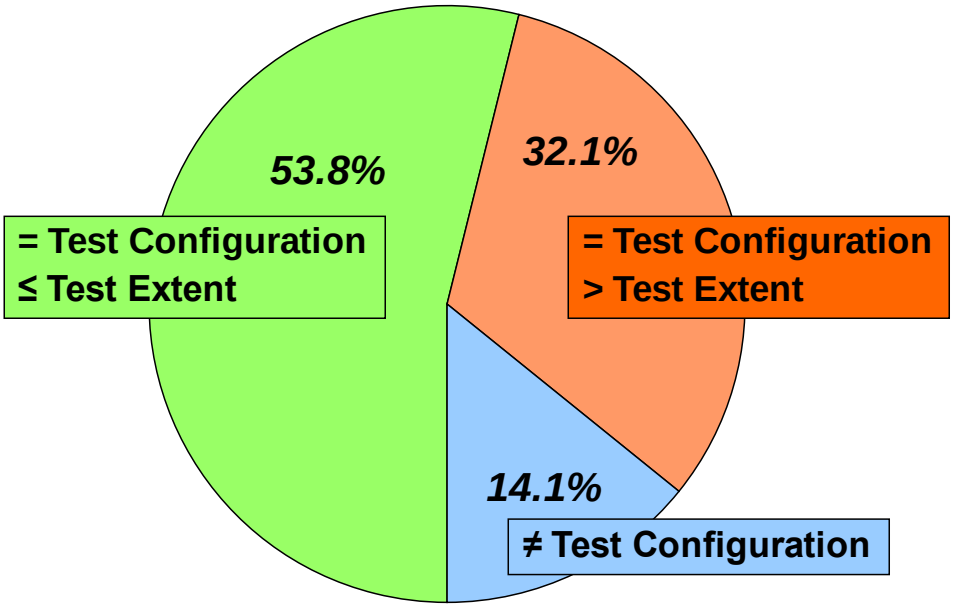

Figure 1. Distribution of U-M CIREN Frontal Cases.

Cases Matching Test Configuration and Extent

Figure 2 shows the distribution of the 53.8% of U-M CIREN crash cases that had configurations similar to and CDC extents less than or equal to current laboratory tests. For frontal crashes, the 0 degree frontal impact category was the most represented in U-M CIREN followed by the left angle or offset category.

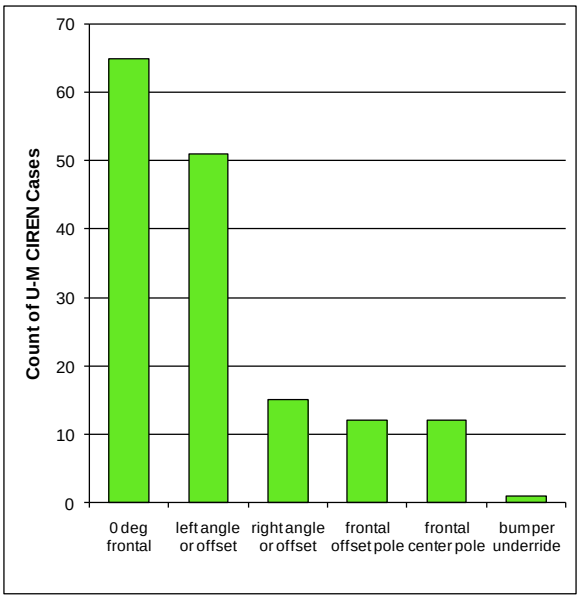

Figure 2. Distribution of U-M CIREN Cases for Crashes with Similar Configurations and CDC Extents Less Than or Equal to a Current Industry Crash Tests.

Cases Matching Test Configuration but with Greater Extent

Figure 3 shows the distribution of the 32.1% of U-M CIREN crash cases that had configurations similar to current laboratory tests with CDC extents greater than current crash tests. Similar to the cases with lesser extents, the 0 degree frontal was the most prevalent frontal impact, followed by the left angle or offset category. There were very few frontal pole crashes with extents greater than the industry crash tests.

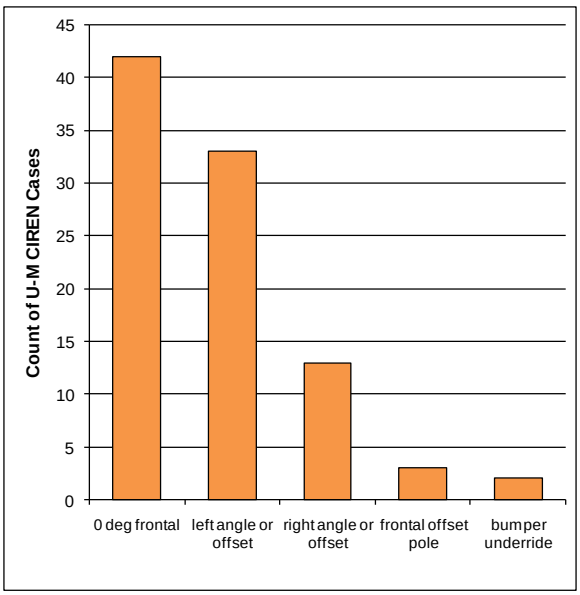

Figure 3 — Distribution of U-M CIREN Cases For Crashes with Similar Configurations and CDC Extents Greater than a Current Industry Crash Test

Cases Not Matching Test Configuration

Figure 4 shows the distribution of the 14.1% of U-M CIREN crash cases that did not match a current industry crash test configuration. The majority of these cases were left or right small overlap crashes. The small overlap crashes had deformations that were typically outside of the longitudinal rails.

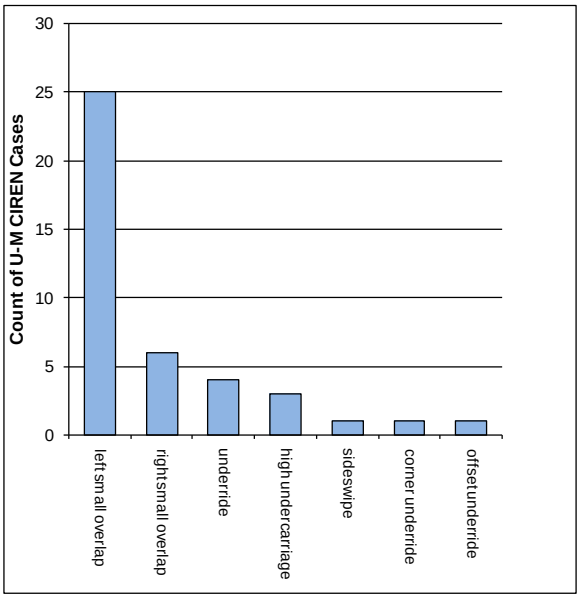

Figure 4. Distribution of U-M CIREN and CIREN Cases for Crashes That do Not Match a Current Industry Crash Test.

