CHARACTERISTICS OF THE INJURY ENVIRONMENT IN FAR-SIDE CRASHES

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ABSTRACT

The population of occupants in far-side crashes that are documented in the US National database (NASS/CDS) was studied. The annual number of front seat occupants with serious or fatal injuries in far-side planar crashes and rollovers was 17,194. The crash environment that produces serious and fatal injuries to belted front seat occupants in planar far-side crashes was investigated in detail. It was found that the median crash severity for serious and fatal injuries was a lateral delta-V of 28 kph and an extent of damage of CDC 3.6. Vehicle to vehicle impacts were simulated by finite element models to determine the intrusion characteristics associated with the median crash condition. These simulations indicated that the side damage caused by the IIHS barrier was representative of the extent of damage in crashes that produce a large fraction of the serious injuries in far-side crashes. Occupant simulations of the IIHS barrier crash at 28 kph showed that existing dummies lack biofidelity in upper body motion. The analysis suggested test conditions for studying far-side countermeasures and supported earlier studies that showed the need for an improved dummy to evaluate safety performance in the far-side environment.

OCCUPANTS EXPOSED TO FAR-SIDE CRASHES are those seated on the side of the vehicle opposite the struck side. Two principal types of crashes produce injuries to far-side occupants. The first category includes all planar crashes in which the crash vector directs the occupant toward the far-side of the vehicle. The second category includes rollover crashes in which the tripping acceleration directs the occupant toward the far-side of the vehicle.

Occupants seated on the non-struck side in side impact crashes have been given limited consideration in safety regulations. In order to develop test procedures to address the safety of this population, a better understanding of the injury environment is needed. An objective of this study is to determine the magnitude and characteristics of injuries to occupants exposed to far-side collisions.

A second objective is to determine the characteristics of the collision environment for far-side front seat occupants in side collisions.

The side impact safety standards that exist today involve crash tests with dummies on the struck side of the vehicle. There are standards that mitigate the head impact with the interior for crashes in all directions. It has been suggested that safety improvements to the near-side such as door integrity and interior padding would also benefit occupants in far-side crashes. However, these improvements do not address the performance of the safety belt in far-side crashes.

Mackay [1991] examined 193 crashes with belt restrained far-side occupants during the period 1983-1989. The 193 cases contained 150 AIS 2 injuries and 15 AIS 3+ injuries. Among those with AIS 2+ head injuries, 35% came out of the shoulder belt.

Fildes [1991] examined injuries sustained in side collisions by drivers in Australia. The study was based on the Monash University crashed vehicle file consisting of 227 vehicles and 267 patients from crashes that occurred in Victoria during 1989 and 1990. The file contained 572 variables to describe the crash and the occupant. Fildes found that the injury rate of AIS 2+ head injuries was twice as high in far-side impacts as in near-side impacts. In far-side impacts, head and chest injury rates were about equal. The four most frequent sources of injuries were the instrument panel, the roof, the door panel, and the other occupant. A continuation of the study found that the frequency and rate of head injuries were higher for far-side impacts than for near-side impacts [Fildes, 1994].

A study of US data found that in far-side crashes, seat belt induced chest and abdominal injuries tended to occur in the lower severity crashes while head injuries predominated in the higher severity crashes [Augenstein 2000]. For belted occupants, far-side crashes were responsible for about 30% of all side impact Harm.

A review of the crash test films available at the NHTSA/FHWA Crash Film Library found only one documented test of a far-side crash. In this crash the crash direction was 90 degrees and the delta-V was approximately 15 kph. The dummy slid out of the shoulder belt. Six far-side crashes were subsequently conducted and documented [Digges, 2001]. In this series of tests, the principal direction of force was 60 degrees and the delta-V was 40 kph. The tests evaluated variations in shoulder belt tension and latch plate design. In all configurations, the Hybrid III dummy slid out of the shoulder belt. It was evident from these tests that added countermeasures would be necessary to limit the excursion of the upper body.

The primary focus of this research is to define the injury environment in far-side crashes where there is no subsequent rollover. This crash mode is defined as a far-side planar crash. However, prior research in rollover suggests that countermeasures for far-side planar crashes could benefit rollover crashes, as well.