ANALYSIS

Injury Trends by Body Region

Figure 5 shows the distribution of AIS 3+ injuries by body region for each of the three frontal impact categories. The body regions with the highest number of injuries were the lower extremity, the thorax and the head.

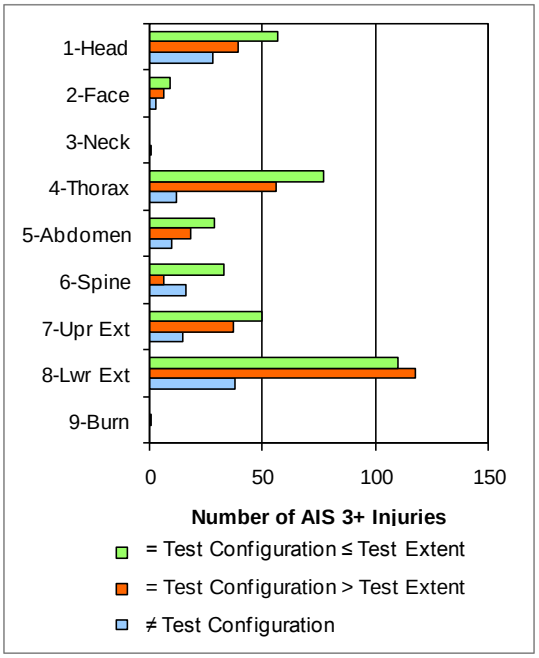

Figure 5. Frontal Impact Crashes – AIS 3+ Injuries by Body Region.

Injury Trends for Frontal Cases Matching Test Configurations and Extent

For frontal cases that had configurations similar to current laboratory tests and had extents less than or equal to current crash tests, the top ten contact locations were identified based on the number of AIS 3+ injuries assigned to that contact location. A contact location assigned to an injury in the CIREN database indicates that the injury was associated with direct contact with that location during the crash event. These contact locations are assigned during CIREN case reviews. The most common contact locations can be seen in Figure 6. 65% of injuries were due to contact with the instrument panel, seatbelt, steering wheel, and airbag while 11% of injuries were due to contact with the vehicle side structure and door. The vehicle side structure includes components such as the A-pillar, B-pillar, roof rail, and door glass.

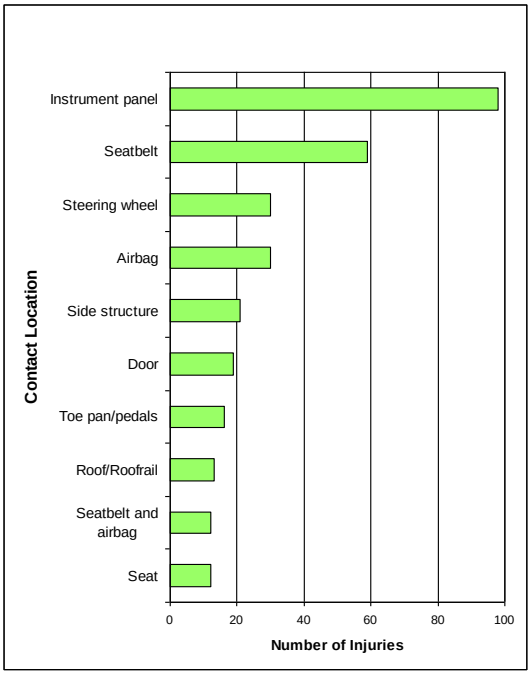

Figure 6. Frontal Impact Crashes - Top 10 Contact Locations - AIS 3+ Injuries.

<u>Injuries Assigned to the Instrument Panel</u> As seen in Figure 7, 72% of the AIS 3+ injuries attributed to the instrument panel were to the lower extremities including the femur, pelvis and tibia.

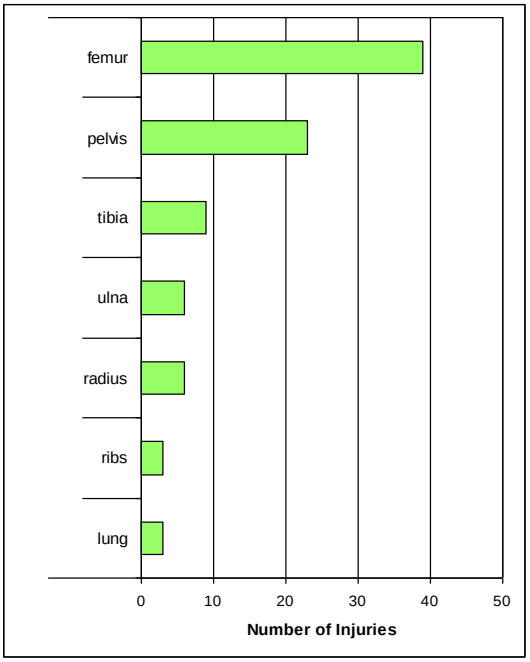

Figure 7. Frontal Impact Crashes - AIS 3+ Injuries Assigned to Instrument Panel (Body regions with ≤ 1 injury/region not shown).

While the majority of people in the frontal cases studied were belted, the majority of lower extremity AIS 3+ injuries occurred to unbelted occupants (Figure 8).

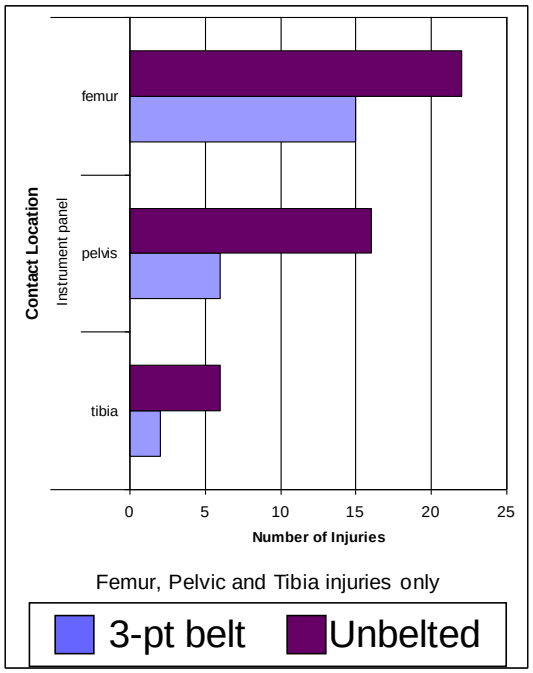

Figure 8. Frontal Impact Crashes - Lower Extremity AIS 3+ Injuries Assigned to Instrument Panel Contact.

Figure 9 shows that women had approximately half as many pelvic fractures as men. Pelvic fractures consist of fractures of any bone in the pelvis, including the acetabulum. In the U-M CIREN database, belt usage rates for men were 50%, while rates for women were 66%. This difference in seat belt usage rates alone did not completely account for the difference in pelvic fractures between men and women.

Wang reported that, men and women have differences in pelvic geometry and weight distribution [4].The male pelvic structure is taller and narrower than that of the female. In the male, the cup of the acetabulum or hip socket is oriented to face more laterally and the head of the femur is usually large in comparison to the relative size of the acetabulum. In contrast, female pelvic structures are wider and shorter. The cup of the acetabulum in the female pelvis faces more anteriorly and the female typically has a smaller femoral head as compared with the male. The laterally facing acetabulum of the male pelvis is more susceptible to fracture in a frontal collision because as the femur is loaded axially in a frontal crash, less surface area of the acetabulum is presented as a reaction surface to the femoral head. In addition the acetabular cup is generally thinner at the edges, and the edges are exposed to more crash forces with the lateral facing male acetabulum. The anteriorly facing acetabulum of the female is more resistant to fractures from the frontal crash forces. In women, the load is more adequately absorbed by the whole cup of the acetabulum rather than just the edge due the orientation of the cup [4].

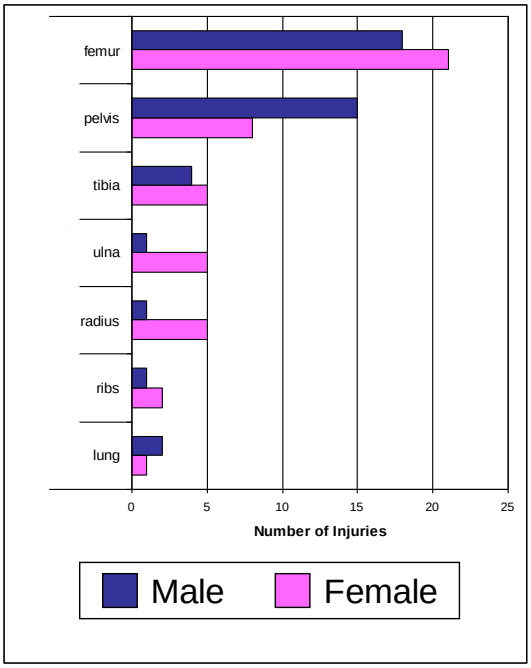

Figure 9. Frontal Impact Crashes - AIS 3+ Injuries Assigned to Instrument Panel (Body regions with ≤ 1 injury/region not shown).

Men and women also tend to carry their weight differently. Men tend to be more apple-shaped and carry their weight in their abdomen (android-type obesity) while women tend to be more pear-shaped and carry their weight in their hips and thighs (gynecoid-type obesity). In a frontal crash, when extra weight is carried more on the hips and thighs, the inertial load of the weight is primarily applied to the femur. When extra weight is carried in the abdomen, the inertial load of the weight is applied to the pelvic structure first and then to the femur. Because men tend to carry more weight in their abdomen, this could be a factor in why men sustained more pelvic fractures than women. Male pelvic structures are forced to carry more of their inertial load in a frontal crash.

Because the pelvis and femur share a load path in a frontal crash, when one of these structures break, the load on the other is relieved [10], [11].Therefore, if a

woman first experiences a femur fracture in an event, it is less likely that she will then also experience a pelvis fracture. This is supported by the data in Figure 9 which showed that women appeared to have slightly more femur and tibia fractures than men.

Femur loads are measured in the Hybrid III crash dummy and regulated in crash tests. Femur fractures, however, still occur in the field. . Potential for femur injury is evaluated by the Hybrid III crash dummy using axial loads cells in the femur (Figure 10). The Hybrid III pelvis does not have direct load measurement capability of the femoral head into the acetabulum. Currently, only femur loads and pelvic accelerations are measured.

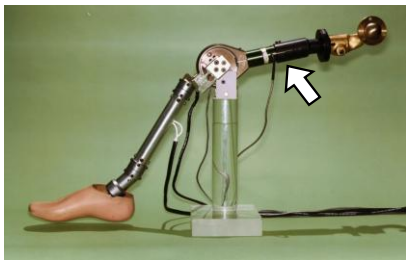

Figure 10. Location of Femur Load Cell.

Federal Motor Vehicle Safety Standard 208 (FMVSS 208) [5] limits for femur force represents a 35% risk of femur or patella fractures [6] (Figure 11). The regulated limit for the 50th percentile male is 10 kN while the limit for the 5th percentile female is 6.8 kN. Femur fractures are AIS 3 injuries and encompass most of the injuries in the case studies. Patella fractures are AIS 2 injuries and would not have been included in this study.

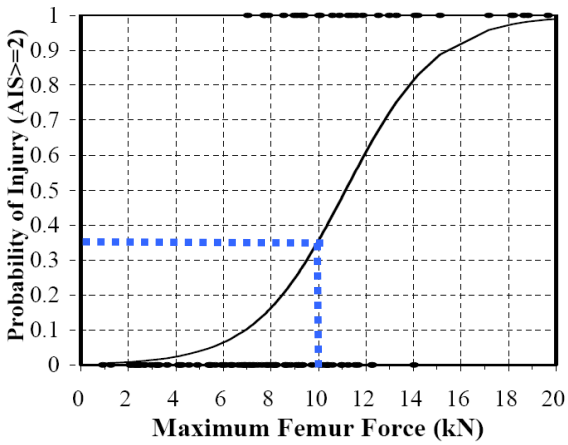

Figure 11. Femur Injury Risk Curve - 50th Percentile Male [7].