Parenteau [2004] reported a lateral head excursion of 900 mm for an unbelted Hybrid III dummy in far-side rollover simulations. The maximum head excursion was in direction of the far-side of the vehicle. Digges [2004] reported far-side rollover testing and modeling that showed the Hybrid III dummy slipping out of the shoulder belt in a far-side rollover conducted using the roll test procedure specified by FMVSS 208. The same paper reported on simulations of a typical single vehicle rollover crash and showed the dummy slipping out of a shoulder belt after a very mild lateral acceleration caused by skidding sideways. Countermeasures for preventing injuries in far-side planar crashes include systems to limit the head excursion and head velocity. These safety systems should also be beneficial in rollover crashes that have injuries induced as a consequence of the lateral acceleration that caused the rollover.

Fildes [2002] reported on efforts to develop a dummy for use in far-side impacts. He found that existing dummies lacked the flexibility in the spine to duplicate the kinematics of a baseline cadaver test. He recommended continuing research to define the injury environment and to develop a dummy and injury criteria so that countermeasures could be evaluated.

To continue the far-side research a team from Australia, Europe and the United States has been assembled and a plan of research has been initiated. The overall research project has been described by Fildes [2005]. The principal focus of the international project is to develop a dummy, computer models and injury measurements to be used to evaluate countermeasures for far-side crash protection. This paper describes the progress in defining the injury producing environment for occupants in far-side crashes.

METHODOLOGY AND DATABASES

In this study, National Automotive Sampling System/ Crashworthiness Data System (NASS/CDS) for the years 1993 to 2003 was used to examine the characteristics of the environment that produces injuries in far-side impacts.

The National Highway Traffic Safety Administration (NHTSA) maintains the NASS/CDS database of vehicle crashes in the United States. The NASS/CDS is a stratified sample of light vehicles involved in highway crashes that were reported by the police and involved sufficient damage that one vehicle was towed from the crash scene.

In the NASS/CDS data query, far-side occupants in planar crashes were defined as drivers in vehicles with right side damage or right front passengers in vehicles with left side damage. Drivers in rollovers that were passenger side leading were classified as being in far-side rollovers. The converse was true for passengers.

Each NASS/CDS case contains a weighting factor that is used by the NHTSA to extrapolate the individual cases to the national numbers. The distributions to follow are based on the NASS/CDS weighted events.

In the tables and analysis to follow, serious and fatal injuries are designated as MAIS 3+F. This designation applies to all injuries MAIS 3 and greater and all fatalities, including those with MAIS 1 and MAIS 2 injuries. In the analysis to follow, the populations will be limited to front seat occupants, age 12 and older. It is anticipated that any countermeasures developed would initially apply to this population. Further, it was found that less than 3% of the serious injuries in far-side crashes was sustained by rear seat occupants.

Table 1 shows the annual distribution of MAIS 3+F injuries by belt use, crash direction and crash mode. For planar crashes NASS/CDS years 1993 to 2003 were used. For rollover crashes, NASS/CDS years 1995 to 2003 were used. The data coding changed for rollovers in 1995 to provide added clarity to the event. These later years were used so that consistent data could be used for the rollover analysis. Both data sets were annualized to make comparisons. The injury data was in Table 1 was weighted. The raw number of MAIS 3+F injuries in far-side crashes was 1,932.

Table 1. Annual MAIS 3+F Injuries from NASS/CDS in Near-side and Far-side Crashes by Crash Type, Direction and Belt Use

Crash Type/ Belt Use	Planar	Roll	Total
Far Belted	2,244	3,499	5,743
Far Unbelted	5,022	6,429	11,451
Far Total	7,265	9,929	17,194
Near Belted	7,620	3,652	11,272
Near Unbelted	7,006	5,695	12,700
Near Total	14,625	9,347	23,972
Near and Far Total	21,891	19,275	41,166
% Due to Far Side	33%	52%	42%

THE ROLE OF EJECTION IN FAR-SIDE CRASHES

Tables 2, 3 and 4 examine the role of ejection in far-side crashes. In Table 2, the populations exposed to planar and rollover far-side crashes are disaggregated by ejection status. Table 3 shows the MAIS 3+F injuries sustained by the population in Table 2. Table 4, disaggregates the belted occupant injuries from the overall injuries reported in Table 3.

Table 2. Annual Number of Front Seat Occupants Exposed to Far-Side Crashes by Crash Mode and Ejection Status

Ejection Status	Planar	Roll	Total
No Ejection	311,483	120,759	432,242
Complete Ejection	1,205	5,533	6,738
Partial Ejection	797	3,849	4,646
Ejection-Unk Degree	6	57	62
Unknown	155	739	894
Total	313,645	130,937	444,583

Table 3. Annual Number of MAIS 3+F Injuries among Front Seat Occupants Exposed to Far-Side Crashes by Crash Mode and Ejection Status

EJECTION STATUS	Planar	Roll	Total
No Ejection	5,978	5,803	11,780
Complete Ejection	649	3,051	3,700
Partial Ejection	570	979	1,549
Ejection-Unk Degree	1	30	31
Unknown if Ejected	68	66	133
Total	7,265	9,929	17,194

Table 4. Annual Number of MAIS 3+F Injuries among Belted Front Seat Occupants Exposed to Far-Side Crashes by Crash Mode and Ejection Status

EJECTION STATUS	Planar	Roll	Total
No Ejection	2,209	2,879	5,088
Complete Ejection	9	28	37
Partial Ejection	5	537	542
Ejection-Unk Degree	-	6	6
Unknown if Ejected	20	49	70
Total	2,244	3,499	5,743

Table 5 shows the distribution of MAIS 3+F Harm in far-side crashes for belted and unbelted front seat adult occupants. The MAIS 3+F Harm is calculated by multiplying each MAIS 3+F injury by its average cost as reported by NHTSA [NHTSA 2001a]. The multiplying factors, normalized by the cost of a fatality, are: MAIS 3-.119; MAIS 4-.269; MAIS 5-.848 and MAIS 6-1.0.

The body region coding in Table 5 is based on the NASS Coding [NHTSA 2001b]. The Face was combined under Head and the Neck was combined under Spine. The Trunk was the combined Thorax and Abdomen. The Extremities were the Upper and Lower Extremities.

Table 5. Distribution of MAIS 3+F Harm among Injured Body Regions in Far-side Planar and Rollover Crashes for Belted and Unbelted

Far-Side	Planar Belted	Planar Unbelted	Rollover Belted	Rollover Unbelted
Head	42%	55%	41%	55%
Spine	5%	9%	16%	10%
Trunk	41%	30%	27%	25%
Extremity	12%	7%	15%	10%

THE FAR-SIDE IMPACT ENVIRONMENT FOR SERIOUS AND FATAL INJURIES

The analysis to follow examines the side impact environment for MAIS 3+ injured belted occupants in planar crashes. A detailed analysis of the crash exposure and injury risk for belted occupants in far-side planar crashes has been published earlier [Gabler, 2005]. This analysis was based on NASS/CDS 1993-2002. The analysis found that about 75% of the MAIS 3+ injuries were born by the drivers. About 82% of the MAIS 3+ injuries occurred in passenger cars. The most frequent directions of force for serious injuries in far-side planar crashes were found to be 60 degrees and 90 degrees. The 60 degree crash accounts for 60% of the MAIS 3+ injuries. The 90 degree crash accounts for 24% of the MAIS 3+ injuries.