Figure 12 shows the occupant BMI distribution for lower extremity injuries and Figure 13 shows the BMI distribution for all frontal impact occupants in the U-M CIREN database.

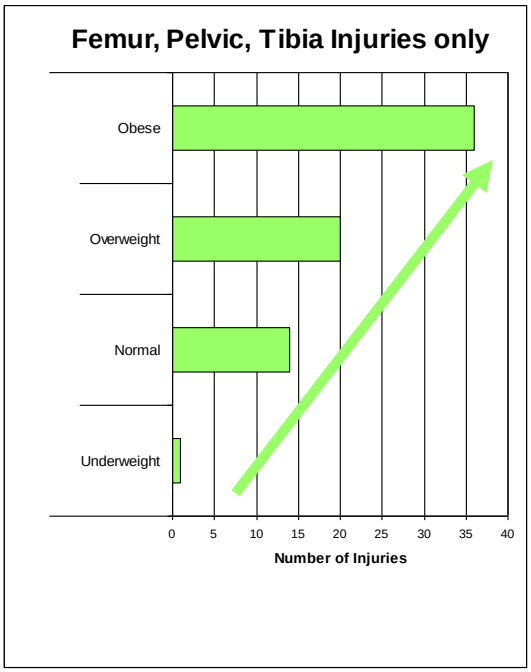

Figure 12. BMI Distribution for Lower Extremity AIS 3+ Injuries Assigned to Instrument Panel.

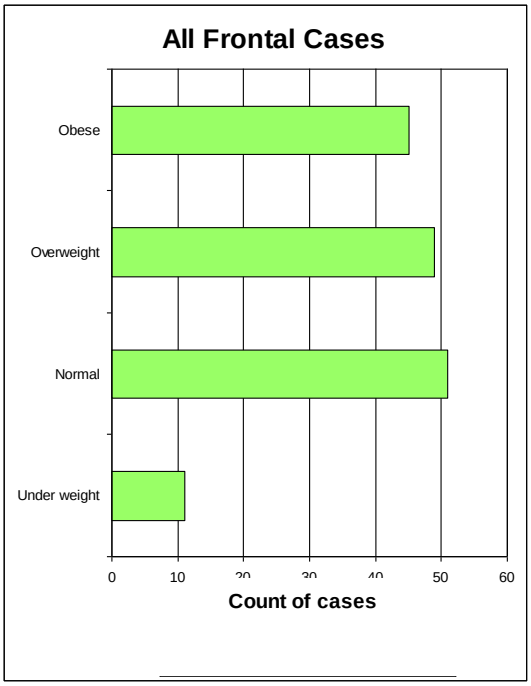

Figure 13. BMI Distribution for all Frontal Impact Occupants.

Obese occupants were over represented in the group with femur, pelvic and tibia injuries. As BMI

increased the number of lower extremity injuries also increased. An individual with a higher BMI has additional overall mass which increases the occupant energy without an equivalent increase in bone strength. This may contribute to the increased number of lower extremity injuries among the overweight and obese case study occupants.

Injuries Assigned to Seat Belts As can be seen in Figure 14, of the 58 AIS 3+ injuries assigned to seat belt contact in frontal impacts similar to current laboratory tests, the most frequent were rib fractures, hollow visceral injuries, and cervical spine injuries.

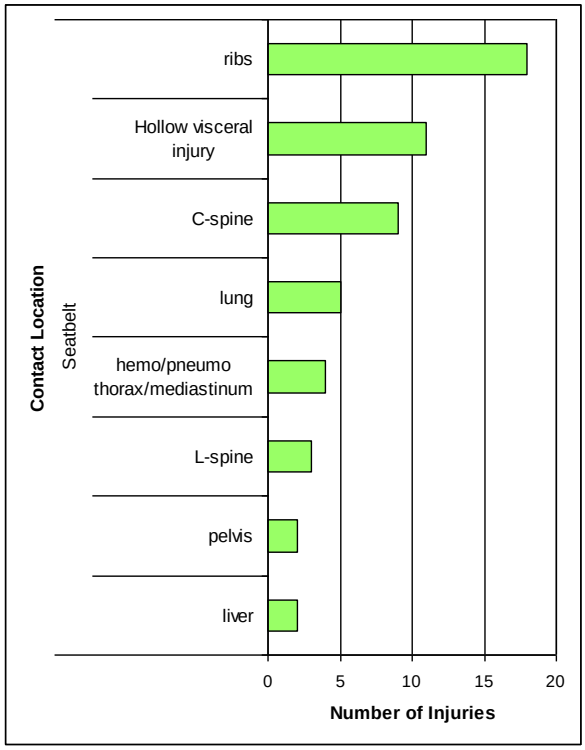

Figure 14. Frontal Impact Crashes - AIS 3+ Injuries Assigned to Seat Belt (Body regions with ≤ 1 injury/region not shown).

Reviewing the specific cases involving rib fracture indicated that older women were over represented in the group with AIS 3+ rib fractures. Of the 18 belted occupants in this group, 12 were women. Of those women, 8 of the 12 were over 50 years of age.

Figure 15 shows the distribution by occupant BMI of rib fractures assigned to seat belt contact.

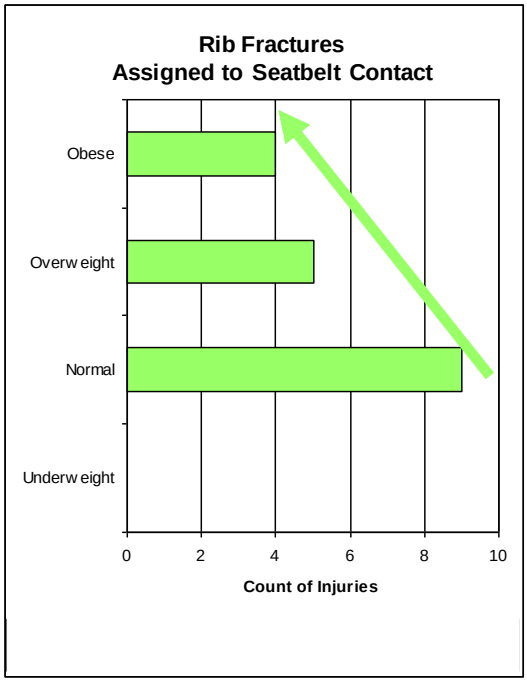

Figure 15. BMI Distribution for Rib Fractures Assigned to Seat Belt.