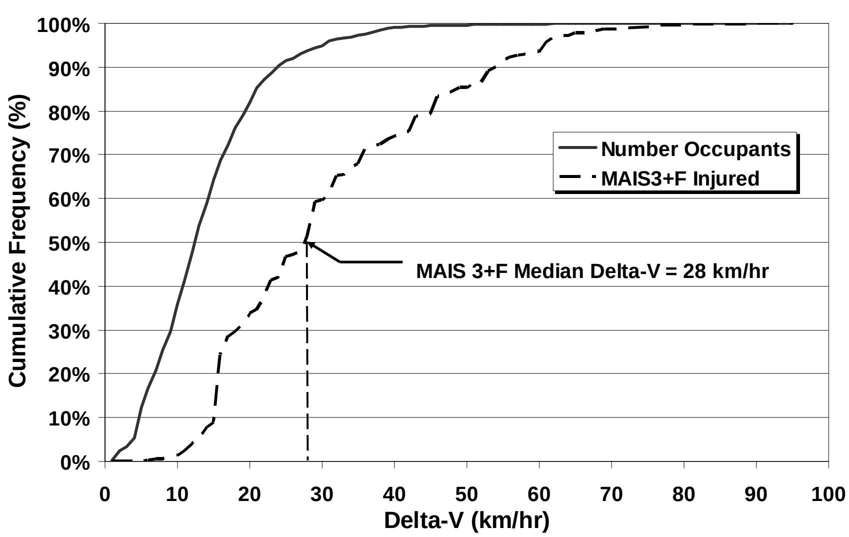

Figure 1. Distribution of Occupants and MAIS 3+F Injuries by Lateral Delta-V (Front Seat Belted Occupants Age 12+)

Impact speed and extent of damage are other important parameters which must be identified in order to design a test procedure to evaluate far-side impact injuries. Figure 1 examines the distribution of far-side MAIS 3+F injuries by lateral delta-V of the struck vehicle.

Another indicator of crash severity is the extent of damage that occurs in the crash. As shown in Figure 2, the SAE collision deformation classification (CDC) scheme divides the struck side of the car into nine zones. The boundary between the fifth and sixth zone corresponds to the centerline of the car. The distribution of exposed belted adult front seat occupants and MAIS 3+F injuries in far-side crashes by extent of damage is plotted in Figure 3.

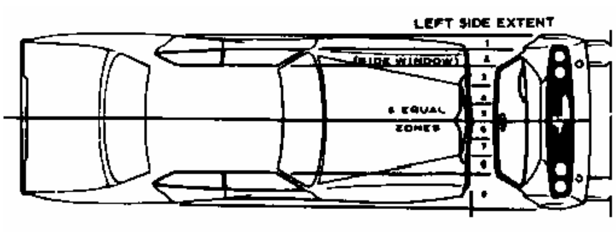

Figure 2. Side Crash Damage Extent

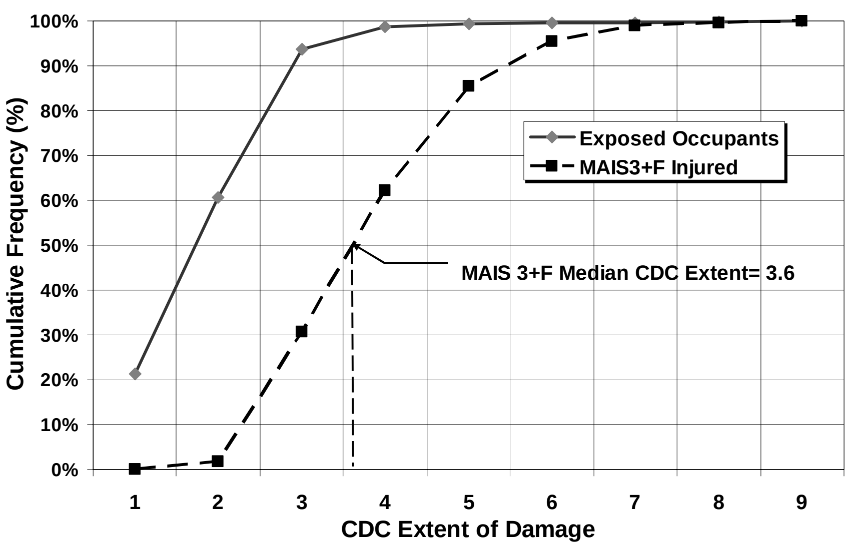

Figure 3. Distribution of Occupants and MAIS 3+F Injuries by Damage Extent (Front Seat Belted Occupants Age 12+)

MODELING THE FAR-SIDE IMPACT ENVIRONMENT

To examine the vehicle intrusion environment produced by injury producing far-side impacts, FEM models were applied. The FEM models were developed by the staff at the National Crash Analysis Center at the George Washington University. A model of the 2004 Ford Taurus was used as the impacted vehicle. This model simulated the complete structure and contained more than one million elements [Guerra, 2004]. The bullet vehicle was a GM C-

1500 pickup. Simulated crashes were conducted at 60 and 90 degrees with a delta-V of 28 kph. In addition, simulations of the NHTSA LNCAP barrier and the IIHS side impact barrier were conducted to provide a comparison with standard test conditions.

The resulting crush profiles taken at the window sill of the Taurus are shown in Figure 4. The maximum deformation for the pickup impact was within 230 cm of the centerline of the Taurus. This produced an extent of damage of approximately 3.6. These results agree reasonably well with the target conditions derived from the NASS data.

The IIHS barrier test produced a deformation shape that was generally similar to the pickup. The NHTSA LNCAP test produced less deformation in the front seat region than the pickup or the IIHS barrier. The damage pattern and crash pulse from the IIHS test condition was selected as a basis for evaluating the occupant motion.

The crash pulse from the IIHS barrier tests was applied to an occupant model to evaluate the expected occupant kinematics. The crash pulse from eleven mid-size cars tested by IIHS were averaged to obtain a representative pulse [Mohan, 2005]. The average delta-V for these eleven tests was 23.6 kph. The resulting average crash pulse was scaled upward to achieve the 28 kph delta-V desired for the far-side crash severity.

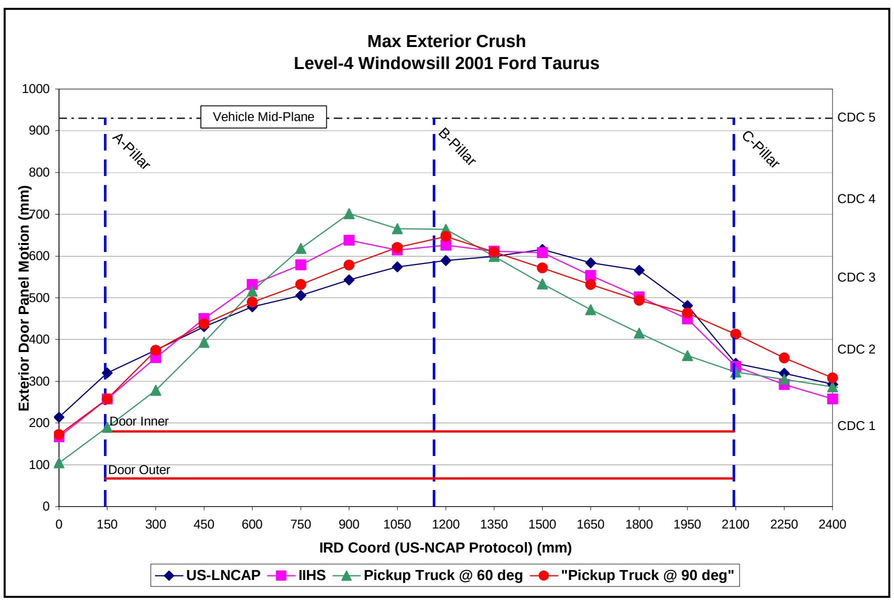

Figure 4. Comparisons of the Taurus Side Deformation at the Window Sill Level after Simulated Impacts by the NHTSA Barrier, the IIHS Barrier, and a C-1500 pickup.

The MADYMO human facet model was initially validated for the far-side crash condition by duplicating the cadaver test reported by Fildes [2002]. The model validation is reported in a separate study [Alonzo, 2005]. The validation results showed good agreement between the head excursion and upper body motion of the human facet model when compared to the cadaver. The model was then used to evaluate dummy kinematics when subjected to a 28 kph delta-V pulse that approximates the one produced by the IIHS barrier. The models of the existing adult dummies far-side and frontal dummies were compared with the human facet model [Alonzo, 2004]. Dummy models compared included the following: Hybrid III, Eurosid, Worldsid, and SID2S.

Figure 5 shows comparison of the lateral kinematics of the human facet model and the Hybrid III dummy model at three time increments. The vertical line designates the extent of intrusion expected for the mean MAIS 3+ injury level, based on NASS/CDS and the FEM model.