While the potential for femur, pelvic, and tibia fractures assigned to instrument panel contact appeared to increase with increased body mass index, the potential for seat belt related rib fractures appeared to decline with increased body mass index. Occupants with body mass indices categorized as overweight or obese were less represented in the group with AIS 3+ rib fractures assigned to seat belts, when compared to the population of all seriously injured occupants in frontal crashes in the U-M CIREN database. Body fat may have had an energy-absorbing and/or load-distributing effect that reduced the potential for rib fractures from belt loading.

The 8 occupants with AIS 3+ hollow visceral injuries were also reviewed. Five occupants were adults, and four of those adults had body mass indices in the over-weight category. The other three occupants with hollow visceral injuries occurred to lap-belt-only restrained children.

There were 7 occupants with cervical spine injury. Five of the cervical spine injury case occupants involved women 56 years of age or older. One occupant with a cervical spine injury involved a lap-shoulder belted 4 year-old female in a booster seat.

Figure 16 shows the distribution of AIS 3+ injuries assigned to seat belt contact by occupant age and gender and Figure 17 shows the age and gender

distribution for all frontal impact occupants in the U-M CIREN database.

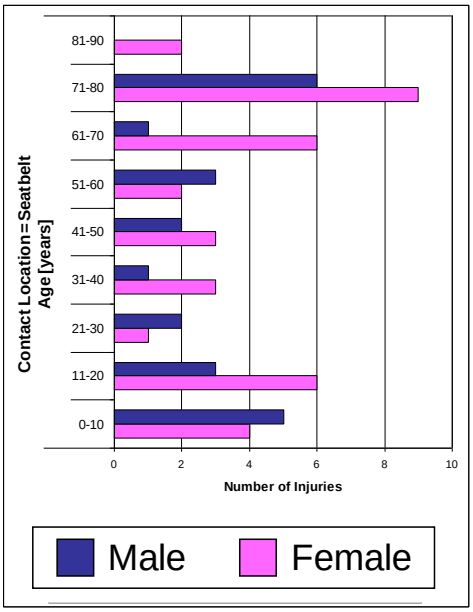

Figure 16. AIS 3+ Injuries Assigned to Seat Belt Contact by Age and Gender.

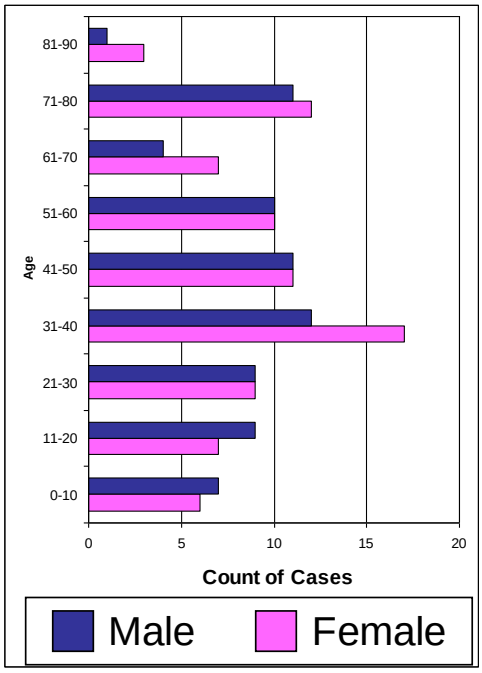

Figure 17. Age and Gender Distribution for All Frontal Impact Occupants.

Younger and older occupants were over represented in the group with injuries assigned to seat belt loading, compared to the population of all seriously injured occupants in frontal crashes in the U-M CIREN database. The greater frailty of older occupants, especially older women, was likely a contributing factor associated with increased potential for rib fracture and cervical spine injury. The relative head size to neck strength of children was likely a factor in the cervical spine injury observed in the one lap-shoulder belted 4 year-old female.

There are various possible explanations why AIS 3+ injuries assigned to seat belts have occurred in crashes even with configurations and damage extents similar to current laboratory tests. Substantial forces must be applied by seat belts to adequately manage the kinetic energy of vehicle occupants in moderate and severe frontal crashes, so it is foreseeable that some injury may result. Other factors include the test dummies, dummy instrumentation, and injury assessment reference values used to predict the potential for injury in current laboratory tests. Test dummies have been developed to represent average infants, 3 year-old children, 6 year-old children, 10 year-old children, small adult females, mid-size males, and large-size males. It is not practical to test, nor do dummies exist to represent all sizes and shapes of people. For example, no dummies exist that represent obese adults. While it is reasonable to assume that safety systems developed using existing test dummies will benefit the range of occupant sizes and shapes, it cannot be expected that injury will be eliminated. The dummies cannot collect data for assessing the potential for all types of injury. Furthermore, injury assessment reference values are set at levels to limit, not eliminate, the potential for certain types of injuries.

The family of Hybrid III ATDs used for frontal impact safety development is capable of measuring chest acceleration on the rigid portion of the spine where the ribs are attached. They are also capable of measuring chest compression on the sternum of the dummy (Figure 18).

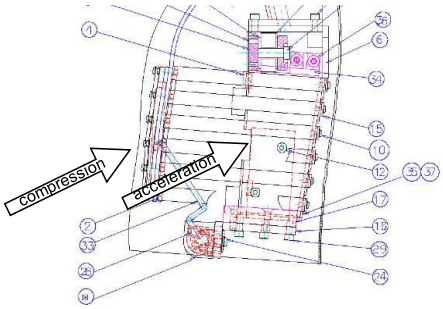

Figure 18. Location of Chest Compression and Acceleration Instrumentation in Hybrid III Dummy.

Chest compression and acceleration are measured in the Hybrid III crash dummy and regulated in crash tests. Rib fractures, however, still occur in the field. FMVSS 208 has regulated chest acceleration for over 30 years and has more recently regulated chest compression. Chest compression measurements have been required with the mid-size male Hybrid III since the 1998 model year but were previously allowed. Recently, the small female was added to the regulation, and the mid-size male chest compression requirements were made more stringent. FMVSS 208 chest compression limits for belt restrained Hybrid III ATDs (63 mm for the mid-size male and 52 mm for the small female)[5] represent an estimated 33 percent risk of AIS 3+ chest injury (Figure 19). Examples of AIS 3 injuries rib injuries are 1 rib fracture with a hemo- or pneumothorax or a flail chest without a lung contusion.

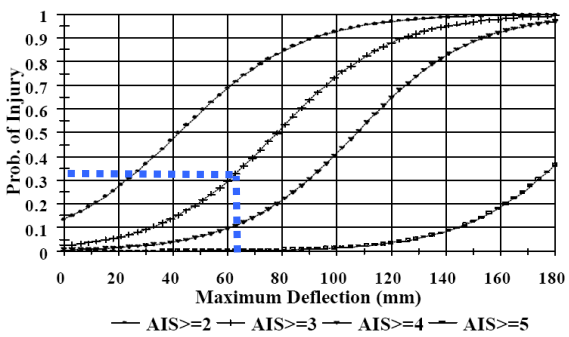

Figure 19. Chest Deflection Injury Risk Curve - Hybrid III 50th Percentile Dummy [8].

Injury Trends for Frontal Cases Matching Test Configuration but with Greater Extent

As is shown in Figure 20, the distribution of U-M CIREN frontal crash cases matching an existing crash test type with CDC extents above and below those generated in tests is similar. To make the comparison more clear, data above and below current test CDC extents were normalized by dividing the number of injuries by the number of cases (Figure 21).

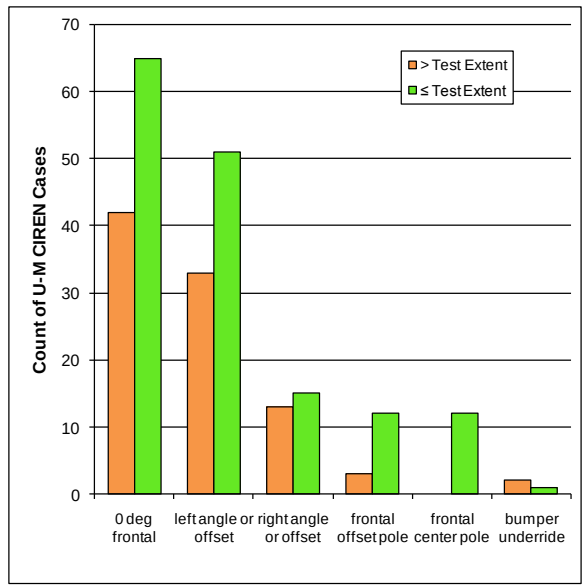

Figure 20. Frontal Cases with Configurations Similar to Current Test Types - CDC Extent Comparison.

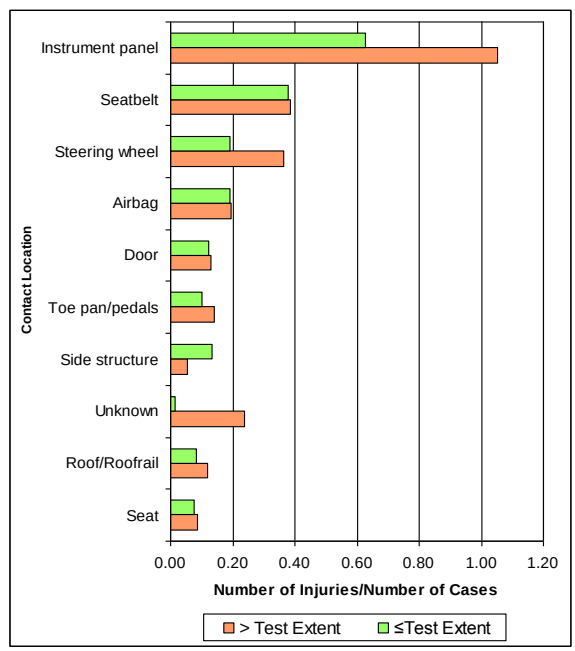

Figure 21. Frontal Impact Case Occupant Injuries by Assigned Contact Location and Extent

The top five vehicle contact locations associated with frontal injuries were instrument panel, seatbelt, steering wheel, airbag, and door. Injuries assigned to instrument panel and steering wheel contact increased with higher extents, however, those assigned to seatbelt and airbag did not increase. This was likely due to the fact that the air bag and seat belt have a finite restraint capacity and once the capacity has been exceeded the next point of contact is the steering wheel and the instrument panel structure behind it. Looking at the number of occupant injuries by assigned contact location and extent, the normalized trend was similar by contact location except for the instrument panel and steering wheel.

Figure 22 shows the distribution of frontal impact femur, pelvis and tibia injuries assigned to the instrument panel for cases with extent less than or equal to crash tests and Figure 23 shows these injuries for cases with extents greater than crash tests. Belts appeared to be more effective in reducing femur, pelvic, and tibia injuries in crashes with lower CDC extents than they were with crashes with higher CDC extents.

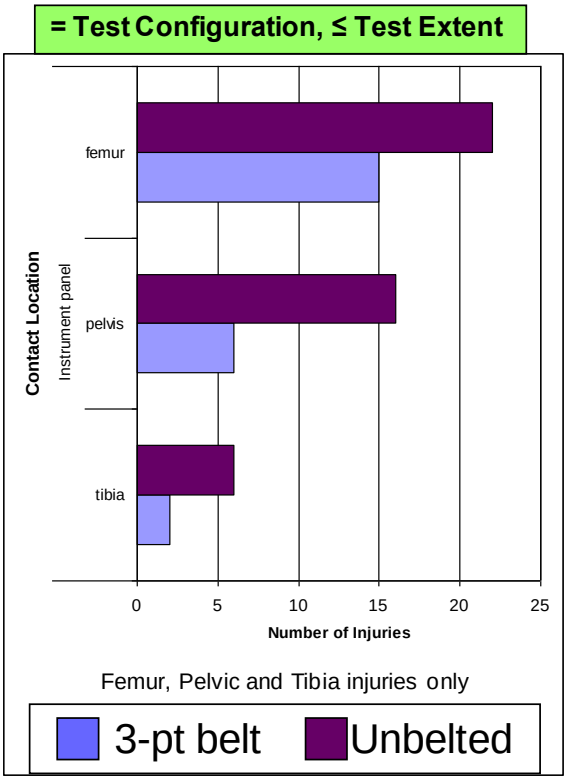

Figure 22. Distribution of Frontal Impact AIS 3+ Pelvic and Tibia Injuries - ≤ Test Extent.