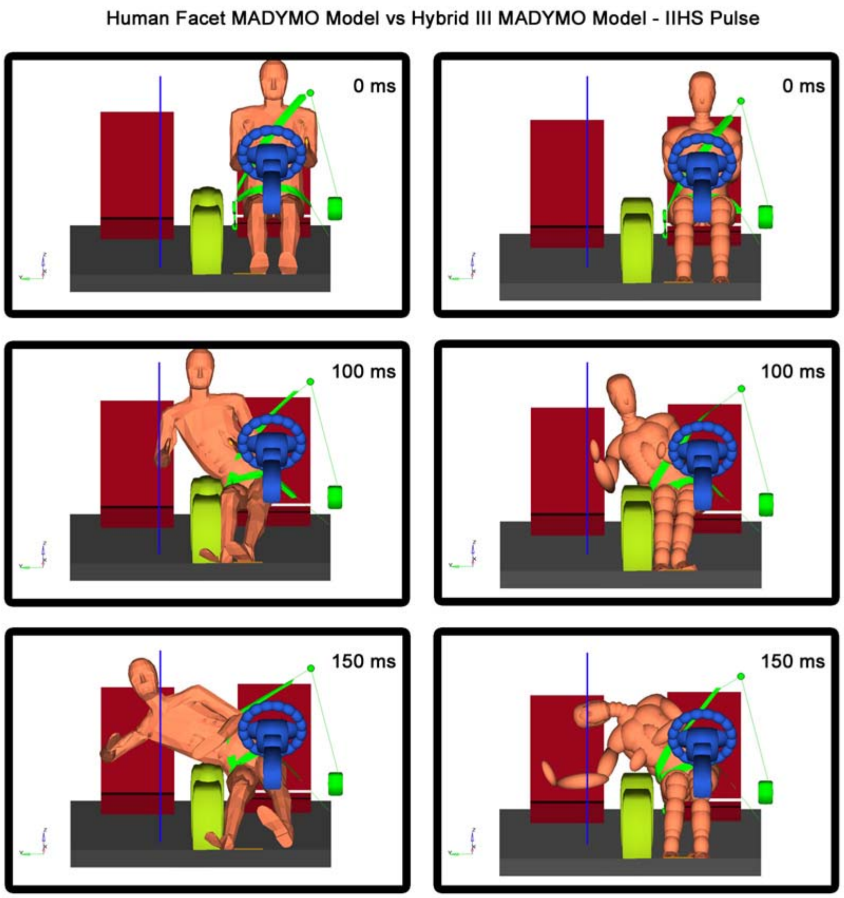

Figure 5. MADYMO Human Facet Model and Hybrid III Model Subjected to Adjusted IIHS Crash Pulse with Intrusion Predicted by FEM Model Shown as Vertical Line

As shown in Figure 5, the shoulder belt in ineffective in preventing the upper body from translating across the vehicle. The Hybrid III dummy model exposed to the same pulse does not have a shoulder contact with the intruding door. The lateral excursion of the shoulder was 500 mm less for the Hybrid III dummy than for the human model. Consequently, the human kinematics were not duplicated by the dummy and the injuries associated with head and shoulder contact would not be accurately predicted if this dummy was used to test far-side countermeasures. All the other dummy models had upper body excursion that was generally similar to the Hybrid III and showed similar deficiencies.

DISCUSSION

A principal objective of this research was to define the crash environment for the protection of adult front seat occupants who are exposed to far-side crashes. The first task was to determine the magnitude of the injured population that could be helped by countermeasures to reduce far-side injuries. Examination of occupant kinematics in crash tests showed a similarity between the initial occupant motion in far-side planar crashes and far-side rollovers. In both crash modes, the occupant slipped out of the shoulder belt after being subjected to relatively low lateral forces. In addition, ejection was found to be a frequent cause of serious injury in far-side rollovers. Countermeasures to reduce upper body excursion or to prevent far-side ejection should be beneficial in rollovers as well as far-side planar crashes. Consequently, rollovers were included in the analysis to define the target population of injured.

The data in Table 1 shows that 42% of the MAIS 3+F injuries to front seat occupants, age 12 and older in side impacts and rollovers occur in far-side crashes. More than half (52%) of the MAIS 3+F injuries in rollover are in far-side rolls. The combined annual planar and roll MAIS 3+F injuries that occur in far-side crashes is 17,194. This compares with 14,625 MAIS 3+F injuries in near-side planar crashes. There is a crash test regulation (FMVSS 214) dealing with near-side planar crashes, but none dealing with far-side planar and rollover crashes.

Tables 2, 3 and 4 provide a breakout the populations in far-side crashes by ejection status. Table 2 shows that ejections are rare events. However, they are a large source of serious injuries in far-side crashes. Table 3 shows that there are 5,249 ejections and partial ejections with MAIS 3+F injuries annually in far-side crashes. About two thirds of these are in rollovers. About 50% of the MAIS 3+F injuries among the ejected and partially ejected are fatal injuries. This compares to 21% fatal injuries foe the MAIS 3+F not-ejected population. Table 4 shows that annually there are 5,088 belted not-ejected front seat occupants who sustain MAIS 3+ injuries in far-side planar and rollover crashes. Of these injured, 43% were in planar crashes.

Table 5 shows the distribution of MAIS 3+F Harm for belted and unbelted occupants by body region. Head Harm is the largest fraction for all categories. Countermeasures to control the upper body motion could be beneficial in reducing the Harm to the head and spine. This result also suggests the desirability of using a test dummy that can adequately reproduce the kinematics of the head and spine in far-side crashes. Test results, data analysis, and occupant modeling has shown that the existing shoulder belt is not effective in preventing lateral head excursion during far-side crashes of injury producing severity.

In examining the crash environment for countermeasure development, the crash severity for belted occupants in planar crashes was established as the target environment. As shown in Figure 1, the median lateral delta-V for all far-side belted occupants was 12 km/hr. The median lateral delta-V for far-side belted occupants with MAIS 3+F injuries was 28 km/hr. As reported earlier, most of the crashes have a longitudinal velocity component as well as a lateral component[Gabler 2005]. The median total delta-V for MAIS 3+F injuries is 2 to 4 kph higher than the median lateral delta-V.

Figure 3 shows that almost no serious injuries were observed for damage extent limited to the first two CDC damage extent zones. However, 60% of the serious injuries were incurred by occupants of a vehicle with a damage extent to zones 3 or 4. This result suggests the need to consider both delta-V and extent of damage in defining the injury producing environment for far-side crashes. The crash condition that produces 50% of the MAIS 3+F injuries to belted front seat adult occupants in far-side planar crashes were found to be a lateral Delta-V of 28 kph and CDC extent of damage equal to 3.6.

Simulations with finite element models showed that the IIHS barrier produced a crash environment that was representative of the damage observed in the NASS for the median of the MAIS 3+F injuries. MADYMO occupant simulations of the median crash environment indicated a need to improve existing dummies for use in testing far-side countermeasures.

CONCLUSIONS

The data shows that about 42% of the MAIS 3+F injuries in side crashes and rollovers occur in far-side crashes. More than half of the MAIS 3+F injuries in rollover are in far-side rolls. The combined planar and roll MAIS 3+ injuries that occur in far-side crashes is 17,194. An additional 9,347 MAIS 3+F injuries in near-side rollovers might receive some benefit from far-side countermeasures, giving a target population of 26,541 MAIS 3+F injuries. This compares with 14,625 MAIS 3+F injuries in near-side planar crashes.

The head is the most frequently injured body region in far-side crashes. For belted occupants in far-side crashes, the head contributes 42% of the MAIS 3+ Harm. For the unbelted, the Harm fraction for head injuries increases to 55%.

The crash condition that produces 50% of the MAIS 3+ injuries for belted adult occupants in planar far-side crashes is as follows: (1) Lateral Delta-V = 28 Kph and (2) Extent of Damage = 3.5. This crash environment was reproduced by a simulated crash of a full size Chevrolet pickup into a Ford Taurus. The damage pattern was found to be generally similar to that produced by the IIHS barrier, but impacted at a higher delta-V than specified in the IIHS test (23.6 kph vs. 27.3 kph)

The IIHS crash pulse, when applied to the MADYMO human model showed that the occupant slips out of the shoulder belt, allowing the upper body to impact the intruding structure. The extent of upper body excursion for the shoulder of the hybrid III dummy was 500 mm less that that of the human model, further demonstrating the need for an improved dummy for testing countermeasures in this far-side environment.

Far-side crashes offer a large opportunity for reducing casualties on motor vehicles. The conditions cited in this paper provide guidance on the test conditions for developing a far-side dummy and for evaluating far-side countermeasures.

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