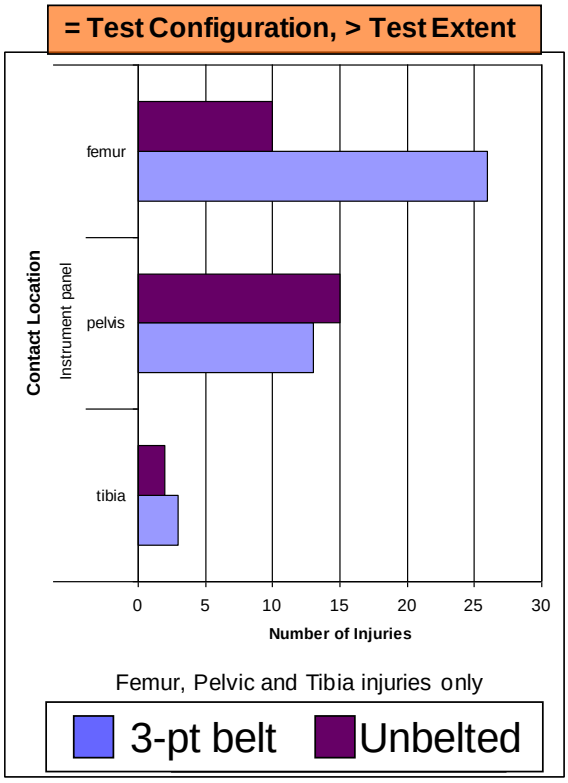

Figure 23. Distribution of Frontal Impact AIS 3+ Femur, Pelvic and Tibia Injuries - > Test Extent.

Overall, the distribution of cases that had an extent greater than the crash test extent was very similar to the distribution of cases that had an extent less than or equal to the crash test extent, however, greater extent cases were over-represented in the UMPIRE database. These cases were high crash severity events and as expected, the occupants were more likely to have injuries that permitted their inclusion in the database. For crashes with lesser extents, injuries were less likely therefore the total proportion of greater extent cases did not represent the actual proportion of these events in the field.

Injury Trends for Frontal Cases Not Matching Test Configurations

Of the 14.1% of frontal cases with configurations that were different from current crash test types, the majority were small overlap crashes. These crash configurations tend to involve localized, concentrated vehicle deformation. While the concentrated loads on the vehicle produced greater maximum crush than for a more distributed frontal crash type, the force generated would have been less, thereby producing lower accelerations of the occupant compartment.

Figure 24 shows the top 10 contact locations for AIS 3+ injuries in frontal crash cases with configurations different from current test types. As with the crash configurations that are similar to test types, injuries assigned to instrument panel contact were the most frequent. A significant difference between the crash cases that are not similar to crash test types and those that are is that injuries assigned to side structure and door contact were more frequent. The higher frequency of AIS 3+ injuries assigned to the side structure and door can be attributed to the greater occupant lateral motion, as well as greater lateral occupant compartment intrusion in small overlap frontal crashes as compared to other frontal crash types.

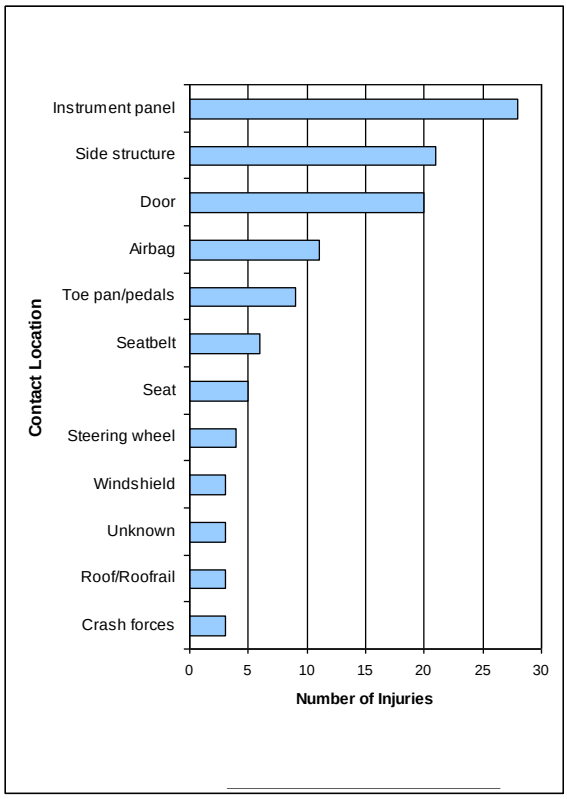

Figure 24. Cases with Frontal Crash Configurations Different from Current Test Types Top 10 Contact Locations (Body regions with ≤ 1 injury/region not shown).

All of the AIS 3+ injuries assigned to the side structure were head injuries attributed to head contact with the A-pillar in five small overlap crashes. These types of head/A-pillar contact injuries may result not only from the vehicle dynamics in small over lap frontal crashes which cause a larger lateral component directing the occupant towards the A-pillar but also due to greater crash induced A-pillar motion.

Figure 25 summarizes the nature of the A-pillar related AIS 3+ head injuries in these small overlap frontal crashes. These were most frequently coded as cerebrum injuries. Injuries to head vessels, basilar skull fractures, and facial fractures were also observed.

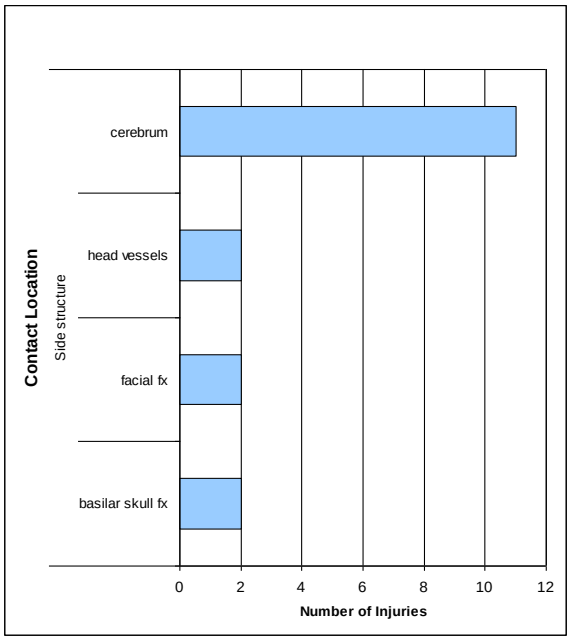

Figure 25. Side Structure Injuries in Cases with Frontal Crash Configurations Different from Current Test Types.

Crash test dummies and injury criteria exist to address these head injuries. The Hybrid III crash test dummy head is designed to measure longitudinal, lateral, and vertical acceleration. These measurements are used to calculate the resultant acceleration of the center of gravity of the head as shown in Figure 26 which in turn is used to calculate Head Injury Criteria (HIC).

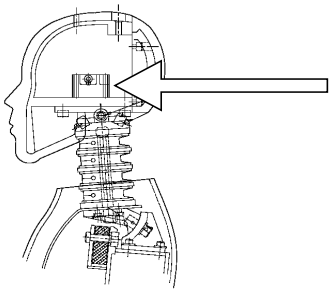

Figure 26. Location of Hybrid III Head Accelerometers.

FMVSS 208 currently limits 15ms HIC to 700. A HIC of 700 represents a 5 percent risk of AIS 4+

brain injury. Brainstem and diffuse axonal injuries are examples of AIS 4+ head injuries. Figure 27 contains the risk curve for AIS 4+ brain injury versus HIC.

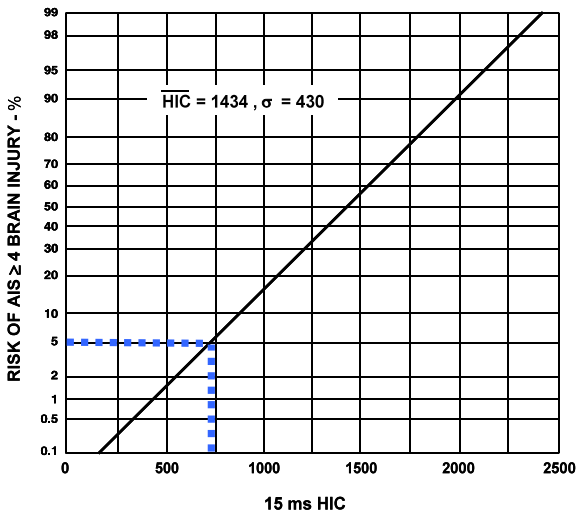

Figure 27. AIS 4+ Brain Injury Risk Curve Adults [9].

While FMVSS 208 and frontal impact air bags address head injuries in most frontal impact configurations, they may not prevent all head to A-pillar contact. FMVSS 201 (Occupant Protection in Interior Impact) currently regulates HIC produced from impacting many areas of the vehicle interior, including the A-pillars, with a head form at 24 km/h (15 mph). However, only a portion of the vehicles in the database met this requirement since it became effective for all new vehicles produced since September 1, 2002.

SUMMARY

Of the 290 UMPIRE frontal crash cases, over half had configurations and CDC extents similar to current crash tests. 65% of injuries in this category were assigned to contact with the instrument panel, seatbelt, steering wheel and airbag, while 11% of injuries were assigned to contact with the side structure of the vehicle and the door. 72% of injuries assigned to contact with the instrument panel were to the lower extremities, and these injuries tended to increase with increased BMI. 31% of injuries assigned to the seatbelt were rib fractures, but these injuries tended to decrease with greater BMI and were more frequent in the older population.

Approximately one third of the frontal cases had configurations that were similar to frontal crash tests but had greater CDC extents than the crash tests. In this category, again, the majority of injuries were assigned to contact with the instrument panel, seatbelt, steering wheel, and airbag. When this category was normalized and compared to the cases with extents less than or equal to those generated in laboratory crash tests, it was noted that injuries assigned to contact with the instrument panel and steering wheel increased with higher extent, whereas those assigned to seatbelt and airbag did not. This difference may be attributed to restraint system characteristics as well as load sharing between the components of the restraint system.

The remaining frontal cases had configurations that were different than current laboratory crash tests, with the majority of these cases categorized as small overlap crashes. As in the other two categories, injuries assigned to contact with the instrument panel were the majority, however, injuries assigned to contact with the side structure of the vehicle and the door were more frequent than in the other categories. All of the injuries assigned to contact with the side structure of the vehicle were head injuries assigned to A-pillar contact. The injuries assigned to the side structure and door may be attributed to the combination of lateral occupant motion relative to the vehicle and A-pillar and door displacement in the small overlap crashes.

RECOMMENDATIONS

Specific recommendations fall within three major observations.

First, the majority of injuries occurred in crashes similar to current tests that are conducted by the industry. Injury trends identified in these cases that match crash tests suggest that further study in some areas may be appropriate. Specifically differences observed in male and female acetabulum fractures suggest that further development of test measurement devices could be considered. As an example, the possible inclusion of direct acetabulum measuring load cell in frontal impact crash dummies could be investigated. In addition trends were identified relative to the effect of BMI on injury risk – some injuries increased with increased BMI while others decreased. An investigation of testing or modeling techniques to evaluate injuries to overweight occupants should also be considered.

Second, rib fractures still occurred despite chest acceleration and chest compression being measured and regulated for model years of essentially all vehicles in the database. The current FMVSS 208 chest compression limit represents an estimated 33

percent risk of AIS 3+ chest injury. The July 2008 revision to NHTSA's frontal NCAP program requires a lower chest compression limit for a vehicle to achieve a 5-star rating. Further investigation into the effects of this change in NCAP may indicate a reduction in rib fractures. In addition, it may be beneficial to research the possibility of new technologies capable of identifying occupants in terms of age, gender, BMI etc. to essentially "individualize" a restraint system to mitigate certain injuries.

Lastly, small overlap crashes comprised the majority of the cases with frontal crash configurations that were different from current crash test types. These crash configurations tend to involve localized vehicle deformation and lateral occupant motion. Current IIHS and FMVSS 208 offset deformable barrier tests have resulted in improvements to the vehicle's front structure and occupant compartment structural integrity. The case vehicles in which the cerebrum injuries occurred were older model years and may not have had the current offset deformable barrier tests or the current FMVSS 201 head impact tests as specific design objectives when they were developed. In addition, new technologies that provide for curtain air bag deployment in frontal impacts and curtain air bag designs which include A-pillar coverage may show a reduction of these injuries. The effect of new performance objectives and new technologies in more recently designed vehicles on injury trends in small overlap frontal crashes should be studied.

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